1. PROJECT 1: HIGH R-VALUE ENCLOSURES

1.1 Executive Summary

High R-value Enclosures Overview

The BSC Industry Team has determined that a 50 percent improvement in the thermal resistance of the exterior wall, roof/ceiling and foundation assemblies must be achieved with a reduction in material and labor costs in order to meet the Building America Program mid term objective to reduce whole-house energy use in new homes by an average of 50 percent by 2015.

The research detailed in this report is divided into four parts:

A. Theoretical Background
B. Prediction: Modeling and Analysis
C. Measurement
D. Implementation

BSC is pursuing research activities in each of these parts simultaneously in a variety of subprojects. The following report discusses theoretical work done to explore the influence of air infitration/exfiltration on thermal performance, and a literature survey of predictions and measurements of below-grade heat loss through slabs and basement walls, as well as recommends appropriate R-values for these components in cold climates.

Under Part B: Prediction: Modeling and Analysis, a thermal performance and durability assessment has been completed on a list of wall assemblies and similar work has been started on foundation, roofs and retrofit assemblies.

In FY09, no physical measurements of high R-value enclosure proposals were completed but BSC did conduct a review of the commissioning and calibration of a precision guarded hot box built to the specifications outlined by John Straube's 2008 paper "Development of a Test Procedure and Apparatus for Measuring High Thermal Performance Walls". It is expected that this equipment will be able to provide specific measurements of large-scale wall assemblies under a range of temperature and air pressure gradients. BSC will observe and report on the results of this work.

In the "Implementation" category, BSC has completed a set of high R-value wall assembly drawings, including details for window and door installation and the treatment of common enclosure penetrations. Similar recommendations for foundations, roofs, and retrofit details have been proposed and are under internal review as further analysis is conducted.

The approach for the remainder of this multi-year plan will be to complete the review of the review of the remaining enclosure details and to continue to explore factors that degrade thermal performance in common construction assemblies and new materials and methods that seem likely to offer additional options for high R-value construction.

Key Results

BSC has produced final recommendations for six high R-value wall assemblies, including details for windows, doors and enclosure penetrations. These recommendations are accompanied by building science notes on thermal performance, durability, cost and constructability, presented as two-page illustrated case studies. In addition, BSC is reviewing and analyzing details for high R-value foundation, roof and retrofit assemblies. These work products are supported by fundamental research into the thermal performance of materials and systems, as well as the known physical heat flow mechanisms (particularly natural and forced convection) and operating conditions that influence thermal performance.

Gate Status

A complete response to each of the Stage Gate Criteria is given in Section 1.3 of this report. Table 1 below provides a brief summary.

Table 1: Stage Gate Status Summary

"Must Meet" Gate Criteria	Status	Summary
Source Energy Savings and Whole Building Benefits	Pass	High R-value enclosures provide significant source energy savings and whole building benefits. BSC's research work aims to establish a set of recommended assemblies for that have approximately 50% greater thermal resistance under installed conditions. The work to date has demonstrated this for Cold Climate walls and has produced promising results for foundation, roof and retrofit assemblies.
Performance-based Code Approval	Pass	All of the high R-value enclosure recommendations detailed under Part D: Implementation meet performance-based safety, health and building code requirements. We consider these enclosure assemblies ready for deployment in prototype research houses. Some BSC prototype houses have employed recommended enclosure assemblies in FY09. Further examination of some code-related issues is expected in FY10.

"Should Meet" Gate Criteria	Status	Summary
Prescriptive-based Code Approval	Partial Pass	Some of the enclosure assemblies have not yet been fully reviewed and do not meet all prescriptive requirements. However, the recommended high R-value wall assemblies detailed under Part D: Implementation have completed internal review and meet prescriptive safety, health and building code requirements for use in new homes, with some restrictions on cladding types and applicable wind zones.
Cost Advantage	Pass	Both the recommended High R-value wall assemblies and the roof, foundation, and retrofit assemblies still under review, provide strong potential for cost benefits relative to current systems when considered as part of the whole building. All of the assemblies developed for this research project have undergone a detailed thermal performance analysis. The assessment is intended to increase our understanding of physical characteristics (such as thermal bridging, susceptibility to convective air looping, resistance to infiltration/exfiltration, etc.) that degrade the performance of the assemblies. We have selected assemblies for our recommended list that will perform as close as possible to the nominal R-value of the insulating materials used – thereby providing the "best value" compared to similar wall assemblies designed and constructed in a manner that results in poorer performance.
Reliability Advantage	Pass	Where possible, BSC has developed high R-value enclosure recommendations that are based on conventional technologies and existing products that offer the level of reliability that would be expected from assemblies with lower thermal performance. Durability assessments have be finished for wall assemblies and are being conducted for roof, foundation and retrofit assemblies, with the goal of providing recommended assemblies that both substantially increase the thermal performance of the enclosure and have less risk of moisture-related problems.
Manufacturer/Supplier/Builder Commitment	Pass	BSC has found that there is generally strong support for this research from both manufacturers and builders. There are some supply issues that have been identified as new enclosure assemblies are developed. Long shank screws suitable for the attachment of thick insulating sheathing, for example, were not found to be available "over-the-counter" at typical residential building supply stores, but were easily sourced in most locations from commercial roofing suppliers. We anticipate that supply issues such as these will be resolved an high R-value enclosures are more widely deployed.

Gaps Analysis	Pass	More detail will be added to our analysis of the major technical and market barriers as research work progresses. However, this research project has already identified a number of important barriers that must be addressed: - Attachment of various cladding materials over insulating sheathing. - Fire-testing of high R-value assemblies with foam sheathing. - Use of combustible foam insulation in exposed applications. - Wind design requirements impact high R-value construction. - Understanding the influence of airflow on heat transfer.

Conclusions

The BSC Industry Team has determined that a 50 percent improvement in the thermal resistance of the exterior wall, roof/ceiling and foundation assemblies must be achieved with a reduction in material and labor costs in order to meet the Building America Program mid term objective to reduce whole-house energy use in new homes by an average of 50 percent by 2015.

In addition, other whole building benefits will be realized with the development of high R-value enclosure technology. In particular, homeowners will benefit from increased thermal comfort (through better control of surface temperatures), homes that are quieter on both the inside and the outside (better sound insulation and airtightness), homes that can be heated or cooled with smaller, more efficient mechanical equipment (reduced enclosure loads and reduction of perimeter cold spots), and buildings that are more durable and healthier than houses typically built today (improved water management, resistance to interstitial condensation, and “vapor open” assemblies).

1.2 Research Plan Overview and Sub-Project Reports

1.2.1. Research Plan

The BSC Industry Team has determined that a 50 percent improvement in the thermal resistance of the exterior wall, roof/ceiling and foundation assemblies must be achieved with a reduction in material and labor costs in order to meet the Building America Program mid term objective to reduce whole-house energy use in new homes by an average of 50 percent by 2015.

Previous work has identified a combination of advanced wood framing, insulating sheathing, spray applied cavity insulation and "smart" membranes as the best approach to meet this mid term target.

The practical limitation in wall assemblies is the wood frame thickness of 5.5 inches (the width of a 2x6). Insulating sheathing thickness is currently limited by constructability issues to 2 inches. Thus, at present, the most commercially viable high thermal resistance wall assembly is a 2x6 wood framed wall with up to 2 inches of insulating sheathing.

The practical limitation in roof assemblies is typically the thickness of the top chord of wood trusses (also 5.5 inches – a top chord of 2x6 which is "pushing" cost and performance limits and requires "re-engineering" as the truss assembly is no longer optimized for strength, but optimized for both strength and "insulatability" – the ease and ability to insulate truss members.

In hot humid climates in flood zones, elevated crawlspaces are the most practical construction approach. Crawlspace construction, particularly vented crawlspace construction provides significant challenges with respect to moisture control, insect and vermin control and fire control. Use of insulating sheathing and spray foams are desirable in these assemblies, but the moisture physics and performance of these approaches has yet to be determined.

In order to improve the thermal performance of these assemblies the cavity insulation values have to be improved/increased. The most commercially viable technology to improve the performance of cavity insulation is the use of spray-applied insulations: spray-applied foam insulation, spray-applied cellulose insulation and spray-applied fiberglass insulation.

Spray insulations have numerous advantages that make it attractive to many custom builders.

They can fill any shape cavity without cutting; some systems (i.e. spray foams) provide air sealing as part of the insulation process; and they can provide high R-value per inch. Higher costs for spray insulations typically limit their use in production and affordable housing. Eliminating exterior structural sheathing can offset some of the extra cost of spray insulations.

As thermal resistance increases, heat flow across the assembly decreases. This is a desirable result from the perspective of energy efficiency. However, it is a liability from the perspective of durability. As the thermal resistance of building enclosures increases the ability of the assemblies to dry decreases. This has lead to an unfortunate linkage between mold, decay and high levels of thermal resistance.

It has been clear that if drying potentials decrease due to increases in thermal resistance, some other means of increasing drying potentials must be provided. Additionally, decreasing wetting potentials must also be provided.

The more vapor open (permeable) the interior and exterior linings of building enclosures, the greater the drying potential of the building enclosures. Installing interior vapor barriers that prevent inward drying is a serious problem that was identified by the work done on moisture control and high-R assemblies.

Additionally, insulating sheathings were identified as one of the most cost effective means of significantly increasing the thermal resistance of building enclosures. However, most insulating sheathings have low vapor permeance and inhibit outward drying. Hence, the ability to dry inwards is a critical requirement for the use of insulating sheathing. Developing vapor open insulating sheathings and vapor open/vapor closed "smart interior linings" are necessary.

Combining all of these differing materials in an integrated manner that is commercially viable – i.e. constructible and affordable with standard trades is the focus of this research project.

The research plan is divided into four phases:

E. Theoretical Background

F. Prediction: Modeling and Analysis

G. Measurement

H. Implementation

Sub-projects have been planned in each of the four phases, some of which run throughout this multi-year plan. The following sections of this report provide a summary of past work complete in each phase, a full report on work completed or in progress during the 2009 calendar year, and planned future research.

Research Partners

Industry Partners participating in this project are:

- Dow Chemical (Material Supplier/Manufacturer)
- Honeywell (Material Supplier/Manufacturer)
- DuPont (Material Supplier/Manufacturer)
- Huber (Material Supplier/Manufacturer)
- US GreenFiber (Material Supplier/Manufacturer)
- Icynene® (Material Supplier/Manufacturer)
- Cosella Dorken (Material Supplier/Manufacturer)
- Georgia Pacific (Material Supplier/Manufacturer)
- Johns Manville (Material Supplier/Manufacturer)
- Owens Corning (Material Supplier/Manufacturer)
- Tamlyn (Material Supplier/Manufacturer)
- Zeta Homes – San Francisco, CA (Builder Partner)
- David Weekley Homes, TX, SC and NC (Builder Partner)

- Synergy Construction, MA (Builder Partner)
- GreenCraft Homes, TX (Builder Partner)
- Nelson Homes, CT (Builder Partner)
- Ark Contractors, CT (Builder Partner)
- Moser Builders, PA (Builder Partner)
- Colter Construction, DE (Builder Partner)
- TKTMJ Construction - "Project Home Again", LA (Builder Partner)

1.2.2. A. Theoretical Background

Phase 'A' projects establish the theoretical background for sub-projects in subsequent phases. In past years, several research papers have been completed. Here is a summary of the past work done under this phase of the research plan:

1. Straube, John F. "Review of the R-value as a Metric for High Thermal Performance Building Enclosures" Completed December 2007.

   Abstract: The report summarizes the extensive existing research of heat flow through walls and highlighted physical mechanisms that are not usually included in codes and designer specifications. From this review, a need was identified for measuring and rating heat flow across a wall under realistic temperature ranges, both cold exterior and hot exterior conditions. The impact of thermal bridging, and convective loops, although well understood, has not been sufficiently well quantified to allow for prediction. Air exfiltration through walls can have a major impact on heat flow, and was identified as a major unquantified heat flow mechanism in current testing.

2. Straube, John F. "Development of a Test Procedure and Apparatus for Measuring High Thermal Performance Walls" Completed December 2008.

   Abstract: The goal of this work is the development of a new metric for the thermal performance of building enclosures that better accounts for the known physical heat flow mechanisms (particularly natural and forced convection) and operating conditions. The metric will employ equipment and techniques based on existing ASTM procedures as much as practical. The new metric is intended to represent actual thermal performance of building enclosure systems in service and will enable marketing staff to make legitimate claims about systems; designers to make informed decisions and accurate load calculations; and builders and contractors to reduce callbacks due to moisture and comfort issues associated with poor thermal performance.

1.2.2.1. Influence of Air Flow on Heat Loss in High R-value Enclosures

This report investigates the role of airflow in heat transfer through high R-value building enclosures, particularly the effects of airflow that are not captured by blower test data converted to heat loss. John Straube discusses air tightness standards for assemblies and enclosures and examines airflow's contribution as a percentage of total thermal performance. Studies involving field and laboratory measurements are then reviewed and it is noted that although many air flow-related influences have been studied, few have been documented in sufficient detail to reliably quantify the affect on thermal performance.

Other flow paths are considered and it is observed that as the R-value of an assembly increases (to R-20 or R-40) even small flows can begin to comprise a significant proportion of total heat loss. Natural convection inside the wall assembly and around cavity insulation is examined as a significant contributor to heat loss in high R-value assemblies. Wind washing of air permeable insulation is also considered and explained.

The following conclusions and recommendations are made:

> *Implications for High R-value Assemblies*
>
> The influence of airflow within and through building enclosures on heat transfer is significant, much more significant than for standard enclosures. For many high R-value walls, basements, and roofs the proportion of heat flow due to airflow effects increases as R-value increases. For wall and roof assemblies with R-values in the order of 30 to 60, airflow affects can dominate performance, whereas for traditional walls (R-10 to R-15 true r-value) the impacts were small enough they could be ignored.
>
> Higher airtightness standards for both whole buildings and assemblies need to be imposed for high R-value enclosures. Airtightness targets that approach 1.0 l/s/m2@75 Pa of enclosure area for total building airtightness should be sought for homes that use very high R-value walls and roofs (e.g. R-40/R-60).
>
> The interaction of airflow and heat transfer is poorly understood. There appears to be a real impact, and for accurate assessments heat flow due to conduction and heat flow due to through-enclosure convection cannot simply be added. However, the precise interaction has not been experimentally quantified and is likely in the order of more than 10% impact for high R enclosures.
>
> Airflow within enclosures influence heat flow in all walls. However, small defects and a limited amount of wind washing can be tolerated in enclosures with R-values of 10 to 20 without serious reductions in performance. For high R-value enclosures, even small, perhaps even unavoidable defects, can begin to have a more significant influence on heat flow for high R-value enclosures. Hence, techniques to reduce the impact of these mechanisms need to be implemented. For example, the use of wind washing barriers, multiple layers of insulation and insulation with higher resistance to airflow may be required.

Final report (see appendix):

- Straube, John F. “Influence of Air Flow on Heat Loss in High R-value Enclosures” December 2009.

1.2.2.2. Heat Losses Below Grade in Low Energy Buildings

This report documents a literature survey of predictions and measurements of below-grade heat loss through slabs and basement walls, as well as recommends appropriate R-values for these components in cold climates (DOE Climate Zones 5 and higher). Methods of prediction of heat loss through slabs are examined and found to be notoriously inaccurate. Field data from several studies is then reviewed and used to develop a better understanding of below slab soil temperatures. With assumptions based on the reviewed literature, straightforward calculations indicate that, among other recommendations, a sub-slab insulation of level at least R5 should be strongly recommended for all cold climate zones.

Final report (see appendix):

- Straube, John F. “Heat Losses Below Grade in Low Energy Buildings” December 2009.

1.2.2.3. Planned Future Work

The following work is planned for FY10:

- "Review of literature on air flow interacting with conductive flow both energy and moisture"

  As the heat flow by conduction drops to very small values, the relative impact of small amounts of air leakage and wind washing on some enclosure systems grows. In the high R wall systems developed to date, the heat flow carried by air leakage is approximately equal in magnitude to the heat flow by conduction. There has been an assumption that airflow and conduction can be simply added to assess the impact. However, this has not been conclusively demonstrated experimentally, and in fact, there is research to indicate a more complicated relationship, especially when moisture effects are considered.

  As a precursor to developing and conducting combined air flow and heat flow testing of high R-value walls, a literature review of the research will be prepared. A test procedure, based on ASTM standards where possible, will be proposed.

- "Limits to High R-value Walls"

  In general, the analysis of most housing designs has shown that the lowest cost means of reducing the energy use was better insulation, windows and airtightness, in short, a high performance building enclosure. Moving to high R-value walls was almost always the lowest cost measure to reduce energy consumption. As the cost of generating energy via photovoltaic's continues to drop, there will come a point at which increasing the performance of the enclosure will be more expensive than generating an equivalent amount of energy by PV. This point is being reached by some of the best of the high R-value walls, roofs, and basements and in some of the milder and sunnier climate zones of the United States. A research project will examine the limit to High R walls in the context of different PV price scenarios, and different types of enclosures and climate zones.

- "High Thermal Resistance Enclosures for Residential Buildings in All Climate Zones"

  On behalf of the BA program, BSC will lead the development of a white paper on "High R" enclosures for high performance residential buildings. This paper will review and synthesize published research conducted in this area by the Building America Program research teams and the National Laboratories supporting the program. Key gaps that currently limit the broad delivery of high thermal resistance enclosures, including below-grade elements, walls, roofs and windows, will be discussed in the context of a systems approach to high performance building design. To prepare the final draft of this paper, BSC will review the findings of projects conducted by BA teams and solicit review comments on the white paper based on the anticipated results of unpublished research. The draft paper will be circulated to designated reviewers on each team for comments. As a tentative plan to be confirmed in 2010, BSC will host a meeting in August of that year to collect further input from industry experts outside the program.

1.2.3. B. Prediction: Modeling and Analysis

Modeling and analysis was continued from 2008 with additions and improvements to the High R-value Wall Report and the development of two page summaries for all High R-value walls analyzed. A new study was conducted on foundations and basements in cold climates to further the advancement of High R-value building enclosures. Future work includes a study on roofs and attics in cold climate construction. A full description of the work conducted is given below.

1.2.3.1. Updates to 2008 High R-value Wall Case Studies Report

The 2008 High R-value Wall report was reviewed both internally and externally in 2009 to address feedback from different groups including contractors, builders and other building scientists. There were four walls added from the Supplemental Case Studies (explained below) but no other major changes to the report. The modified High R-value Walls report is included as an appendix to this report.

Two page "case study" summaries of the original eight proposed walls from the High R-value Walls report were developed as quick reference guides that can be used and understood by homeowners, builders and consultants with references to further explanation and information on the internet or in other reports. The case studies were posted on BSC's website.[1] The two page summaries have been included in the appendix for all of the High R-value wall systems.

1.2.3.2. High R-value Wall Supplemental Case Studies

Following the completion of the High R-value report, it was decided based on feedback, that four additional walls should be added to the analysis. These were:

- Case 9: Hybrid system with closed cell foam spray foam and fibrous insulation
- Case 10: Double Stud wall with 2" of closed cells spray foam and fibrous insulation
- Case 11: Offset Frame Wall with exterior closed cell spray foam and fibrous insulation in the wall cavity
- Case 12: Exterior Insulation Finish Systems (EIFS)

The same approach was used for the four new walls analyzing the performance based on thermal control, durability, buildability, cost and material use.

It was found that the hybrid (flash and fill) system performed better than standard construction with less potential for air leakage condensation but the thermal bridging through the framing decreased the thermal benefits of adding closed cell spray foam.

The double stud wall with 2" of closed cell spray foam had less risk of air leakage condensation than a traditional double stud wall, but there was still significant risk in cold climates if the interior air barrier system is not perfectly detailed. The air leakage condensation risk could be minimized by:

- Perfect interior air barrier
- Increasing the amount of closed cell spray foam to raise the temperature of the condensation plane
- Use a more vapor permeable sheathing material to allow the wall to dry to the exterior.

These ideas resulted in the development of a double stud wall that is constructed with an interior structural wall of 2x6 advanced framing, sheathed in structural fiberboard, and an exterior 2x3 framed wall also sheathed in fiberboard. This wall has several improvements over traditional double stud walls:

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[1] http://www.buildingscience.com/documents/information-sheets/high-r-value-wall-assemblies/

- An extra level of air tightness with taped or sealed structural fiberboard in the center of the insulation
- The wall has a lower permeance exterior sheathing able to dry to the exterior
- Electrical and plumbing can be run inside of the structural fiberboard so fewer penetrations are required
- The extra insulation is placed on the exterior of the structural wall instead of the interior resulting in increased interior space.

CAD design drawings were done for this wall system, but thermal and hygrothermal simulations are required for all cold climates to determine any limitations of this wall construction technique.

The offset frame wall in the supplemental report is an excellent wall system that can be used for new construction or retrofits that uses closed cell spray foam on the exterior of the sheathing as a drainage plane, as well as air and vapor barrier. This is a very durable, energy efficient wall system, and could be used in remote locations very easily since spray foam is shipped as liquids.

Exterior Insulation Finish Systems (EIFS) have had a tarnished reputation based on poor construction installation in the past but is a very durable wall system provided it is drained properly. It performs very similarly to advanced framing with insulated sheathing, but provides the look of a stucco finish, which is often desirable from an architectural perspective.

All four of these supplemental case studies were added directly to the High R-value Wall report, shown in the appendix. Two page summaries for quick reference were also designed for these walls and are included in the appendix.

1.2.3.3. High R-value Foundation Case Studies

Following the completion of the High R-value Wall Report, basements and foundations in cold climates were analyzed for energy and moisture related performance.

Fourteen Basement insulation strategies were analyzed representing historical construction practices, current practices, and recommended best practices listed here;

1. Uninisulated Foundation wall and slab
2. R10 continuous roll batt with poly
3. 2x4 wood framed wall with R13 fiberglass batts
4. 1” XPS against foundation, 2x4 wood framed wall with R13 fiberglass batts
5. 2” XPS against foundation, 2” foil faced polyisocyanurate (PIC)
6. 3.5” 2.0 pcf closed cell spray foam
7. 6” 0.5 pcf open cell spray foam
8. 2” XPS against foundation, 2x4 wood framed wall with R13 fiberglass batts
9. 2” PIC against foundation, 2x4 wood framed wall with R13 fiberglass batts
10. 6” 0.5 pcf open cell spray foam, 2x4 wood framed wall offset from foundation 2”
11. 4” XPS on the exterior of the foundation wall
12. 4” XPS in the center of the foundation wall
13. ICF – 2” XPS on the interior and exterior of concrete foundation wall
14. 2” XPS against foundation, 2x6 wood framed wall with R19 fiberglass batt

Similar to the High R-value Wall report these 14 wall systems were analyzed and compared based on thermal control, durability, buildability, cost and material use.

Thermal analysis on all proposed wall systems was conducted with Basecalc developed from the Mitalas method from the NRC. Basecalc has a simple menu driven user interface but calculates energy lost based on complicated finite element analysis.

A sensitivity analysis was conducted with Basecalc to determine the differences in heating energy by changing the amounts of foundation wall insulation, underslab insulation, and thermal break insulation around the perimeter between the slab and the foundation wall, which showed that compared to an uninsulated wall, even a small amount of insulation created large energy savings. A practical analysis was conducted using a Building America prototype house in Westford MA, designed by Building Science Corporation.

Hygrothermal analysis was conducted with WUFI, similar to High R-value Wall report. The moisture regime for a foundation wall is much more complicated than an above grade wall since both the temperature changes over the entire height, and the relative humidity is different for the above grade and below grade portions of the wall.

Wetting in the basement can come from bulk water movement, vapor diffusion, air leakage condensation and capillary wicking. Only vapor diffusion and air leakage condensation are simulated in this report, although capillary wicking is considered qualitatively.

All of the walls are given a rating between 1 to 5, one being poor, and 5 being excellent in five categories including

1. Thermal control
2. Durability (wetting/drying)
3. Buildability
4. Cost
5. Material Use

The scores for each of the criteria are added for the total score for each proposed wall system. The advantage of this comparison system is that it can be done qualitatively, without knowing exact values for the criteria. For example, the cost of fiberglass batt will always be less expensive that open cell foam which will be less expensive than closed cell regardless of geographic area or the specific prices of each insulation. Also, it is easy to judge that a 2x6 wall will use more material than a 2x4 wall with the same stud spacing, but assigning a quantitative value for material use is difficult.

	Thermal Control	Durability (wetting/drying)	Buildability	Cost	Material Use	Total
Criteria Weighting	1	1	1	1	1	
Case 1: uninsulated	-	-	-	-	-	
Case 2: R10 continuous with poly (roll batt)	1	1	5	5	5	**17**
Case 3: R13 batt, 2x4 wall with poly	1	1	4	4	5	**15**
Case 4: 1" XPS, 2x4 framed wall with fgb	2	3	3	3	4	**15**
Case 5: 2" XPS, 2" PIC	4	4	3	3	3	**17**
Case 6: 3.5" 2.0pcf cc spuf	4	5	5	3	3	**20**
Case 7: 6" 0.5pcf oc spuf	4	4	5	4	4	**21**
Case 8: 2" XPS, 2x4 framing with fgb	3	3	3	3	4	**16**
Case 9: 2" PIC, 2x4 framing with cellulose	3	3	3	3	4	**16**
Case10: 2.5" 0.5 oc spuf, 2x4 framing with same foam	4	4	4	3	3	**18**
Case 11: 4" XPS on the exterior	4	4	2	2	3	**15**
Case 12: 4" XPS in the centre of foundation wall	4	4	3	1	3	**15**
Case 13: ICF - 2" XPS interior and exterior	4	5	4	1	3	**17**
Case 14: 2" XPS, 2x6 framing with fgb	5	4	3	2	3	**17**

Figure 1 : Analysis matrix for High R-value Basement Proposed Wall Systems

In the current analysis matrix, all of the comparison criteria are weighted evenly. Another advantage of this analysis method is that the criteria can be weighted to reflect the concerns of the homeowner or designer. The five criteria can be ranked in order of importance from 1 to 5 as a multiplier for the scores in that criteria and then summed for a total score out of 75.

A final draft of this analysis report is included in the appendix. The next step for this analysis report is to undergo a rigorous review and feedback period, first internal, and then for external review before it is published in its final form.

1.2.3.4. Planned Future Work

The following work is planned for FY10:

- High R-value Roof Case Studies

  Another proposed task is the analysis of different roof and attic insulation systems similar to the wall analysis report described above. This analysis will be conducted in Minneapolis climate, similar to the wall analysis, and conclusions may also be made for other climate zones. Some comments will be made about unvented and vented attics in general as well as some of the reasons that they are chosen, as well as air leakage problems. Cathedral ceilings will also be considered in the analysis. Possible construction techniques for analysis may include:

  - Standard vented attic construction (fiberglass/cellulose)
  - Attic plus Spray foam against ceiling
  - Unvented sloped roof with spray foam
  - Unvented Densepack cellulose
  - Spray foam and spray applied fiber (fiberglass densepack cellulose)
  - Exterior foam board insulation (polyiso, XPS, EPS)
  - Hybrid - foam board on exterior and fibrous fill between rafter
  - Cathedral ceiling with spray foam

- Low slope roofs

- High R-value Enclosures for Retrofit Applications

  In FY10, BSC will expand our high R-value enclosure work to develop recommendations for existing buildings. The work products will be of a similar form to research reports and case studies for new construction. The work will rely on analysis work already completed as part of the High R-value Enclosure project. It is expected that some aspects of this research work will overlap with existing building prototypes and communities, including low-rise multi-family buildings.

- High R-value Wall Research Integration

  NREL has begun to use 3-D heat flow models of high R-value wall systems. BSC will collaborate with NREL by comparing the modeling assumptions and wall designs we have used to those of NREL. For similar agreed up walls, BSC and NREL will compare the results of pseudo-3D 2D Therm models and full 3D models. Results from full-scale testing of large high-R wall systems will be used to calibrate both BSC and NREL models. Any results from ORNL will also be included to begin the process of developing a large database of well-documented test and simulation results for high R-value walls.

1.2.4. C. Measurement

In FY07 BSC completed a report entitled "Review of the R-value as a Metric for High Thermal Performance Building Enclosures" that summarized the extensive existing research of heat flow through walls and highlighted physical mechanisms that are not usually included in codes and designer specifications. The impact of thermal bridging, and convective loops, although well understood, has not been sufficiently well quantified to allow for prediction. Air infiltration and exfiltration through the wall assembly were identified as a major unquantified heat flow mechanisms in current approach to building enclosure thermal testing. From this review, a need was identified for measuring and rating heat flow across a wall under realistic temperature ranges (both cold & hot exterior conditions) and under the influence of air movement (both in and through the building enclosure).

This was followed by a FY08 report entitled "Development of a Test Procedure and Apparatus for Measuring High Thermal Performance Walls" that outlined a new metric for the thermal performance of building enclosures. New equipment and techniques, based on existing ASTM standards, were proposed to better account for the known physical heat flow mechanisms (particularly natural and forced convection) and operating conditions.

BSC assembled a consortium of 6 building product manufacturers to participate in the privately funded development of the new thermal performance metric and the associated test method. These partners include:

- NAIMA (North America Insulation Manufacturer's Association) with technical representatives from Certainteed and Johns Manville
- Huntsman Polyurethanes
- Honeywell
- Icynene
- Dow Chemical
- US Greenfiber

BSC designed and built a novel hot box apparatus to permit the highly accurate measurement of heat flow under realistic operating conditions. This following section summarizes the apparatus commissioning and calibration that was undertaken by the research partners in 2009.

1.2.4.1. Laboratory Studies – Hot Box Calibration and Commissioning Report

The R-value has long been the industry standard for assessing the thermal performance of insulation materials. Building designers directly apply R-value to the thermal performance of building enclosures. This practice has recently come into question as energy-cost and security issues have generated demand for building enclosures that exhibit higher levels of thermal performance. The market has responded with new insulation products and novel building enclosure systems such as: various types of spray foam and spray-applied fibrous insulations, exterior insulated sheathing, Structural Insulated Panel Systems (SIPS), Insulated Concrete Forms (ICF), and Radiant Barrier Systems (RBS), etc.

Because contemporary insulation materials and systems control heat flow in different, new and non-traditional ways, they are more or less sensitive to thermal bridging, workmanship (i.e. quality of installation), internal convection and through convection (i.e. infiltration, exfiltration, windwashing & re-entrant looping). The impact of such 'anomalies' and 'defects' is not captured in the R-value metric. Furthermore, the discrepancy between the real heat flow and that predicted by combining R-values increases the absolute temperature, the temperature difference and the net resistance to heat flow increase. These realizations have generated an increasing amount of interest in the development of a new metric for the thermal performance of building enclosures.

The goal of this report is to document the development of a new metric for the thermal performance of building enclosures that better accounts for the known physical heat flow mechanisms (particularly natural and forced convection) and operating conditions. The metric employs equipment and techniques based on existing ASTM procedures as much as practical, making use of a special test apparatus (pictured below).

Figure 2: Precision Calibrated Hot Box

In general the test apparatus has been designed & constructed in accordance with ASTM C1363, "Standard Test Method for Thermal Performance of Building Materials and Envelope Assemblies by Means of a Hot Box Apparatus." A number of modifications were made to meet the specific objectives of the research.

The key improvements over other (i.e. conventional) hot box testing is the ability to test higher R-value enclosure assemblies (which have lower heat fluxes), a procedure and apparatus that exposes enclosure wall samples to realistic temperature differences while maintaining the interior temperature at normal room temperatures, and the ability to measure the impact of imposed air flow.

The TM hot box uses some novel systems and features to maximize its operating modes while reducing as many errors and as much noise as possible. Early calibration and testing work demonstrate that the apparatus meets the objectives laid out in BSC's FY08 report entitled "Development of a Test Procedure and Apparatus for Measuring High Thermal Performance Walls".

Final report (see appendix):

- Schumacher, Christopher. "Building America High-R Enclosures Research Project: Construction, Commissioning & Calibration of a Novel Hot Box Apparatus for High-R Enclosure Performance Measurement" December 2009.

1.2.4.2. Planned Future Work

The following work is planned for FY10:

- "Measure impact of flaws in insulation installation" (to support the HERS installation rating of insulation)

  HERS ratings currently have a multi-stage approach to inspecting and de-rating fiberglass batt insulation. There is little research indicating what the energy-consumption consequences of different flaws are. There is even less information available to support quantification of the impact of insulation flaws for other systems, such as foam sheathing, spray applied cellulose, densepack cellulose, spray foam, etc. We would propose to conduct testing in a precision hot box to provide this information.

- "Drying of High R-value Walls"

  The reduction of heat flow that is the goal of high R-value walls carries with it the natural consequence that less heat is available to dry materials with walls should they become wet during construction or via leaks during the service life.

  One of the potential challenges is the drying of retained water that is retained on drainage planes behind insulating foam sheathing. The location of a drainage plane / air barrier behind the foam sheathing has the advantage that it is protected from extremes of temperature, and hence is more likely to perform over the long term. Another benefit this that the housewrap is supported on both sides in this application, increasing its durability (by reducing wind loads) and increasing its airtightness. One disadvantage is that some drainwater may be retained between the foam sheathing and the wood framing. The rate at which this water will dry in a high R-value wall is uncertain. Testing of drainage, retention and drying would help answer this question and define the risks.

1.2.5. D. Implementation

To assist builders and designers with implementation of high R-value assemblies, detailed design drawings were drawn in CAD format for recommended high R-value enclosure strategies for walls, foundations, and roofs. BSC has also undertaken a multi-year project to implement advanced framing at a production scale. This project involves most BSC research prototype houses and communities in a number of climate zones.

1.2.5.1. High R-value Enclosure Details

To accompany the analysis reports for high R-value walls, foundations and the proposed analysis report on roofs and attics, detailed design drawings were drawn to assist builders and designers with properly implementing high R-value enclosure strategies. These detailed drawings clearly specify all of the required components and details for successful implementation.

The table below shows the High R-value Enclosure Detail Packages and their status. All of the design details for implementation are included in the appendix.

High R-value Topic	**Status**
High R-value Walls	Recommended, Complete
High R-value Foundations/Crawlspaces/ Slab-on-grade	Proposed – Under review pending analysis
High R-value Roofs/Attics	Proposed – Under review pending analysis
High R-value retrofit penetration details	Recommended, Complete

Future work for 2010 includes revising all proposed drawing details and determining the recommended design drawings based on thermal, and hygrothermal simulations and experience in the field. Also in the future, we will continue to add to our library of recommended retrofit details based on projects we work on the specific requirements for those retrofit projects. We expect significantly more retrofit-based research projects in 2010.

The following detail drawings have been developed. Final and draft versions have been included as an appendix to this report.

Table of Recommended High-R Wall Types – Cold Climate

Wall Type	**Exterior finish**	**Insulation, Nominal R-Value**	**Air Barrier**
Wall-02-1: 2X6 with 1.5” exterior insulating sheathing	Vented lap siding	5.5” cellulose in cavity + 1.5” foil-faced polyisocyanurate rigid insulation, **R-29**	Airtight Drywall Approach
Wall-02-2: 2X6 with 2” exterior insulating sheathing	Vinyl or aluminum siding	5.5” cellulose in cavity + 2” XPS rigid insulation, **R-29**	Airtight Drywall Approach
Wall-02-3: 2X6 with 4” exterior insulating sheathing	Vented lap siding	5.5” cellulose in cavity + 4” foil-faced polyisocyanurate rigid insulation, **R-45**	Airtight Drywall Approach
Wall-02-4: 2X6 with 4” exterior insulating sheathing	Wood shingles over ½” plywood nail base	5.5” cellulose in cavity + 4” foil-faced polyisocyanurate rigid insulation, **R-45**	Airtight Drywall Approach

Wall Type	Exterior finish	Insulation, Nominal R-Value	Air Barrier
Wall-04-1: double stud wall with interior load bearing wall	Vented siding	10.5” cellulose in cavity, **R-37**	Fiberboard sheathing to exterior side of interior stud wall
Wall-11: 11” wide 2X6 stud wall with 2x3 exterior offset framing	Vented lap siding	5’5” cellulose in cavity + 4.5” closed cell spray foam on exterior, **R-46**	Exterior closed cell spray foam

Table of Foundation Types

Type	Foundation Wall Type	Finished or Unfinished	Location of Insulation	Type of Insulation	Climate
#1	8” Concrete	Unfinished	Interior	2” XPS slotted insulation + 2” foil-faced polyisocyanurate	Cold Climates
#2	8” Concrete	Unfinished	Interior	3.5” closed cell SPF (high density 2.0 pcf)	Cold Climates
#3	8” Concrete	Unfinished	Interior	6” open cell SPF (low density 0.5 pcf)	Cold Climate Zone 5
#3A	8” Concrete	Unfinished	Interior	6” open cell SPF (low density 0.5 pcf)	Cold Climate Zone 6
#3B	8” Concrete	Unfinished	Interior	6” open cell SPF (low density 0.5 pcf)	Cold Climate Zone 7
#4	8” Concrete with interior insulated 2x4 wall offset 2” from fdn wall	Finished	Interior	2” XPS + 3.5 unfaced fiberglass batts in cavity	Cold Climates
#5	8” Concrete with interior insulated 2x4 wall offset 2” from fdn wall	Finished	Interior	2” foil-faced polyisocyanurate + 3.5” cellulose in cavity	Cold Climates
#6	8” Concrete with interior insulated 2x4 wall offset 2.5” from fdn wall	Finished	Interior	6” open cell SPF (low density 0.5 pcf) in and behind cavity	Cold Climate Zone 5
#7	8” Concrete	Unfinished	Exterior	4” XPS	Cold Climates
#8	ThermoMass (2 - 4” concrete layers)	Unfinished	Middle of wall	4” XPS	Cold Climates
#9	ICF (8” concrete core)	Unfinished	Exterior and Interior	4” XPS	Cold Climates

Table of Crawlspace Types

Type	Vented or Unvented	Foundation Wall	Crawl Space Floor	Insulation	Climate
#1	Unvented	Brick veneer + 14” CMU	Polyethylene ground cover	4” XPS insulation internal to walls	Cold Climates
#2	Unvented	8” CMU foundation	2” concrete slab	4” rigid insulation internal to	Cold

				walls and 4” rigid insulation under slab	Climates
#3	Unvented	8” concrete foundation	Polyethylene ground cover	3.5” high density interior spray foam with spray on thermal barrier	Cold Climates
#4	Vented	Piers	No ground cover	6 1/3” high density spray foam in floor joists	Cold Climates

Table of Slab-on-Grade Types

Type	Slab Type	Insulation	Climate
SG Type #1A	Monolithic slab (slab with integrated grade beam) with brick veneer shelf	4” XPS under slab and on interior and exterior sides of integrated grade beam; 2” XPS below grade beam; 2” XPS horizontal frost protection	Cold Climates
SG Type #1B	Monolithic slab (slab with integrated grade beam) with brick veneer shelf	1” XPS on exterior side of integrated grade beam	Mixed Humid Climates
SG Type #2	Independent slab w/ concrete stem foundation walls	4” XPS on interior side of foundation wall; 4” XPS under slab	Cold Climates
SG Type #3	Independent slab w/ concrete stem foundation walls	4” XPS on exterior of foundation wall; 4” XPS under slab	Cold Climates

Table of Roof Assembly Types

Roof Type	Structure	Vented/ Unvented, Attic/Cathedral	Location of Insulation	Type of Insulation	Climate
#1	2x12 rafters	Vented, Attic	Perimeter and attic floor	Perimeter: 2” foil-faced polyisocyanurate + high density spray foam; Attic floor: 18” cellulose	Cold climates
#2	2x4 raised truss	Vented, Attic	Perimeter and attic floor	Perimeter: 6” high density spray foam; Attic floor: 10” cellulose over 3” high density spray foam	Cold climates
#3	2x12 rafters	Unvented, Cathedral	Above roof deck and in rafter cavities	Above roof deck: 4” foil-faced polyisocyanurate; Rafter cavities: 11 1/4” netted cellulose	Cold climates up to Zone 6
#4	2x10 rafters	Unvented, Attic	Above roof deck, perimeter, and in rafter cavities	Above roof deck: 4” foil-faced polyisocyanurate; Perimeter: 6” high density spray foam; Rafter cavities: netted cellulose	Cold climates up to Zone 6
#5	2x10 rafters	Unvented, Cathedral	In rafter cavities/perimeter and below rafters	Rafter cavities/perimeter: 9 1/4” high density spray Below rafters: 1” rigid insulation	Cold climates
#6	2x4 raised truss	Unvented, Attic	Under roof deck and at perimeter	Under roof deck/perimeter: 10” high density spray foam	Cold climates

Table of Retrofit Assembly Details

Drawing No.	Location of Window Flange Relative to Insulating Sheathing	Detail Title	Climate
Win-1	Interior side	Window Details	Cold
Win-2	Interior side	Window Installation Sequence	Cold
Win-3	Interior side	Window Trim Installation Sequence	Cold
Win-4	Interior side	Enclosure Assembly with Window Opening	Cold
Win-1A	Interior side	Window Details	Cold
Door-1	Interior side	Door Details	Cold
Door-2	Interior side	Door Installation Sequence	Cold
Door-3	Interior side	Door Trim Installation Sequence	Cold
Pen-1	Interior side	Penetration Details – Exterior Light	Cold
Pen-2	Interior side	Penetration Details – Electrical Box	Cold
Pen-3	Interior side	Penetration Details – Vent Pipe/Duct	Cold
Pen-4	Interior side	Penetration Details – Vent Pipe/Duct Installation Sequence	Cold
Win-1	Exterior side	Window Details	Cold
Win-2	Exterior side	Window Installation Sequence	Cold
Win-1A	Exterior side	Window Details	Cold
Door-1	Exterior side	Door Details	Cold
Door-2	Exterior side	Door Installation Sequence	Cold
Pen-1	Exterior side	Penetration Details – Exterior Light	Cold
Pen-2	Exterior side	Penetration Details – Electrical Box	Cold
Pen-3	Exterior side	Penetration Details – Vent Pipe/Duct	Cold
Pen-4	Exterior side	Penetration Details – Vent Pipe/Duct Installation Sequence	Cold

1.2.5.2. Advanced Framing Implementation

This report investigates the implementation of advanced framing in both production and prototype built homes built in a variety of climate regions across the USA. The current industry standard wall is being replaced by a 2×6 frame at 24 in. centers with single top plates, two-stud corners, no jack studs, no cripples and single headers (and in many cases no headers at all).

The advanced framing system is cheaper because it uses 5% to 10% less board feet of lumber, and it is faster because it uses 30% fewer pieces. It saves energy because it provides a 60% deeper cavity (which allows 60% more cavity insulation) and because it reduces the framing factor from 25% to 15%. Advanced framing can save energy, greenhouse gas emissions, and money if properly implemented. Through BSC's experience we have found that builders can save $1000 per house on advanced framing. To maximize cost savings and energy savings for the homeowner, the builder financial savings are best shifted to implementing more energy saving measures.

The following projects have implemented advanced framing in 2009:

Builder	Number of Homes

Ark Ventures, LLC	1
C.Nelson	7
Colter Construction	1
David Weekley Homes	77
Greencraft LLC.	5
Moser Builders	1
Project Home Again	32
Synergy Companies Construction LLC	1
Zeta Communities	1
Grand Total	126

In 2010 BSC will continue deployment of advanced framing where possible with its Building America partners. More detail about current and future work can be found in the full interim report, which is attached as an appendix.

Interim report (see appendix):

- Lstiburek, Joseph and Aaron Grin. "Advanced Framing Deployment – Interim Report" December 2009.

1.2.5.3. Planned Future Work

The following work is planned for FY10:

- "High R Attic Insulation: Raised Heel Roof Truss Systems and Knee Walls"

  Roof assemblies have aspects of their design that can reduce the overall effectiveness of the thermal enclosure. These aspects, while often ignored with respect to the overall performance of the attic or roof assembly lead to a reduction the performance of the thermal enclosure. In traditional vented attic assemblies, insulation levels at the exterior perimeter are often reduced where the truss or rafter bears on the exterior wall. Similarly, cathedral ceilings often run into space limitations due to the traditional available space for cavity insulation (and space for ventilation) created by the depth of rafter. Both systems also have additional concerns with air exfiltration which can be both and energy as well as a material durability concern for the assemblies.

  The intent is to develop cost effective means to create high R-Value attic and roof assemblies that achieve consistent insulation levels over the entire attic as well as increase the enclosure air tightness. The deliverable will be a research report that will examine the over thermal performance of the proposed assemblies as well as consider the specific construction and cost implications of the assemblies.

- "High R Windows Installations"

  We propose to develop installation details for High R-Value windows in high performance walls. Consideration will be given to factors affecting the window units themselves, such as frame sizes shapes as well as potential increases in weight from additional glass. Representative generic window profiles will be developed based on a review of current manufacturer's high R-Value window systems.

Integration of the windows in different high performance wall systems will be developed in order to maintain continuity of the water management system, air barrier, and thermal enclosure. The deliverable will be a series of isometric window installation sequences that illustrate the install of a high R-Value window in several high R-Value wall assemblies.

The details will be supplemented with case studies of actual installations discussing construction and installation, cost, and final performance of the windows.

- "Advanced Framing Deployment"

  BSC will work with builder partners to implement advanced framing on a large scale. From past experience, we know that it takes framing crews 5-10 houses to work efficiently with advanced framing methods. As part of this research task, BSC will conduct training and produce information resources. Anticipated resources include documentation of the material and labor savings, and an explanation of the energy efficiency benefits of this technology for different climate zones.

  BSC will also work as needed with local code officials to understand and overcome implementation issues.

- "Support for Foundations Working Group and Handbook"

  BSC will provide input and technical support for the Foundations Working Group activities and the production of a foundation manual being prepared by the group. BSC's work under this subtask will include supplemental research to address known knowledge gaps, possible input into the form and contents of the manual, and the production of drawings and other information. The specific support will be determined with the Foundations Working Group in early 2010.

1.3 Project Evaluation

The following sections evaluate the research project results based on performance benefits and the ability to develop performance specifications for advanced systems. References are made to the results from bench top tests, lab tests, tests in lab/research homes and energy simulations, which are included as an appendix to this report.

1.3.1. Source Energy Savings and Whole Building Benefits

Requirement:	*New whole house system solutions must provide demonstrated source energy and whole building performance benefits relative to current system solutions based on BA test and analysis results.*
Conclusion:	***Pass***

High R-value enclosures provide significant source energy savings and whole building benefits. BSC's research work aims to establish a set of recommended assemblies for that have approximately 50% greater thermal resistance under installed conditions. The work to date has demonstrated this for Cold Climate walls and has produced promising results for foundation, roof and retrofit assemblies.

As an example of this work, the High R-value Walls case study analysis (Part B: Prediction and Analysis) gave the following table summarizing the calculated "whole wall" R-values for walls examined in the study.

Table 16 : Summary of all calculated R-values

Case	Description	Whole Wall R-value	Rim Joist	Clear Wall R-value	Top Plate
1bii	2x4, 16"oc, R13FG + OSB (25%ff)	**10.0**	9.8	10.1	9.8
1b	2x4 AF, 24"oc, R13FG + OSB	**11.1**	9.8	11.5	9.8
1aii	2x6, 16"oc, R19FG + OSB (25%ff)	**13.7**	12.3	14.1	12.5
6a	SIPs (3.5" EPS)	**14.1**	12.3	14.5	10.6
1a	2x6 AF, 24"oc, R19FG + OSB	**15.2**	12.3	16.1	12.5
7a	ICF - 8" foam ICF (4" EPS)	**16.4**		16.4	
8b	2x6 AF, 24" o.c., 5.5" R21 0.5 pcf SPF, OSB	**16.5**	13.1	17.2	16.6
7c	ICF - 14" cement woodfiber ICF with Rockwool	**17.4**		17.4	
9	2x6 AF, 24"oc, 2" SPF and 3.5" cellulose	**17.5**	13.2	18.4	17.7
8a	2x6 AF, 24" o.c., 5" 2 pcf R29 SPF, OSB	**19.1**	13.6	20.3	19.5
2a	2x6 AF, 24"oc R19FG + 1" R5 XPS	**20.2**	18.5	20.6	20.3
7b	ICF - 15" foam ICF (5" EPS)	**20.6**		20.6	
3	2x6 AF, 24"oc, 2x3 R19+R8 FG	**21.5**	13.4	23.5	18.4
4	Double stud wall 9.5" R34 cellulose	**30.1**	14.4	33.5	28.8
12	2x6 AF, 24"oc, EIFS - 4" EPS	**30.1**	23.8	31.4	31.1
10	Double stud with 2" 2.0 pcf foam, 7.5" cell.	**32.4**	15.9	36.2	28.5
2b	2x6 AF, 24"oc R19FG + 4" R20 XPS	**34.5**	29.0	35.6	35.4
6b	SIPs (11.25" EPS)	**36.2**	14	41.6	28.2
5	Truss wall 12" R43 cellulose	**36.5**	18.6	40.5	34.4
11	Offset frame wall with ext. spray foam	**37.1**	18.8	40.6	41.9

*AF - Advanced Framing

Walls listed below the lower line (4, 12, 10, 2b, 6b, 5, and 11) are considered to be high R-value assemblies appropriate for deployment in Building America research Prototype homes. Other walls in the study had high nominal R-values but are predicted to perform less effectively and would, therefore, not realize the whole house energy use reduction aimed for by the BA program.

Not all of the improvements in thermal performance can be secured by design choices – additional work was done to measure the influence of other factors, such as convective looping and air pressure differences. Another part of the work described in this report (Part C: Measurement) aims to more accurately measure the thermal performance of wall assemblies. The development of reliable measures of high R-value walls, including all heat transfer mechanisms, will allow for the adoption of new enclosure wall assemblies that reduce heat flow. This in turn can have a major benefit to the energy consumption of American homes.

Other whole building benefits will be realized with the development of high R-value enclosure technology. In particular, homeowners will benefit from increased thermal comfort (through better control of surface temperatures), homes that are quieter on both the inside and the outside (better sound insulation and airtightness), homes that can be heated or cooled with smaller, more efficient mechanical equipment (reduced enclosure loads and reduction of perimeter cold spots), and buildings that are more durable and healthier than houses typically built today (improved water management, resistance to interstitial condensation, and "vapor open" assemblies).

1.3.2. Performance-based Code Approval

Requirement:	*Must meet performance-based safety, health, and building code requirements for use in new homes.*
Conclusion:	***Pass***

All of the high R-value enclosure recommendations detailed under Part D: Implementation meet performance-based safety, health and building code requirements. We consider these enclosure assemblies ready for deployment in prototype research houses. Some BSC prototype houses have employed recommended enclosure assemblies in FY09. Further examination of some code-related issues is expected in FY10. These issues are described in sections below.

1.3.3. Prescriptive-based Code Approval

Requirement:	*Should meet prescriptive safety, health and building code requirements for use in new homes.*
Conclusion:	***Partial Pass***

Some of the enclosure assemblies have not yet been fully reviewed and do not meet all prescriptive requirements. However, the recommended high R-value wall assemblies detailed under Part D: Implementation have completed internal review and meet prescriptive safety, health and building code requirements for use in new homes, with some restrictions on cladding types and applicable wind zones. More discussion on research progress with these restrictions is discussed in Section 1.3.7 below. The following table summarizes the recommended wall assemblies:

Table of Recommended High-R Wall Types – Cold Climate

Wall Type	Exterior finish	Insulation, Nominal R-Value	Air Barrier

Wall Type	Exterior finish	Insulation, Nominal R-Value	Air Barrier
Wall-02-1: 2X6 with 1.5" exterior insulating sheathing	Vented lap siding	5.5" cellulose in cavity + 1.5" foil-faced polyisocyanurate rigid insulation, **R-29**	Airtight Drywall Approach
Wall-02-2: 2X6 with 2" exterior insulating sheathing	Vinyl or aluminum siding	5.5" cellulose in cavity + 2" XPS rigid insulation, **R-29**	Airtight Drywall Approach
Wall-02-3: 2X6 with 4" exterior insulating sheathing	Vented lap siding	5.5" cellulose in cavity + 4" foil-faced polyisocyanurate rigid insulation, **R-45**	Airtight Drywall Approach
Wall-02-4: 2X6 with 4" exterior insulating sheathing	Wood shingles over ½" plywood nail base	5.5" cellulose in cavity + 4" foil-faced polyisocyanurate rigid insulation, **R-45**	Airtight Drywall Approach
Wall-04-1: double stud wall with interior load bearing wall	Vented siding	10.5" cellulose in cavity, **R-37**	Fiberboard sheathing to exterior side of interior stud wall
Wall-11: 11" wide 2X6 stud wall with 2x3 exterior offset framing	Vented lap siding	5'5" cellulose in cavity + 4.5" closed cell spray foam on exterior, **R-46**	Exterior closed cell spray foam

Several important building code considerations were identified and resolved.

First, the IRC provides specific prescriptive guidance on cladding attachment and allows attachment of cladding at 24" centers. A summary of the prescriptive requirements was developed as an "Information Sheet" for posting on BSC's website and for handout to builders of BA Prototype houses. This summary is repeated below.

> In the 2006 International Residential Code (IRC) cladding attachment requirements are covered in *Section R703 Exterior covering* with the majority of the requirements summarized in *Table R703.4 Weather-resistant siding attachment and minimum thickness*.
>
> When sheathings other than wood or wood structural panels are used (such as foam plastic insulating sheathing), the code requires that the cladding be fastened back to the studs. The stud spacing is not specifically stated in *Table R703.4 Weather-resistant siding attachment and minimum thickness* and therefore other sections of the code must be referenced for acceptability of stud spacing. This information is found in *Section R602.3.1 Stud size, height and spacing* in conjunction with *Table R602.3(5) Size, height and spacing of wood studs* listing that studs spaced at 24" centers are acceptable for certain walls.
>
> Depending on the type of cladding, thickness of cladding, and type and thickness of sheathing different fasteners may be required. The penetration depth of the fastener into the stud is the basic requirement. For most claddings the fastener length is specified since the cladding and sheathing thickness is known, a minimum penetration depth is assumed. Where the sheathing thickness is variable (such as with foam plastic insulating sheathing), the fastener size needs to take into account the siding thickness and thickness of sheathing and still provide a minimum of 1" to 1.5" penetration (depending on the cladding type) into the stud.
>
> *Table R703.4 Weather-resistant siding attachment and minimum thickness* is basically unchanged from the 2003 IRC except for the addition of fastener requirements for fiber cement siding over foam plastic sheathing. Where previously no direction was listed (a dash mark was listed in the box) the 2006 IRC now allows the fastening of fiber cement siding over foam plastic sheathing with the use of minimum 6d corrosion resistant nails with the provision that the nail length take into account the thickness of the sheathing a provide a minimum penetration of 1.5 inches into the stud framing.

In many cases furring strips are included in the design of the wall cladding to create a ventilation and drainage space behind the cladding. In this configuration it is often preferable to fasten the cladding to the furring strips instead of back to the studs. Unfortunately the code does not specifically cover this cladding system configuration so engineering may be required to design the cladding attachment to meet the cladding wind load requirements for the area.

Applicable Code Sections

2006 International Residential Code for One- and Two-Family Dwellings

* R602.3.1 Stud size, height and spacing

* Table R602.3.1 Size, height and spacing of wood studs

* R703 Exterior covering

* Table R703.4 Weather-resistant siding attachment and minimum thickness

Second, prescriptive requirements for vapor retarders with insulating sheathing were examined and the code issues summarized as follows:

In climate zones 1, 2, 3, 4A, and 4B a vapor retarder is not required regardless of the use of exterior insulation (*Section N1102.5 Moisture control – Exception 2*). In all other climate zones, the addition of insulation boards on the exterior of the assembly helps reduce the potential for wintertime condensation occurring in the wall assembly. If enough insulation is added to the outside, then a vapor retarder on the inside is not necessary. Also, it is good practice to allow a wall assembly to be able to dry to at least one side, and since many insulation boards can be classified as vapor retarders, removing the vapor retarder from the inside allows increased drying of the assembly to the inside and improves the performance of the wall. The code recognizes this and addresses it in *Section N1102.5 Moisture Control under Exception 3*, which allows for the vapor retarder to be removed "where other means to control condensation are provided." However this still requires some calculations to demonstrate that the potential for condensation is managed in the proposed design.

The current 2007 Supplement to the International Residential Code (IRC) has made some changes to the definition and use of vapor retarders. These changes provide some clarity on vapor retarders, and can be used as guidance.

So what actually is a "vapor retarder"? The current 2006 IRC describes a vapor retarder as a material that has a permeance rating of 1.0 perms or less (*Section R202 Vapor retarder*). This seems simple enough, but there is in reality a large variation in performance between a product with a 1.0 perm rating and a product with a 0.1 perm rating. To address this, the International Code Council (ICC) added a new definition to Chapter 2 of the 2007 Supplement to the IRC for Vapor retarder class.

The 2007 Supplement to the IRC currently defines vapor retarders under three classes:

Class I: 0.1 perm or less (Sheet polyethylene, non-perforated aluminium foil)

Class II: 0.1 perm <= 1.0 perm (Kraft faced fiberglass batts)

Class III: 1.0 perm <= 10 perm (Latex or enamel paint)

With the new definition for vapor retarder classes, new code language concerning the use for the new classes was also included. Class I and Class II vapor are needed to be installed on the warm in winter side of the insulation in Climate Zones 5, 6, 7, 8 and Marine 4 (*Section N1102.5 Vapor retarders*); however, Class III vapor retarders can now be used instead of Class I or II vapor retarders if the conditions of *Table N1102.5.1 Class III vapor retarders* (as listed below) are met.

Zone	Class III vapor retarders permitted for:
Marine 4	Vented cladding over OSB Vented cladding over plywood Vented cladding over fiberboard Vented cladding over gypsum Insulated sheathing with R-value >= 2.5 over 2x4 wall Insulated sheathing with R-value >= 3.75 over 2x6 wall
5	Vented cladding over OSB Vented cladding over plywood Vented cladding over fiberboard Vented cladding over gypsum Insulated sheathing with R-value >= 5 over 2x4 wall Insulated sheathing with R-value >= 7.5 over 2x6 wall
6	Vented cladding over fiberboard Vented cladding over gypsum Insulated sheathing with R-value >= 7.5 over 2x4 wall Insulated sheathing with R-value >= 11.25 over 2x6 wall
7 and 8	Insulated sheathing with R-value >= 10 over 2x4 wall Insulated sheathing with R-value >= 15 over 2x6 wall

Applicable Code Sections

2006 International Residential Code for One and Two-Family Dwellings

* R202 Vapor Retarder
* N1102.5 Moisture Control

2007 Supplement to the 2006 International Residential Code for One and Two-Family Dwellings

* R202 Vapor retarder Class
* N1102.5 Vapor retarders
* N1102.5.1 Class III vapor retarders
* N1102.5.2 Material vapor retarder class

Finally, for houses in wind zones less than 110 mph, BSC looked at wall bracing requirements for walls with insulating sheathing. The following information was developed:

Braced wall panels can be used instead of completely covering the entire building with plywood or OSB. While many types of braced wall panels are acceptable, the most common type of braced wall panels are: 1. A 4-foot wide sheet of plywood or OSB for outside walls and 2. Gypsum installed on interior walls. The various types of braced wall panels are described in *Section R602.10.3 Braced wall panel construction methods*. Standard braced wall panels need to a full 4 foot width with no cut outs from doors or window opening. Narrower panels can be used if the requirements of *Section R602.10.6 Alternate braced wall panels* are met.

A braced wall line and is made up of multiple braced wall panels on a wall. The number and location of the braced wall panels on a braced wall line depends on the wind speed, size and shape of the house, and number of stories. At minimum, braced wall panels are required at the corners and every 25 feet along the braced wall line; however the number may be increased depending on the shape and size of the house. This information can be found in *Table R602.10.1 Wall bracing*. This amount may need to be adjusted based on the weight of the roof assembly. The adjustment factors can be found in *Table R301.2.2.2.1 Wall bracing adjustment factors by roof covering dead load*.

Every house has multiple braced wall lines running in parallel directions. A braced wall line is commonly required every 35 feet; however there are some exceptions to this rule. Keep in mind that the braced wall lines must run in both directions on a house (front to back and side to side). The number and spacing of braced wall lines is given in *Section R602.10.1 Braced wall lines*.

Dwellings in wind zones greater than 110 mph are not covered under this section of the International Residential Code. In cases where the window zone is greater than 110 mph, the design and construction of the structural elements must be in accordance with accepted engineering practice (*Section R602.10.10 Design of structural elements*).

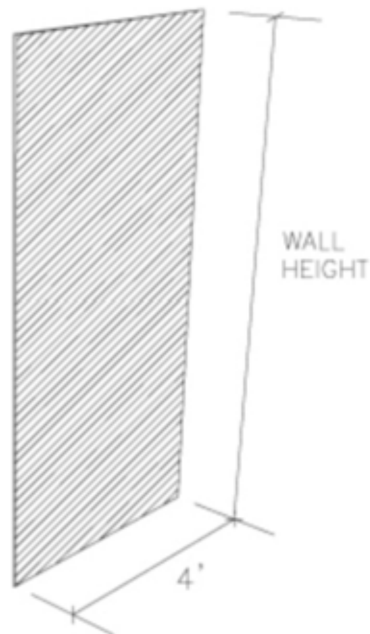

Figure 1: Braced wall panel

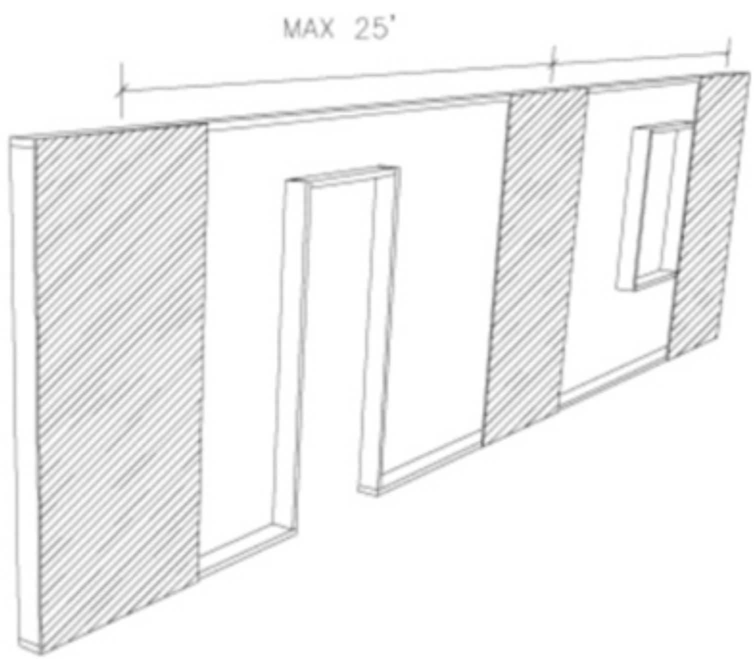

Figure 2: Braced wall line

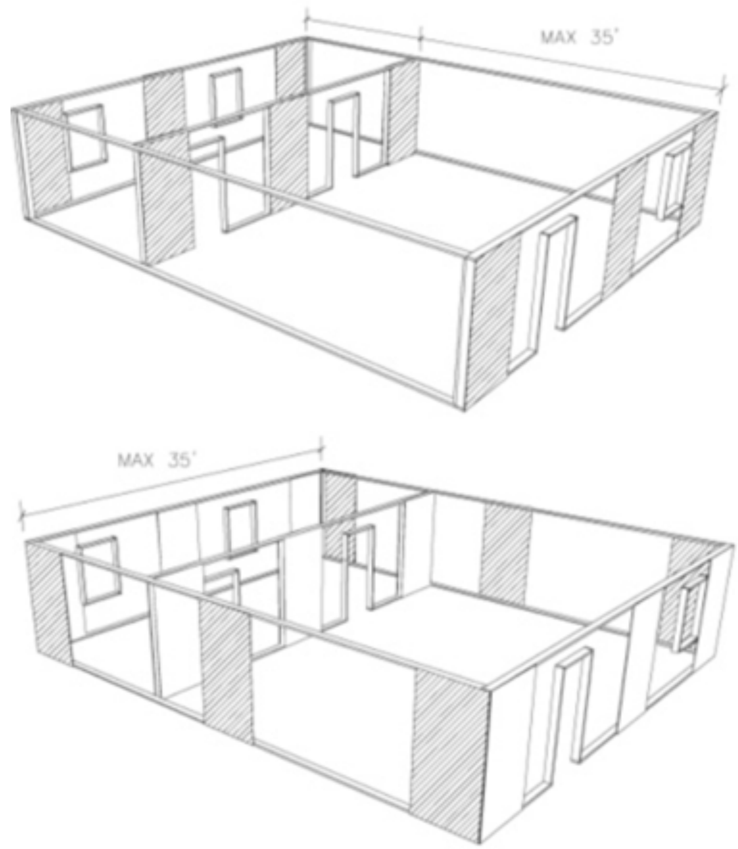

Figure 3: Braced wall lines spaced at 35 feet offsets in both directions

Applicable Code Sections

2006 International Residential Code for One- and Two-Family Dwellings

* R301.2.2.2.1 Weight of materials
* Table R301.2.2.2.1 Wall bracing adjustment factors by roof covering dead load
* R602.3 Design and construction
* R602.10 Wall bracing
* R602.10.1 Braced wall lines
* R602.10.3 Braced wall panel construction methods
* R602.10.10 Design of structural elements

Available Resources

* WFCM 110 mph Guide to Wood Construction in High Wind Areas
* WFCM section 3.4.4.2 Exterior Shear Walls

Some of the code issues that remain as limitations on the above recommended wall assemblies—mainly fastening certain types of cladding to furring strips, and the combustibility of foam insulations—are discussed in more detail in Section 1.3.7: Gaps Analysis below.

1.3.4. Cost Advantage

Requirement:	*Should provide strong potential for cost benefits relative to current systems within a whole building context.*
Conclusion:	***Pass***

Both the recommended High R-value wall assemblies and the roof, foundation, and retrofit assemblies still under review, provide strong potential for cost benefits relative to current systems when considered as part of the whole building.

Aside from the energy-savings-related cost reduction for homeowners described in Section 1.3.1 above, the proposed construction assemblies should provide for significant additional cost benefits. All of the assemblies developed for this research project have undergone a detailed thermal performance analysis. The assessment is intended to increase our understanding of physical characteristics (such as thermal bridging, susceptibility to convective air looping, resistance to infiltration/exfiltration, etc.) that degrade the performance of the assemblies. We have selected assemblies for our recommended list that will perform as close as possible to the nominal R-value of the insulating materials used – thereby providing the "best value" compared to similar wall assemblies designed and constructed in a manner that results in poorer performance.

For the completed set of wall assemblies recommendations, detail of this assessment can be found in "Building America Special Research Project—High-R Walls Case Study Analysis", which is attached to this report as an appendix.

1.3.5. Reliability Advantage

Requirement:	*Should meet reliability, durability, ease of operation, and net added value requirements for use in new homes.*
Conclusion:	***Pass***

Where possible, BSC has developed high R-value enclosure recommendations that are based on conventional technologies and existing products that offer the level of reliability that would be expected from assemblies with lower thermal performance. Durability assessments have be finished for wall assemblies and are being conducted for roof, foundation and retrofit assemblies, with the goal of providing recommended assemblies that both substantially increase the thermal performance of the enclosure and have less risk of moisture-related problems.

1.3.6. Manufacturer/Supplier/Builder Commitment

Requirement:	*Should have sufficient logistical support (warranty, supply, installation, maintenance support) to be used in prototype homes.*
Conclusion:	***Pass***

BSC has found that there is generally strong support for this research from both manufacturers and builders. There are some supply issues that have been identified as new enclosure assemblies are developed. Long shank screws suitable for the attachment of thick insulating sheathing, for example, were not found to be available "over-the-counter" at typical residential building supply stores, but were easily sourced in most locations from commercial roofing suppliers. We anticipate that supply issues such as these will be resolved an high R-value enclosures are more widely deployed.

1.3.7. Gaps Analysis

Requirement:	*Should include system's gaps analysis, lessons learned, and evaluation of major technical and market barriers to achieving the targeted performance level.*
Conclusion:	***Pass***

More detail will be added to our analysis of the major technical and market barriers as research work progresses. However, this research project has already identified a number of important barriers that must be addressed:

- **Attachment of various cladding materials over insulating sheathing.** Cladding attachment details are needed for re-cladding and over-cladding foam and other exterior insulating sheathings. A table of values for 1x4 furring connections installed over various thicknesses of foam sheathings to support fiber cement and wood siding needs to be developed. This needs to be done for masonry block and concrete walls. Values are needed for 2 to 10 inch thick insulating sheathings under a variety of cladding systems.

- **Fire-testing of high R-value assemblies with foam sheathing.** For the fire testing of assemblies the base case framing is always 2x6. Sometimes it will be on 24-inch centers - most of the time it will be on 16-inch centers. Sometimes it will be single top plate - most of the time it will be double top plate. The primary test will be 24-inch centers and single top plate. The others will not need to be tested, as they are more conservative.

  The thickness of the insulating sheathing should be 1.5 inches of polyisocyanurate. (Sometimes it will be 1 inch of polyisocyanurate so this should be tested as well).

  The primary test should test 2x6 framing at 24 inch centers with single top plates and 1.5 inches of polyisocyanurate.

  Sometimes - probably at least 40 percent of the opaque area of the wall - we will need 1/2 inch OSB for shear. So we will need an acceptance for a 2x6 wall at 24-inch centers with single top plates and 1/2 inch OSB covered with 1-inch polyisocyanurate. Sometimes the OSB will only be covered with 1/2 inch of polyisocyanurate.

  The wall cavity insulation should be damp spray cellulose. Interior lining should be 5/8 Type X fire rated gypsum board.

  For the fire testing proposed the goal is approvals for both 1.5-inch and 1-inch polyisocyanurate over 2x6 advanced framing and 2x6 standard framing. Cavities should be insulated with cellulose with interior linings consisting of 5/8 inch Type X fire rated gypsum board. The shear wall versions of these assemblies also need to be tested (that means a wall with 1 inch polyisocyanurate and 1/2 inch OSB and another wall with 1/2 inch polyisocyanurate and 1/2 inch OSB).

For the structural testing a table of single headers for window and door openings needs to be developed in a building code compatible version to make it easy on a prescriptive basis to do this piece of the advanced framing package.

- **Use of combustable foam insulation in exposed applications.** High R-value enclosures require increased levels of insulation in areas that are often poorly insulated such as attics, crawlspaces and basements. The building code requires a thermal barrier for foam insulations installed in these areas in any case that the space is also accessible to the occupants. Current thermal barrier options are often expensive or difficult to apply. Many production builders, in particular, need options for insulation in exposed areas that they wish to leave unfinished at the time of sale. There is a cost hurdle to overcome here.

- **Wind design requirements impact high R-**value construction. Wind design guidelines in some areas of the country require modifications to current high R-value enclosure recommendations. These modifications need to be explored in more detail.

- **Understanding the influence of airflow on heat transfer.** Observing the commissioning and calibration of BSC's precision calibrated hot box, it was learned that quantifying the heat flow resistance of walls is much more than just R-value. Although there has been research conducted in the past, there is still no clear single performance metric that can be used to communicate high performance walls to designers, code officials or owners. Proving that the performance of the new test apparatus can meet the demanding targets set is not yet complete.

  The influence of airflow within and through building enclosures on heat transfer is significant, much more significant than for standard enclosures. For many high R-value walls, basements, and roofs the proportion of heat flow due to airflow effects increases as R-value increases. For wall and roof assemblies with R-values in the order of 30 to 60, airflow affects can dominate performance, whereas for traditional walls (R-10 to R-15 true r-value) the impacts were small enough they could be ignored.

  Higher airtightness standards for both whole buildings and assemblies need to be imposed for high R-value enclosures. Airtightness targets that approach 1.0 l/s/m2@75 Pa of enclosure area for total building airtightness should be sought for homes that use very high R-value walls and roofs (e.g. R-40/R-60).

  The interaction of airflow and heat transfer is poorly understood. There appears to be a real impact, and for accurate assessments heat flow due to conduction and heat flow due to through-enclosure convection cannot simply be added. However, the precise interaction has not been experimentally quantified and is likely in the order of more than 10% impact for high R enclosures.

  Airflow within enclosures influence heat flow in all walls. However, small defects and a limited amount of wind washing can be tolerated in enclosures with R-values of 10 to 20 without serious reductions in performance. For high R-value enclosures, even small, perhaps even unavoidable defects, can begin to have a more significant influence on heat flow for high R-value enclosures. Hence, techniques to reduce the impact of these mechanisms need to be implemented. For example, the use of wind washing barriers, multiple layers of insulation and insulation with higher resistance to airflow may be required.

In addition, several minor barriers were noted:

- **Impact of increased wall thickness.** For most high R-value assemblies, the additional insulation material increases the thickness of the exterior wall. For builders, this may interfere with interior space plans or, because of typically very tight fit between house and lot, impact the entire community plan. For new house designs, this additional thickness can likely be accommodated with minimal difficulty but for existing house plans in use by production builders, a modification to the exterior wall is a major change.

- **Global warming potential of insulation materials.** As homeowners become more attuned to the global warming potential of the products that they buy, alternates for many commonly used insulation materials must be found.

- **First or capital cost of building high R-value enclosures.** The initial cost of high R-value enclosures can be significant. Our research has focused on the development of enclosure systems that will meet the BA neutral cost criteria but several of the gaps above need to be addressed in order to bring the first cost down for the builder. Changing thermal resistance requirements in building codes reduce the effective cost to the builder and pass the same amount on to the homeowner – who will benefit from the energy savings of these measures – but may also be faced with a higher purchase price.

- **Availability of new insulation materials.** Not all of the insulation materials that are listed in BSC recommendations are available in all regions. For example, it is currently difficult to get damp sprayed cellulose in some areas and SPF is hard to get in other areas. This situation is expected to change slowly but should be monitored.

1.4 Conclusions/Remarks

The BSC Industry Team has determined that a 50 percent improvement in the thermal resistance of the exterior wall, roof/ceiling and foundation assemblies must be achieved with a reduction in material and labor costs in order to meet the Building America Program mid term objective to reduce whole-house energy use in new homes by an average of 50 percent by 2015.

In addition, other whole building benefits will be realized with the development of high R-value enclosure technology. In particular, homeowners will benefit from increased thermal comfort (through better control of surface temperatures), homes that are quieter on both the inside and the outside (better sound insulation and airtightness), homes that can be heated or cooled with smaller, more efficient mechanical equipment (reduced enclosure loads and reduction of perimeter cold spots), and buildings that are more durable and healthier than houses typically built today (improved water management, resistance to interstitial condensation, and "vapor open" assemblies).

BSC has produced final recommendations for six high R-value wall assemblies, including details for windows, doors and enclosure penetrations. These recommendations are accompanied by building science notes on thermal performance, durability, cost and constructability, presented as two-page illustrated case studies. In addition, BSC is reviewing and analyzing details for high R-value foundation, roof and retrofit assemblies. These work products are supported by fundamental research into the thermal performance of materials and systems, as well as the known physical heat flow mechanisms (particularly natural and forced convection) and operating conditions that influence thermal performance.

Detailed descriptions of work planned for FY10 can be found at the end of each section of this report. As an overview, BSC will conduct additional analysis of roof, foundation and retrofit assemblies and will report on the measurement of full wall assemblies. High R-value enclosure drawings and details that are currently under review will be modified to reflect information gained from these and other research subprojects. Enclosure recommendations applicable to all climate zones will be developed.

1.5.1. Influence of Air Flow on Heat Loss in High R-value Enclosures

by John Straube, December 2009

Building America High R-value Enclosures Research Project:

Influence of Air Flow on Heat Loss in High R-value Enclosures

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Building Science Corporation, Somerville, MA
December 2009

Abstract:

This report investigates the role of airflow in heat transfer through high R-value building enclosures, particularly the effect of airflow that is not captured by blower test data converted to heat loss (High R-value enclosures are those with about double the R-value of current enclosure assemblies). The analysis and literature review points to the need for increased airtightness standards for both whole houses and assemblies for high-R wall, roof and basement systems. For wall and roof assemblies with R-values in the order of 30 to 60, airflow affects can dominate performance, whereas for traditional walls (R-10 to R-15 true r-value) the impacts were small enough they could be ignored. Airtightness targets that approach 1.0 l/s/m^2@75 Pa of enclosure area for total building airtightness should be sought for homes that use very high R-value walls and roofs (e.g. R-40/R-60).

Influence of Air Flow on Heat Loss in High R-value Enclosures

It has long been recognized that the control of air flow is a crucial and intrinsic part of heat and moisture control in modern building enclosures [Wilson 1963, Garden 1965]. That this statement is true for all climates has been a more recently developed awareness [Lstiburek 1994]. A large fraction of a modern, well-insulated building's space conditioning energy load is due to uncontrolled air leakage. Wintertime condensation of water vapor in exfiltrating air (or summertime condensation of infiltrating air) within assemblies is one of the two major sources of moisture in the above-grade enclosure (driving rain being the other). Air flow through the enclosure can also carry, exhaust gases, odors, and sounds through enclosures as well as mold spores and off gassing generated within the enclosure. Uncontrolled air leakage through the enclosure is therefore often a major cause of performance (e.g. comfort, health, energy, durability, etc.) problems.

This report investigates the role of airflow in heat transfer through high R-value building enclosures, particularly the effect of airflow that is not captured by blower test data converted to heat loss. High R-value enclosures are those with about double the R-value of current enclosure assemblies, i.e., high R-value enclosure true R-values are in the range of R-25 to R-50 for walls, 40 to 80 for roofs and basement walls have R-values of 15 to 30.

Airflow transports heat in a well-understood manner. The heat transfer of any fluid can be calculated by:

$$q = dm/d\theta \; c_o \cdot \Delta T \qquad [1]$$

where θ represents time and

$dm/d\theta$ is the mass flow rate of the fluid (kg/s) per unit time,

c_o is heat capacity of the fluid (J / (kg·K)), and

and ΔT is the temperature difference (K).

Equation (1) can be re-written in volumetric terms and US standard units as

$$Q = 1.08 \; dV/d\theta \;\; \text{(in Btu/hr/°F/cfm)} \qquad [1b]$$

Air leaking out of a building must be replaced with infiltrating outdoor air which requires energy to condition it. Approximately 30% to 50% of space conditioning energy consumption in many well-insulated buildings is due to air leakage through the building enclosure. This is well known and can be controlled both by increasing the airtightness of the enclosure and reducing excessive air pressures across it.

The air flow rate is typically measured in Air Changes per Hour (ACH). The volumetric flow of air per second is then:

$$dV/d\theta = (ACH) \cdot V \cdot (1 \text{ hour} / 3600 \text{ seconds}) \qquad [2]$$

where V is the volume of the buildings conditioned space (m^3).

Hence, heat flow, Q (in Watts/°C) as a function of ACH is

$$Q = c_o \cdot \rho \cdot dV/d\theta \cdot \Delta T = c_o \cdot \rho \cdot (ACH)\, V / 3600 \cdot \Delta T \qquad [3]$$

which for room temperature (20°C / 68 °F) air with a density of 1.2 kg/m^3 (0.75 lb/ft^3) and a heat capacity of 1000 J/kg, heat flow becomes:

$$Q = 1\,000 \cdot 1.2 \cdot (ACH) \cdot V / 3600 \cdot \Delta T \qquad [4a]$$

$$= 0.3 \cdot (ACH)\ V \cdot \Delta T \text{ (in Watts/°C)}$$

In US standard units of Btu/hr, °F, and cubic feet, equation 4 can be re-written as:

$$Q = 0.0177 \cdot (ACH)\ V \cdot \Delta T \quad \text{(in Btu/hr/°F)} \qquad [4b]$$

Sherman [1998] cites a widely used rule of thumb, that a house under natural conditions will exchange approximately (within about 20%) ACH natural = ACH@50Pa/20. Therefore, for houses with blower door test data of 2 to 4 ACH@50 (a common range of Building America research houses[1]), natural exchange rates are between about 0.1 and 0.2 ACH.

The pressure that acts across a wall over the heating season is in the order of 4 Pa (ASHRAE 2009) but varies with exposure to wind, height of the house, and temperature difference. This pressure difference is often used by ASHRAE standards in assessing airflow across walls and windows. For one-storey homes in mild climates 4 Pa significantly overestimates the average stack effect (buoyancy) pressures that will act on the home. However, 4 Pa is a reasonable estimate of a multi-storey house in cold weather when the effects of wind are considered in addition to stack effects.

Building enclosures as a whole or as components (e.g., windows, walls) are often tested for their air flow characteristics by imposing a series of pressure differences, monitoring the flow rate at each pressure, and fitting the data to a standard equation with test-specific coefficients. A general power law has been found to fit the data from most such leakage tests [Baker et al 1987]. This equation has the form:

$$dV/d\theta = C \cdot (\Delta P)^n \qquad [5]$$

where n is the flow exponent and C is a flow coefficient

In this equation, the flow coefficient is a measure of the leakage of the tested enclosure assembly and includes the area, flow path, flow regime, friction, and temperature-density effects. The flow exponent through normal building enclosures is very often in the range of 0.6 to 0.7, and is widely assumed to be 0.65. Equation 5 allows us to convert test data at one pressure to airflow under another pressure difference.

The U.S. Department of Energy Building America Program sets an enclosure air permeance requirement of 1.65 $l/s/m^2$@75 Pa (0.325 cfm/sf@0.3in w.c.) for residential buildings. ASTM E-1677-00 *Standard Specification for an Air Retarder Material or System for Low-Rise Framed Building Walls* currently calls for an assembly air permeance requirement of 0.30 $l//s/m^2$@75 Pa (0.06 cfm/sf @0.3in w.c.)

Using Equation 5 to convert airflow at a test pressure of 75 Pa to airflow at a pressure representative of in-service (4 Pa) one can merely multiply by (4/75)^0.65 or 0.149. Hence the BA overall enclosure value can be converted to 0.245 $l/s/m^2$@4 Pa (0.048 cfm/sf) and the ASTM enclosure value is 0.045 $l/s/m^2$@4 Pa (0.009 cfm/sf).

The preceding information allows one to estimate the impact of airflow on thermal transfers through High-R walls. By considering the range between the whole building Building America

[1] Tbe Building America Program is a housing research program sponsored by the US Department of Energy. For more information, visit www.buildingamerica.gov.

standard (0.045 cfm/sf) and ASTM assembly tightness (0.009 cfm/sf), the heat flow by conduction through opaque elements and the flow by convection can be compared. Note that this is a pressure suitable for cold climates and two or three storey homes.

Figure 1 shows the influence of airflow on enclosure heat transfer. For the Building America overall enclosure target of 1.65 l/s/m2@75 Pa, the contribution of air to heat flow (using equation 1) can be seen to significant. If this level of airtightness is tolerated, the contribution of air leakage to heat flow can rise to 50% at an R-value of only R-20 (heat flow via conduction is 3.5 Btu/hr/sf at R-20, whereas the heat flow is 7 Btu/hr/sf when air leakage is included).

Most of the enclosure air leakage is leaking through joints, penetrations, and windows not the wall or roof assembly. The much stricter assembly tightness target of 0.30 l//s/m^2@75 Pa (0.06 cfm/sf @0.3in w.c.) is difficult for many walls and some roofs to achieve. However, it can be seen from the figure that even at this tightness level, airflow comprises 25% of the total flow for an enclosure of R-25, and 1/3 of the total heat flow for an R-50 enclosure. For roof assemblies with R-100, fully half of the heat flow will be carried by air leakage even with strict assembly air leakage targets.

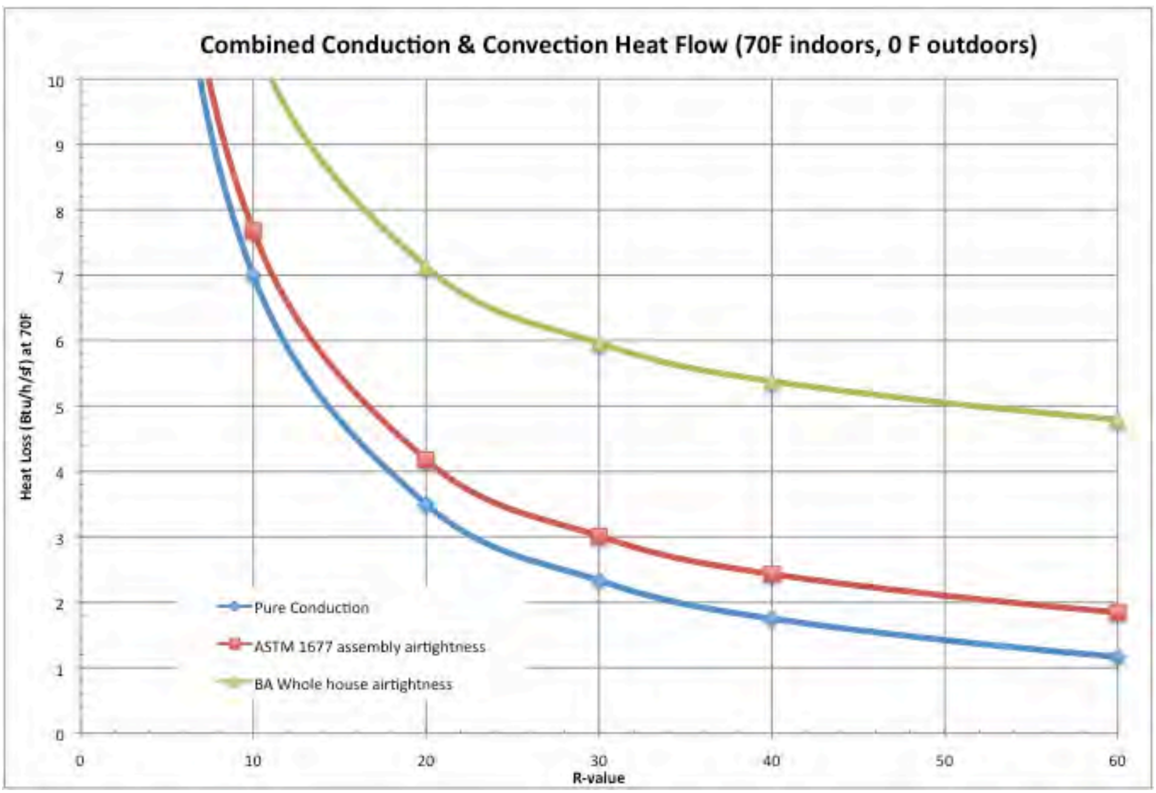


Figure 1: Airflow Contribution to cross-enclosure heat flow for two different air leakage rates

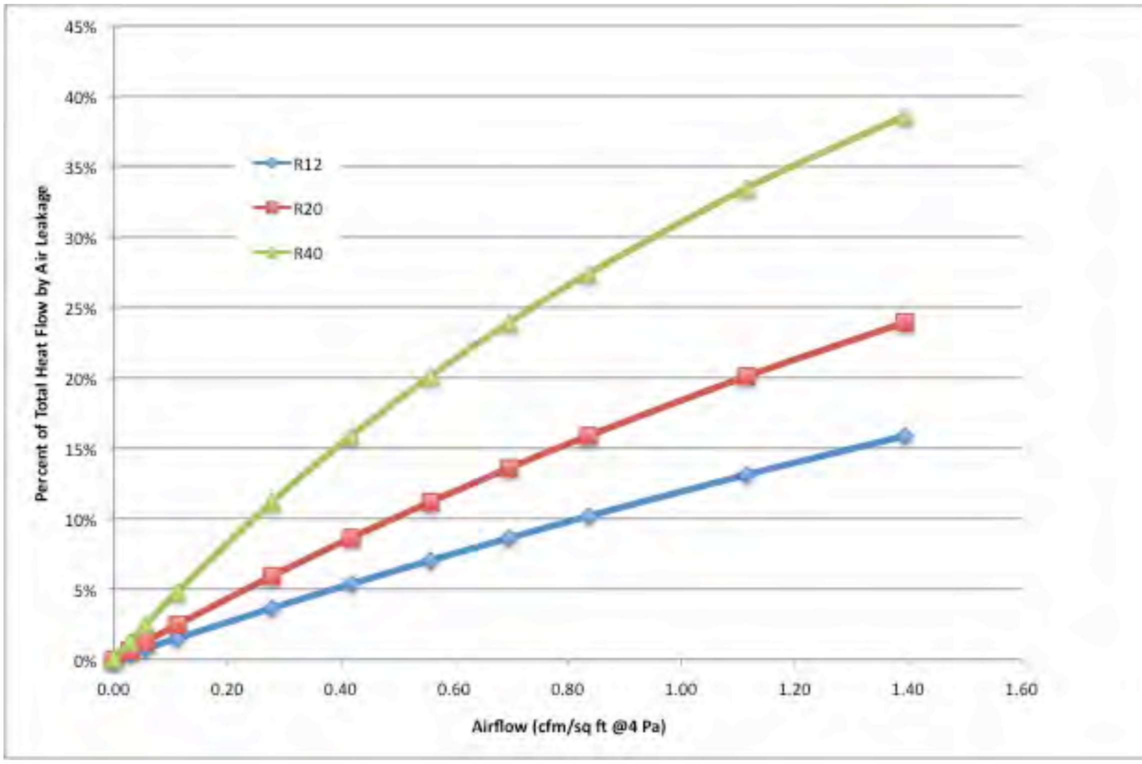


Figure 2: Proportion of heat flow carried by air leakage as function of air leakage and base R-value

Experimental Measurements of Airflow and Energy

The only comprehensive tests made of airflow through enclosure walls in a hot box where conducted by Jones, Ober, and Goodrow (1995). They undertook the hot box measurements of 40 different assemblies with and without air leakage. The base wall was a traditional nominal R-12 2x4 wall with R-2.5 foam sheathing. The air leakage of the walls covered a wide range from as little as 0.3 l/s/m2@75 Pa to over 1.2 l/s/m2@75 Pa. They showed that for simple exfiltration: “Test results for the wall assemblies reveal that airflow rates as low as 0.2 L/s/m^2 can produce a 46% increase in apparent thermal conductance”. The influence of wind washing, although not studied in detail due to equipment limitations, was projected to reduce the thermal resistance by 18%. These percentages would be much higher for high R walls.

Using a combination of field measurements and calculations, Ten Wolde et al (1995) concluded that airflow in a ventilated wall with modest airtightness (about 0.6 l/s/m^2@75) experienced a 33% reduction in thermal resistance from the nominal R-19 during winter conditions in Madison WI. These measured results are in the order of those calculated above for the same conditions.

This analysis and literature review points to the need for increased airtightness standards for both whole houses and assemblies for high-R wall, roof and basement systems.

Airflow through an enclosure can change the flow of heat within insulation by changing the relative contribution of radiative and conductive heat flow. It is often assumed that the heat flow through an airtight insulated assembly

$$Q = 1/R \cdot A \cdot \Delta T \qquad [6]$$

Can be added to Equation 1 to predict the total heat flow:

$$Q = [dm/d\theta \, c_o + 1/R \cdot A] \cdot \Delta T \qquad [7]$$

Yarbrough and Graves [1996] presented results of airflow through fibrous insulation in a modified ASTM C518 apparatus. They found that Equation 7 failed to predict heat flow by almost +/-15% at high airflows. At lower, more representative of service, flow rates, the deviation between theory and measurement was closer to 5%. They conducted tests in both infiltration and exfiltration unlike most of the literature. Unfortunately, this work was not extended to full-scale walls, and no explanation for the deviation has been developed.

ASHRAE has sponsored significant work on this topic at the University of Alberta [Ackerman 2006-1, ASHRAE 2006-2]. As heat flow is difficult to measure directly, these researchers measured temperatures within wall samples in a cold chamber and inferred from these that infiltration could have 10% or more less heat flow than predicted by Equation 7 because of heat recovery. When the researchers conducted a field test hut study to carefully measure the energy flows through the walls, no impact could be found. It was postulated that the highly variable airflow and temperature around real buildings may have masked any small impact.

This concept of infiltration heat recovery through insulation walls has been studied as the "Dynamic Wall" concept for several decades. Timusk [1988] is the only known researcher in North America who has built and monitored a Dynamic wall house. Taylor et al [1996] developed equations that predicted additional (above that of Equation 7) heat gain from infiltration and additional heat loss during exfiltration. The attached plot from Taylor et al (Figure 3) shows total heat flux/static heat flux increasing with airflow outward in cold weather and decreasing with inward flow in cold weather. For low insulation levels, the effect is smallish (note the log plot) and at low R-value (RSI 1.28=R8) the curves are nearly symmetrical. However, as the R-value increases, even small airflows can result in impacts on predicted heat flow that are well over 10%, and asymmetrical (exfiltration heat loss is more than infiltration heat gain).

No controlled hotbox studies have been conducted to accurately study this phenomenon, likely because such equipment is not widely available.

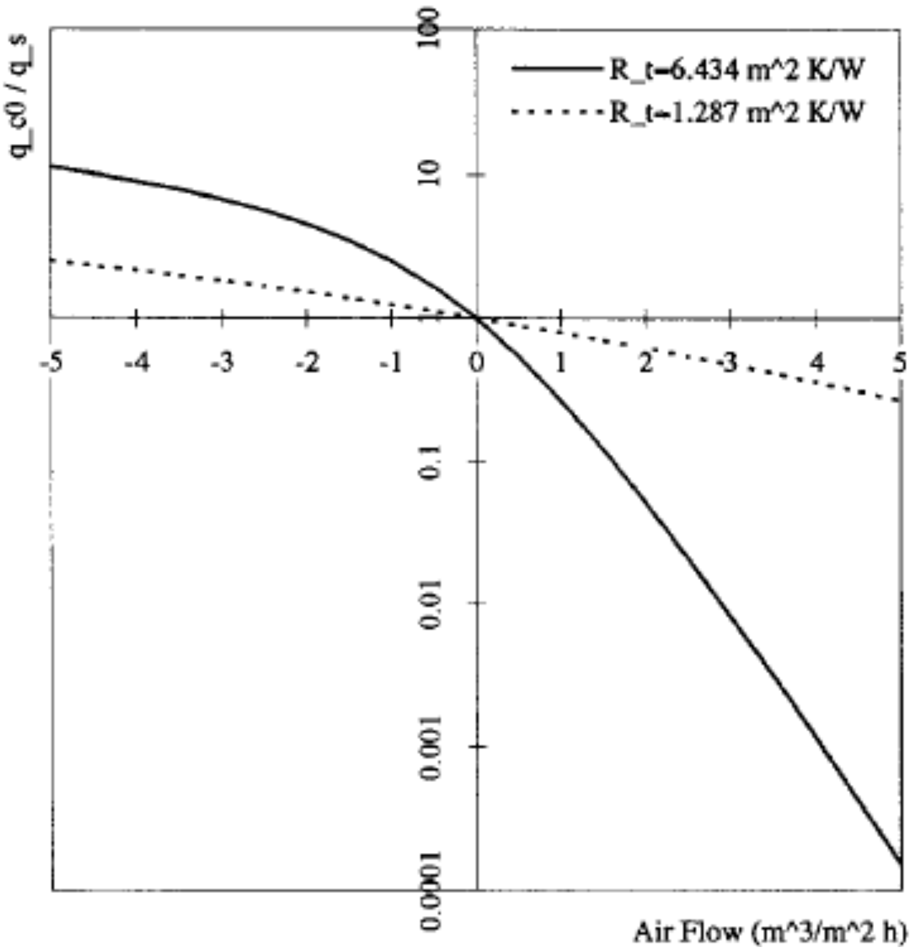


Figure 3: Ratio of total heat flux to (q_{c0}) to heat flux with no airflow ($q_{\_s}$) as a function of airflow rate and insulation level

Other Flow Paths

There are numerous paths that airflow can take through an assembly insulated with air permeable insulation. These paths are shown in Figure 4. Path 1 is the airflow path that has been considered in preceding discussion.

Flow paths that combine 1, 2 and 3 are complex and increase the contact time and thus the potential impact on heat flow. Very little research has been undertaken in this area, but Chebil et al (2003) did investigate these impacts using a computer model, and showed significant influences 8 to 15% changes in heat flow for reasonable ranges in air leakage depending on flow path.

Both thermal buoyancy (i.e., *natural convection* or stack effect) and differential wind pressures cause natural and forced convective air flows *within* building enclosures. These internal airflows can short-circuit thermal insulation and bypass air barriers with the attendant increase in heat transfer and risk of moisture deposition. Providing an excellent air barrier system will not necessarily control these problems, since no air flow need occur through an ABS for either of these phenomena to cause performance problems.

These are other types of airflow can play an important role in thermal performance. For enclosure assemblies with lower R-values, eg true R-value of 10, these secondary airflow effects play a small role. As the R-value of an assembly increases (to R-20 or R-40) even small flows can begin to comprise a significant proportion of total heat loss.

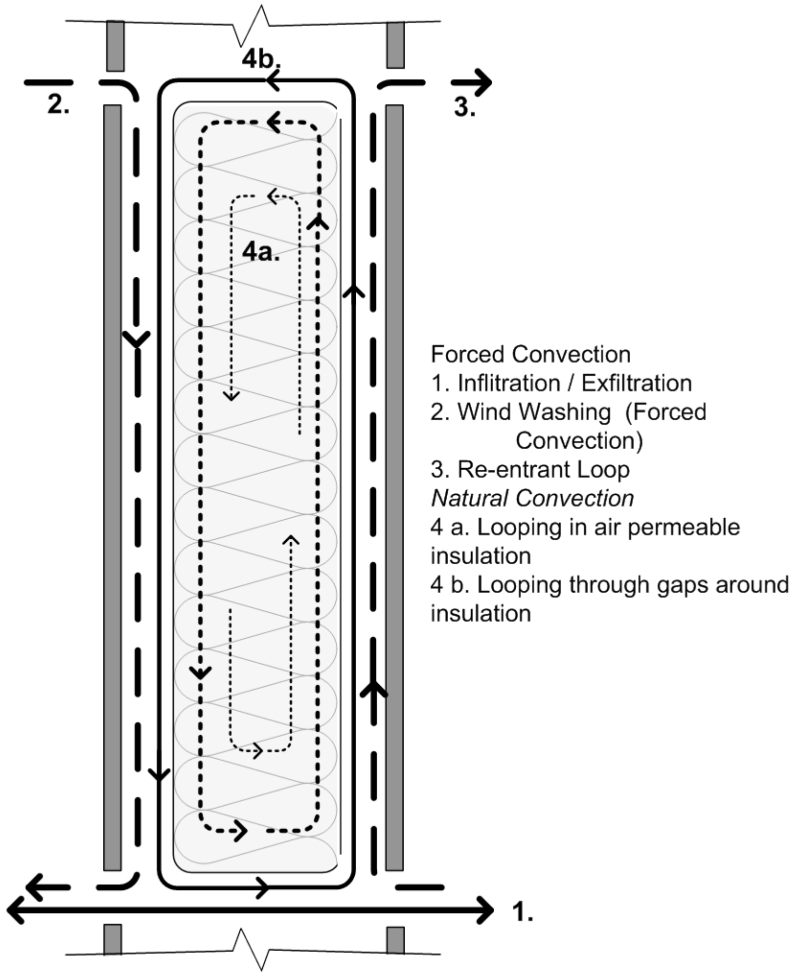


Figure 4: Airflow paths within and through an insulated enclosure

Natural Convection

The density of air varies with temperature. The greater the height of a column of air, the greater the potential difference in pressure if that column is at a different temperature. The pressure difference generated by a column of air h meters high with temperature difference between indoor and outdoor air at standard temperature and pressure is approximately:

$$\Delta P = 3465 \cdot \Delta h \cdot (\frac{\ }{\ } - \frac{\ }{\ })\ [Pa] \qquad [5]$$

where To and Ti are the outdoor and indoor temperatures respectively, (in Kelvin = Celsius + 273).

For example, if the air in a one meter high cylinder, open at the bottom and containing room temperature air (20 °C/68 °F) is connected to a space at a temperature of -10 °C (14 °F), an outward pressure of 1.34 Pa would act at the top. An inspection of Equation 5 shows that the size of the pressure driving buoyancy-induced flow is primarily affected by two factors: the magnitude of the temperature difference and the difference in height. The amount of air flow that can be moved by this pressure is of course dependent on the geometry of the flow path and/or the air permeability of the material along the path.

As the thickness of insulation increases to meet high R-value targets, the temperature differences across the insulation increases. This increases the pressure difference that drives loops. At the same time, as R-value increases, the impact, as a proportion of the total heat flow, of very small airflows increases. Countering this trend is the movement to higher density (and thus usually higher air flow resistance) insulation to achieve higher R-values per inch. The R-value and airflow resistance to flow through an insulation increases linearly with thickness, but the heat flow across the insulation decreases as the inverse, $^1/_R$. Hence, for thick layers, the increase in airflow resistance of flow paths through the insulation increases faster than the temperature difference across the insulation, and thus convective loops are less of a challenge. However, the driving force for air loops *around* insulation continues to grow with high-R walls, and this mechanism becomes more and more important proportionately.

If a continuous air loop, even 1 mm ($^1/_{25}$") in width, connects two sides of a layer of insulation a convective loop can form, robbing energy efficiency and causing moisture problems (Figure 3). Research [e.g., Lecompte 1990] has shown that significant heat losses and moisture transport can result from connected air gaps of only 1-2 mm width. To ensure no flow paths connect air spaces on the warm side of the insulation to the cold side, insulation with sufficiently low air permeability should always be placed in tight contact along at least one surface. Semi-rigid cavity insulation must be firmly attached to one side of the air space in which it is installed to avoid such convection loops. Full bed or serpentine adhesive patterns are preferred to isolated daubs (which create continuous vertical gaps) for the same reasons.

Flow within air permeable insulation usually occurs if large temperature differences act across a thin layer of insulation – the pressure difference is large if the temperature difference is large and the flow resistance is small as the airflow path distance (the thickness) is small. This is often a concern in horizontal insulation (e.g., attics). One solution is the use of higher density blown-in insulation which reduces the air permeability of the material, and thus its propensity for convection losses. The use of multiple layers (i.e., in the form of insulating sheathing or layers of batts) reduces the temperature drop across each layer and thus the driving force for convection. Very thick layers of attic insulation (e.g., 12"/300 mm or more) helps increases the flow resistance as well.

Batt insulation with low airflow resistance (roughly correlated to density) may not restrict air loops even within its body when driven by large temperature-induced pressure differences (see Figure 4), whereas semi-rigid or rigid insulation usually does. Modern batt insulation products are designed with sufficient air flow resistance as to control internal looping if the batts are installed to perfectly fills the stud cavity, and temperature differences are kept within normal ranges.

Batt insulation is manufactured slightly oversized so that when it is compressed (or friction fit) by the drywall gaps and wrinkles are minimized. If installation is not careful, and experience has shown that sufficiently careful installation is rare, small gaps will form and allow loops to form around the batt. The pressure generated by the mechanism shown in Figure 5A and Figure 6 increases linearly with height (usually 8 ft or 2.44 m for residential walls) and practically linearly with temperature difference. Research at IRC [Brown et al 1993] has shown that small gaps, such as shown in Figure 5, can greatly impact heat flow (from 15% at ΔT=25°C to 35% at ΔT=55 C).

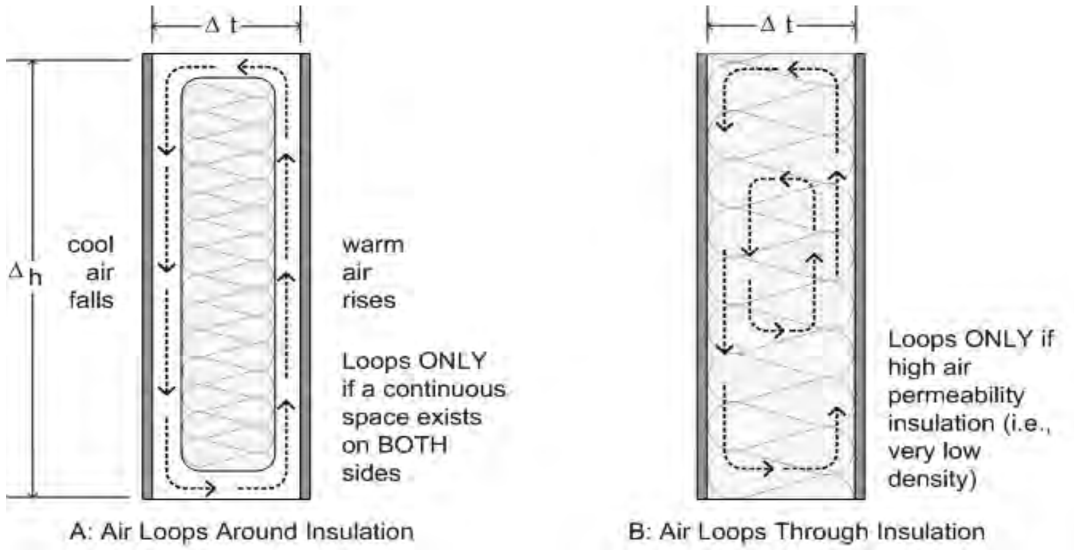


Figure 5: Natural Convection Air Flow Around and Through Insulation

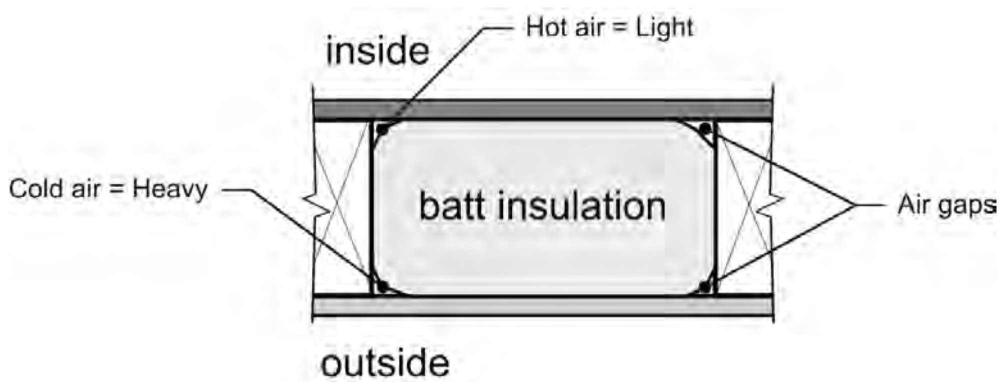


Figure 6: Natural Convection around Batt Insulation (plan view)

Multiple layers of insulation are often specified for low-slope roofs, partly to reduce or eliminate the convective loops that could occur in the small joints that inevitably form between boards. The driving pressure for flow in two independent 2”/ 50 mm high gaps (a typical board thickness) is small enough and the temperature difference is half as much as a single 4” /100 mm layer. The two factors together mean that the pressures driving looping are ¼ as much for two layers as one. An even greater effect is that the flow path from the interior to the exterior is now much more tortuous and low air permeance.

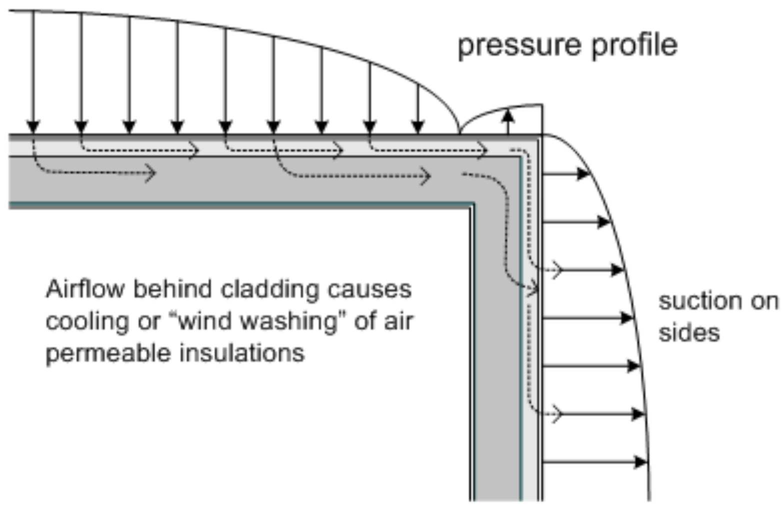
Wind Washing

High velocity air flowing behind the cladding or sheathing can also increase the amount of heat loss by penetrating the structure of low-density fibrous insulations (hence, batt insulation is very vulnerable). This phenomenon is often called wind washing, or *forced convection* and can cause surface condensation in outside corners, increased heat loss and other problems [Timusk et al 1991]. Building corners and parapets are especially susceptible because the wind induces very steep pressure gradients in these areas (Figure 7). Pressure gradients of 100 Pa/m can form, and even small air flow paths can allow excessive air flows with such large pressures.

Air impermeable layers placed outside low-density fibrous insulation can control this form of heat loss. In Scandinavia and Europe, secondary, outer layers of airflow resistance are called wind barriers or convection barriers. To control wind-driven convective heat losses Finnish research [Uvslokk 1988, Ojanen 1995] has recommended limiting the maximum permeability of the wind barrier to between 10 and 25 x 10^{-6} $m^3/(m^2$ Pa s). Some high-density mineral fiber insulations, and rigid foam insulations, housewraps, building paper, and sheathing (all with taped or otherwise secured joints) can provide this level of control.

In-plane air flow resistors provide *compartmentalisation*, which helps to confine air leakage to limited areas of the enclosure, reduces wind washing effects, and can also improve pressure moderation performance. Compartmentalisation should be provided in all assemblies, either provided by tight separators at discrete intervals (e.g., sheet metal) or by the distributed resistance of low-permeance materials (e.g., dense-pack cellulose and foam). Corner separators are often the most useful because of the high pressure gradients acting around corners.

Framing members can also provide resistance to in-plane flow. Wood blocking, or draft stops, have long been used in wood framed construction to prevent the spread of fire and smoke. Wood framing may not be sufficiently airtight at corners because drying shrinkage causes small cracks between the framing and the siding (or drywall). Metal studs tend to have “knock outs” for services which allow unimpeded lateral air flow. In all cases, if air driven by exterior wind pressures enters a stud cavity filled with air permeable insulation, the thermal performance will be seriously degraded.



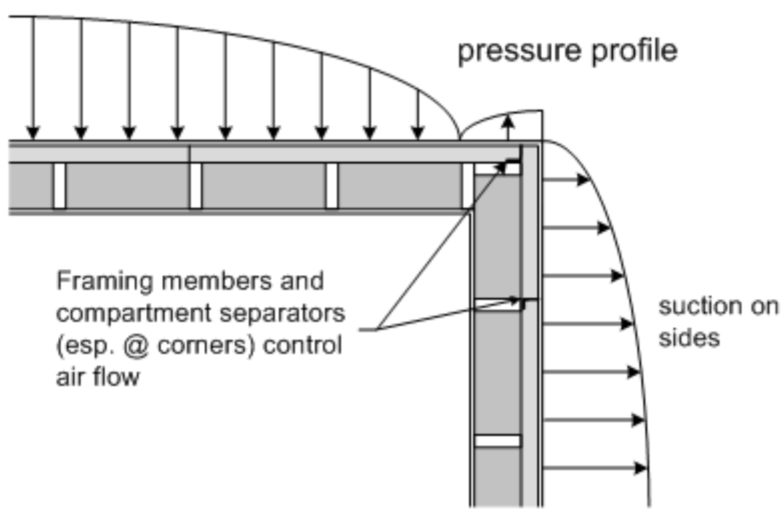


Figure 7: Wind Forced Convection ("Wind Washing")

Practical Solutions To Forced and Natural Convective Flow

Given our current understanding practical advice can be given to designers and builders of high R-value assemblies. There is, however, little quantitative experimental evidence of how the air flow interacts with conduction.

The primary means of controlling convective loops and wind-washing effects are:

- Insulation with low air permeance (foams, or faced fibrous insulation) should be used when exposed to large air pressures such as wind washing.
- Some airtightness in the form of housewraps, taped rigid sheathing etc., should be provided behind cladding and to the exterior of any air permeable fibrous insulations to control wind-washing effects on any enclosure.
- Low air permeance materials (such as foams, and very high density fibrous insulation)

must be placed fully in contact with one airtight surface to avoid looping.

- Good workmanship and inspection must be employed to avoid air gaps around both rigid, semi-rigid and low-density fibrous insulation. Semi-rigid insulation offers the ability to be fitted or pressed to conform to rough surfaces like blockwork and concrete. This may not control convection in low-density batt insulation which must completely fill the space into which it is installed (i.e., no gaps or wrinkles).
- The temperature difference across individual layers of insulation can be reduced by using multiple layers of insulation with non-aligned joints (e.g., insulated sheathing over batt insulation).
- The height of the connected space (h in Eq. 5) can be reduced in roofing details by using multiple layers of insulation.
- The ability of lateral air flow can be reduced by providing air flow resistors around corners and other changes in plan. This can be achieved by compartmentalizing to limit vertical height and horizontal extent, and is especially important at corners and parapets.

Implications for High R-value Assemblies

The influence of airflow within and through building enclosures on heat transfer is significant, much more significant than for standard enclosures. For many high R-value walls, basements, and roofs the proportion of heat flow due to airflow effects increases as R-value increases. For wall and roof assemblies with R-values in the order of 30 to 60, airflow affects can dominate performance, whereas for traditional walls (R-10 to R-15 true r-value) the impacts were small enough they could be ignored.

Higher airtightness standards for both whole buildings and assemblies need to be imposed for high R-value enclosures. Airtightness targets that approach 1.0 $l/s/m^2$@75 Pa of enclosure area for total building airtightness should be sought for homes that use very high R-value walls and roofs (e.g. R-40/R-60).

The interaction of airflow and heat transfer is poorly understood. There appears to be a real impact, and for accurate assessments heat flow due to conduction and heat flow due to through-enclosure convection cannot simply be added. However, the precise interaction has not been experimentally quantified and is likely in the order of more than 10% impact for high R enclosures.

Airflow within enclosures influence heat flow in all walls. However, small defects and a limited amount of wind washing can be tolerated in enclosures with R-values of 10 to 20 without serious reductions in performance. For high R-value enclosures, even small, perhaps even unavoidable defects, can begin to have a more significant influence on heat flow for high R-value enclosures. Hence, techniques to reduce the impact of these mechanisms need to be implemented. For example, the use of wind washing barriers, multiple layers of insulation and insulation with higher resistance to airflow may be required.

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1.5.2. Heat Losses Below Grade in Low Energy Buildings

by John Straube, December 2009

Building America High R-value Enclosures Research Project:

Heat Losses Below Grade in Low Energy Buildings

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December 2009

Abstract:

This report documents a literature survey of predictions and measurements of below-grade heat loss through slabs and basement walls, as well as recommend appropriate R-values for these components in cold climates (DOE Climate Zones 5 and higher). Methods of prediction of heat loss through slabs are examined and found to be notoriously inaccurate. Field data from several studies is then reviewed and used to develop a better understanding of below slab soil temperatures. With assumptions based on the reviewed literature, straightforward calculations indicate that, among other recommendations, a sub-slab insulation of level at least R5 should be strongly recommended for all cold climate zones.

Heat Losses Below Grade in Low Energy Buildings

Introduction

The three components of above-grade building enclosures, walls, roofs, and windows, are well studied. Over the last decade, Building Science Corporation has developed and demonstrated technology for delivering high R-value enclosures. Building America teams have used a wide variety of techniques and technologies to achieve high R-value above-grade enclosure components. Much of the research work BSC has conducted to date on basements has involved durability and air quality aspects.

Building codes such as the IECC and ASHRAE 90.1 now require full-height basement insulation of R10 to R15. However most building codes do not require insulation under slabs over the entire area: in many cases, only perimeter insulation is required for slab-on-grade homes and no insulation at all is required below slabs in basements. As such, the slab is the last remaining component of the building enclosure not required to be insulated by code. Given the heightened expectations for energy performance, sub-slab insulation may be an economically sound decision for homes with High R enclosure components in cold climates (Zone 4 and higher).

The investigation below will focus on energy savings. However, insulating below slabs also has the benefit of decoupling the slab temperature from the ground temperature and instead coupling it closely to the interior air temperature. This results in improved radiant and foot comfort and dramatically reduces the chance of condensation and mold growth, particularly below furniture, carpet and boxes.

The goal of this report is to document a literature survey of predictions and measurements of below-grade heat loss through slabs and basement walls, as well as recommend appropriate R-values for these components in cold climates (DOE Climate Zones 5 and higher).

Predicting Heat Loss Through Slabs

The prediction of heat loss through slabs is notoriously inaccurate. A literature survey of measured temperatures and heat loss of slabs and basements was conducted with the goal of collecting cold climate examples of measured heat loss or temperatures through insulated slabs. There are a remarkably few such studies.

Conductive heat flow can be predicted by

$$Q = U \cdot A \cdot \Delta T = 1/R \cdot A \cdot \Delta T \qquad [1]$$

Where U (=1/R) includes the heat transfer coefficient of air to slab. This interior heat flow coefficient for heat flow downward to a cool slab is 6.1 $W/m^2 {}^\circ C$ or R0.93 according to the ASHRAE Handbook of Fundamentals. The thermal resistance of concrete is negligible: for normal density unreinforced concrete, the thermal conductivity ranges from 1.5 to 2.5 W/mK depending on aggregates and moisture content, which translates to a thermal resistance of R0.20 to R0.35 for 3.5" slabs. A value of R0.27 is used below as a mid-range estimate.

Hence, for a standard unfinished and uninsulated slab on grade, the heat flow per unit area (flux) can be estimated as:

$q = 1/R \cdot \Delta T = \Delta T / R = \Delta T / 1.2$ in °F and square feet.

The addition of a carpet can increase the thermal resistance to by R0.5 to R2.0 depending on the nature and thickness of the carpet and underlayment. This small quantity of insulation can result in a significant reduction in heat flow. However, this reduction in heat flow also causes colder slab temperatures, and increases the risk of condensation.

As a first order estimate, if the soil temperature is 55°F and the interior basement air temperature is 70°F, the heat flow through a 1,000 square foot unfinished basement slab would therefore be about 12,500 Btu/hr, or half as much with an R1.2 carpet and underlayment. This is a significant heat loss in a low energy home, as houses with 1,000 to 2,000 sf of above-grade floor area and high R enclosures will have peak design heat losses in the range of 25,000 to 40,000 Btu/hr. Heat losses through uninsulated slabs are also significant in that the exterior temperature (55°F in the previous example) is essentially constant for months at a time.

The soil temperature below a site varies over the year (Figure 1, from Minneapolis MN). However, at 5 to 10 m (15 to 30 ft) below the surface the temperature is quite stable. Figure 2 shows the range of deep earth temperatures from various sources as it varies across the continental United States. Deep soil temperatures of 40 to 60°F are present across much of DOE Climate Zones 5, 6 and 7.

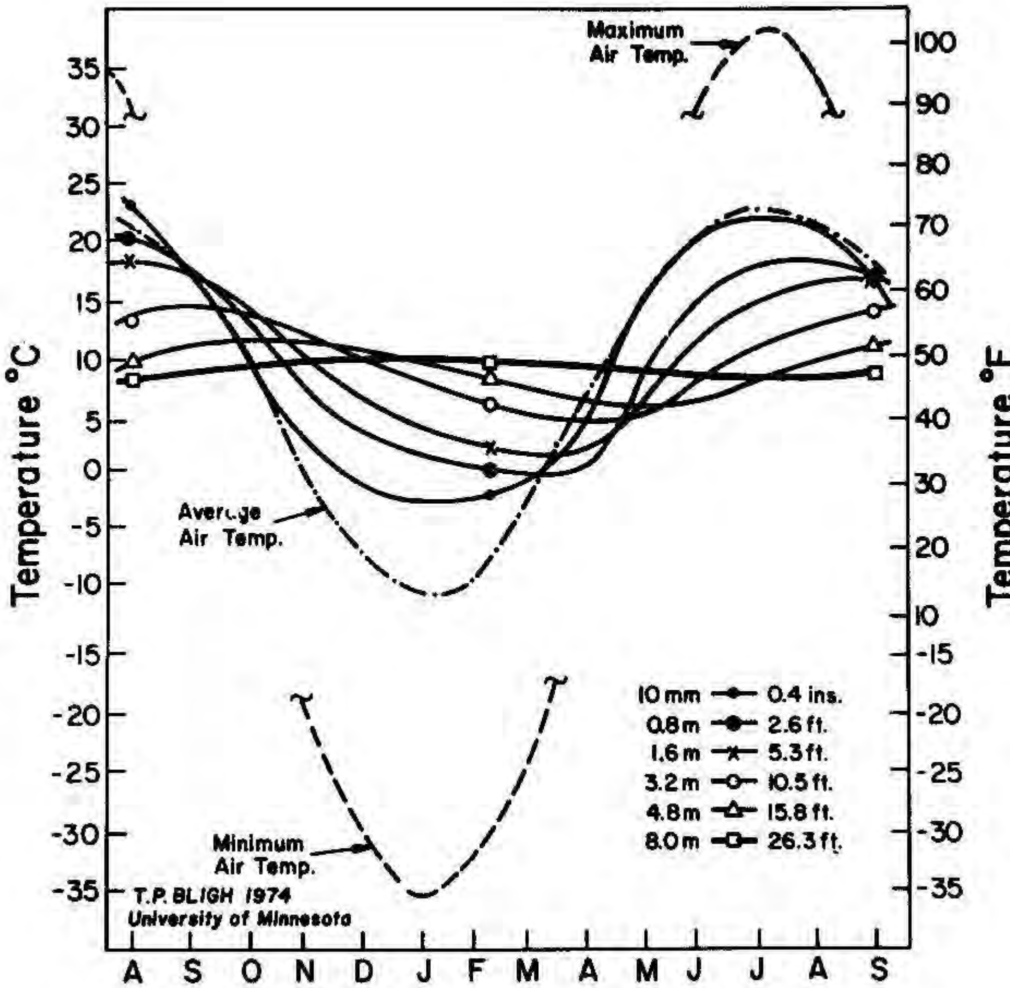

Figure 1: Soil temperature variation (away from any buildings) as a function of depth and time of year

The construction of a building disturbs these temperatures. Heat flows outward from a building heated to 65 or 70°F to the cooler soil (or 40 to 60°F). This heat loss warms the soil in a "bubble" of warmer soil. The actual soil just below the slab will therefore vary with: interior air temperature over the year, the insulation of the slab and basement, the thermal conductivity of the soil (which is influenced by moisture content), the level of the water table, and the shape of the building, among other variables.

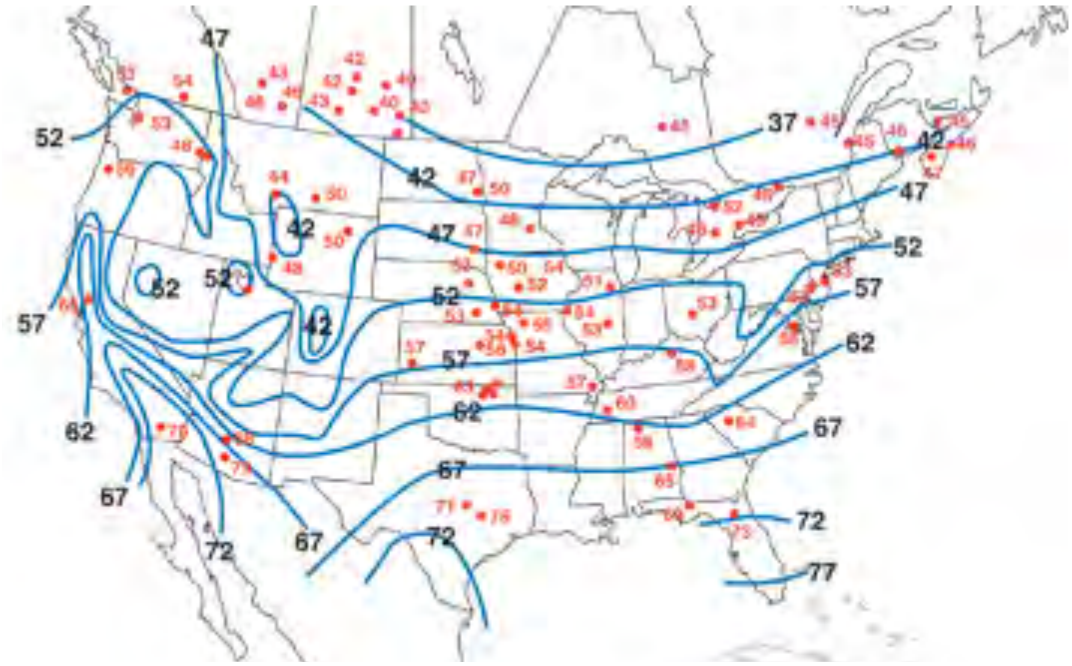

Figure 2: Deep ground annual average soil temperature

The large number of variables make it difficult to predict heat loss as reliably as above-grade models, which can use the air temperature measured at thousands of sites across the country.

To predict heat loss a better understanding of the sub-slab soil temperatures are required, and the deep ground temperature is definitely not the correct temperature: the actual soil temperature under a building will always be warmer.

The most applicable field data found reported the temperatures monitored for a year under a slab-on-grade insulated to R32 in Finland [Rantala 2005], which had an average heating season (6 month) soil temperature of 10-12 °C (50-53 °F). In other work, slabs insulated to R15 [Rantala and Leivo, 2004] exhibited slightly warmer temperatures over 12.5 °C (55 °F).

A more recent paper [Rantala and Leivo 2009], shows even higher temperatures, with averages of 15 °C/60 °F in the winter, except near the edge where they dropped to a minimum of 10 °C/50°F (the overall heating season average temperature was over 15°C/60°F however). They also report, based on numerous of their own measurements, and a review of dozens of models and measurements that: “The average temperature of the fill layer beneath a heated building is relatively high and even throughout the year. This is true especially at the central part of the slab, where the influence of short-term or seasonal fluctuations in the outdoor air temperature is less effective”.

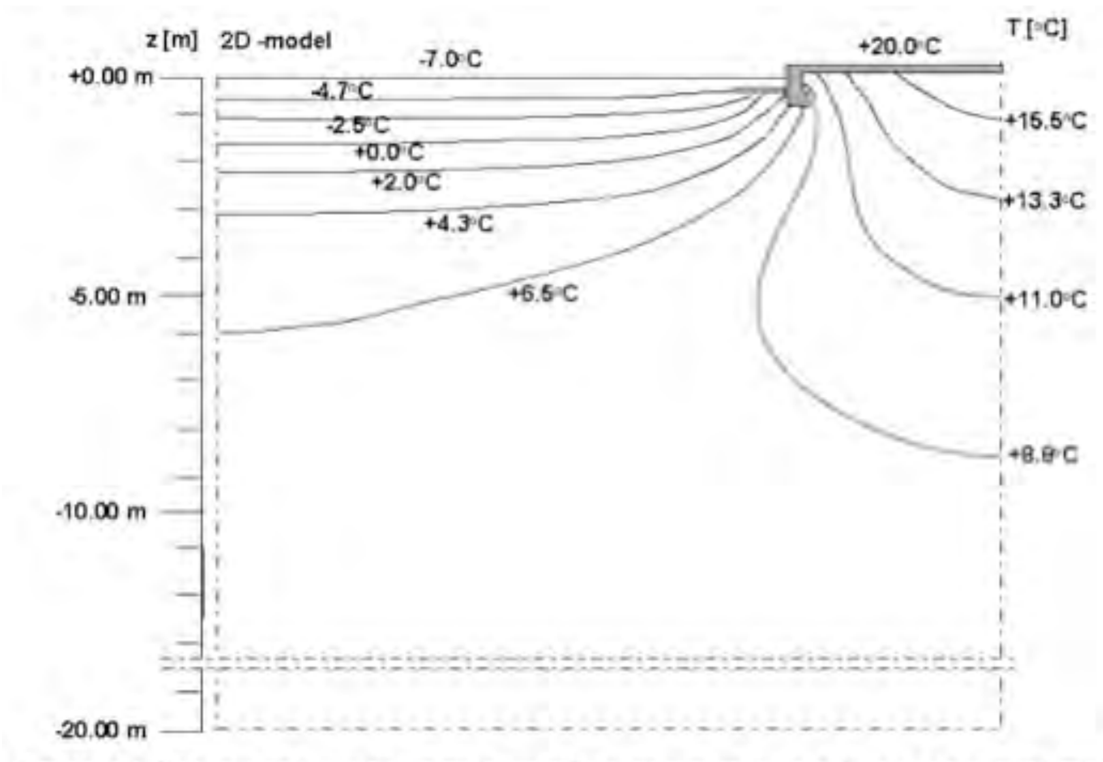

Figure 3: Predicted subsoil temperatures below a R16 slab in a cold climate [Rantala and Leivo 2004].

In Norway, another cold climate country that builds many slabs on grade (due to the prevelance of poor soil and high groundwater conditions), a paper in the 7th Nordic Symposium on Building Physics on slab heat loss [Gunderson 2005] reported "In Norwegian climatic conditions, with a yearly mean soil temperature varying from 2 ~ 7°C, we can use 12±1°C as a default value for the inner zone reference soil temperature". Soil temperatures of 2 to 7°C (36 to 45°F) are equivalent to the colder parts of Zones 6 and 7 deep earth temperatures, and 12°C is 54°F Fahrenheit. It stands to reason that if annual average soil temperatures are higher, in the 40 to 45°F range, design soil temperatures of 55°F would reasonable.

NREL designed a low-energy house for the National Park Service [Balcomb 1999]. The house was carefully measured, modeled, and monitored. Part of the measurement campaign in 1997 included real measurements of the heat loss through the insulated slab on grade floor. The slab on grade was around 1,000 square feet in size, insulated with R10 insulation below the slab and R10 along the perimeter stem walls. The heat loss through the slab was found to be less than the predictions for a number of reasons, but the net effect is that even with only R10, the slab insulation was very effective as only 2.3 MMBtu/yr was lost. Sub-slab temperatures were found to be in the 58-60°F range during the winter period. Appendix A provides more information about this useful project.

Hence, during the heating seasons the average temperature between soil and indoor air is about 15°F. Compare this to an average winter month in Zone 5 and Zone 6, where the average outdoor air temperature is 30°F or 40°F, yielding an average temperature difference of 30°F or 40°F. For example, in Burlington VT, the 6-month heating season’s average air temperature is 31°F and that of Minneapolis is 28°F. That is, 2 or 3 times as large a temperature difference acts across the walls windows and roofs as slabs. Since heat loss is a direct function of temperature difference, to reduce heat flux to the same level, one would expect that slab R-values would be 1/2 or 1/3 as much as walls.

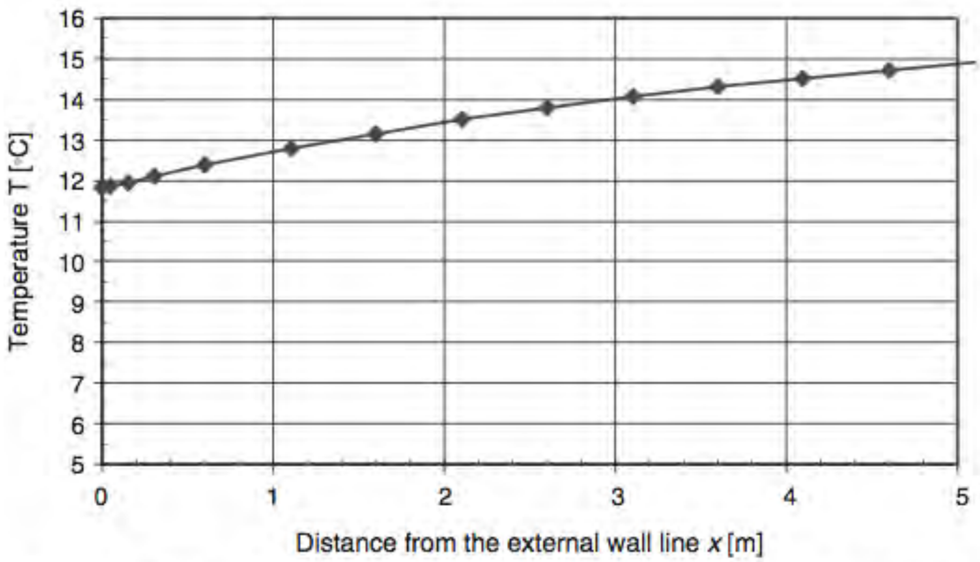

Figure 4: Computer model extrapolation of measured mean annual temperature underneath a 33 ft wide R32 slab-on-grade for a cold Finnish climate with a deep soil temperature of 45° F [from Rantala 2005].

As a rough estimate of heat loss over the year, a comparison can be made to Heating Degree Days (HDD). An average sub-slab soil temperature of around 55°F can be roughly converted to heating degree days (since the temperature is so stable) with a 65F base and a 180 days heating season by

(65-55)*(180 days) = 1800 heating degree days 65°F.

Six months, or 180 days, is a long heating season, and 65°F is a higher than the balance temperature of a well-insulated home, but the comparison to HDD65 climate is reasonably valid. Using this approach, the slab heat loss per unit area over the season would be predicted to be about 1/4 of the above-grade enclosure of the same R-value as a 7200 HDD65 climate (such as Burlington VT) through the walls and roof. More detailed analysis and measurements suggest that this ¼ heat flux ratio is more appropriate for slabs in basements and a 1/3 ratio may be more appropriate for slabs at grade level.

Predicting Below-grade Heat Loss

The DOE 2.1 programming code that underlies many computer models used to predict home energy consumption (such as EnergyGauge USA) uses a simple model which bases the temperature difference between the indoor conditions and monthly, climate specific undisturbed soil temperatures. This approach results in an over estimate of heat loss. Other models result in significant errors in prediction because the ground temperature is assumed to be equal to the average air temperature. This is a rough estimate, but the differences between average air temperature and measured ground temperature are significant. Bahnfleth [1990] showed that using mean air temperature for mean annual ground temperature results in significant (25%) errors. His study considered mostly uninsulated slabs and did not compare model results to real measurements.

EGUSA, a DOE 2.2 model used by many Building America teams, does not even allow the entry of slab insulation and hence does not show the benefits of slab insulation at all.

The most accurate model, based on comparison of measured field energy consumption over a number of years, with numerous houses in a range of cod climates, remains the Mitalas model developed many years ago at the Division of Building Research [Mitalas 1983, 1987]. Ackerman [1987] and Emery [2007] are two further field measurement results that conclude that the Mitalas method is the most accurate method that is simple enough to be general (e.g., it does not require a finite element model with the precise boundary conditions and soil properties).

This model can be implemented with a spreadsheet or with a more sophisticated computer program called BASESIM. The heat loss on a month-by-month basis are produced (see Figure 5), which can then be used to assess the heat loss during the period of the year during which heating is needed in the above-grade portions of the house.

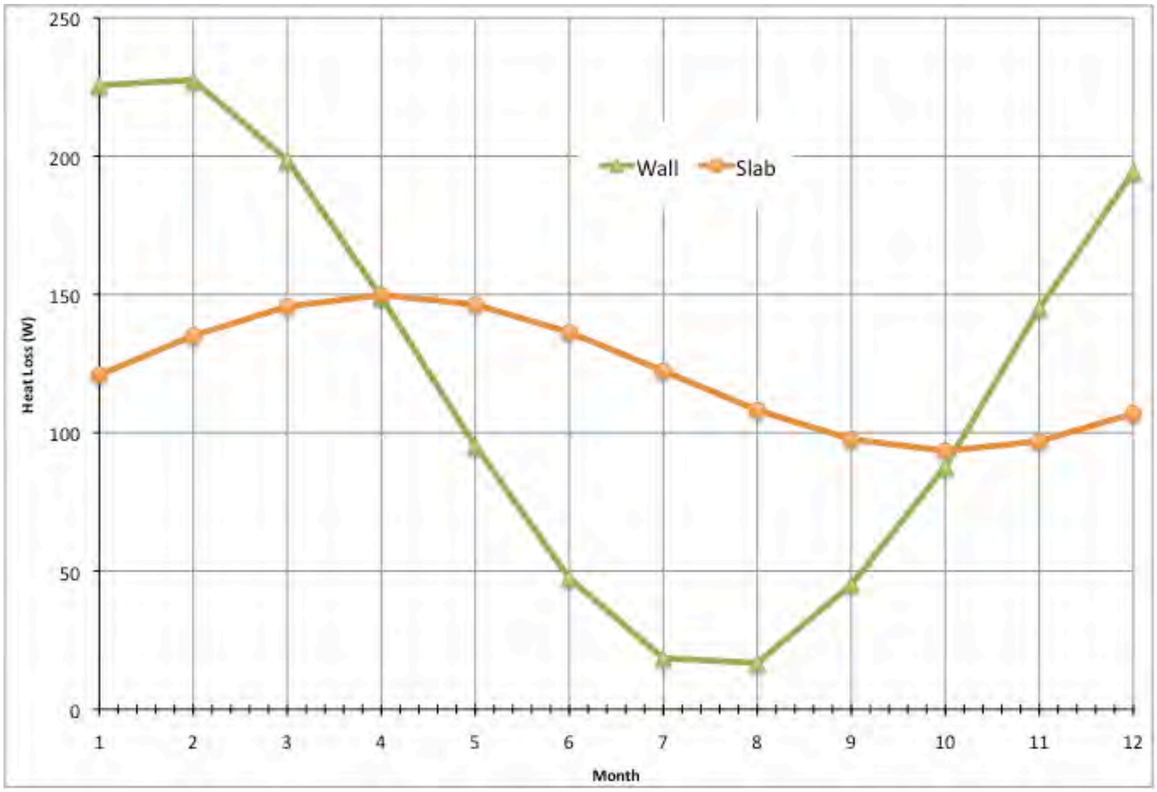

Figure 5: Monthly Average Heat Flow through Basement walls and Slab using the Mitalas model

Results for the standard implementation are shown in Figure 6 for a single-storey 26 x 40 ft house with an 8' high basement (1' above grade) and 15% Window-to-Wall ratio. The 6-month heating season heat loss is predicted to be 7.94/4.70/3.94/2.84 MMBtu for R10/R20/R30/R40 basement walls (above grade portions included) and 4.78/3.89/3.29/2.86/2.27 MMBtu for a R5/R10/15/20/30 basement slabs. The total below-grade proportion of the wall heat loss was predicted to be 4.40 MMBtu.

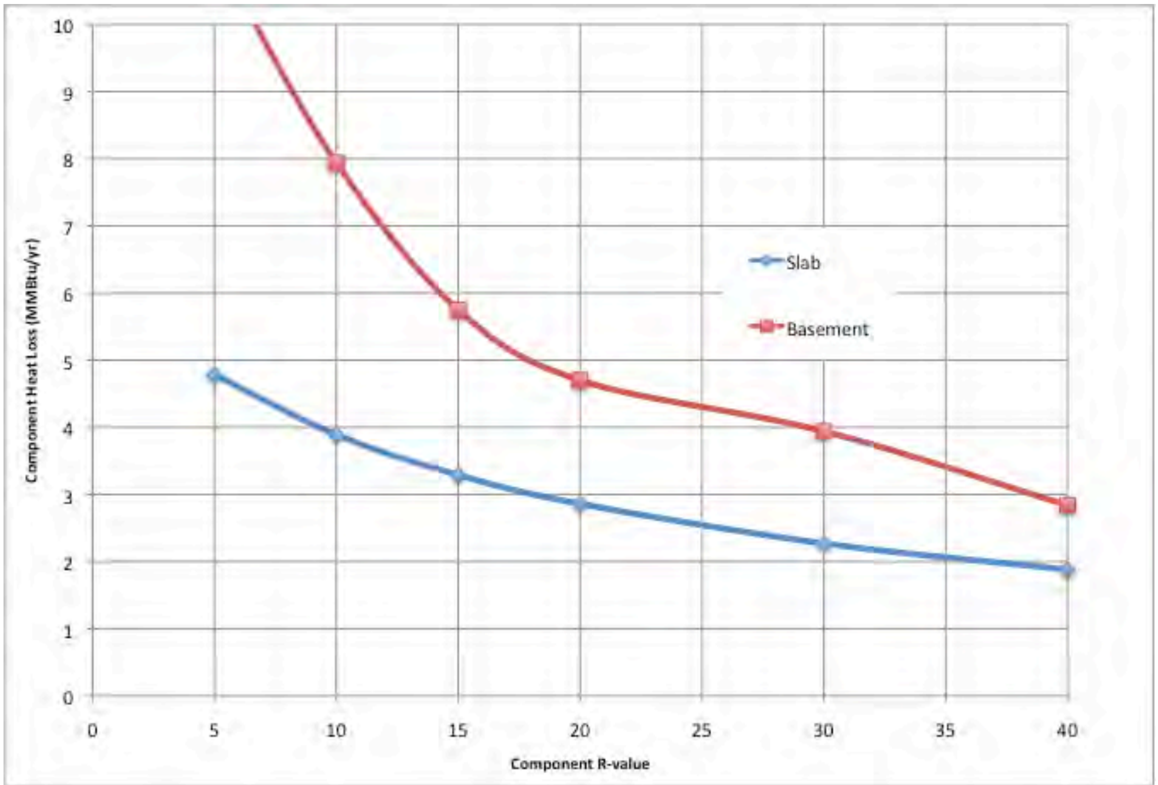

Figure 5: Heating Season Heat Loss as Function of Component R-value for Example Cold-Climate House Basement

Using a simple HDD65 approach to predict heat loss, and assuming a 7200 HDD65 (Zone 6) climate, the heat losses through representative above-grade components can be compared. The total loss is predicted to be 26.6 MMBtu/yr.

These results are representative of a wide range of simulations for Zone 5-7 homes of average size and simple plan shape: by selecting a basement slab basement wall and above-grade wall insulation level in the ratio of 1:2:4, heat loss through each component will be roughly equivalent. Window heat loss can be the largest of all of these components, even if modest areas of triple-glazed R5 windows are specified. Air leakage rates of 2.5ACH@50 Pa would increase this heat loss component to 6.77 MMBtu and make air leakage the dominant heat loss path.

Component	MMBtu	kWh	% of Total
Roof (R60)	3.00	878	11%
Walls (R40)	4.36	1278	16%
Basement wall (R20)	5.13	1504	19%
Basement slab (R10)	3.89	1140	15%
Windows (R5)	6.16	1805	23%
Air Leakage (1.5ACH@50)	4.06	1189	15%
Total	**26.6**	**7794**	**100**

Table 1: Heat Loss over Heating Season for Example House by Component

These conclusions do not take any account of the cost or other performance implications of insulating each of the components.

The cost of insulating below a slab are relatively modest: adding foam insulation to above-grade walls not only costs the increase in foam material, but also the labor, increased fastening, and increased roof area and opening trim costs. Adding insulation below the slab can be relatively inexpensive: currently about 10 cents per R per square foot (i.e., $1/sf for R10). The only other cost increase with thickness (assuming one layer of labor cost is the same regardless of thickness) is the cost of excavation. Excavating an additional depth of 2" or 4" within the area of the floor slab is typically negligible.

Increasing the R-value of walls has other added costs, such as larger window return trim, longer screws, bigger overhangs, more roof area, etc. This is not usually a large premium, but it is a real one. Hence, when one needs to choose between R6/inch polyiso or R4/in expanded polystyrene (EPS), the 50% thicker insulation is one reason polyiso is often chosen, especially for high-R wall with R-30 to R45 insulation levels.

The cost of insulating a ventilated trusses attic with loose fill insulation is much less than either walls or slabs. Loose fill insulation in an attic can be installed at a cost of 2 to 4 cents per R per square foot. The cost of cathedral ceiling insulation is higher: both the need for some more expensive air impermeable insulation and the cost of thicker framing and/or trim makes this component more expensive to insulate than slabs.

Not all of the components can be simply separated. Air leakage through the rim joist area can be a significant heat loss and should be addressed (practically it must be addressed to achieve a 1.5 ACH@50 Pa tightness target). This area can be targeted with spray foam to both insulate and airseal. The cost of the insulation and application (in the order of 15 to 20 cents per R per square foot) should be distributed between energy savings from air sealing and energy saving from insulation.

Practical Implications for High R Assemblies

The slab is the last building enclosure component for which insulation levels are not required by code or installed in practice. The per unit area heat loss through slabs installed at grade level with stem wall insulation can be expected to be about 1/3 that of the above-grade walls. Slabs that are installed deeper in the earth, at floor level of a basement (i.e., 5 to 8 ft below grade), will exhibit a heat loss closer to ¼ that of above grade walls. Sub-slab insulation of at least R5 should be strongly recommended for all cold climate zones.

In general, a slab insulated to R10 has relatively low heat loss compared to other components of a highly insulated building enclosure. In some cases (low cost insulation, expensive renewable energy) it might make sense to increase the floor slab insulation to R20 in a very low energy home. The heat loss would drop from 3.9 to 2.9 MMBtu per year in the example home. This is a rather marginal reduction (about 4% of the total heat loss or 309 kWh/yr), which would cost about $1000 in additional insulation. Given that the cost of providing space heating is currently in the order of 4 to 10 cents per kWh, R20 sub-slab insulation would have an exceptionally long payback period (even assuming a fuel escalation rate of 7% per annum) with no more durability or comfort benefits than R10.

Increasing basement walls insulated from R10 to R20 results in about a 2 MMBtu/yr annual energy saving, and since a cost-effective combination of fibrous (fiberglass, cellulose or rockwool) and foam insulation can be used, the cost of increasing the R-value from 10 to 20 is relatively small. (Note: Other BSC work has shown that a 2x4 stud frame with R12 batt insulation is not moisture safe. A layer of foam insulation is necessary outboard of the wood frame. Hence, adding 2" of XPS to an R13 batt insulated 2x4 stud wall is the upgrade path to an R20 basement wall). A reasonable increase in basement R-value to R30 can be achieved by changing from R13 to R19 batt in 2x6 framing at 24" o.c. framing, and 2" of polyiso insulation (R13) outboard of this. Upgrading to R30 is not a significant cost (perhaps 50 cents per square foot of wall area) and yet results in an almost 2 MMBtu/yr energy savings. Hence, increasing basement wall insulation may be a viable upgrade path, and will usually be significantly more economical than increasing basement slab insulation beyond about R10.

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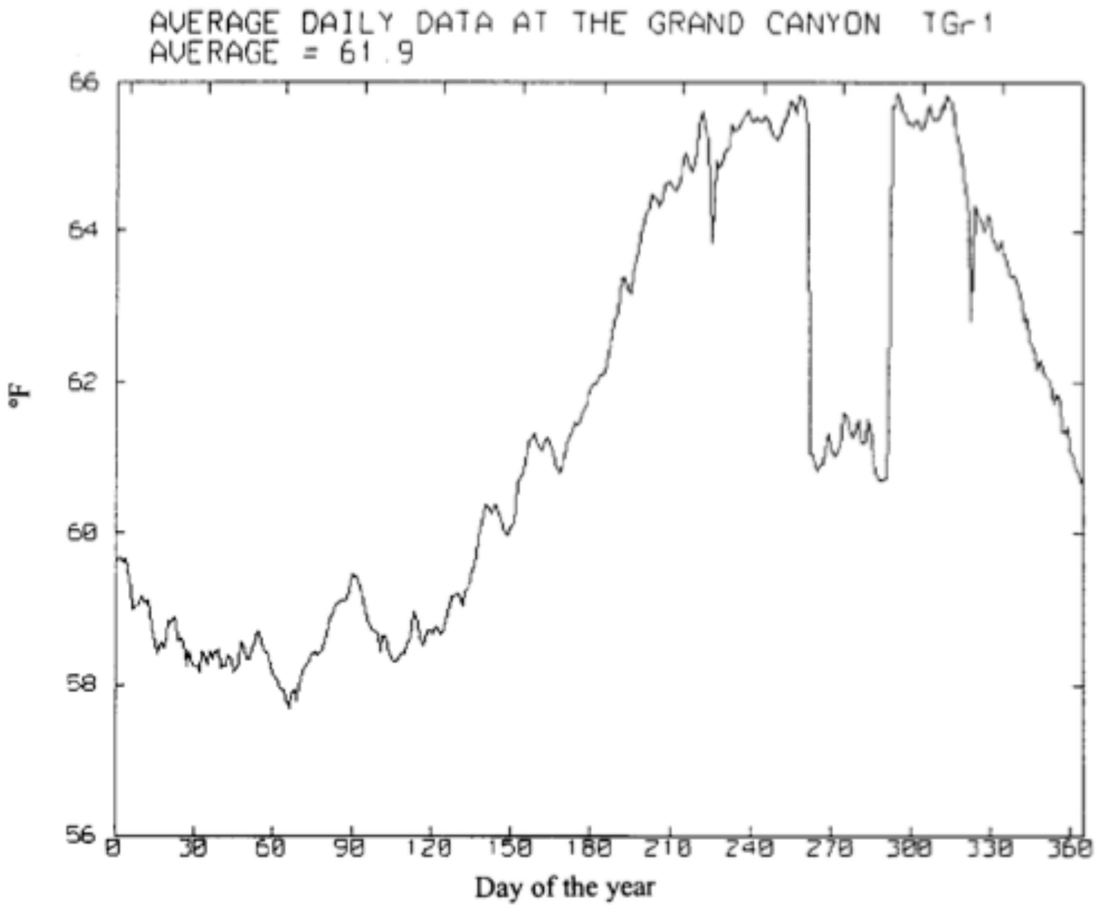
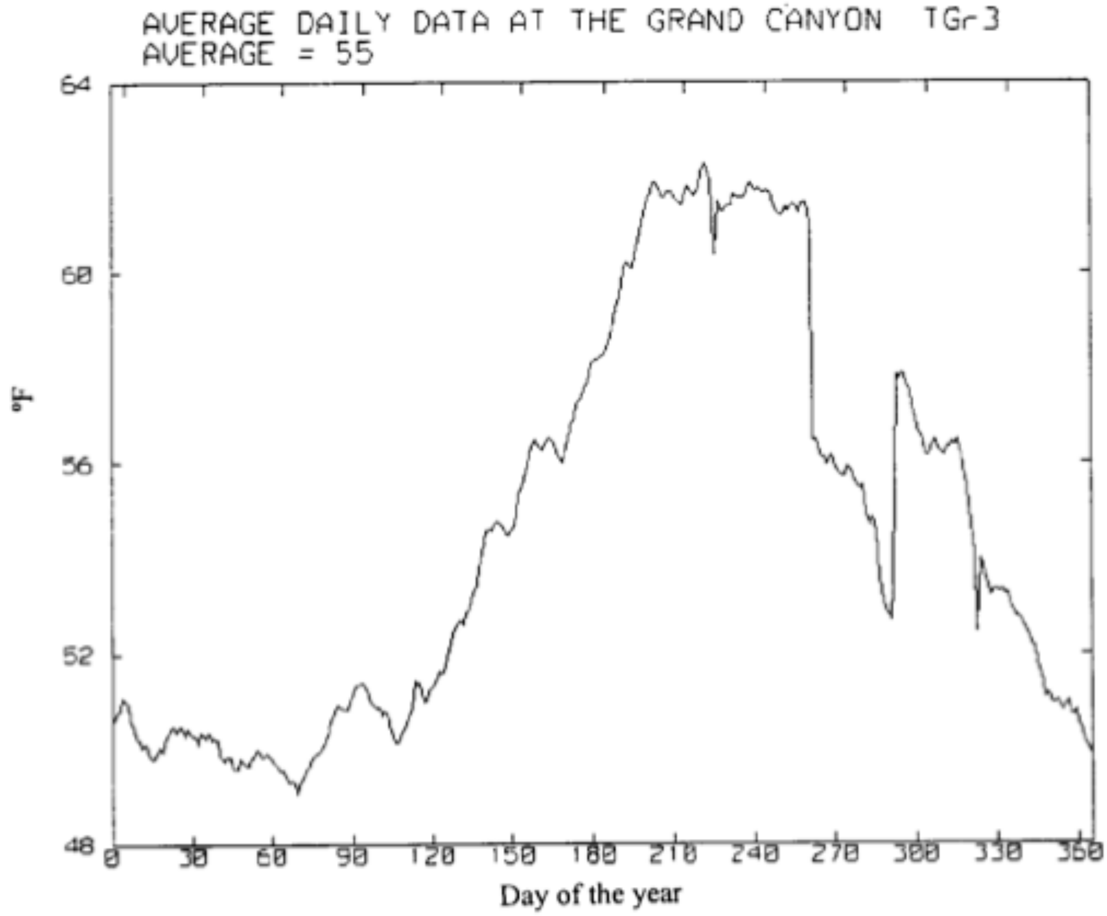
Appendix A: NREL Grand Canyon Research House



Measured Temperature under the Sub-Slab Insulation over the year near the edge of the house



Measured Temperature under the Sub-Slab Insulation over the year near the edge of the house

Floor Heat Loss Estimate

The Grand Canyon house floor is well insulated against heat loss to the ground by 2 in. of rigid foam under the slab and 2-in. perimeter insulation on the exterior of the footings. As a convenient by-product of the under-slab insulation, researchers measure the heat flow to the ground by measuring the temperature difference (ΔT) across the insulation. The floor heat loss is calculated by assuming a conductance value for the 2 in. of rigid foam insulation of 0.1 Btu/h•°F•ft^2, an area of 200 ft^2 for the perimeter floor area and 800 ft^2 for the center floor area (the area of the floor slab is roughly 1000 ft^2).

Tables of monthly average values of the temperatures and ΔTs are given in Appendix C along with plots showing daily variations by month, daily averages for each day of the year, and hourly data for the mid-winter months. Note that although there are large changes in the two ΔTs from month to month, the daily variation is very small. The total floor heat loss is highest in the summer at about 800 Btu/h and lowest in winter at about 400 Btu/h. The reason for this contradictory-sounding statement is that the inside temperature is higher in summer than in winter and the ground temperature does not change much.

The striking result is that the floor loss is small, averaging only 621 Btu/h over the year (182 W). The October-through-March average is 536 Btu/h for a total of 2.3 million Btu or 682 kWh. Researchers concluded that the floor insulation is very effective. The small value of 682 kWh is significant compared to the 2089 kWh of back-up heat required.

The measured winter ground heat loss of 536 kWh is 22% of the value of 2418 kWh predicted by the model. This is not surprising, in retrospect, because (1) the model accounted only for short-term dynamics,* (2) the model did not account for annual heat storage in the ground, and (3) it was assumed that the room temperature would be constant (i.e., within the range of thermostat settings) throughout the year. The first assumption is probably not too far from reality; however, the last two assumptions were not realistic.

The most important factor is the variation in inside temperature with seasonal changes. This is a lifestyle issue that would vary from resident to resident. The more complex models, including models that solve for ground heat flow, using finite-element calculations of two- or three-dimensional heat flow, would not be of much help because of the unpredictable variation in house temperature.

1.5.3. High-R Wall Case Study Analysis

by Jonathan Smegal, March 2009, with 2-page Case Studies

Building America Special Research Project: High-R Walls Case Study Analysis

Research Report - 0903

March 11, 2009 (rev. 8/7/09)

John Straube and Jonathan Smegal

Abstract:

Many concerns, including the rising cost of energy, climate change concerns, and demands for increased comfort, have lead to the desire for increased insulation levels in many new and existing buildings. More building codes are being modified to require higher levels of thermal control than ever before. This report considers a number of promising wall systems that can meet the requirement for better thermal control. Unlike previous studies, this one considers performance in a more realistic matter, including some true three-dimensional heat flow and the relative risk of moisture damage.

Building America Special Research Project
High-R Walls Case Study Analysis

2009 08 07

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A. Introduction

Many concerns, including the rising cost of energy, climate change concerns, and demands for increased comfort, have lead to the desire for increased insulation levels in many new and existing buildings. More building codes are being modified to require higher levels of thermal control than ever before. This report considers a number of promising wall systems that can meet the requirement for better thermal control. Unlike previous studies, this one considers performance in a more realistic matter, including some true three-dimensional heat flow and the relative risk of moisture damage.

In some cases, increasing the quantity of insulation may result in an increased risk of moisture-related issues when the exterior surfaces of the enclosure are kept colder in cold weather, and the interior surfaces are kept cooler in warm weather. This may result in increased condensation, and increased freeze thaw potential or decay potential of the assembly in different situations. Analysis is required to predict the potential hygrothermal risks due to increasing the amount of insulation (R-value) in the enclosure.

High R-values for framed wall assemblies are defined here as ranging from approximately R18 to R40 and above depending on the geographic location and climate conditions. A high R-value wall in the south will be considerably less than a high R-value in a cold climate. The analysis in this report includes a summary of historical wall construction types and R-values, current construction strategies, as well as walls that will likely become popular in the future based on considerations such as energy and material availability.

Previous work, largely stemming from research in the 1970's and 1980's, involved postulating newer assemblies with improved R-values. R-value was, and often still is, defined as the "clear wall" R-value (no framing effects accounted for) or the total amount of insulation installed in the assembly. The increased moisture risks were rarely considered.

A study currently being conducted by the National Research Council of Canada (NRC) is investigating and developing durable and energy efficient wall assemblies for Northern Canada. In the first stage of the NRC study, meetings with the northern communities and investigations of the houses were conducted. A literature review covering selection criteria for possible envelope assemblies in Northern Canada, current wall systems and systems to consider was written (Saïd 2006). Walls are currently undergoing extreme temperature testing in the NRC laboratory in Ottawa, Canada. All of the walls being tested by the NRC are constructed with a polyethylene air and vapor barrier and none of the walls are constructed with exterior insulation (Rousseau, et al. 2008).

The Cold Climate Housing Research Center (CCHRC) of Alaska has conducted field monitoring tests on different wall systems, specifically to assess the moisture-related performance of high performance wall systems. Several tests were conducted on a test hut at the University of Alaska Southeast, in Juneau AK (8574 HDD65 or 4763 HDD18) (Smegal and Straube 2006), and others were conducted on the CCHRC main office building in Fairbanks Alaska (13980 HDD65 or 7767 HDD18) constructed in 2007. Streaming data and wall drawings can be viewed on the CCHRC website showing the thermal performance of the wall systems (CCHRC 2007). CCHRC also successfully completed construction of a high R-value house as part of the Building American program in Haida, AK, and the report can be found online (BSC 2008).

Some of the walls for this high R-value study were chosen based on the literature review of the NRC report, and references to construction techniques from both the NRC and CCHRC will be made throughout this report. Some walls have been built by niche builders since the early 1980's.

1. OBJECTIVE

The objective of this study is to identify highly-insulated building enclosure wall systems based on selected criteria, resulting in a durable affordable, and resource efficient enclosure that provides a comfortable living environment in different climate zones. This report will present the analysis of different enclosure wall strategies and present their advantages and disadvantages according to several comparison criteria.

2. SCOPE

This study is limited to wall systems for cold climates. Further studies should be conducted to address other components of the building enclosure such as roofs and foundations. In general, only cold climates are considered in this report since enclosures in cold climates benefit the greatest from a highly insulated building enclosure, but important conclusions can also be drawn for other climate zones.

3. APPROACH

This study examines thermal and moisture control, durability, buildability, cost and material use. The quantitative analysis for each wall system is based on a two-dimensional steady-state heat flow modeling program and a one-dimensional dynamic heat and moisture (hygrothermal) model. Minneapolis, MN in IECC climate Zone 6 was used as the representative cold climate for most of the modeling, because of the cold winter weather, and fairly warm and humid summer months. In cold climates, a building's enclosure is often the most important factor limiting heat loss, both in terms of insulation and air tightness.

B. Analysis

1. WALL ASSEMBLIES REVIEWED

Because there are a number of variables possible for each possible wall system depending on the local practices, climate, and architect or general contractor preferences, an attempt was made to choose the most common wall systems and make notes and comments about other alternatives during analysis. This list of chosen systems is explained in more detail in the analysis section for each wall system.

- Case 1a : Standard Construction Practice with 2x6 framing
- Case 1b : Standard Construction Practice with 2x4 framing
- Case 2a : Advanced Framing with 1" of XPS insulated sheathing
- Case 2b : Advanced Framing with 4" of XPS insulated sheathing
- Case 3 : Interior 2x3 horizontal strapping
- Case 4 : Double Stud
- Case 5 : Truss Wall
- Case 6 : Structural Insulated Panel Systems (SIPs)
- Case 7 : Insulated Concrete Forms (ICFs)
- Case 8a : Advanced Framing with low density (0.5 pcf) spray foam
- Case 8b : Advanced Framing with high density (2.0 pcf) spray foam
- Case 9: Hybrid system with high density (2.0 pcf) (Flash and Fill) spray foam and fibrous insulation
- Case 10: Double Stud wall with 2" of high density (2.0 pcf) spray foam and fibrous insulation
- Case 11: Exterior high density (2.0 pcf) (Offset Frame Wall) spray foam with fibrous cavity insulation
- Case 12: Exterior Insulation Finish System (EIFS)

2. ANALYSIS CRITERIA

A comparison matrix will be used to quantitatively compare all of the different wall system strategies. A value between 1 (poor performance) and 5 (excellent performance) will be assigned, upon review of the analysis, to each of the comparison criteria for each wall. An empty comparison matrix is shown below in Table 1 as an example.

Table 1: Criteria comparison matrix

	Thermal Control	Durability (wetting/drying)	Buildability	Cost	Material Use	Total
Criteria Weighting	1	1	1	1	1	
Case 1: Standard Construction						
Case 2: Advanced Framing with Insulated Shtg						
Case 3: Interior Strapping						
Case 4: Double Stud						
Case 5: Truss Wall						
Case 6: SIPs						
Case 7: ICF						
Case 8: Sprayfoam						
Case 9: Flash and Fill (2" spuf and cell.)						
Case10: Double stud with 2" spray foam and cell.						
Case 11: Offset Framing (ext. Spray foam insul.)						
Case 12: EIFS with fibrous fill in space						

The criteria scores will be summed for each test wall, and the walls with the highest scores are the preferred options assuming all of the comparison criteria are weighted equally. It is also possible to weight the different comparison criteria asymmetrically depending on the circumstances surrounding a particular wall design. The weightings for each wall will fall between 1 (least important) and 5 (most important). The weighting is multiplied by the comparison criteria score and added to other weighted values. An example of the weighted conclusion matrix will be shown in the Conclusions section.

One of the benefits of using a comparison matrix is that it allows a quantitative comparison when some of the criteria, such as cost may be poorly defined or highly variable. For example, even though the exact costs of different insulations may be uncertain, fiberglass batt insulation is always less expensive than low density (0.5 pcf) spray foam which is less expensive than high density (2.0 pcf) spray foam, so these systems can be ranked accordingly regardless of the actual costs.

2.1 Heat flow analysis

Two dimensional heat flow analysis was conducted for each test wall using Therm 5.2, a two-dimensional steady-state finite element software package developed by the Lawrence Berkeley National Laboratory at the University of California. Therm was used to calculate the thermal performance of each of the different proposed assemblies including thermal bridging effects.

In many cases, it is generally assumed that installing an R13 fiberglass batt into a 2x4 stud wall leads to wall performance of R13. This does not take into account thermal bridging of the wall framing including the studs, rim joist and top and bottom plates which allows heat to bypass the insulation decreasing the whole wall R-value. Therm can predict the impact of thermal bridging and determine a whole wall R-value that considers the rim joist, wall framing and top plate(s).

The effect of thermal bridging and different framing details requires a metric more complex than just a single R-value to allow for meaningful comparisons. Five R-values have been and are used in the building industry. Oak Ridge National Labs (ORNL) proposed a number of definitions in (Christian and Kosny 1995). We have found it useful to add some and extend their definitions.

1. **Installed Insulation R-value**

This R-value is commonly referenced in building codes and used by industry. This is simply the R-value labeled on the product installed in the assembly.

2. Center-of-Cavity R-value

The R-value at a line through an assembly that contains the most insulation, and the least framing, typically, the middle of a stud-bay in framed construction.

3. Clear wall R-value

R-value of an assembly containing only insulation and minimum necessary framing materials at a clear section with no windows, corners, columns, architectural details, or interfaces with roofs, foundations or other walls.

4. Whole-wall R-value

R-value for the whole opaque assembly including all additional structural elements (such as double studs), and typical enclosure interface details, including wall/wall (corners), wall /roof, wall/floor, wall/door, and wall/window connections.

5. True R-value

The R-value of an enclosure assembly that includes all thermal bridging, air leakage, wind washing, convective loops, radiation enhancements, thermal and hygric mass, and installation defects.

Each of these measures is progressively more realistic. The True R-value is very difficult to measure without field samples.

The whole-wall R-value will be approximated in this analysis. To accurately calculate this whole-wall R-value, the wall in question was divided into three sections, modeled individually, and then the results were combined with a weighted average.

The R-value of the wall section was simulated in plan view to best represent the thermal bridging effects of wall studs as shown in Figure 1. This section is similar to a clear-wall R-value except that the studs are placed closer together to more accurately represent actual numbers of wood framing elements used in real wall systems. The height of the wall section for simulation purposes is 92 inches.

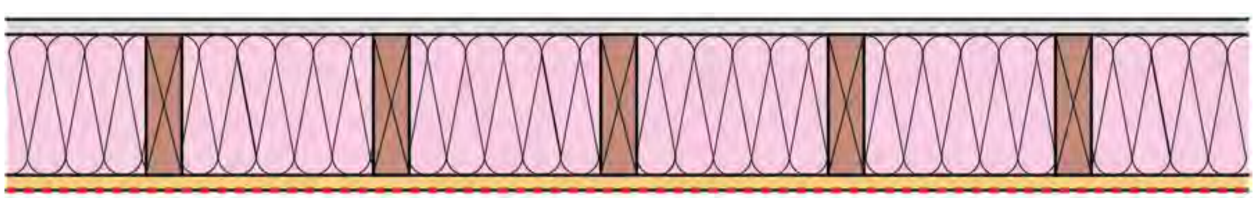

Figure 1 : Plan view of wall section for Therm simulation

The top plate was simulated in section view to assess the importance of the thermal bridging of the top plate(s). This section was eight inches in height since the thermal effect of the top plate will influence the effectiveness of the cavity insulation in its vicinity. The R-value of this detail was calculated over the entire height as indicated by the red dashed line in Figure 2.

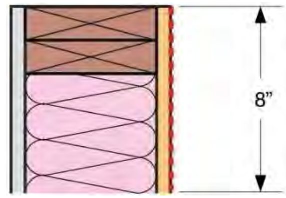

Figure 2: Top plate simulation with 8” of wall

The rim joist was also simulated in a vertical section to take into account the thermal bridging effects of the bottom plate, sill plate, floor sheathing and rim joist. It was simulated with eight inches of wall above the floor sheathing to take into account any changes in the insulation caused by thermal bridging effects.

The concrete foundation was included beneath the rim joist to determine the effects of the interface between the foundation and wood framing, but the concrete was not included in the R-value calculation as indicated by the red dashed line in Figure 3.

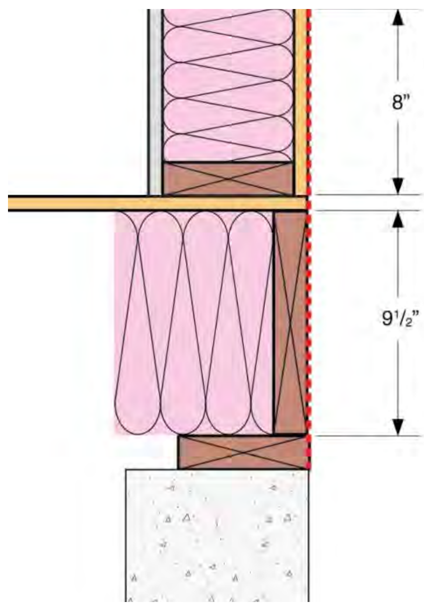

Figure 3 : Rim joist simulation with 8" of wall

Although Therm is a two-dimensional modeling software it was used to model three-dimensional geometries. For example, at the rim joist, there are floor joists connected to the rim joist alternating with pockets of insulation. When this is drawn and modeled in plan view (Figure 4), the effective R-value of just this section through the assembly can be determined.

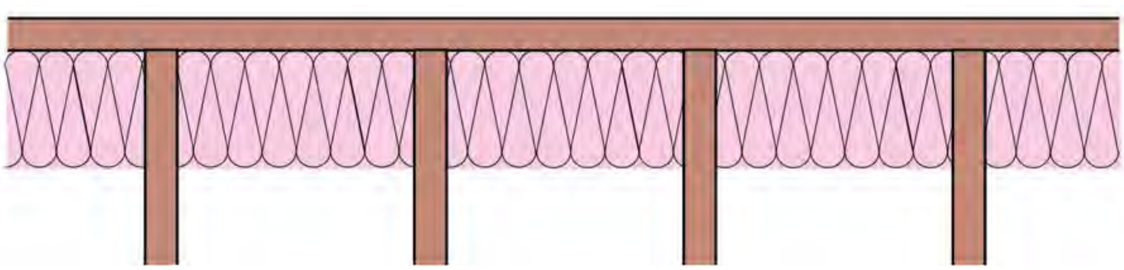

Figure 4 : Plan section of rim joist, floor joists, and fiberglass batt insulation

A fictitious material is then made in the Therm library that has the effective thermal properties of the insulation and floor joists and used in the section profile for modeling of the rim joist system (shown in red in Figure 3).

Once the R-values are calculated for all three sections of a wall system, The Whole Wall R-value is calculated by taking the weighted average of the individual components as shown in the equation below. The total wall height from the bottom plate to the top plate is nine feet.

$$\text{Total wall R-value} = \text{R-value top plate x } \frac{\text{height of top plate}}{\text{overall wall height}} + \text{R-value of rim joist x } \frac{\text{height of rim joist}}{\text{overall wall height}} +$$

$$\text{R-value of wall section x } \frac{\textit{height of wall section}}{\text{overall wall height}}$$

One drawback of Therm is that it cannot accurately represent air leakage and insulation installation defects, both of which can significantly lower the effective R-value of the assembly by bypassing the insulation in the wall system. There are four main ways in which air leakage affects interact with the enclosure as shown in Figure 5.

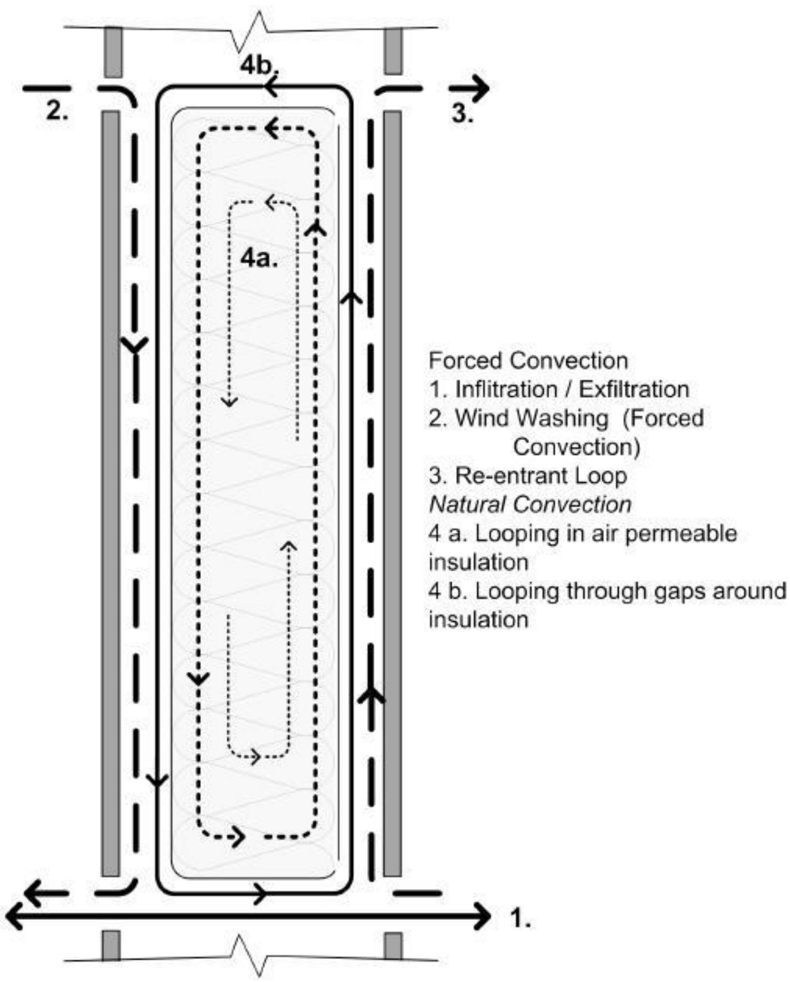

Figure 5 : Common Convective Heat Flow Paths in Enclosures

One of the most common areas for air leakage is at the rim joist where fiberglass batts are often stuffed into the cavities between the ceiling joists. In houses that are constructed using this method it is quite common to feel air leakage through the assembly at the rim joist bypassing the insulation even without imposing a pressure difference across the enclosure. Air tightness of the building enclosure has begun to improve in cold climates for the most part to address occupancy comfort issues and contractor call-backs.

Both cellulose and fiberglass batt insulation have similar R-values per inch according to ASTM testing standards, but in practice, standard installation for both fiberglass batt and cellulose generally result in higher installed R-values for cellulose compared to fiberglass batt. Fiberglass batts are almost always installed with air gaps against either the drywall or exterior sheathing and fiberglass installers are generally not careful installing fiberglass batts, leading to air gaps around plumbing, electrical and other obstacles in the stud space. These air gaps can lead to convective looping in the stud space as well as poorly insulated locations resulting in cold spots around obstacles that could increase the risk of moisture condensation.

Cellulose installation is blown into place, and fills the entire stud space between the exterior sheathing and drywall, around all obstacles without leaving air gaps. Cellulose has also been shown to have better convection suppression resulting in less convective looping and, in some studies, tighter building enclosures. Neither cellulose nor fiberglass batt is an air barrier, so an air barrier should always be used with either insulation.

Since air leakage cannot be simulated using Therm, the increased convective looping and air movement around poorly installed batt insulation relative to cellulose insulation, and to a lesser extent blown-in or sprayed fiberglass cannot be captured numerically in this study. Also, the convection suppression through the cellulose insulation relative the fiberglass batt insulation cannot be fully appreciated using this analysis.

All of the Therm analysis were conducted with an interior temperature of 20°C (68°F) and an exterior temperature of -20°C (-4°F) so the results could be compared. Because the R-value is a weak function of the temperature difference across the enclosure, the results may vary slightly for different temperatures.

A list of some of the most common materials and their respective conductivities used in the two dimensional Therm analysis are shown in Table 2. Where there was some discrepancy in the choice of conductivity that should be used for modeling, values from the ASHRAE Handbook of Fundamentals were selected.

Film conductance values of 8.3 W/m^2K for the interior surface and 34.0 W/m^2K for the exterior surface were used for all Therm simulations

Table 2 : Conductivity values used for two dimensional heat flow analysis

Enclosure Component	Thermal Conductivity k [W/mK]	R-value per inch [hr·°F·ft^2/Btu]
R8 Fiberglass Batt (2.5")	0.045	3.1
R13 Fiberglass Batt (3.5")	0.039	3.7
R19 Fiberglass Batt (5.5")	0.042	3.4
Extruded Polystyrene (XPS)	0.029	4.9
Expanded Polystyrene (EPS)	0.038	3.7
Framing lumber	0.140	1.0
Cellulose Insulation	0.040	3.5
0.5 pcf spray foam	0.037	3.8
2.0 pcf spray foam	0.025	5.7
OSB	0.140	1.0

One of the considerations for thermal modeling was the number of framing components in the wall system. This is usually measured as using the “framing factor”, or percentage of a wall cross-sectional area that is comprised of framing elements. For example, a 2x4 stud spacing in a typical wall system is sixteen inches (405 mm) on centre. Modeling the wall with a stud spacing of 16 inches o.c. (Figure 6) results in a framing factor of approximately 9%. This method of analysis ignores many of the framing members present in real walls including double studs at windows, partition walls, corners, etc.

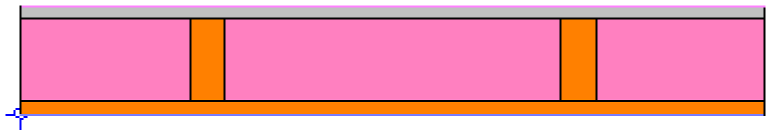

Figure 6 : Typical framing 16" o.c. - 9% framing factor

Field studies have shown that the actual average framing factor, using 16" o.c. framing, including studs, bottom plate and top plates throughout an entire house are closer to 23-25% (Carpenter and Schumacher 2003). Modeling was conducted to investigate the impact on effective R-value for a wall system with 23% (Figure 7) framing factor and with 9% framing factor. It was found that the Clear Wall R-value of a wall section insulated with R13 fiberglass batt decreased from R12.6 to R10.1 when a more realistic 25% framing factor was used. This results in a Whole Wall R-value decrease from R12 to R10 when the more realistic 25% framing factor was used. The reason that neither wall section achieved a Clear wall or Whole Wall R13 is because of the thermal bridging effects of the studs, one of the underlying issues in using Installed Insulation R-values to describe enclosure systems.

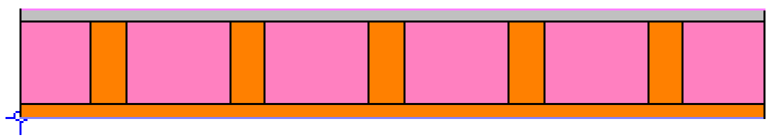

Figure 7 : Actual average framing factor of 23% in standard construction

Most of the framed walls in this analysis were proposed with advanced framing techniques (also described as Optimum Value Engineering, OVE) that include 2x6 framing, 24" o.c., and single top plates. Field studies have also been conducted on advanced framed walls, and it was found that the average framing factor is approximately 16%. For comparison purposes, all of the standard wood framed wall sections were simulated with a framing factor of 25% and advanced framed walls were modeled with 16% framing factor.

Table 3 shows all of the Whole Wall R-values calculated using Therm simulations. The thermal performance is further discussed for each wall system in the following sections.

Table 3 : R-values for analyzed wall systems

Case	Description	Whole Wall R-value	Rim Joist	Clear Wall R-value	Top Plate	Framing Fraction
1a	2x6 AF, 24"oc, R19FG + OSB	**15.2**	12.3	16.1	12.5	16%
1aii	2x6, 16"oc, R19FG + OSB (25%ff)	**13.7**	12.3	14.1	12.5	25%
1b	2x4 AF, 24"oc, R13FG + OSB	**11.1**	9.8	11.5	9.8	16%
1bii	2x4, 16"oc, R13FG + OSB (25%ff)	**10.0**	9.8	10.1	9.8	25%
2a	2x6 AF, 24"oc R19FG + 1" R5 XPS	**20.2**	18.5	20.6	20.3	16%
2b	2x6 AF, 24"oc R19FG + 4" R20 XPS	**34.5**	29.0	35.6	35.4	16%
3	2x6 AF, 24"oc, 2x3 R19+R8 FG	**21.5**	13.4	23.5	18.4	16%
4	Double stud wall 9.5" R34 cellulose	**30.1**	14.4	33.5	28.8	
5	Truss wall 12" R43 cellulose	**36.5**	18.6	40.5	34.4	
6a	SIPs (3.5" EPS)	**14.1**	12.3	14.5	10.6	
6b	SIPs (11.25" EPS)	**36.2**	14	41.6	28.2	
7a	ICF - 8" foam ICF (4" EPS)	**16.4**		16.4		
7b	ICF - 15" foam ICF (5" EPS)	**20.6**		20.6		
7c	ICF - 14" cement woodfiber ICF with Rockwool	**17.4**		17.4		
8a	2x6 AF, 24" o.c., 5" 2 pcf R29 SPF, OSB	**19.1**	13.6	20.3	19.5	16%
8b	2x6 AF, 24" o.c., 5.5" R21 0.5 pcf SPF, OSB	**16.5**	13.1	17.2	16.6	16%
9	2x6 AF, 24"oc, 2" SPF and 3.5" cellulose	**17.5**	13.2	18.4	17.7	16%
10	Double stud with 2" 2.0 pcf foam, 7.5" cell.	**32.4**	15.9	36.2	28.5	
11	Offset frame wall with ext. spray foam	**37.1**	18.8	40.6	41.9	16%
12	2x6 AF, 24"oc, EIFS - 4" EPS	**30.1**	23.8	31.4	31.1	16%

*AF - Advanced Framing

2.2 Hygrothermal Analysis

Hygrothermal analysis is the combined analysis of heat and moisture movement. For this research, WUFI® from the Fraunhofer Institut Bauphysik was used to determine the hygrothermal performance of the chosen wall systems.

WUFI® was used only to investigate wood framed walls. ICF and SIPs walls are not subject to the same moisture-related failure mechanisms as wood framed walls and hence, to model with WUFI® would provide little useful information.

Vinyl siding was chosen as the cladding system for the analysis as it is the most widely used residential cladding system in North America, and it can be found in almost any geographic area.

Minneapolis MN was chosen as the climate to compare all of the chosen wall systems. Minneapolis is in DOE climate zone 6, which experiences cold wintertime temperatures as well as some warm humid summer temperatures.

A Class I or II vapor retarder is required according to the International Residential Building Code (IRC) on the interior of the framing in zones 5,6,7,8 and marine 4. This will control vapor condensation on the sheathing in the winter months as shown in Figure 9. The RH at the sheathing did not reach elevated levels in Case 1 (framed walls with OSB sheathing) with the Class I vapor retarder in WUFI®. There are some exceptions to the interior vapor control layer if a sufficient amount of insulation and vapor control is installed on the exterior.

Often times, the 6-mil polyethylene vapor barrier is also used as the air barrier. This is very difficult to detail correctly, and because it may not be air tight, there is a considerable risk to air leakage condensation on the sheathing should interior air leak into the enclosure.

WUFI® was used to simulate three different scenarios which can cause performance problems for wall systems; wintertime condensation, summer inward vapor drives, and simulated drying following a wetting event.

2.2.1. Moisture Balance

Assessing moisture related durability risks involves three different moisture processes; wetting, drying and moisture redistribution. These three processes in combination with the safe storage capacity will determine the risk of moisture damage to a building enclosure assembly (Figure 8).

Wetting of the enclosure is most often caused by rain, air leakage condensation, vapour condensation, plumbing leaks and built in construction moisture. Minimizing these sources with good design details for shedding rain, air tightness, and vapour control will help decrease the risk of moisture related durability failure.

Drying is important since nearly all building enclosures will experience wetting at some point. Assemblies that can dry to both the interior and exterior generally have an advantage and can manage more frequent wettings.

The safe storage capacity of an individual material or enclosure system is fundamental to good building design. Over the last 50 years, there have been changes to buildings that decrease the safe storage capacity and increase the risk of moisture related durability. Four of these changes are listed below (Lstiburek 2007).

1. Increasing the thermal resistance of the building enclosure
2. Decreasing the permeability of the linings that we put on the interior and exterior of the enclosure
3. Increasing the mould and water sensitivity of the building materials
4. Decreasing the buildings ability to store and redistribute moisture.

These changes to building enclosures and materials increase the need for good enclosure design with water management details and maximizing the drying potential. It is rarely economical to build an enclosure with no risk of wetting but managing the risk is important. In any building enclosure, building materials should be chosen based on moisture tolerance that correlate to the risk of moisture in the enclosure. In all cases drying should be maximized, and attention to good design details should be used.

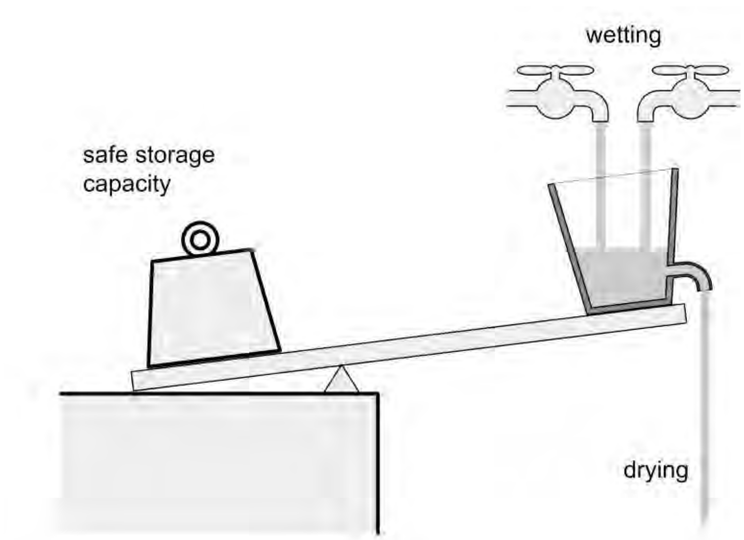

Figure 8 : Moisture balance

2.2.2. Wintertime Condensation

Wintertime diffusion and air leakage condensation potential was determined for each case. The diffusion condensation potential was determined by analyzing the relative humidity at the interior surface of the sheathing (or other condensation plane) during the cold winter months. The interior relative humidity for these simulations was sinusoidal condition varying from a minimum of 30% in the winter to a maximum of 60% in the summer. The interior relative humidity is strongly correlated to occupancy behavior and ventilation strategies. Typically, the relative humidity in a cold climate will decrease to between 20% and 30% in the winter months. In extremely cold climates this could decrease even further. If humidification is used, or there is inadequate ventilation in a relatively airtight enclosure, the RH could increase to 40 or 50% which increases the risks significantly.

In the 2007 supplement to the International residential code, three classes of vapor control were defined for enclosure systems (1 US perm = 57.4 ng/(s·m^2·Pa))

- Class I: 0.1 perm or less (eg. sheet polyethylene)
- Class II: 0.1 < perm ≤ 1.0 perm (eg. kraft faced fiberglass batts , some vapor barrier paints)
- Class III: 1.0 < perm ≤ 10 perm (latex paint)

Class I or II vapor retarders are required on the interior side of framed walls in Zones 5, 6, 7, 8 and marine 4 (IRC N1102.5). Under some conditions, such as vented claddings or insulated sheathings, a Class III vapor retarder is allowed by the code (IRC Table N1102.5.1).

Figure 9 shows a comparison of the relative humidity caused by vapor diffusion at the sheathing for Case 1, standard construction, and Case 2, advanced framing with insulated sheathing. A polyethylene vapor barrier is installed on the interior of the framing in Case 1, vapor barrier paint is used for Case 2 with 1" of XPS insulated sheathing, and latex paint is used for Case 2 with 4" of XPS insulated sheathing. Table 4 shows the vapor control strategies and permeance values for all four walls compared in Figure 9.

Table 4 : Vapor control strategies and permeance values for Case 1 and 2

Case	Description	Vapor Control	Permeance [US perms]	Permeance [ng/(s•m^2•Pa)]
1a	2x6 AF, 24"oc, R19FG + OSB	poly	0.07	4.0
1b	2x4, 16"oc, R13FG + OSB	poly	0.07	4.0
2a	2x6 AF, 24"oc R19FG + 1" R5 XPS	vapor retarder paint	1.0	57.8
2b	2x6 AF, 24"oc R19FG + 4" R20 XPS	latex paint	10.7	616.7

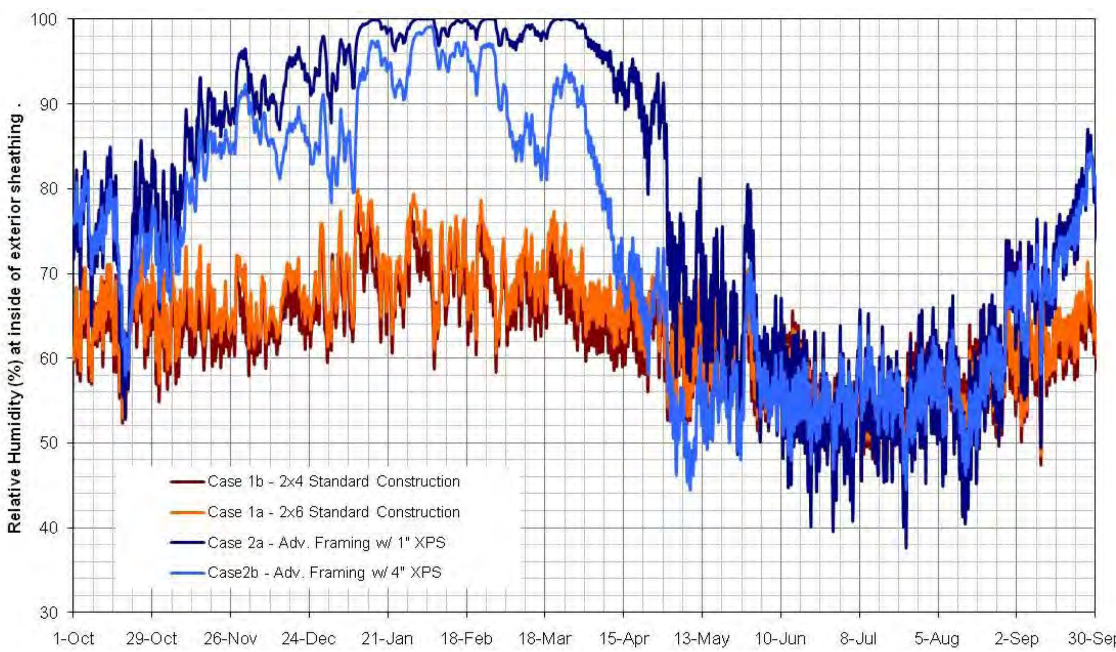

Figure 9 : Winter time sheathing relative humidity for Case 1 and Case 2

The advanced framing wall (Case 2) with 1" of XPS was modeled with the minimum amount of vapor control required (Class II vapor retarder - 1 perm or 57 ng/Pa•s•m2) according to the IRC. The elevated moisture levels during the winter months are only a small concern, since the XPS is not moisture sensitive, and temperatures are quite low in the winter months, minimizing moisture related risks. The advanced framing wall with 4" of XPS insulated sheathing does not require any extra vapor control layers according to the IRC because it qualifies as having more than R-11.25 insulated exterior sheathing over 2x6 wood framing.

Figure 10 shows the potential for air leakage condensation for Case 1 and Case 2. This analysis shows the dewpoint of the interior air and the temperature of the sheathing for both Case 1 and Case 2. When the temperature of the sheathing falls below the interior dewpoint line (black line) the potential for air leakage condensation exists. The severity of condensation increases the further below the dewpoint line the sheathing temperature falls and the length of time the sheathing temperature is below the interior air dewpoint line, since drying is minimal during periods of condensation.

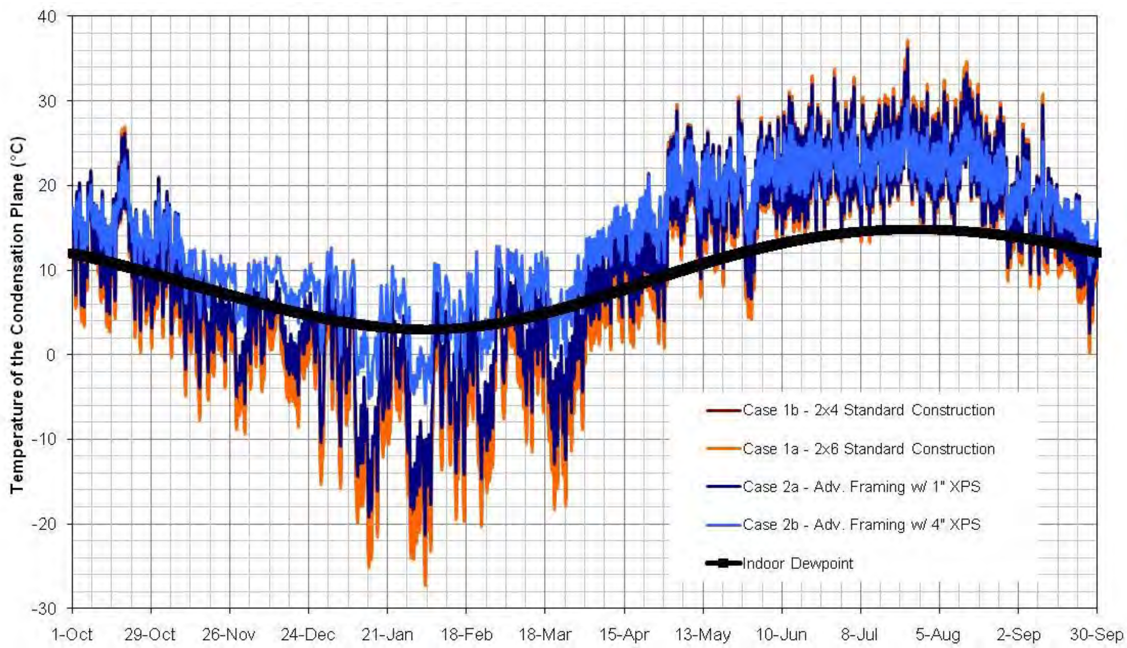

Figure 10 : Winter air leakage condensation potential for Case 1 and Case 2

The risk of air leakage condensation is greatest on the standard construction walls, and slightly improved on the advanced framing wall with 1" of XPS. The wall with 4" of insulated sheathing has the least risk of moisture related durability issues from air leakage condensation because of the short periods of time the interior face of the sheathing is below the dewpoint. When the hours of potential condensation are added together over the entire year, Case 1 with 2x4 construction and 2x6 construction have approximately 4400 and 4500 hours respectively of potential condensation. Case 2 with 1" of insulated sheathing experiences approximately 3800 hours of potential condensation and Case 2 with 4" of insulated sheathing only experiences 1200 hours of potential air leakage condensation.

One method of improving the risk of air leakage condensation in standard construction is by using a hybrid wall system (Case 9). In our analysis a hybrid wall system consists of advanced framing (2x6 24"oc) with OSB sheathing and 2" of high density (2.0 pcf) spray foam installed against the interior of the sheathing. This spray foam can be an excellent air barrier if installed properly and because it is vapor semi-impermeable, the temperature of the condensation plane increases (Figure 11). Two inches of high density spray foam was chosen because it is reported as being the maximum thickness that can be sprayed in one pass on any surface. This hybrid wall has approximately the same amount of condensation potential as Case 2 with 4" of exterior XPS and will be significantly less expensive than Case 8 with 5" of high density spray foam. Unfortunately, it also has much less R-value, and still suffers from thermal bridging.

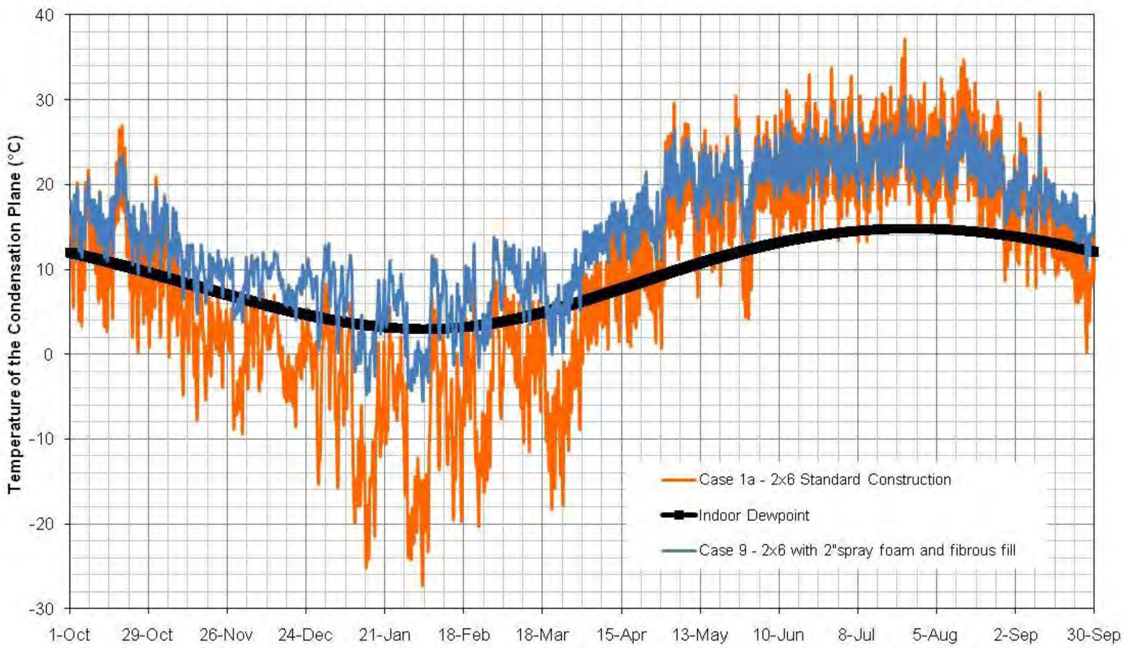

Figure 11 : Winter air leakage condensation potential for Case 1 and Case 9

The winter time sheathing relative humidities for Cases 3, 4, and 5 without air leakage are shown in Figure 12. Constructing these walls with a Class I - 6-mil polyethylene vapor control layer, there is no risk to moisture related issues on the sheathing from vapor diffusion in the winter.

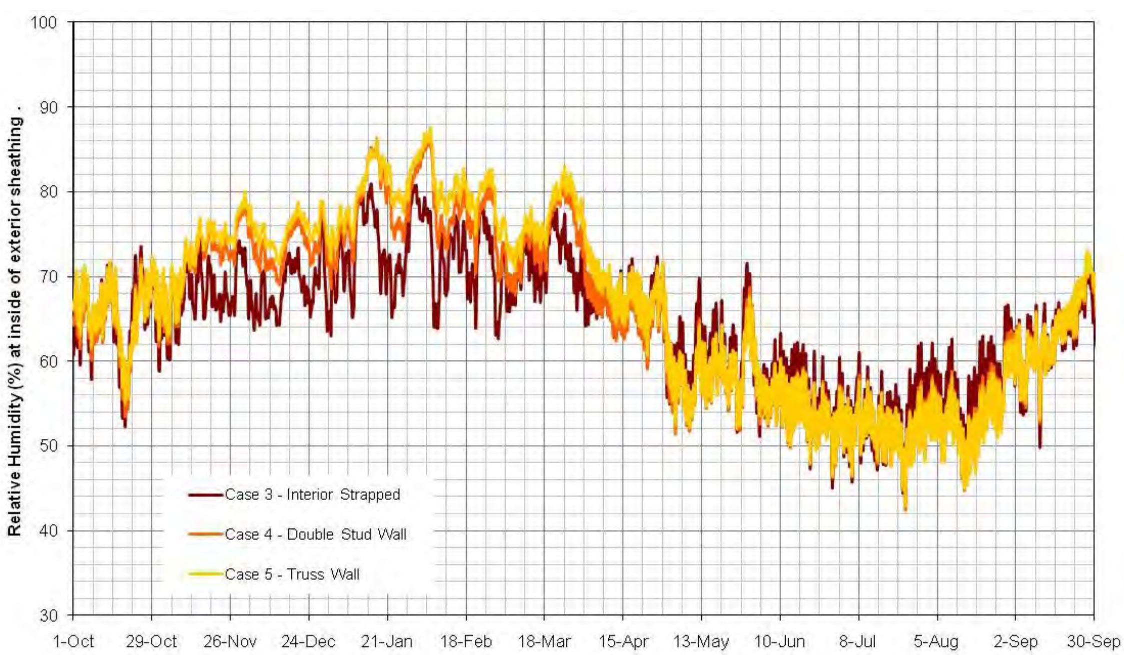

Figure 12 : Winter time sheathing relative humidity for Case 3, Case 4, and Case 5

Winter time air leakage condensation potential for Cases 3, 4, and 5 are shown in Figure 13. The sheathing temperatures of all three of the walls spend a significant portion of the year below the dew point of the interior air because of the increased thermal resistance of the wall system. This means that considerable care must be given to all air tightness details, or there will be a high risk of moisture related durability issues from air leakage.

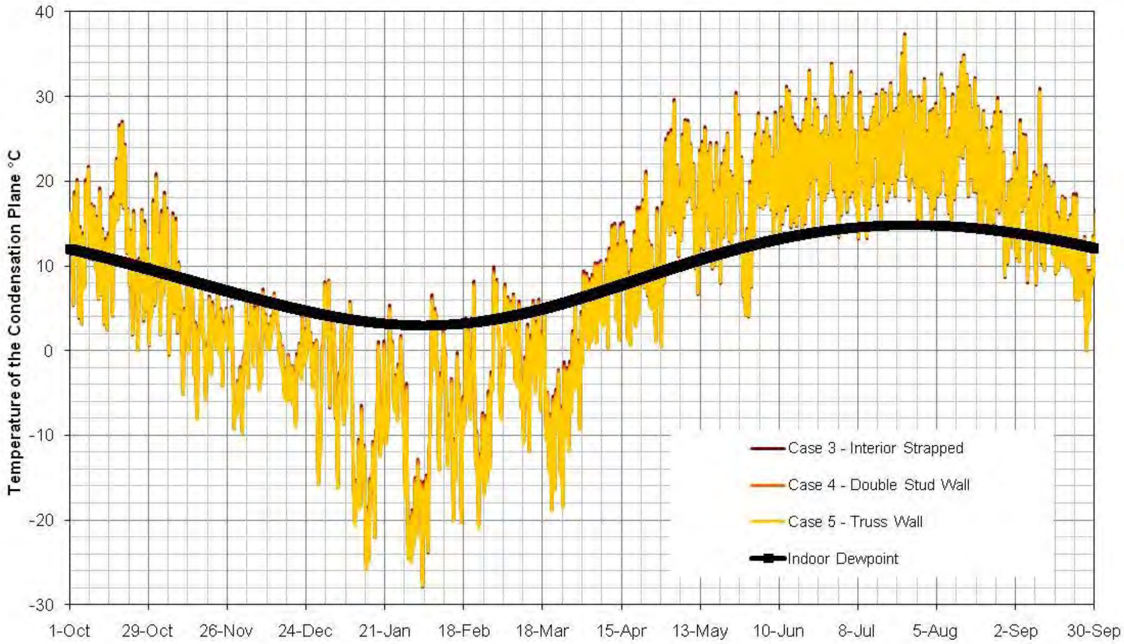

Figure 13 : Winter air leakage condensation potential for Case 3, Case 4, and Case 5

Increasing the temperature of the condensation plane can be done by adding spray foam to the interior surface of the exterior sheathing. Case 10 is a double stud wall with 2" of high density foam sprayed against the sheathing from the interior. Increased vapor resistant insulation raises the temperature of both the diffusion and air leakage condensation planes. Analysis showed that the condensation plane temperature was increased throughout the winter months but that there was still a risk of condensation related damage to the enclosure if air leakage occurs. Figure 14 shows that in Minneapolis (DOE climate zone 6) 2" of high density spray foam may not be enough to reduce the potential condensation risk to a satisfactory level.

Case 10 with 2" of spray foam spends considerably more time below the interior dewpoint compared to Case 9 (hybrid wall) which also has 2" of high density spray foam. The difference in condensation potential is caused by the ratio of the insulation amounts on the interior and exterior of the condensation plane. The remaining 3.5" of the stud space can be filled with an R19 FG batt or cellulose. The increased convection suppression of cellulose insulation is not as critical to this enclosure assembly because of the air tightness of the two inches of spray foam insulation, but will still do a better job of reducing gaps around services, and other places that fiberglass batt is prone to convective looping. The increased thermal resistance of the double stud wall ensures that the condensation plane is kept much cooler. This is a critical consideration to designing a wall enclosure for a specific climate. The double stud walls with 2" of high density spray foam would likely work successfully with little risk in a Climate zone 6 or lower. Alternately, open cell foam could be used to fill the double stud wall although a vapour retarding coating would be needed in cold climates. A mid-density foam, with moderate vapor permeance could also be used as a full fill.

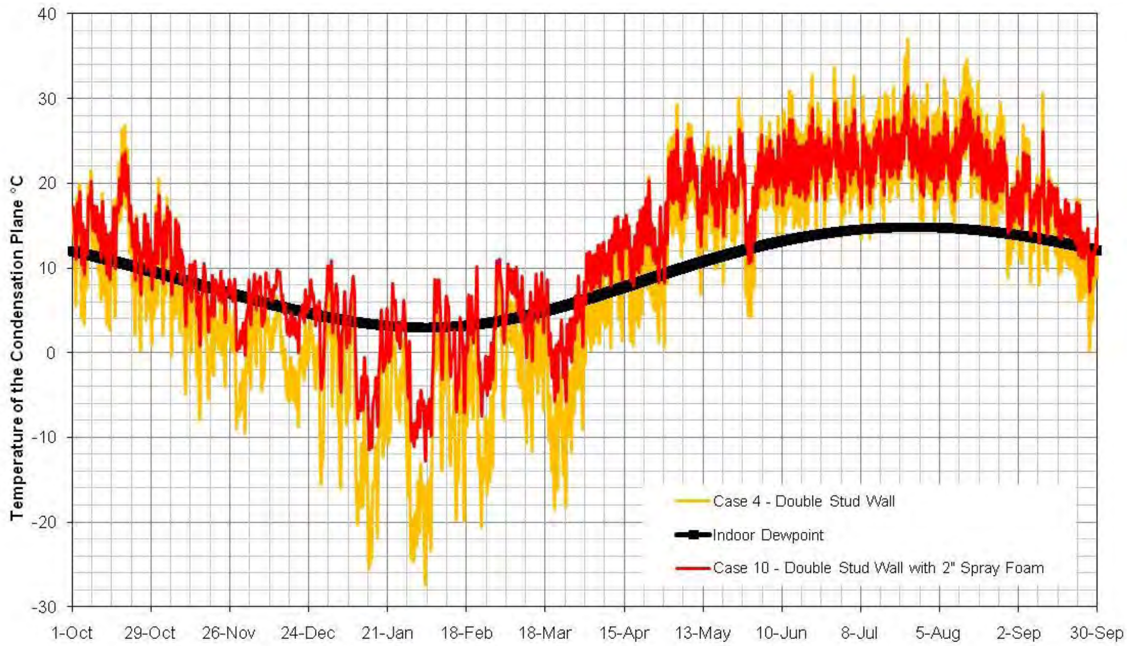

Figure 14 : Winter air leakage condensation potential for Case 4 and Case 10

One wall system becoming more popular in cold climates is a wall constructed with exterior foam insulation, sometimes referred to as an Offset frame wall. This has many advantages over traditional wall construction techniques, and can be used for both new construction and retrofits. Figure 15 shows high density spray foam being installed over the existing exterior sheathing during a retrofit. The surface of the foam becomes the drainage plane, air barrier and vapor barrier of the enclosure. Cladding can be attached directly to the exterior framing that tie back to the framing of the house, and are very stiff and supportive once the foam has been installed.

In this case, the exterior framing was attached with 8" spikes using a spacer to ensure that the exterior framing was the correct distance from the sheathing. Because of the strength and rigidity of the high density spray foam insulation, no additional support is needed for fiber cement siding.

Figure 15 : Installation of high density spray foam in an Offset Framed Wall in a cold climate

In the case of new construction, wood sheathing may not be necessary on the exterior of the structural wall framing to support the spray foam. Removing the sheathing would decrease the cost and work considerably. Other membranes, such as housewraps may be used to support the foam during installation, but more analysis and research may be required before installing spray foam directly on housewraps.

Analysis of the possible wintertime condensation for a Truss Wall constructed with 12" cellulose insulation (Case 5) and constructed with 4.5" of exterior high density foam and 5.5" of fibrous fill in the stud cavity (Case 11) is shown in Figure 16. The sheathing (or foam supporting membrane) never reaches the interior dew point temperature in DOE climate zone 6. In a very extreme cold climate, more foam could be added to the outside or the stud space insulation could be removed which would also decrease the condensation potential.

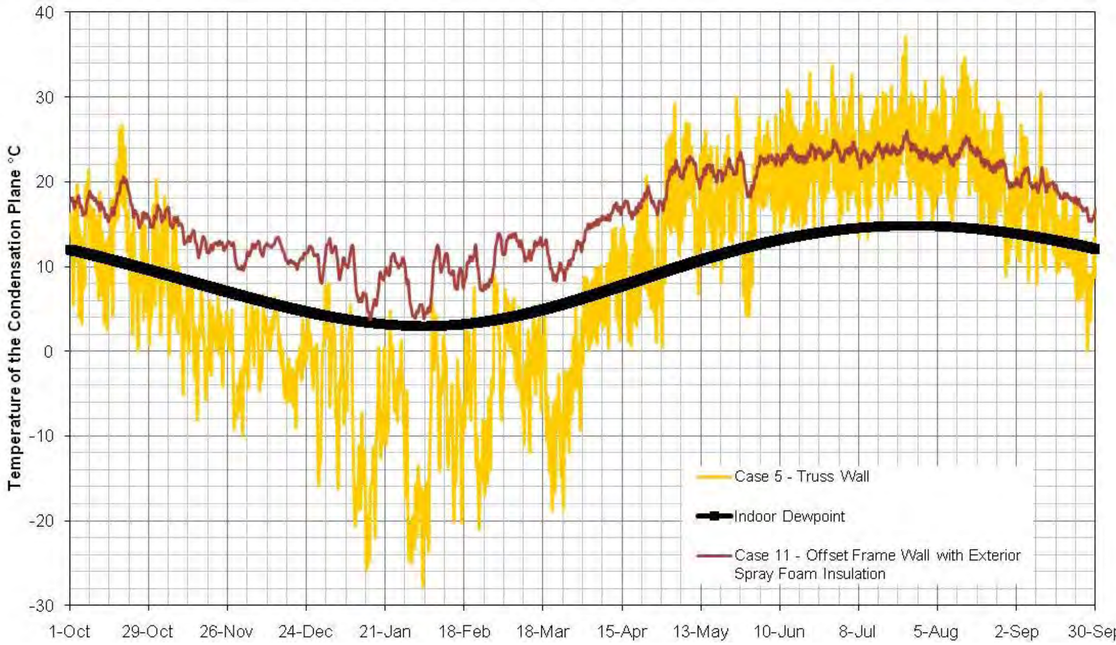

Figure 16 : Winter time air leakage condensation potential for Case 5 and Case 11

There are other advantages to an offset frame wall with exterior foam besides the decreased risk for condensation potential in the enclosure. A house can be dried in very quickly with exterior spray foam insulation, which means that the house is weather proof against rain and snow. This is very important in arctic regions with a very short construction season. Once the foam is installed on the exterior, interior work such as insulation, drywall and finishes can be finished as desired.

There were complaints from the remote areas of Northern Canada (according to the NRC) that when foam board was shipped to be used as exterior insulation, it always arrived broken, which is why they preferred not to use it. High density spray foam is shipped as two liquid components that are combined during the foam installation process. Many more board feet of spray foam can be shipped on the same truck than the equivalent board feet of EPS or XPS board foam insulation. This application is ideal for remote climates.

The sheathing relative humidities for Case 8, the spray foam wall, is shown below in Figure 17. The sheathing relative humidities with high density foam, and low density foam with a vapor barrier show no risks of moisture related issues caused by vapor diffusion. The wall system with low density foam and no vapor control layer may experience some risk to moisture related durability issues depending on the climate.

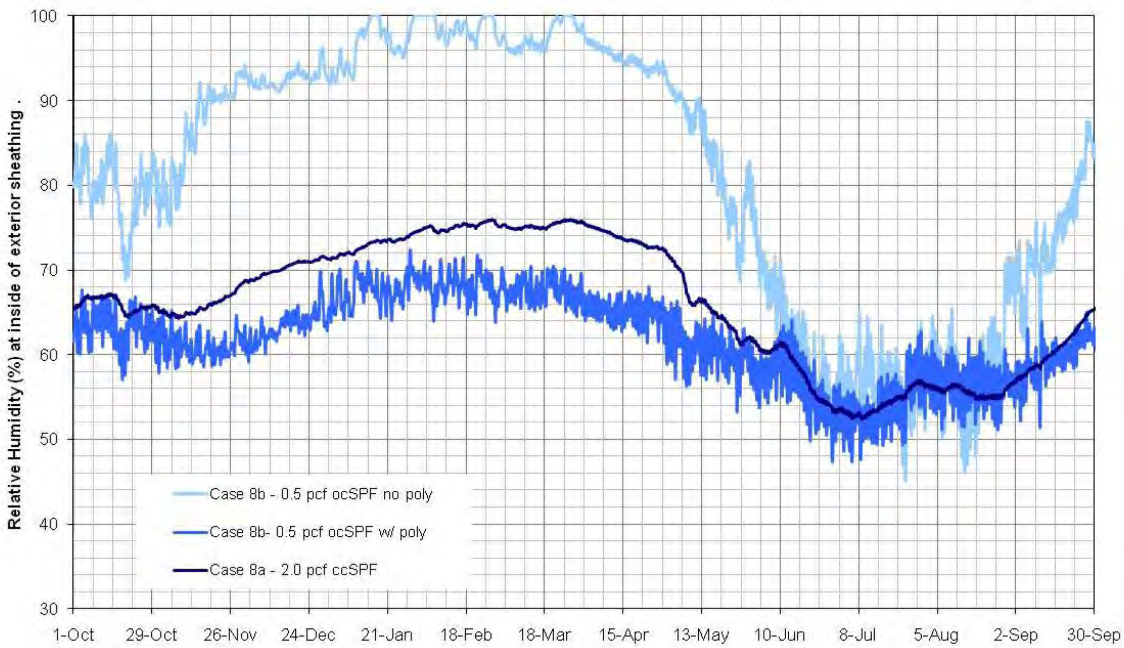

Figure 17 : Winter time sheathing relative humidity for Case 8

A vapor control layer should be used with low-density foam in climate zone 6 based on this hygrothermal analysis. More analysis is required to determine what level of vapor control is required to minimize risk. It may be possible to use a Class II vapor barrier (IBC 2007 supplement). In climate zones warmer than climate zone 6, it may be possible to use 0.5 pcf spray foam with much less risk of moisture related durability issues. More analysis should be conducted on this specific case in different climate zones before design recommendations can be made.

Air leakage condensation potential of Case 8 is shown in Figure 18. Because both low and high density spray foams form an air barrier when installed properly, interior air will not pass the interior surface of the foam. There is no risk of any moisture related durability issues in the walls insulated with spray foam in this analysis.

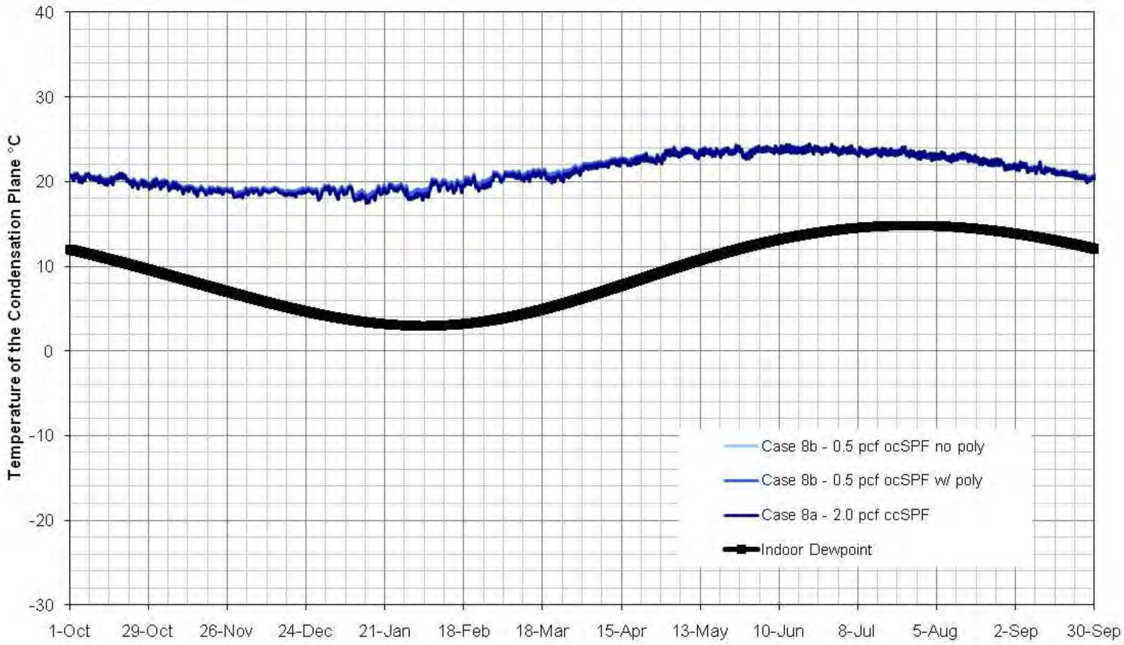

Figure 18 : Winter air leakage condensation potential for Case 8

2.2.3. Summer Inward Vapor Drives

Summer inward vapor drives occur when moisture stored in the cladding is heated and driven into the enclosure by a large vapor pressure gradient. Both field testing, and modeling have shown that assemblies that have reservoir claddings such as stucco, adhered stone veneer and concrete, that absorb and store water, are much more susceptible to summer inward vapor drives. During field testing, moisture has been observed condensing on the interior polyethylene vapor barrier and may run down the polyethylene to the bottom plate if enough water condenses.

Inward vapor drives were compared in this analysis using vinyl siding as the cladding. This type of cladding does not stress the wall systems from an inward vapor drive perspective but still gives a basis for comparison of the different wall systems. More analysis should be done in the future to more accurately predict the amount of inward vapor drive in cold climates using reservoir claddings (masonry, stucco, adhered stone etc.).

Analysis was conducted by graphing the relative humidity at the vapor barrier, or drywall surface in the absence of a vapor barrier, between the months of May and September.

Figure 19 shows the comparison of Case 1, standard construction, Case 2, advanced framing with insulated sheathing, and Case 9 hybrid wall. Standard construction experiences higher relative humidities at peak times because of the polyethylene vapor barrier, and lack of vapor control on the exterior. The advanced framing with insulated sheathing walls have some vapor control at the exterior surface of the wall system, and no polyethylene vapor barrier to limit drying to the interior. The advanced framing wall with 1" of XPS has a slightly elevated relative humidity when compared to the wall with 4" of XPS because of the 1 perm (57 ng/Pa•s•m2) paint layer on the drywall slowing drying to the interior, and less vapor control at the exterior surface. The hybrid wall performs very similarly to the advanced framing with 4" of XPS

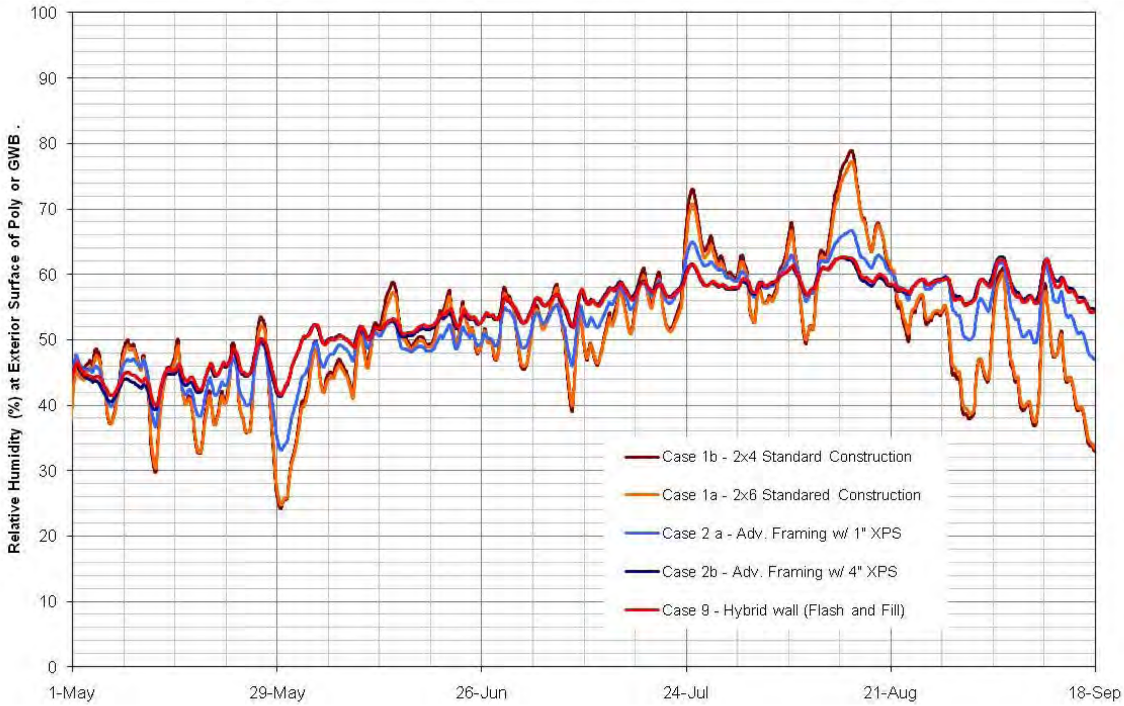

Figure 19 : Inward vapor drive relative humidity of poly or GWB for Case 1, Case 2, and Case 9

Inward vapor drives of Cases 3, 4, and 5(Figure 20) show there is very little performance difference between the test walls, and none of the walls experience any moisture related durability issues caused by inward vapor drives. Case 4, double stud construction, and Case 5, truss wall, experience slightly lower relative humidities because of the moisture buffering effect of the cellulose insulation.

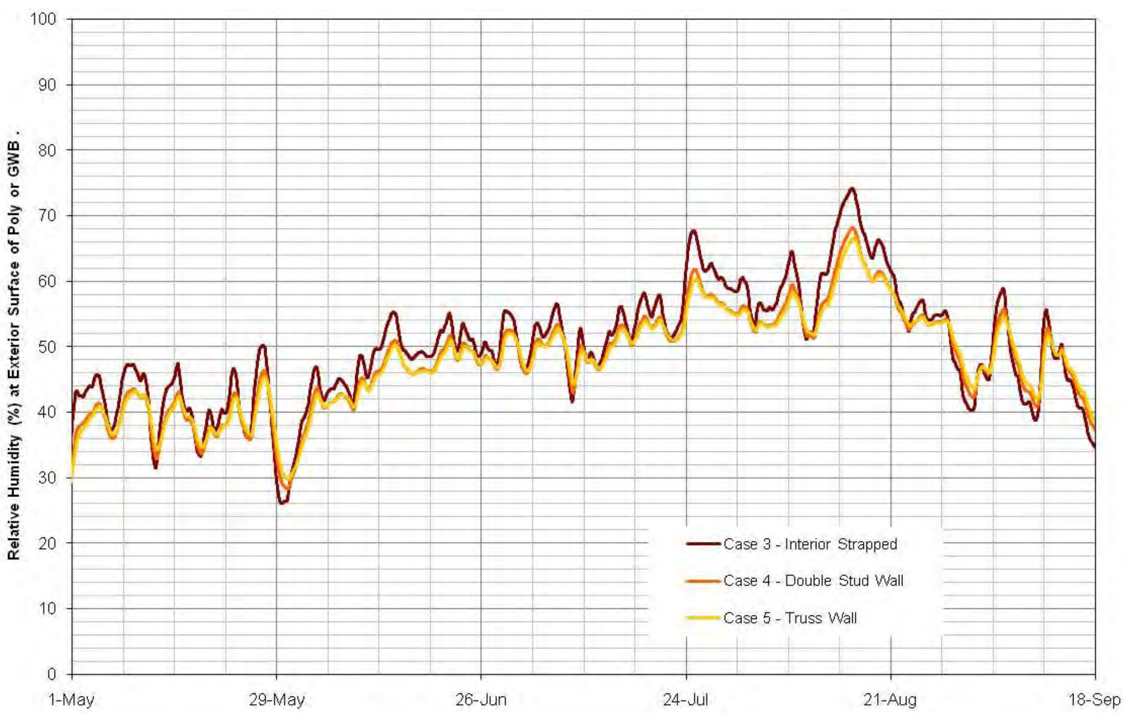

Figure 20 : Inward vapor drive relative humidity of poly or GWB for Case 3, Case 4, and Case 5

A double stud wall with 2" of high density foam (Case 10) with and without an interior vapor barrier was compared to Case 4, a double stud wall filled with cellulose in Figure 21. There was an improvement in performance when two inches of foam were used on the exterior and an interior vapor barrier was installed. The foam restricted the inward vapor drive, and the poly controlled vapor from the interior environment. Although this wall showed lower relative humidities with respect to summer inward vapor drives, it is never recommended to have a high level of vapor control on both sides of the wall system. This substantially increases the risk of moisture related durability issues, should any water get into the wall cavity. This could be improved by adding more foam to the exterior surface, and less vapor control to the interior, with a Class II or III vapor control layer depending on climate. More specific analysis is required before design recommendations can be determined.

Case 10 without an interior vapor barrier experiences slightly elevated relative humidity levels, likely due to the interior relative humidity. In a more severe testing condition for summer inward vapor drives, this wall would likely have lower relative humidity to Case 4, the standard double stud wall.

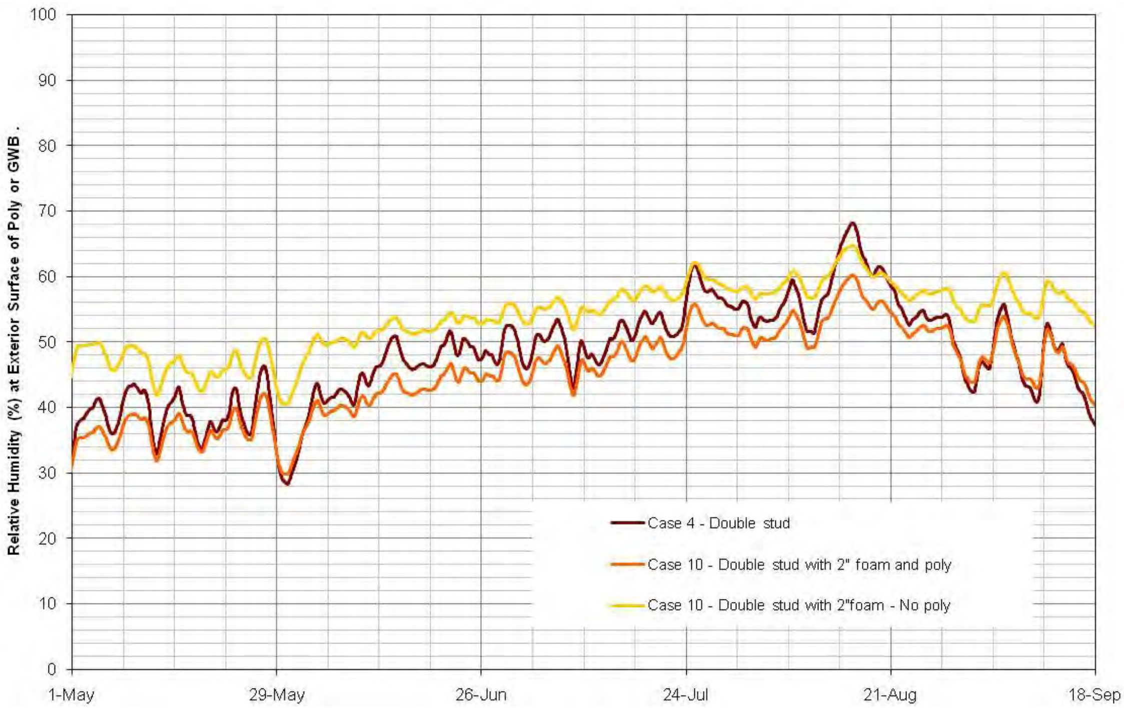

Figure 21 : Inward vapor drive relative humidity of poly or GWB for Case 4, and Case 10

Analysis of inward vapor drives on the spray foam walls shows that the walls without polyethylene vapor barrier dry adequately to the interior, but the low density spray foam wall with poly has elevated relative humidities because of the vapor control layer (Figure 22).

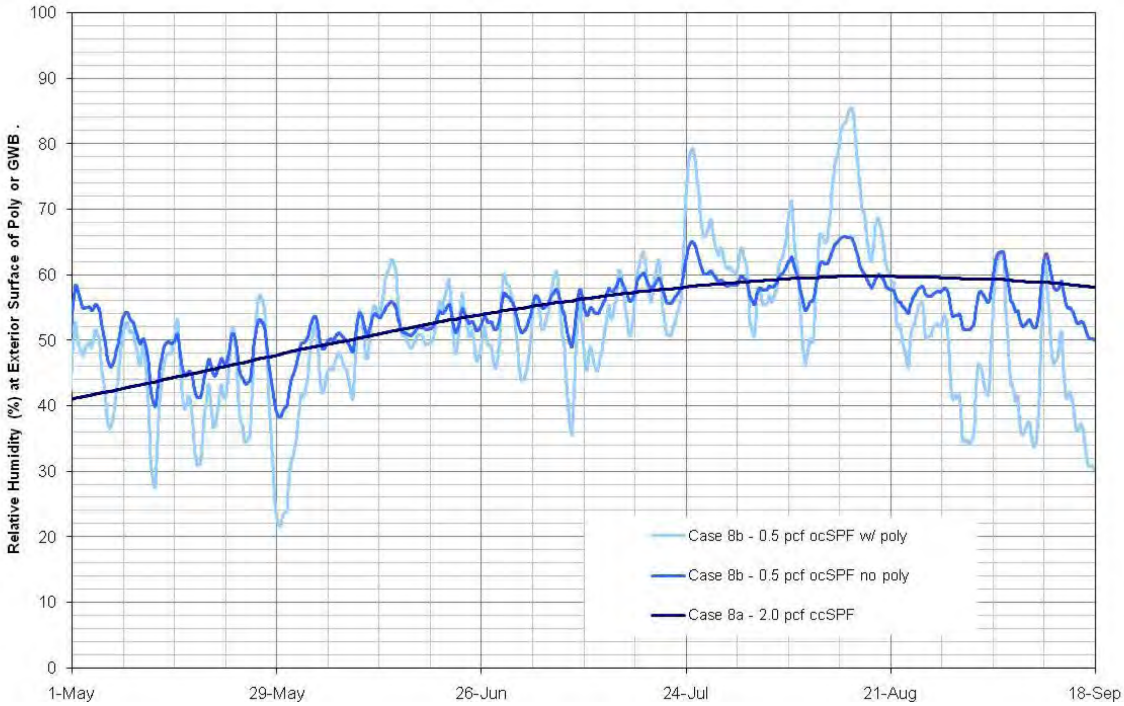

Figure 22 : Inward vapor drive relative humidity of poly or GWB for Case 8

The inward vapor drive for the offset frame wall (Case 11) with exterior foam insulation was compared to Case 3, a truss wall with only cellulose insulation, and Case 8 with 5 ½" of high density spray foam in the cavity space in Figure 23.

Both Case 8 and Case 11 perform very similarly, with slightly higher relative humidities than Case 4, although there is no risk of moisture related damage from inward vapor drives in of the walls (Figure 23). Had the cladding been a moisture storage cladding, it is suspected that both Case 8 with spray foam in the stud space, and Case 11 with exterior foam would have much lower relative humidities than Case 5 because of the vapor control of the high density spray foam.

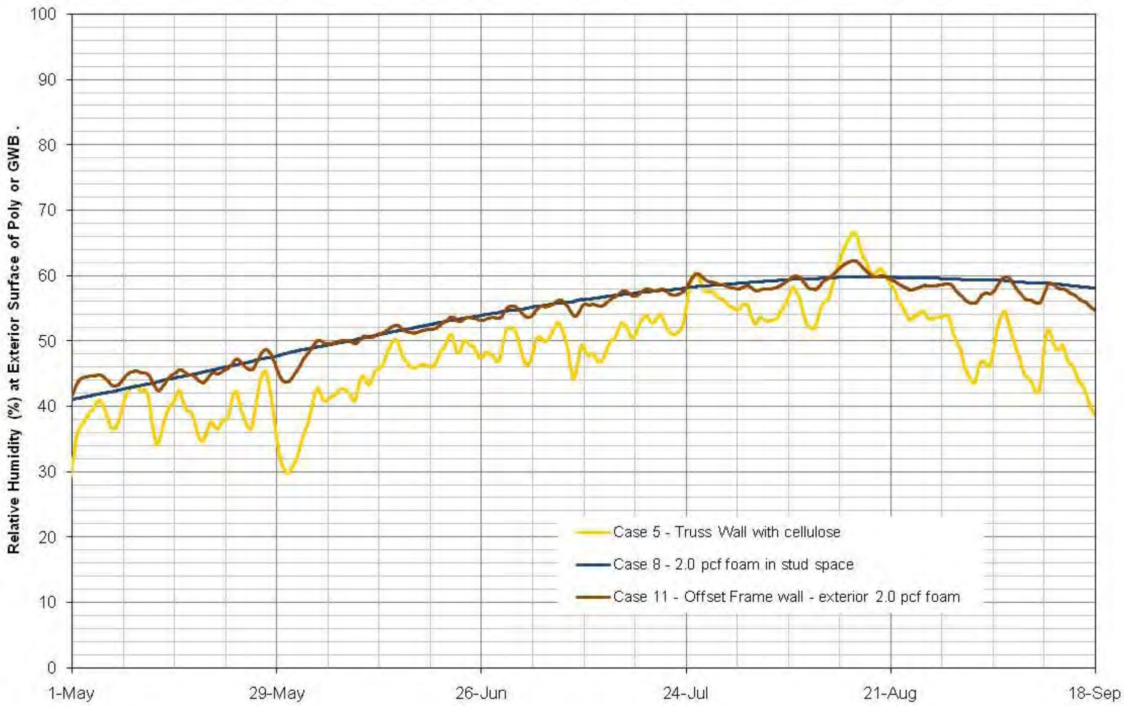

Figure 23 : Inward vapor drive relative humidity of poly or GWB for Cases 5, 8, and 11

2.2.4. Wall Drying

The third analysis conducted by using WUFI® hygrothermal modeling is the drying ability of the different wall systems. Drying was quantified by beginning the simulation with elevated sheathing moisture content (250 kg/m3) in the wall systems and observing the drying curve of the wetted layer. In walls without OSB sheathing a wetting layer was applied between the insulated sheathing and fiberglass batt insulation with similar physical properties to fiberglass insulation. Drying is a very important aspect of durability since there are many sources of possible wetting including rain leakage, air leakage condensation and vapor diffusion condensation. If a wall is able to try adequately, it can experience some wetting without any long-term durability risks.

The drying curves of Case 1 (standard construction), and Case 2 (advanced framing with insulated sheathing) are shown in Figure 24. The slowest drying wall is the advanced framing with 1" of exterior insulation and interior vapor control paint because there are lower permeance layers on both the interior and exterior of the enclosure. The OSB in the standard construction walls dry only marginally quicker than advanced framing with insulated sheathing, which is likely insignificant in the field. In the advanced framing wall, the wetting layer is immediately interior of the XPS sheathing, and drying is predominantly to the interior.

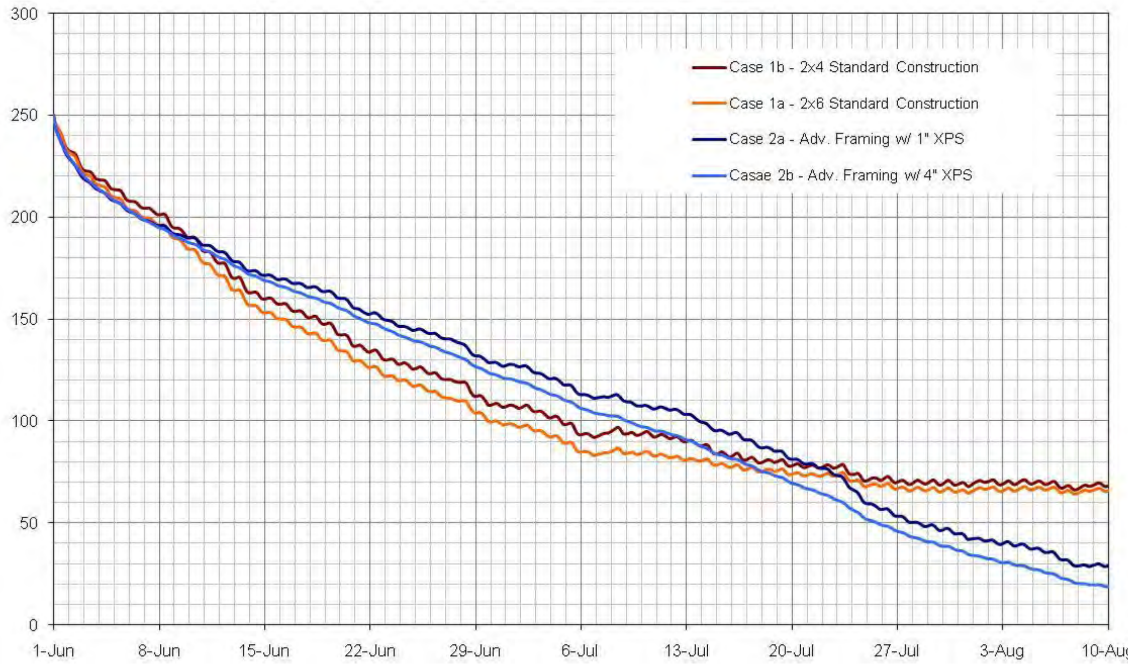

Figure 24 : Drying Curves for Case 1 and Case 2

Figure 25 shows that the drying curves of the interior strapped wall, the double stud wall, and the truss wall are all very similar, with no significant differences. These three walls perform very similarly to the standard construction walls in Figure 24.

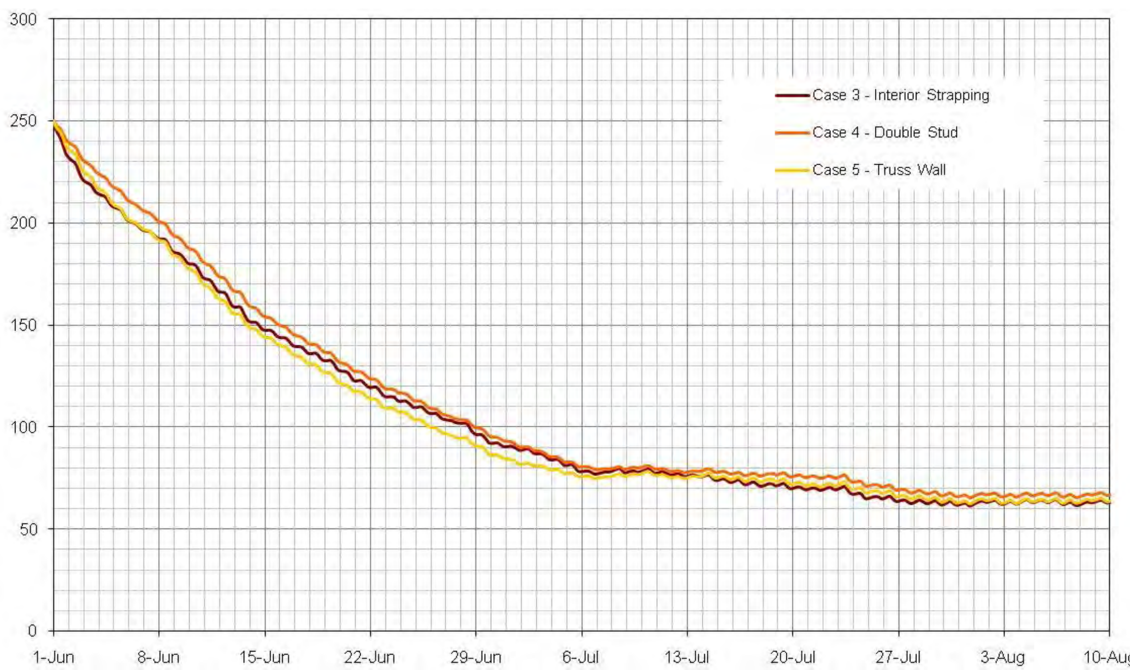

Figure 25 : Drying curves for Case 3, Case 4, and Case 5

The drying curves for spray foam insulated walls, Case 8, are shown in Figure 26. The quickest drying wall is the low density spray foam without a poly vapor barrier. Both the high density spray foam and the low density spray form with poly both dry more slowly because of the decreased permeance of the building enclosure and inhibited drying

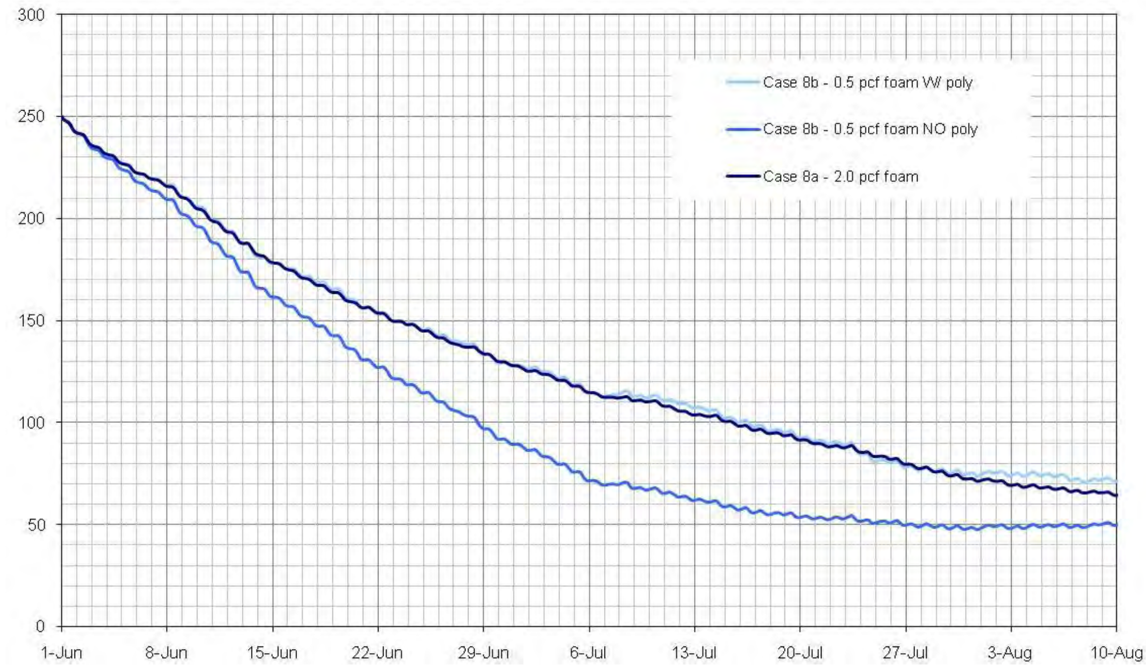

Figure 26 : Drying curves for Case 8

Comparing the double stud wall with cellulose insulation (Case 4) with the double stud wall with spray foam and cellulose (Case 10), Case 4 dried more quickly than Case 10 both with and without a interior polyethylene vapor barrier. With 12" of moisture buffering cellulose insulation in Case 4, it appears that the wall is able to quickly buffer and redistribute the moisture of a single wetting event and then release it slowly, mostly to the exterior of the OSB. Neither wall would suffer moisture related durability issues following a single wetting event but repeated wetting events to the OSB will increase the risk of moisture related durability issues.

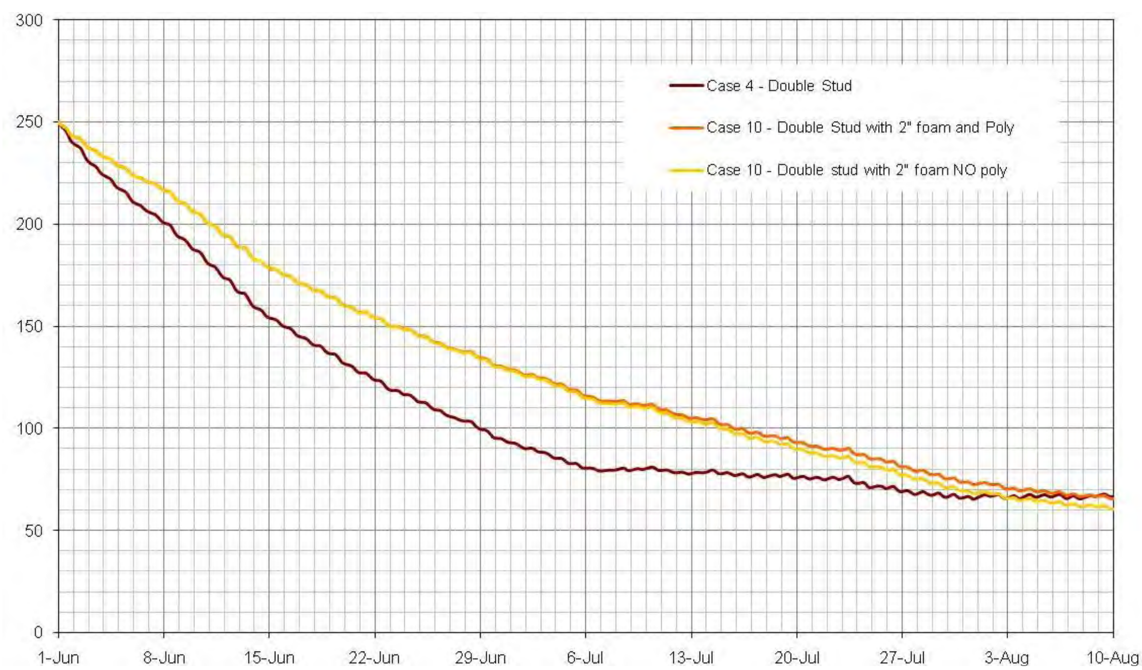

Figure 27 : Drying Curves for Case 4, and Case 10 with and without a poly vapor barrier

The offset wall enclosure with exterior spray foam dried very slowly compared to the truss wall of Case 5 with cellulose insulation. The wall system with exterior high density spray foam is unable to dry to the exterior due to the vapor control of the spray foam. The interior relative humidity is elevated in the spring and summer months which would also affect the vapor pressure gradient and drying potential. The sheathing in Case 11 is not significantly affected by the solar energy of the sun and the warm summer temperatures, nor is it in contact with cellulose insulation to buffer the wetting event.

In Case 5, with cellulose insulation against the wet OSB sheathing, the cellulose absorbed and redistributed the moisture, helping the OSB dry more quickly. Installing fiberglass batt insulation against the sheathing does not redistribute moisture and the OSB will stay wetter longer. Cellulose insulation is more susceptible to repeated wetting events because of its organic nature than fiberglass batt. Both of these wall systems would be at risk for moisture related damage if they were wetted repeatability and both walls are able to handle rare wetting events.

Figure 28 : Drying Curves for Case 5 and Case 11

2.3 Enclosure Durability

Durability of the building enclosure system was also used to classify the different wall construction scenarios. Durability is used in this report to group together multiple durability related criteria such as rain control, drying of water leakage events, air leakage condensation, built in moisture, and susceptibility of different building materials to moisture related issues. The durability assessment will be determined from hygrothermal modeling, as well as qualitatively based on the knowledge and experience of building material characteristics such as vapor permeability, and hygric buffering capacity, and susceptibility to moisture related damage..

2.4 Buildability

Buildability is a key comparison criteria for practical purposes. Often the general contractor and trades will influence design decisions based on the perceived complexity of different construction techniques or deviation from their standard practice. Any enclosure system and detailing should be buildable on a production level to achieve the greatest benefit even though the trades are often resistant to changes in construction practices. The susceptibility of the enclosure system to poorly constructed water management details and poor workmanship is also considered in buildability.

2.5 Material Use

Material use is becoming a critical design issue with the increasing concerns of depleting resources, and increasing costs of materials and energy. Some construction strategies use more construction materials such as the double stud wall, and the advantages of increased thermal control should be balanced against the disadvantages of increasing the building materials and embodied energy. In some cases, materials that have less embodied energy, or recycled material, such as cellulose insulation could be used instead of the more energy intensive fiberglass batt insulation.

2.6 Cost

The factor which generally has the greatest influence on implementation of a building enclosure strategy, particularly for production builders, is cost. Because the cost of some materials varies significantly depending on location and case-specific relationships between builders and suppliers, the cost of a building enclosure system will be perceived relative to other systems. For example, it's accepted that R19 fiberglass batt is less expensive than low-density (0.5 pcf) spray foam, which is less expensive than high density (2.0 pcf) spray foam. The strategy of a comparison matrix for the test wall assemblies is able to use relative values for cost rather than exact costs.

C. Results

1. CASE 1: STANDARD CONSTRUCTION PRACTICE

For this analysis, standard construction practice includes OSB sheathing, 2x4 or 2x6 framing 16" oc, fiberglass batt insulation, a 6-mil polyethylene vapor barrier and taped and painted ½" drywall. (Figure 29) Historically, this has been used for residential wall construction in most areas of North America.

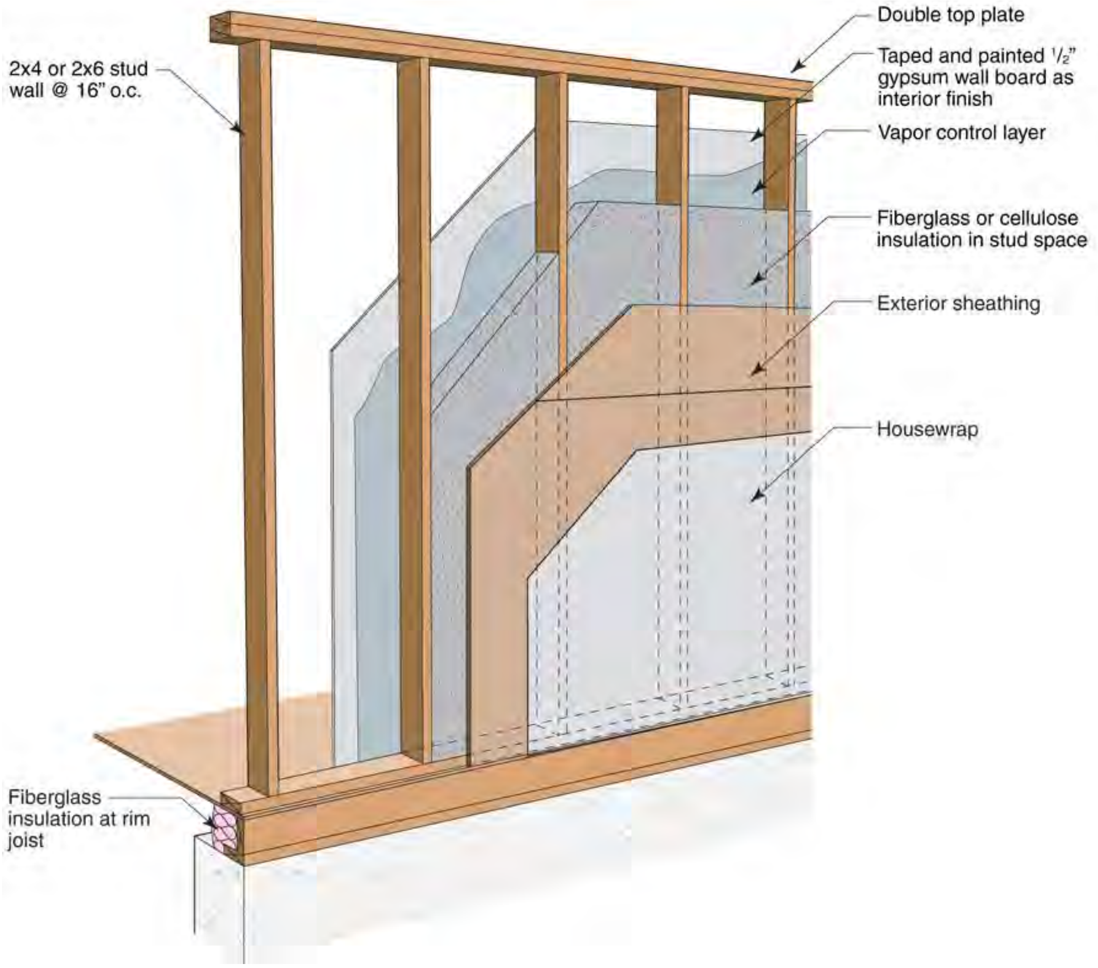

Figure 29 : Standard construction practice

1.1.1. Thermal Control

Fiberglass batt installed in a 2x4 wall system has an installed insulation value of R13, and fiberglass batt in a 2x6 wall system has an installed insulation value of R19. There are several different densities that can be used to provide slightly different R-values (e.g., 3.5" thick batts are available in R11, R12, R13 and R15 ratings). Other insulations that could be used in this assembly include densepack or spray applied cellulose, spray applied fiberglass, and spray foam (Case 8). Regardless of the insulation used in the cavity space, the framing components of the wall act as thermal bridges between the interior drywall and the exterior sheathing and this affects the whole wall R-value of the assembly. Figure 30 shows the vertical and horizontal wall sections used in Therm to determine the whole wall R-values for standard construction practices.

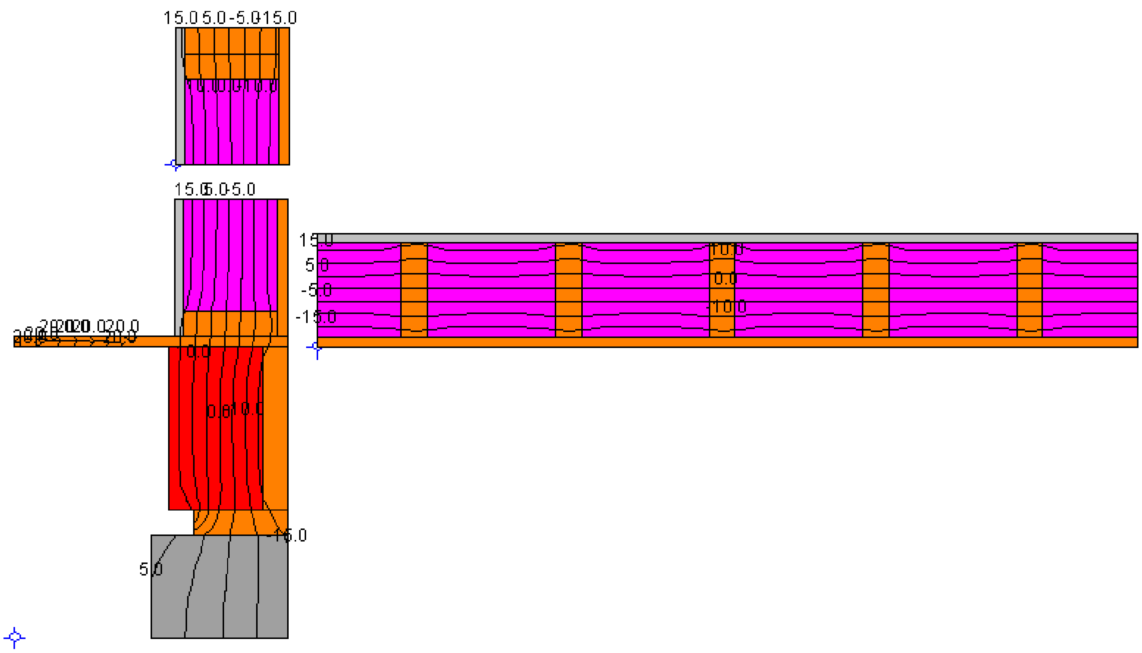

Figure 30 : Therm modeling of Case 1 - 2x6 construction

As stated previously, studies have shown that even when using a stud spacing of 16"o.c., which corresponds to a framing factor of approximately 9%, the actual average framing factor can be considerably higher, between 23 and 25%. For comparison between the different cases, framing factors of 16% were used to limit the variables and determine the effects of other variables.

Table 5 shows a summary of the R-values calculated for the three different components of both the 2x4 and the 2x6 standard construction practice. These insulation values are not considered high-R wall systems in cold climates.

Table 5 : Summary of R-value results from Therm modeling for Case 1

Case	Description	Whole Wall R value	Rim Joist	Clear Wall R value	Top Plate
1a	2x6 AF, 24"oc, R19FG + OSB	**15.2**	12.3	16.1	12.5
1aii	2x6, 16"oc, R19FG + OSB (25%ff)	**13.7**	12.3	14.1	12.5
1b	2x4 AF, 24"oc, R13FG + OSB	**11.1**	9.8	11.5	9.8
1bii	2x4, 16"oc, R13FG + OSB (25%ff)	**10.0**	9.8	10.1	9.8

Neither of the two most common insulations, fiberglass or cellulose, control air flow. Cellulose does a better job of suppressing convection because it fills the gaps that are typically left during typical fiberglass batt installation. Blown-in fiberglass also helps address the gaps left during fiberglass batt installation but is relatively new, and not as widely used as cellulose.

Air tightness can be significantly improved by using an airtight insulation such as sprayfoam at the rim joist.

1.1.2. Moisture Control

Analysis of the air leakage condensation potential from a poorly detailed air barrier results in approximately 4400 and 4500 hours of potential condensation for the 2x4 and 2x6 standard construction walls respectively when the temperature of the exterior sheathing is less than the dew point of the interior air. (Figure 10)

These walls are unable to dry to the interior, but generally are able to dry fairly well to the exterior depending on the cladding type. WUFI® showed that with a ventilated cladding like vinyl siding, the sheathing in both of the standard construction walls decreased from 250 kg/m3 to 100 kg/m3 in 29-34 days (Figure 24).

1.1.3. Constructability and Cost

Generally speaking, all of the trades and construction industry are very familiar with building the Case 1 wall system. Cladding attachment is straightforward, and the only education necessary may be air tightness details to increase the overall building performance.

1.1.4. Other Considerations

The amount of material used in this type of construction is the standard against what other walls will be compared since it has been the standard of construction in many places of many years. Standard construction uses less framing and wood sheathing than a double stud wall construction (Case 4), but more than advanced framing material. Using cellulose insulation instead of fiberglass not only increases the fire resistance for the enclosure wall, it also decreases the embodied energy used in construction.

1.2 Case 2: Advanced framing with insulated sheathing

Advanced framing techniques are becoming more popular for residential construction because of several advantages. These practices have been adopted by some smaller builders, but not on many large scale production developments. The main difference with advanced framing is 2x6 framing lumber on 24" o.c. with a single top plate. The idea of advanced framing is to reduce the framing factor of the wall system in the areas by good design, such as corners and penetrations. A single top plate is structurally possible if stack framing is used, which means the framing from one floor is lined up directly with the framing above and below it to create a continuous load path. In many cases of advanced framing, insulated sheathing is used either in place of or in combination with wood sheathing. This is important for thermal performance to minimize thermal bridging effects.

For this analysis, 1" and 4" insulated sheathing is considered (Figure 31). Insulating sheathing up to 1.5" thick does not change any of the other details such as windows installation and cladding attachment, but insulating sheathing at thicknesses of 2" and greater requires some slightly different design details for window and door installation as well as cladding attachment. Most of these details have already been designed and can be found in building science resources.

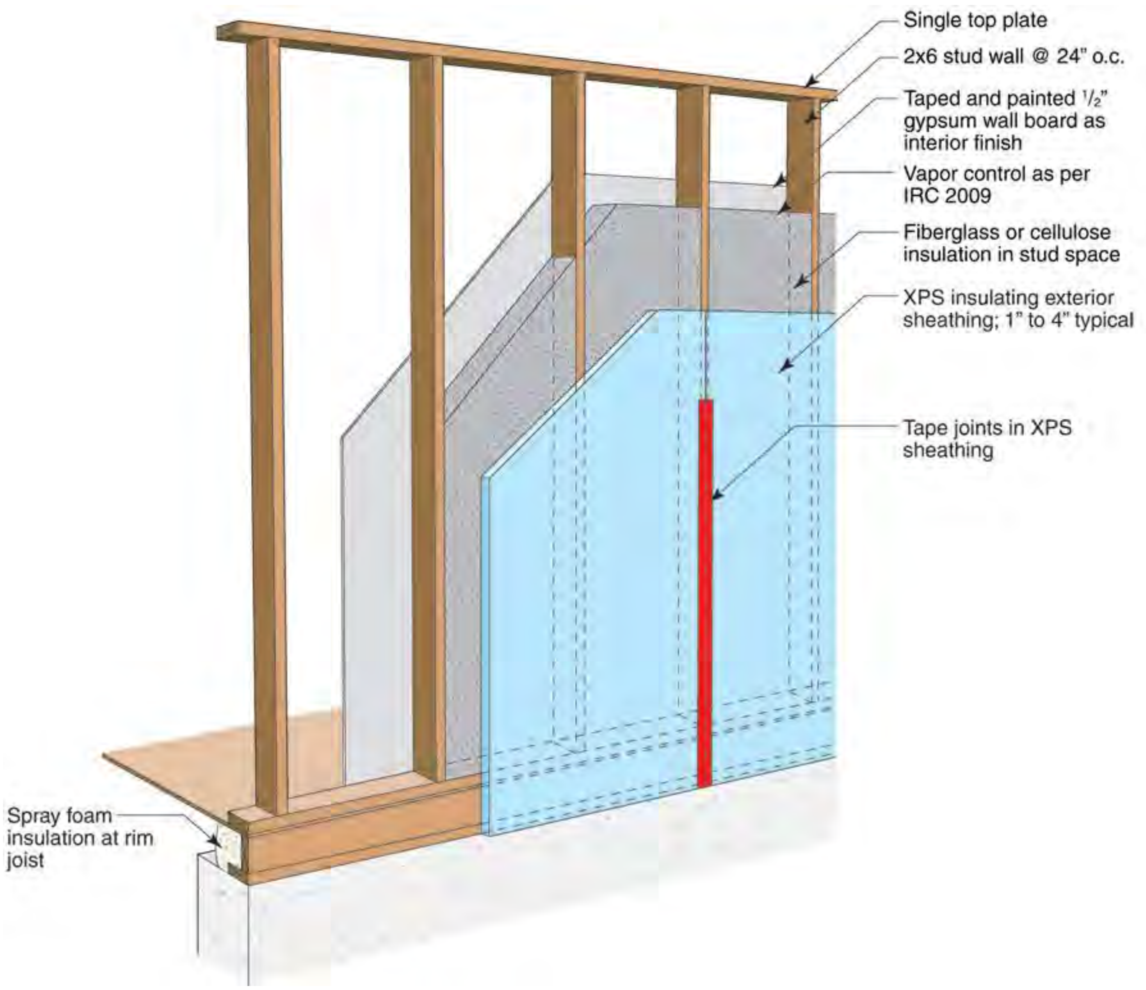

Figure 31 : Advanced framing construction

1.2.1. Thermal Control

Thermal control is improved over standard construction practices by adding insulating sheathing to the exterior of the framing in place of OSB. This insulation is typically board foam which includes expanded polystyrene (EPS), extruded polystyrene (XPS) and polyisocyanurate (PIC). PIC is often reflective aluminum foil faced which also helps control radiation losses in some cases. Thicknesses of insulation have been installed that range from ¾" to 4" on wall systems. Often times, when 4" of insulation is added, it will be done with two 2" layers with the joints offset both horizontally and vertically. Fiberglass batt, blown fiberglass or cellulose could be used in the stud space. The biggest thermal advantage of the insulating sheathing is decreasing the thermal bridging of the framing members through the thermal barrier.

Drawings from Therm show the vertical and horizontal sections which indicate increased thermal protection at both the rim joist and top plate, decreasing heat flow through the thermal bridges.

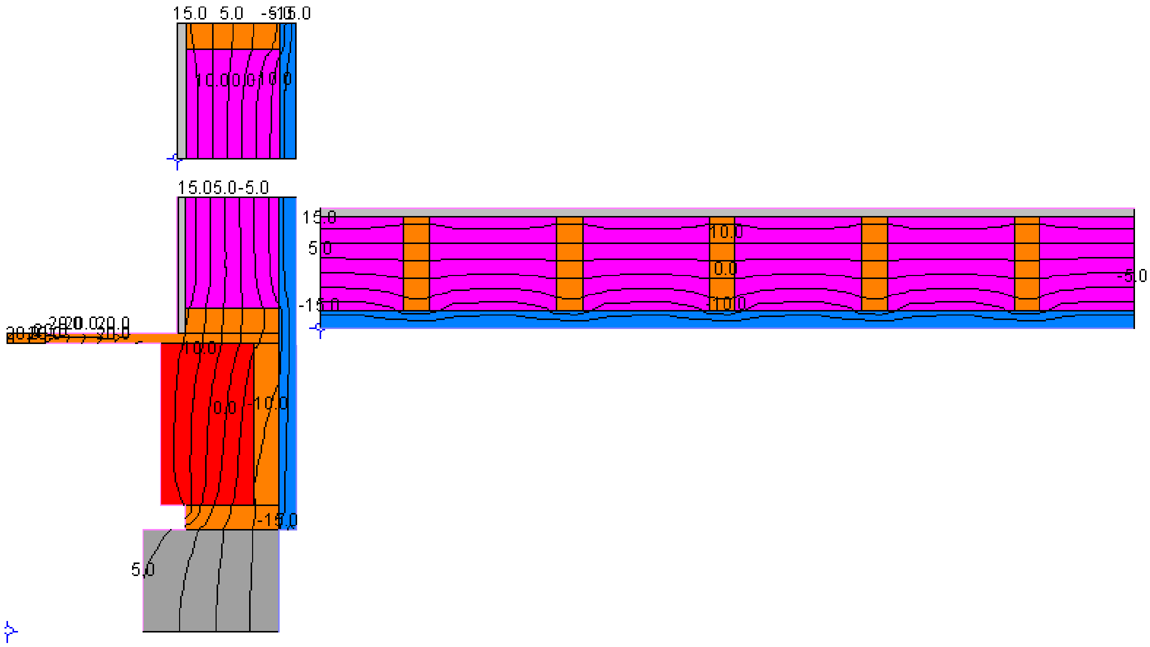

Figure 32 : Therm modeling of Case 2 advanced framing with 1" XPS insulated sheathing

Analysis shows that when substituting 1” of XPS (R5) for the OSB in a standard 2x6 wall with a 16% framing factor, the clear wall R-value increases from R16.1 to R20.6, an increase of R4.5. Since the OSB was removed from the standard construction wall, this is actually a difference of R5.1, which is greater than the R-value of the insulation that was added. If the framing factor was higher, or metal studs were used, an even greater increase in the R-value for 1” of XPS can be seen. For example, increasing the conductivity of the studs by an order of magnitude results in an increase of R6.5 for 1” of R5 XPS sheathing over standard construction. This is an example of the importance of reducing the thermal bridging through the enclosure.

The calculated R-values for both of the advanced framing walls are shown in Table 6.

Table 6 : Summary of R-value results from Therm modeling for Case 2

Case	Description	Whole Wall R value	Rim Joist	Clear Wall R value	Top Plate
2a	2x6 AF, 24"oc R19FG + 1" R5 XPS	**20.2**	18.5	20.6	20.3
2b	2x6 AF, 24"oc R19FG + 4" R20 XPS	**34.5**	29.0	35.6	35.4

1.2.2. Moisture Control

The Therm results show that the interior surface of the foam is at a higher temperature than the standard construction wall which will decrease the potential for both vapor diffusion condensation and air leakage condensation. According to the IRC, a Class I or II vapor retarder is still required depending on the R- value of the insulated sheathing and the wall framing used. Table N1102.5.1 from the IRC shows that for climate Zone 6, with insulating sheathing R>= 11.25 on a 2x6 wall, only a Class III vapor retarder is required.

There is some risk of winter time condensation from vapor diffusion depending on the level of vapor retarder and the interior temperature and relative humidity conditions. Figure 9 shows that with 1” of XPS some condensation is possible on the surface of the insulated sheathing. Since the XPS is not moisture sensitive, some condensation will not affect the durability of the wall system.

Air leakage condensation may still be a concern, although not as great as with standard construction. There are approximately 3800 hours and 1200 hours of potential air leakage condensation when the temperature of the insulated sheathing is below the dew point of the interior air for 1” of XPS and 4” of XPS respectively.

Both of the advanced framing walls dry slower than the standard construction walls because drying to the exterior is throttled by the low vapor permeance XPS (Figure 24).

There is less inward vapor drives in the advanced framing walls with insulated sheathing than the standard construction since vapor is slowed at the sheathing, and allowed to dry more readily to the interior (Figure 19). The relative humidity peaks are considerably higher in the standard construction walls than the advanced framing walls.

1.2.3. Constructability and Cost

There is some education and training required for the successful construction of advanced framing walls with insulated sheathing. The changes are very minimal for insulated sheathing thicknesses of 1.5” and less, but for insulating sheathing thicknesses of 2” and greater, special details are required for cladding attachment and window and door installation.

Some solutions have been found for cladding attachment directly to 3/4” strapping anchored to the framing members, but in some areas, building code officials require letters from the specific building materials companies before allowing construction.

1.2.4. Other Considerations

The R-value of a wall system can be increased more than the added value of insulation by minimizing the thermal bridging with exterior insulating sheathing. Advanced framing techniques use less framing lumber than traditional construction, which is a savings of both money and embodied energy while reducing the framing fraction. Similar to traditional construction, using cellulose in the stud space will decrease the embodied energy of the insulation and increase the fire resistance of the wall system.

1.3 Case 3: Interior 2x3 horizontal strapping

Horizontal interior strapping is a method of reducing the thermal bridging through the wall framing, protecting the vapor barrier against penetrations, and adding more insulation.

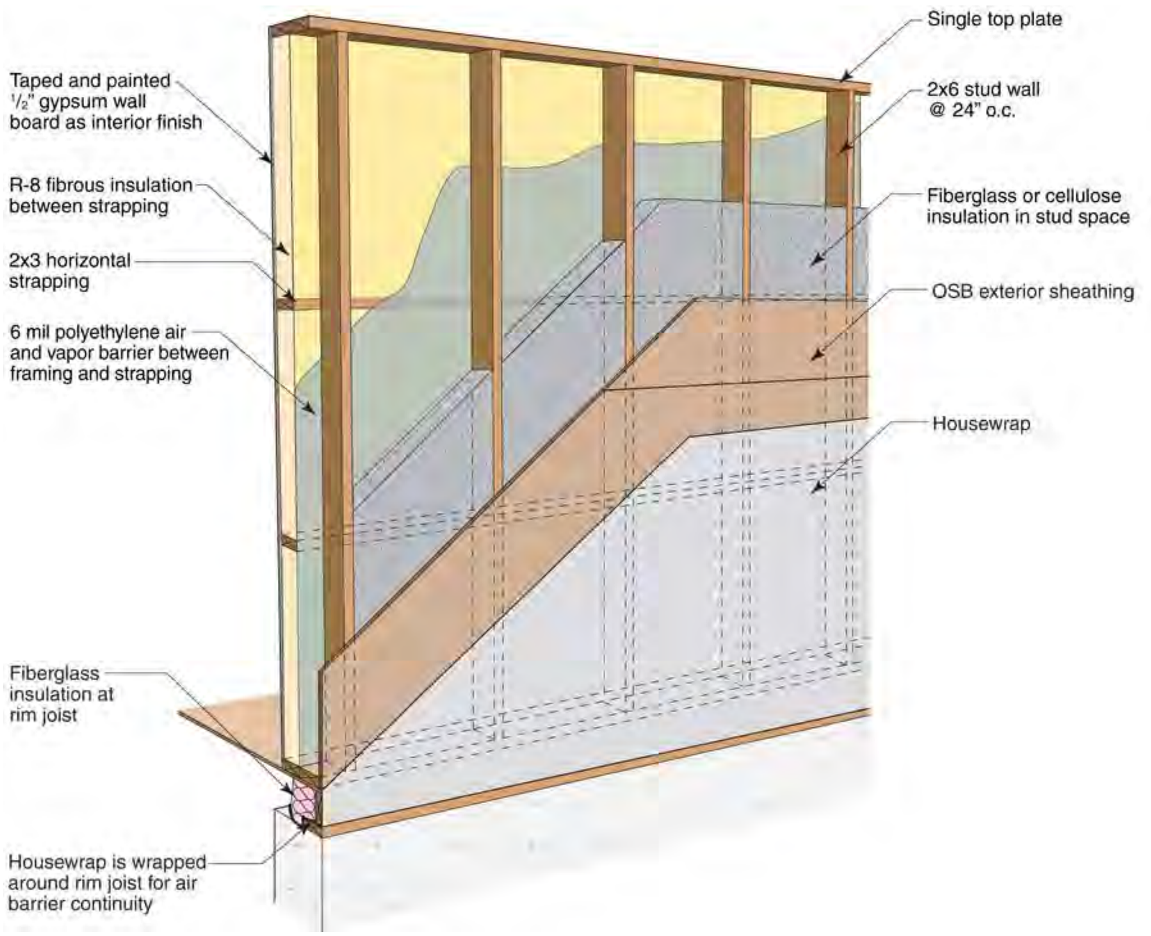

Figure 33 : 2x6 wall construction with interior strapping

1.3.1. Thermal Control

The horizontal strapping added to the wall allows for an extra 2.5" of insulation. This is commonly in the form of R8 fiberglass, which totals an installed insulation R-value of R27 for the wall assembly. For the Therm simulation four interior strapping elements were used as shown in the drawing.

Thermal bridging is decreased through the vertical studs but there is still thermal bridging at the top and bottom plates. Thermal losses due to air leakage are likely been minimized by installing the polyethylene vapor barrier against the wall framing. This means fewer penetrations are required for services and wiring resulting in greater air tightness than standard construction.

Therm was used to determine the whole wall R-value of the interior strapping wall. Figure 34 shows the horizontal and vertical sections from the Therm analysis.

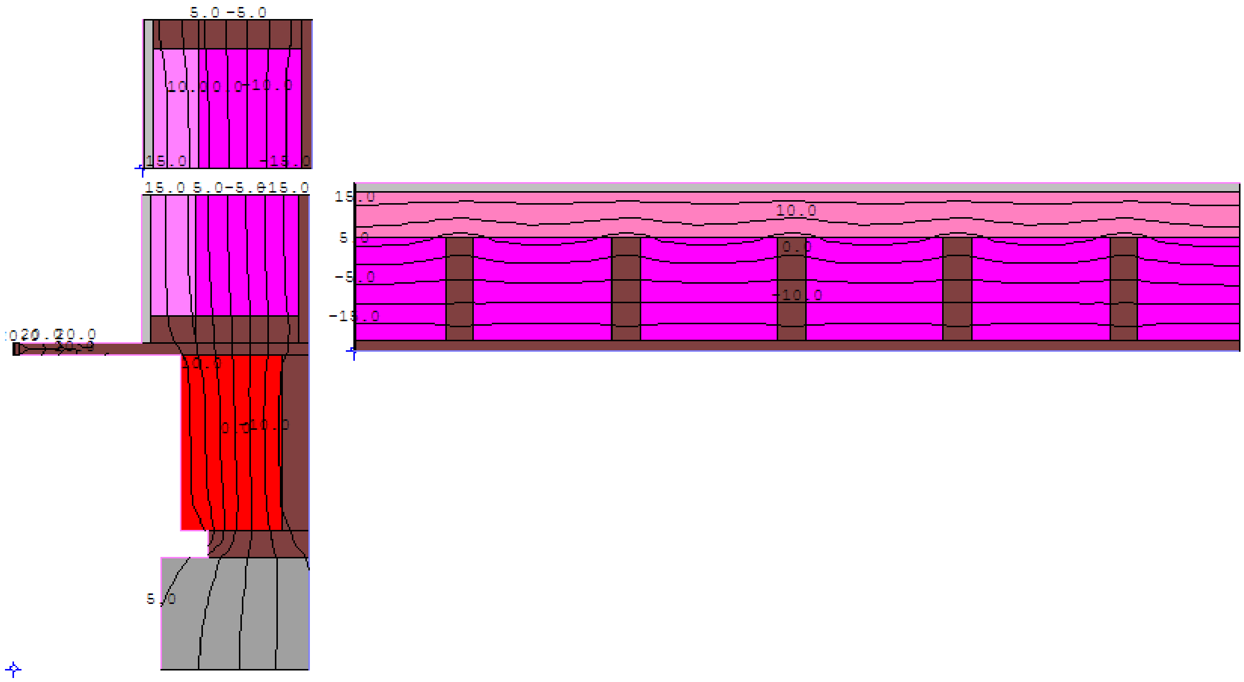

Figure 34 : Therm analysis of horizontally strapped wall

The Whole wall R-value of the wall assembly was determined to be R21.5 (Table 7). This means that even by adding R8 to the standard 2x6 wall, this results in an increase of R6.3 because of the thermal bridging that is not addressed. The rim joist R-value can be improved with more insulation, and better airtightness.

Table 7 : Calculated R-value of an interior horizontal strapped wall

Case	Description	Whole Wall R value	Rim Joist	Clear Wall R value	Top Plate
3	2x6 AF, 24"oc, 2x3 R19+R8 FG	**21.5**	13.4	23.5	18.4

1.3.2. Moisture Control

The control of both vapor diffusion condensation and air leakage condensation is increased since there are fewer penetrations in the air/vapor barrier of the wall assembly.

The potential for vapor diffusion condensation is very similar to the standard construction assemblies (Figure 12). The temperature of the sheathing is kept only slightly colder because of the increased insulation beyond standard construction which results in a small increase in the potential intensity of air leakage condensation. There does not appear to be any risk of moisture related durability from vapor diffusion assuming the vapor barrier is adequately installed.

Air leakage condensation potential is slightly increased from the standard construction walls with a total of approximately 4600 hours of potential condensation through the winter.

Analysis of the summertime inward vapor drives shows very similar results between the standard construction practices in Case 1 and the interior strapped wall.

Drying of the interior strapped wall shows slightly improved performance over the standard construction practice, by a few days for the OSB to reach 100 kg/m3.

The interior strapped wall performed very similarly to the standard construction practice in terms of moisture control.

1.3.3. Constructability and Cost

Constructing a wall with interior horizontal strapping is not a normal construction technique in most places. It would require some education and training in the design details, such as window installation, but cladding attachment is the same, and the wall system would be less susceptible to workmanship issues on the vapor barrier, since there are far fewer penetrations required through the air/vapor barrier. Additional costs would be incurred due to the addition of both horizontal strapping and the installation of additional batt insulation as well as some more installation time. The mechanical and electrical services should see a reduction in cost since that the horizontal framing does not require as much drilling or modification to distribute the services. The mechanical and electrical trades would also not have to take the time to seal as many locations as in standard vapor and air barrier practices.

1.3.4. Other Considerations

It would be possible to use cellulose insulation between the polyethylene vapor barrier and the exterior sheathing, which would increase the fire resistance, and decrease the embodied energy. There is more framing required to construct these walls, and the tradeoff in adding insulation is not quite made up in the overall R-value of the assembly.

1.4 Case 4: Double Stud

Double stud walls are most commonly used as interior partition walls in multifamily construction because of their noise reducing effect and increased fire resistance. They can also be used as a highly insulated exterior enclosure wall in cold climates.

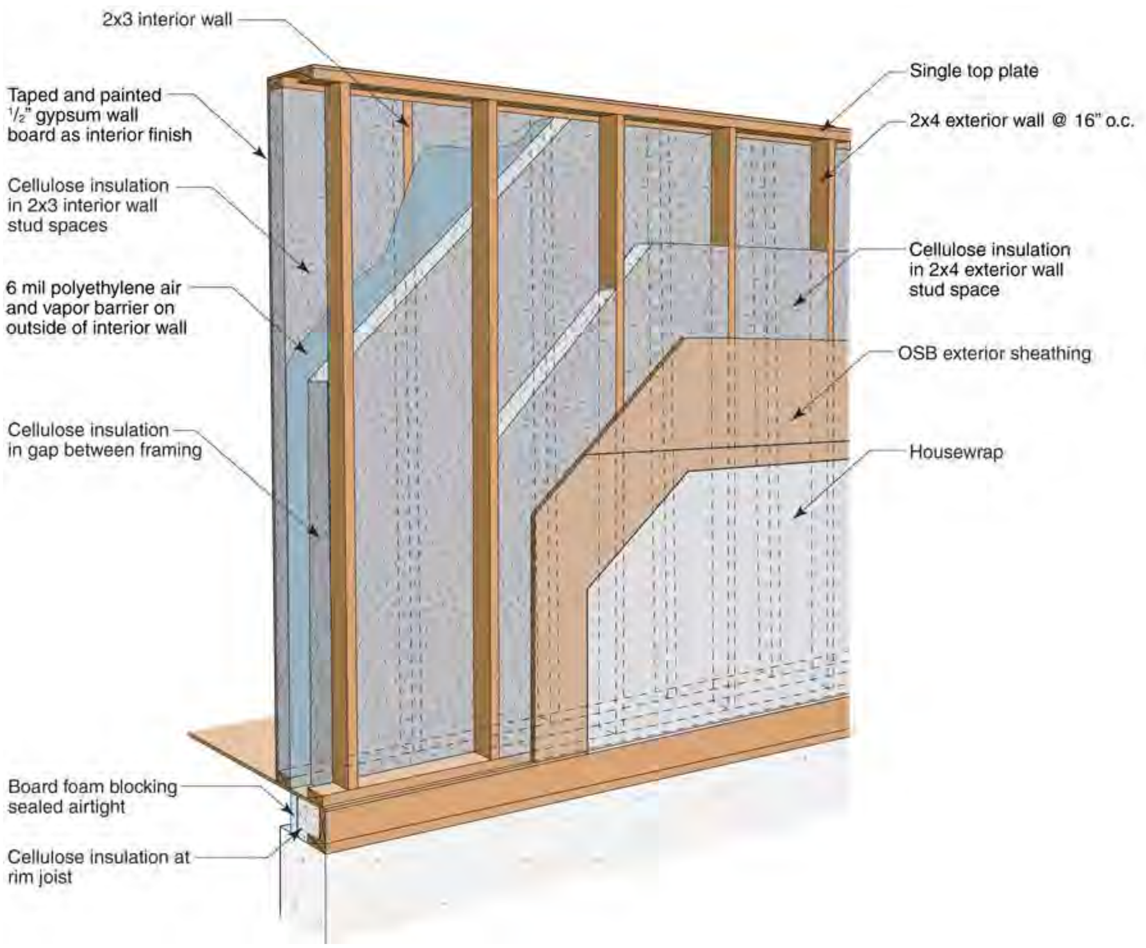

Figure 35 : Double stud wall

1.4.1. Thermal Control

This wall is typically built with an exterior structural wall using standard construction practices, a gap on the interior filled with insulation, and a second wall that is non-structural, used to support services and drywall. The interior wall studs are often installed further than 16" o.c. since it is not used for structural purposes. For the Therm simulation the exterior structural members were spaced 16"o.c. and the interior framed wall used to support the drywall and insulation was spaced at 24"o.c. The framing spacing becomes less important for simulations, and field installation, when there is a significant thermal break between the exterior and interior environments. The actual placement and alignment of interior and exterior framing members will depend on many variables such as windows, doors, corners, and the building practices of the framing crew. It is also common to use a double top plate on the exterior structural wall but for this analysis a single top plate was simulated. As with the framing members, a single or double top plate has less impact on the thermal performance for walls with significant thermal breaks between the interior and exterior. It is possible to install the 6-mil polyethylene Class I vapor barrier on the back of the interior wall by installing the plastic when the wall is on the floor, and then lifting the wall into place and securing, making sure to seal the plastic at the top and bottom. This produces a more continuous air/vapor barrier since fewer penetrations are needed for services when compared to the standard framing methods although this may increase the perceived complexity to an unsatisfactory level for some builders.

One advantage observed in the field of installing the air/vapor barrier on the interior framing is one large cavity space that is easier and quicker to insulate with cellulose insulation.

The gap between the two walls can be varied, and produces a much more effective thermal bridge between the two rows of framing than the horizontal interior strapping in Case 3. Often the insulation of choice is cellulose because it is easy to install in wide wall cavities, and will not have the spaces that can occur if fiberglass batt were installed incorrectly (as it commonly is).

The Therm model (Figure 36) shows the space between the two separate walls that helps act as thermal break. Since the gap between the walls can be changed, the R-value will depend on the designed wall thickness. In this analysis, 9.5" of cellulose was used which has an installed insulation R-value of approximately R34. Therm analysis shows that with the existing thermal bridging and rim joist, the whole wall R-value of the system is approximately R30 which is only a slight reduction from the clear wall R-value. The R-value can be improved by improving the rim joist detail: more insulation, better airtightness, and better insulation of the concrete foundation.

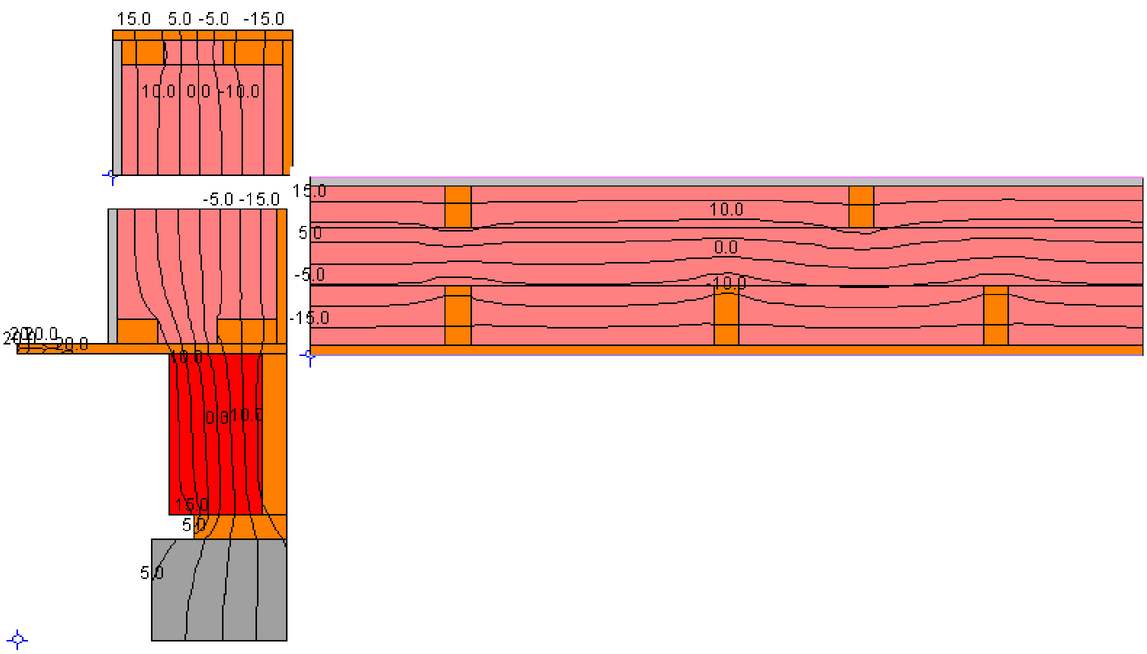

Figure 36 : Therm model of the double stud wall

Table 8 : Calculated R-value of a double stud wall

Case	Description	Whole Wall R value	Rim Joist	Clear Wall R value	Top Plate
4	Double stud wall 9.5" R34 cellulose	**30.1**	14.4	33.5	28.8

1.4.2. Moisture Control

Moisture control in the form of air leakage condensation and vapor diffusion condensation is controlled with a 6-mil polyethylene vapor barrier that can be installed on the back side of the interior wall or directly behind the drywall. Installing the poly on the back side of the interior wall, if possible, helps reduce the amount of air leakage condensation because fewer penetrations are needed and the air barrier can be more continuous.

Because of the greatly increased thermal performance, the sheathing is kept colder than standard construction and therefore the probability and intensity of vapor diffusion and air leakage condensation increases. There are approximately 4600 hours of potential wintertime condensation hours, similar to Case 3 with interior horizontal strapping but because the temperature of the sheathing is colder, the amount of condensation would increase for the same amount of air leakage (Figure 13).

In the summer time the potential inward driven moisture condensation is slightly less than the standard construction walls (Figure 20). This is because the cellulose in the insulation cavity has some buffering effect of moisture, so with a non-reservoir cladding such as vinyl siding, the buffering capacity is not overcome. The outcome may be different with a cladding such as stucco or adhered stone veneer.

In the drying analysis, the double stud wall performs very similarly to the standard construction practice as well as the interior strapped wall drying to 100 kg/m3 in 28 days (Figure 25).

1.4.3. Constructability and Cost

There is some education and training required with this construction technique, mostly with the window boxes and window installation. In any construction where the wall is much thicker than standard construction, window bucks (plywood boxes) are required for window installation. The cladding attachment is the same as normal construction practices.

1.4.4. Other Considerations

There is considerable extra framing required for the double stud wall which should be considered during design. If the exterior dimensions of the building are fixed, there is also a significant reduction in the interior floor area because of the thickness of the walls. Cellulose increases the fire resistance of the wall system, and allows for buffering and redistribution of enclosure moisture as long as the buffering capacity is not overwhelmed.

1.5 Case 5: Truss Wall

The truss wall is a construction technology that is not as widely known as the other cases being considered. It provides a great deal of insulation space, minimizes thermal bridging through the wall by using plywood gusset plates, and covers the rim joist with insulation (the rim joist is generally a location of significant air leakage and thermal bridging). Also, unlike the double stud wall, the increased wall width is to the exterior of the structural wall, which does not compromise indoor floor area.

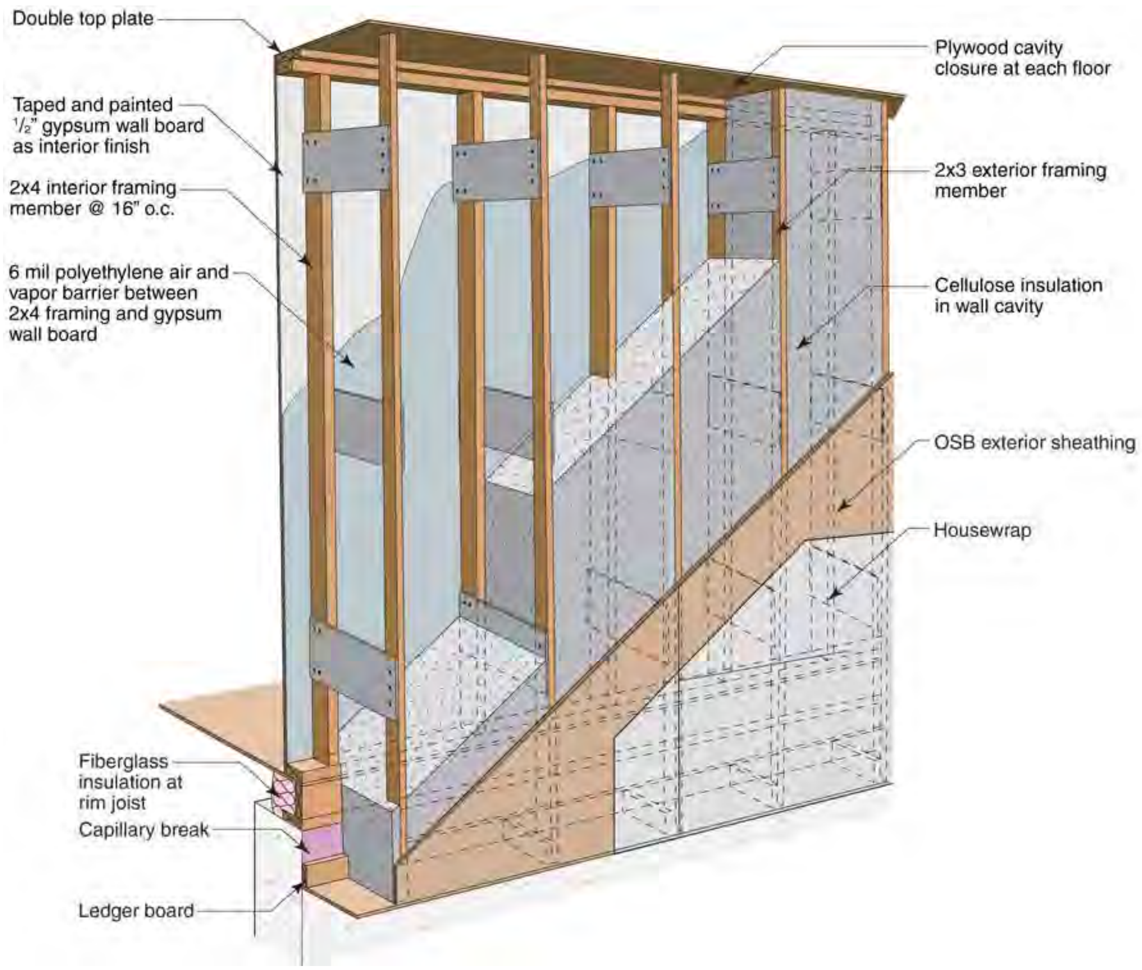

Figure 37 : Truss wall construction

1.5.1. Thermal Control

The goal of this wall is to provide as much space as possible for insulation to increase the thermal performance. In this analysis, an insulation cavity of 12 inches was constructed through the wall system. This was filled with cellulose to achieve a nominal R-value of R43, the highest R-value of any of the walls analyzed.

Therm was used to predict the whole wall R-value of this high-R assembly (Figure 38), and a value of R36.5 was calculated. Looking at the three individual components, the clear wall R-value is R40, but both the top plate and rim joist exhibited lower values. It is likely that a high heel truss with wide overhangs would be utilized for the attic and the attic space insulation would extend out over the top plate creating continuous insulation over the plates reducing the thermal bridging. This is not a commonly constructed wall but it was felt that a double top plate is more likely to be used than a single top plate for construction. It is possible to construct the same wall with a single top plate instead.

The wall schematic in Figure 37 shows that every structural wall stud has a corresponding exterior framing member for cladding attachment. In practice this is unlikely to happen because of extra framing studs commonly used for construction. It is more likely that there will be some structural wall members without a corresponding exterior framing member as was simulated in Therm (Figure 38). Similar to the double stud wall, the actual number and spacing of structural members has little influence on the whole wall R-value because of the significant thermal break of the insulation between the interior and exterior framing members.

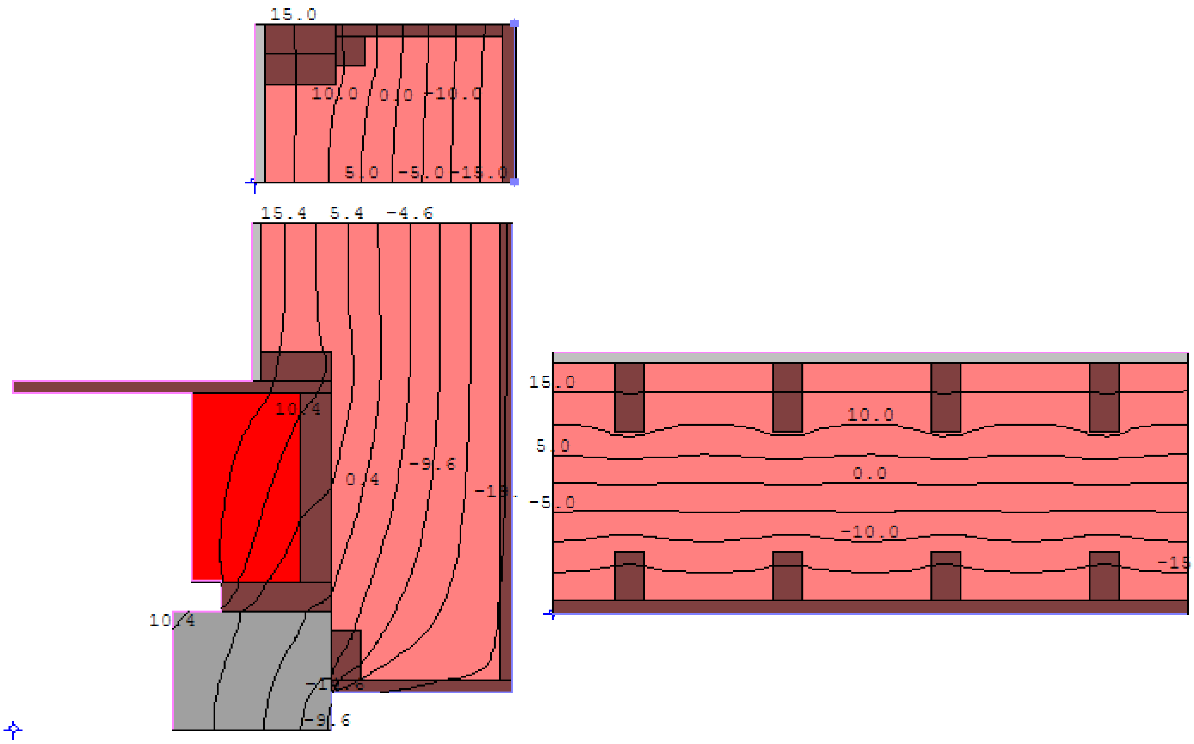

Figure 38 : Therm results of the truss wall

Table 9 : Calculated R-value for truss wall

Case	Description	Whole Wall R value	Rim Joist	Clear Wall R value	Top Plate
5	Truss wall 12" R43 cellulose	**36.5**	18.6	40.5	34.4

1.5.2. Moisture Control

Vapor diffusion control and air leakage control are particularly important in this assembly since it has the greatest insulation value and the coldest winter sheathing temperatures. The truss wall has similar winter sheathing relative humidities to the double stud wall, but the relative humidities are slightly higher because of the lower sheathing temperature. There are approximately 4600 hours of potential winter time condensation, but the intensity of condensation is slightly greater than the double stud wall, again, because of the lower sheathing temperature (Figure 13).

The truss wall is very similar to the double stud wall although slightly lower in summertime inward vapor drive relative humidity at the vapor barrier (Figure 20). This is likely because of the increased moisture distribution and buffering from the increased amount of cellulose insulation in the truss wall.

Analysis of the drying results shows that the truss wall dries two or three days faster than both the double stud wall and the interior strapping wall (Figure 25) which is also because of the greater redistribution and buffering of moisture.

There is an increased risk of problems with the vapor control layer in the truss wall than both the double stud wall and the interior strapping wall, since the polyethylene vapor barrier will have penetrations for services and wiring. If the polyethylene sheet is also being relied on as the air barrier, which is common, this could lead to the highest risk of moisture related durability issues in all three similar test walls.

1.5.3. Constructability and Cost

The truss wall appears to require more time and energy to construct than the double stud wall. This strategy would likely not be considered by a production builder under normal conditions. Cladding attachment will be the same as the traditional construction. This wall appears to be highly dependent on good workmanship (even more so than the double stud Case 4 and interior strapping Case 3), as holes in the air barrier could result in serious moisture related durability issues from air leakage condensation. If a proper airtight drywall approach is used, this could help resolve any issues with holes in the polyethylene air and vapor barrier.

1.5.4. Other Considerations

This system seems both energy and work intensive, constructing gussets, and installing the exterior framing wall and is unlikely to be used except possibly in the coldest of locations where extremely high R-values are required. There are other alternatives that may have more appeal and less risk such as Cases 10 and 11 further in this report.

1.6 Case 6: Structural Insulated Panel Systems (SIPs)

SIPs are constructed by sandwiching foam board on both sides with OSB. The foam most commonly used is EPS because of its low cost and availability, but SIPs have also been produced with XPS and even PIC in some cases to increase the R-value per inch.

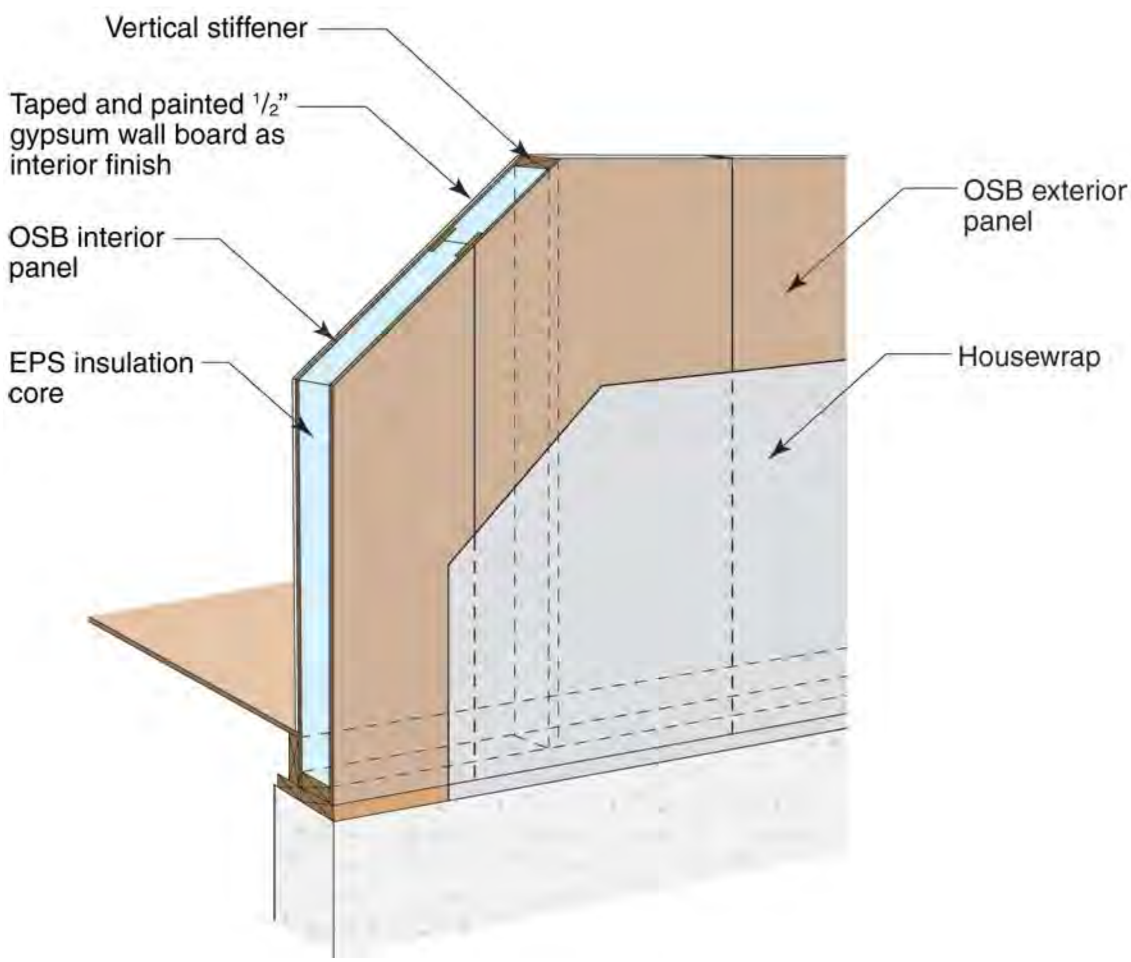

Figure 39 : SIPs wall construction

1.6.1. Thermal Control

SIPs are generally constructed with a thickness of EPS foam that matches the thickness of standard framing lumber (ie. 3.5", 5.5", 7.5"). This allows framing lumber to be inserted between the sheets of OSB in places where it is structurally required. EPS has a range of conductivity values but was modeled for this report using an R-value of R3.7/inch.

SIPs panels provide a fairly continuous plane of insulation, but quite often there are considerable thermal bridges around punched openings, the top and bottom of the panels, and sometimes through vertical reinforcement between panels.

The nominal value of this SIPs panel is R13, but because of a lack of thermal bridging through the wall (Figure 39), the calculated clear wall R-value of the wall is approximately R14.5 when the OSB and air films are taken into account. The whole wall R-value is approximately 13.6 when the top and bottom plate thermal bridges are accounted for (Table 10), which is actually higher than the installed insulation R-value.

Generally the cladding is applied directly to the exterior over a sheathing membrane, and possibly a drainage cavity, and the drywall is applied directly to the inside face. It is possible to increase the R-value of the assembly by adding insulation to the interior or exterior of the SIPs panel but it may not be cost effective.

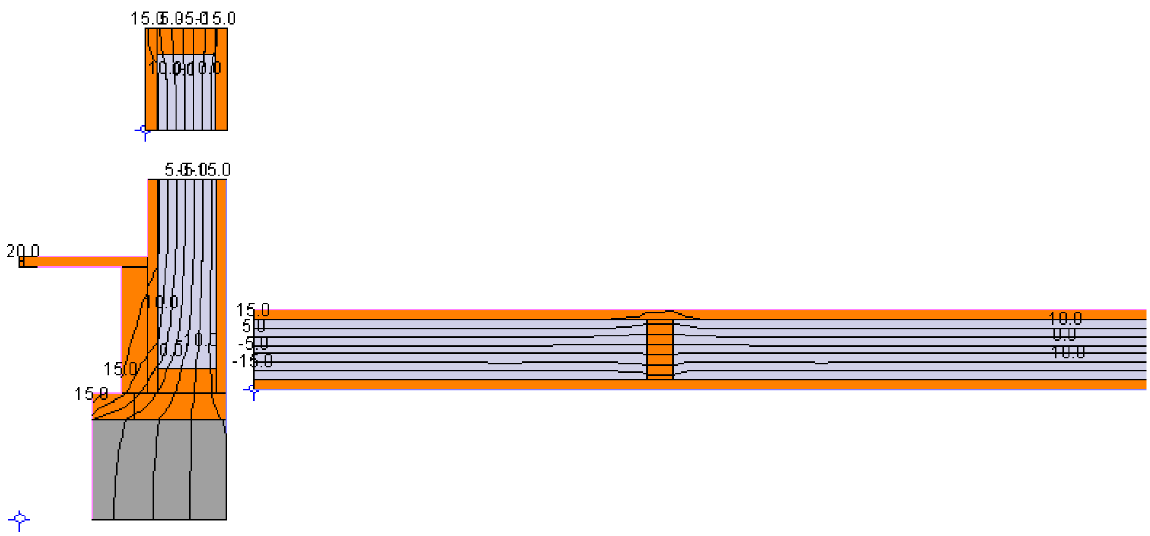

Figure 40 : Therm results of SIPs panel analysis

Table 10 : Calculated R-value for a Sips wall system

Case	Description	Whole Wall R value	Rim Joist	Clear Wall R value	Top Plate
6a	SIPs (3.5" EPS)	**14.1**	12.3	14.5	10.6
6b	SIPs (11.25" EPS)	**36.2**	14	41.6	28.2

1.6.2. Moisture Control

The plane of the SIPs wall provides a good air and vapor barrier between the interior and exterior environments. Historically, there were problems at the joints between SIPs panels where air would leak from the interior space to the exterior surface and condense against the back of the sheathing during the heating season in cold climates (SIPA 2002). Many SIPs failures have been reported to be caused by this air leakage condensation mechanism.

Currently there are better practice guides and standards applied to the installation and construction of SIPs panels and in new buildings these moisture-related durability issues are rare.

1.6.3. Constructability and Cost

Construction with SIPs panels requires training and education about construction techniques and design details. Generally, houses built from SIPs panels have very simple layouts and roof designs to help simplify the design of details at SIPs joints and roof-wall interfaces.

1.6.4. Other Considerations

This is a fairly simple, yet durable solution if constructed properly. EPS foam is the least energy intensive to produce of all the board foams, and this technique requires far less framing lumber than other standard techniques, but twice as much OSB as normal framing with a single layer of exterior sheathing. During field installation it has been observed that there are often significant thermal bridges around penetrations, and depending on the structural loading of the SIPS panel, there may be multiple vertical stiffeners which also act as thermal bridges. As with all cases, the whole wall R-value makes assumptions regarding the occurrence of framing member thermal bridging, and in the field it is likely that the whole wall R-value is slightly lower than simulations indicate.

The 3.5" SIPs panel is not considered a High-R wall system, but as the thickness level, and insulation are increased, this system could be considered for more extreme cold climates.

1.7 Case 7: Insulated Concrete Forms (ICFs)

The most common type of ICF consists of two sides of EPS of varying thickness and a poured in place concrete core. This combination of insulation and concrete provides both the thermal component and the structural component of the enclosure. Some ICFs are constructed of a cement wood fiber instead of EPS, and have varying amounts of insulation.

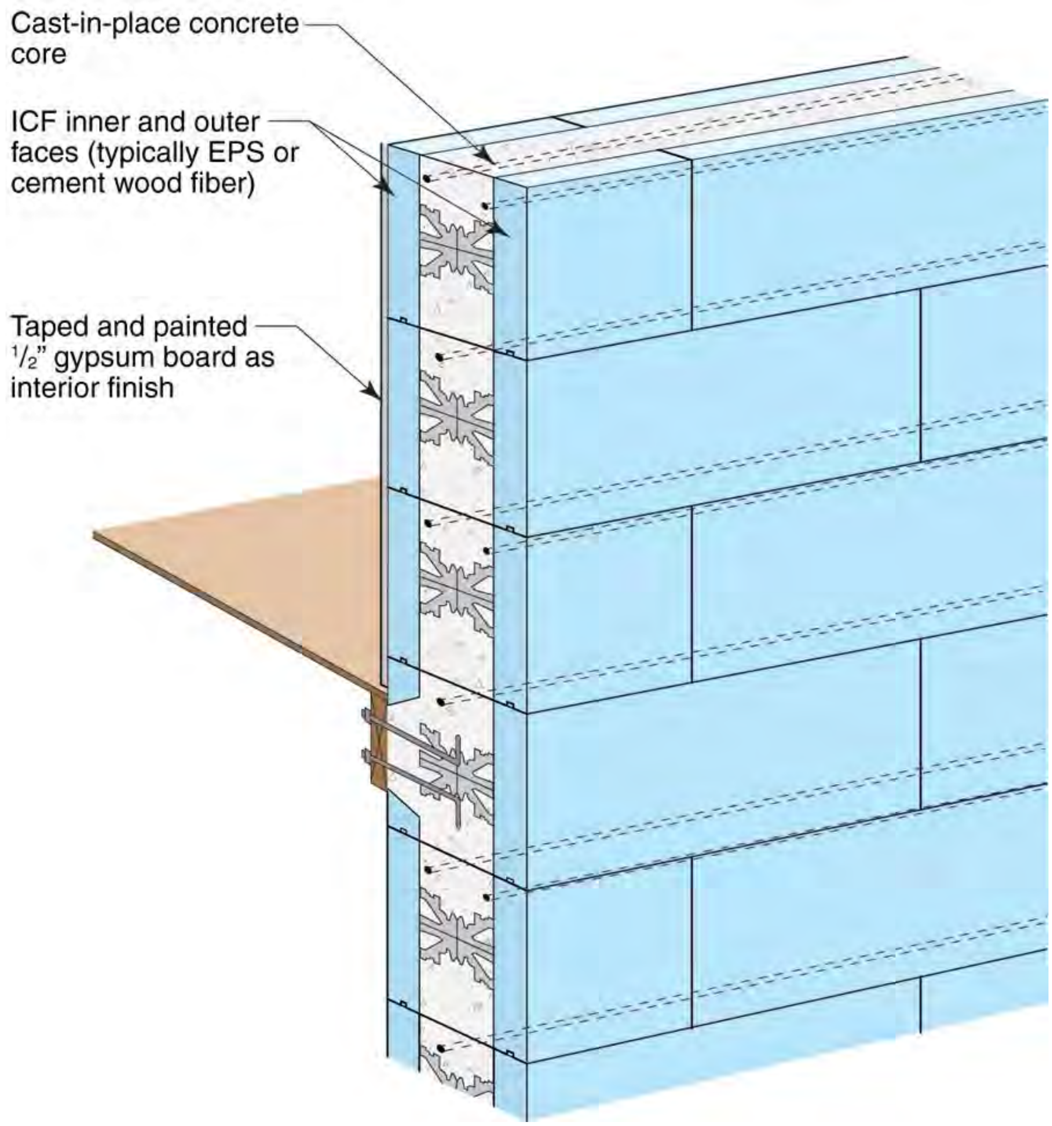

Figure 41 : ICF wall construction

1.7.1. Thermal Control

The ICF wall provides a barrier to both vapor and air flow across the enclosure. Care must still be taken at the penetrations for windows, doors and services to prevent air from moving through the enclosure, reducing the effectiveness of the insulation.

Therm analysis was used to determine the whole wall R-value of two different ICF systems. Figure 42 shows an 8" ICF with 2" of EPS on both the interior and exterior, and 4" of concrete. This has an R-value of 16.4. In comparison a 15" foam ICF with 5 total inches of EPS has an R-value of 20.6

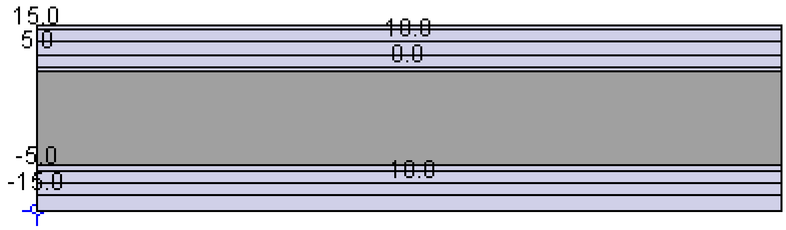

Figure 42 : Eight inch foam ICF with four inches of EPS

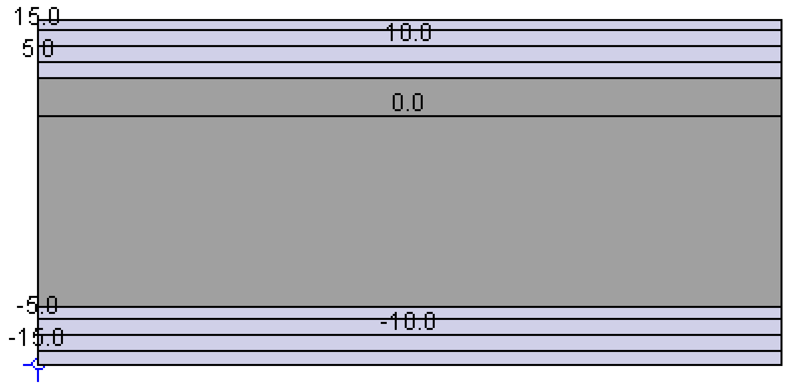

Figure 43 : Fifteen inch foam ICF with five inches of EPS

Neither of these ICF strategies would be considered a high-R enclosure in a cold climate, but these could be combined with an interior insulated framed wall or a layer of spray foam on the exterior to increase the thermal performance. The good airtightness, and the use of convection-immune rigid foam insulation means that the thermal performance is reliably delivered.

1.7.2. Moisture Control

Most ICF walls are vapor barriers that do not allow vapor to pass through easily. This also means that the wet concrete in the ICF form will retain an elevated moisture content for an extended period of time. The ICF wall system should be designed to allow to dry as easily as possible, in both directions if possible.

One of the failure mechanisms of ICF walls is improperly flashed openings that allow water to drain into the enclosure through windows, and doors, and service penetrations. Since there is no storage component to the enclosure materials, all of the water will pass through, affecting the interior finishes.

1.7.3. Constructability and Cost

ICFs are generally easy to use with some training on where and how to use steel reinforcement if necessary and installing services. Blocks are simply stacked on top of each other and concrete is poured into the centre. There have been reported issues with gaps left in the concrete or blocks breaking under the internal pressure of the concrete, and there may be issues with lining up the interior edges of the ICF blocks to provide a perfectly flat substrate for drywall installation, but all of these problems can be dealt with by better training and quality control.

1.7.4. Other Considerations

An ICF wall uses less concrete than the comparison structural wall made of only concrete, but concrete requires significantly more embodied energy than some other alternative building materials such as wood framing. ICFs appear to be ideally suited to use in areas where there is a risk of flooding or severe moisture damage, since it is much more tolerant of severe wetting events. The resistance to hurricane wind loads and debris damage is also very high.

There are many different design possibilities for ICF construction with regards to design details, which may have an effect on both the durability and thermal performance. Field investigations have shown that this construction strategy is not immune to serious moisture related risks such as bulk water leakage, window leakage, and mould if installed incorrectly.

1.8 Case 8: Advanced framing with spray foam

Polyurethane spray foam can be used in the stud cavity instead of fiberglass or cellulose insulation. Spray foam forms a very good air barrier when installed correctly and can be installed as low density (0.5 pcf) or high density (2.0 pcf) foam.

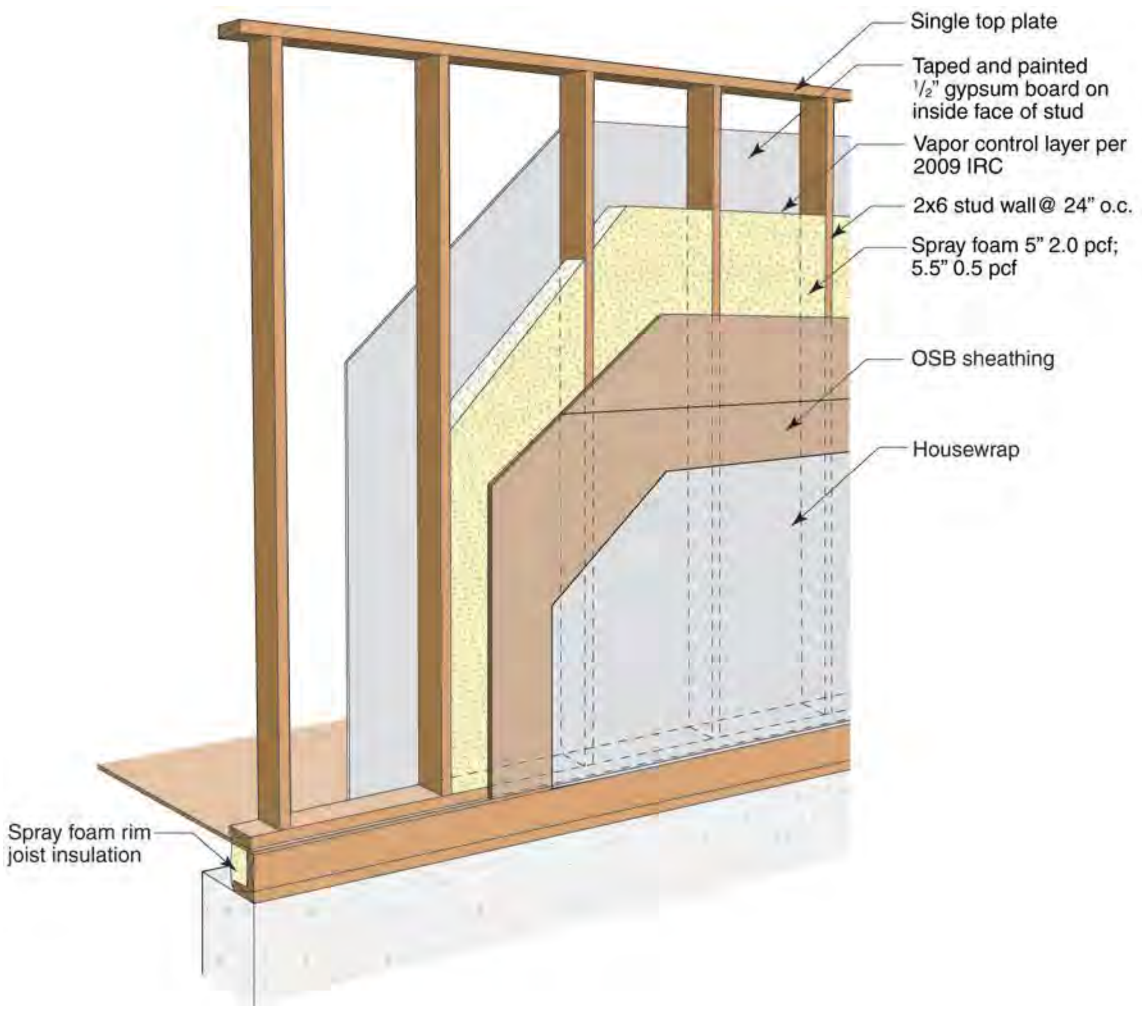

Figure 44 : 2x6 wall construction with spray foam insulation

1.8.1. Thermal Control

Using Therm to model different wall enclosure strategies does not accurate represent the benefits of spray foam insulation. Properly installed spray foam insulation completely stops air flow movement through and around the insulation so decreases in R-value associated with air leakage do not occur, either in the stud space or at the rim joist. There are different published R-values for both low and high density insulation but in this analysis for Case 8, 5.5" of R21 low density foam, and 5" of R28 high density foam were used. High density foam is installed short of the edge of the cavity to minimize trimming of the foam, while low density foam is softer, and installed to the edge of the cavity so that the excess can be trimmed flush with the stud wall framing.

Similar to standard construction practices, using spray foam does not address the concern of thermal bridging through the framing material as can be seen in Figure 45.

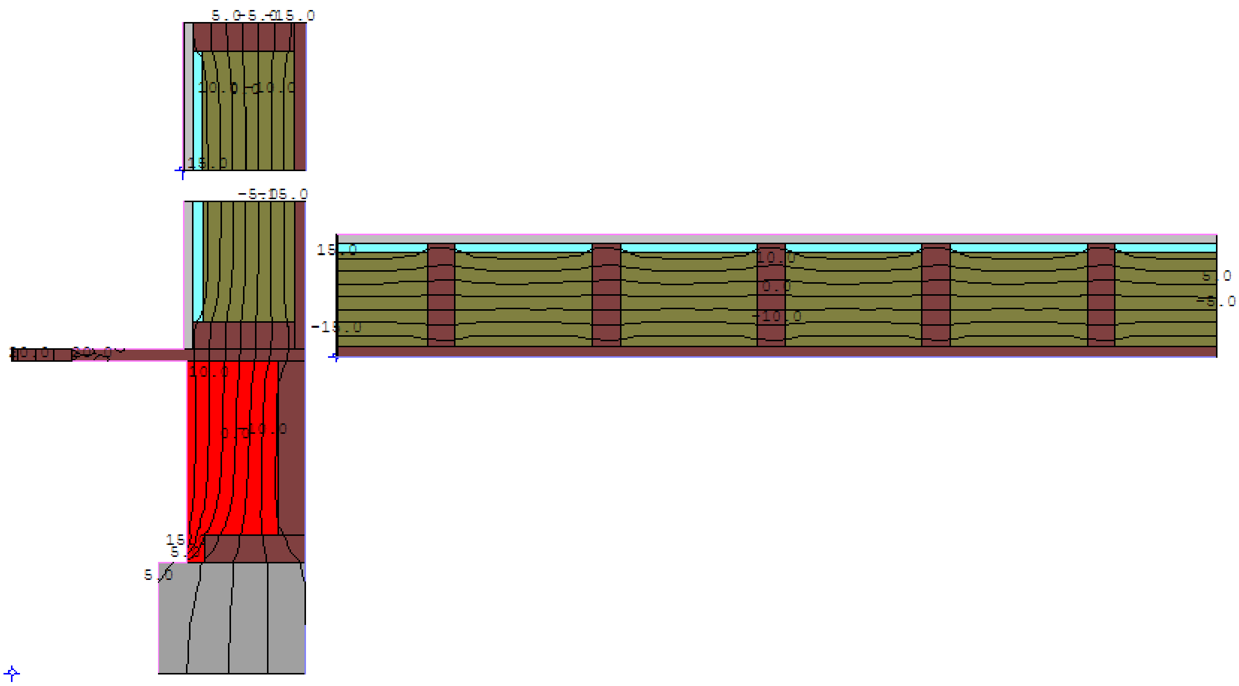

Figure 45 : Therm modeling of spray foam wall and rim joist

Calculating the whole wall R-values for the two spray foam assemblies results in R-values of R19.1 for high density spray foam, and R16.5 for the low density spray foam. The whole wall R-value of low density foam decreased by almost R4.5 versus the installed insulation R-value (from R20.9 to R16.5) because of thermal bridging. The whole wall R-value of the high density foam insulated wall decreased R9 from the installed insulation R-value due to the thermal bridging.

Table 11 : Therm results of spray foam insulation analysis

Case	Description	Whole Wall R value	Rim Joist	Clear Wall R value	Top Plate
8a	2x6 AF, 24" o.c., 5" 2 pcf R29 SPF, OSB	**19.1**	13.6	20.3	19.5
8b	2x6 AF, 24" o.c., 5.5" R21 0.5 pcf SPF, OSB	**16.5**	13.1	17.2	16.6

1.8.2. Moisture Control

High density spray foam is both an air and vapor barrier. This limits the movement of moisture vapor and air leakage condensation. Low density foam is an air barrier, but it is permeable to water vapor and is susceptible to vapor diffusion condensation. Low density foam was modeled both with and without a class I vapor retarder to determine the performance differences of a class I vapor barrier with low density foam in climate Zone 6.

Both the high density foam and the low density foam with a vapor barrier had some of the lowest sheathing relative humidities in the winter months of all of the tested wall cases. The low density foam without a vapor barrier experienced high sheathing relative humidities sustained above 95% through the winter months (Figure 13).

Analysis of air leakage condensation shows that because the spray foam is an air barrier, there would be no condensation caused by air leakage, since the surface temperature of the interior face of the foam was always warmer than the dew point of the interior air (Figure 14).

Analysis of the summertime inward vapor drive shows that the low density sprayfoam with a poly vapor barrier experienced the highest relative humidity peaks of any of the test walls, approximately 5% higher than standard construction practice.

The high density foam and the low density foam without a vapor barrier experienced some of the lowest relative humidities of test walls because they were allowed to dry very easily to the interior.

Drying results (Figure 21) showed that the low density foam without poly dried to 100 kg/m3 in approximately 28 days similar to some of the other test walls, but the high density foam and low density foam with a vapor barrier took approximately 43 days to dry to 100 kg/m3.

1.8.3. Constructability and Cost

This wall is easier to build than a standard construction wall, since no care is required at installing fiberglass batts. The costs can be perceived as prohibitively expensive which is why sprayfoam is often only used where a perfect air barrier is required, and may be difficult to install, such as garage-house interface and rim joists.

1.8.4. Other Considerations

With the new era of environmentally friendly products, many spray foam companies are marketing green spray foams that are less or harmful to the environment. In most cases, spray foam may need to be protected with a fire rated material according to the code.

1.9 Case 9: Hybrid Wall Insulation – Flash and Fill

In this analysis, hybrid walls consist of two inches of 2.0 pcf closed cell foam sprayed against the interior surface of the exterior sheathing, and three and a half inches of fiberglass. Instead of fiberglass batt, cellulose or sprayed fiberglass could also be used. Flash and Fill or Flash and Batt is often used to describe the combination of spray foam and cellulose, or spray foam and fiberglass batt respectively. The framing strategy used is advanced framing with 2x6s 24" on centre with a single top plate. Spray foam insulation helps considerably with the air tightness of the wall assembly and will increase the temperature of the potential wintertime condensation plane. Two inches of high density spray foam in the cavity also decreases the need for an interior vapor control layer which simplifies construction.

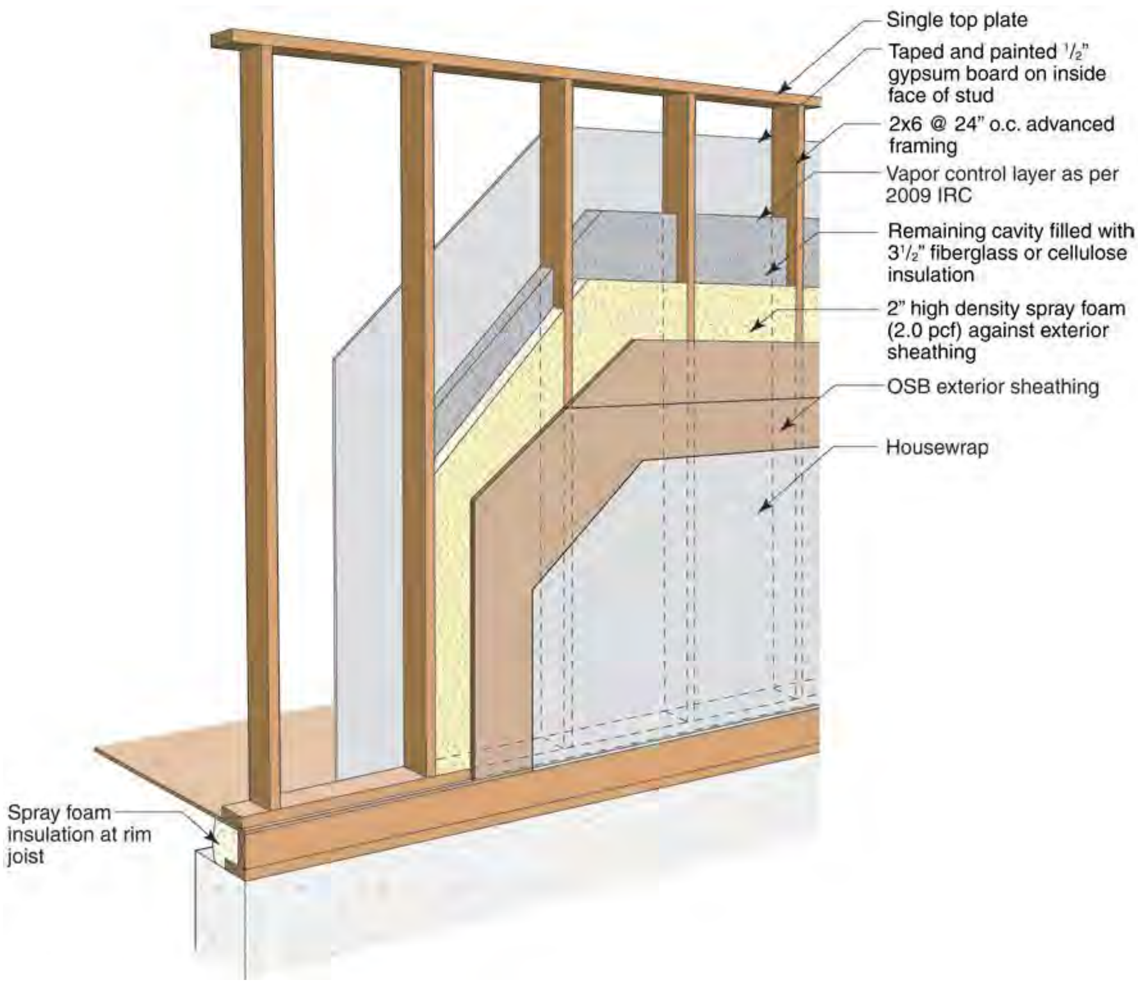

Figure 46 : Hybrid wall construction with 2" spray foam and fibrous fill

1.9.1. Thermal Control

The hybrid wall provides an increase in thermal control over the standard wall construction. Unfortunately, adding a high quality, air tight insulation between the framing does not address the issue of thermal bridging of the framing materials. Heat lost by air leakage can be greatly reduced by using the spray foam insulation, thus increases the true R-value. The whole wall R-value increases from R15.2 to R17.5 when comparing the same framing strategy with only fiberglass insulation (Case 1a) to Case 9. This improvement alone may not be enough to justify the added cost, but the heat lost from air leakage would also be greatly reduced through the wall and rim joist improving energy efficiency and human comfort.

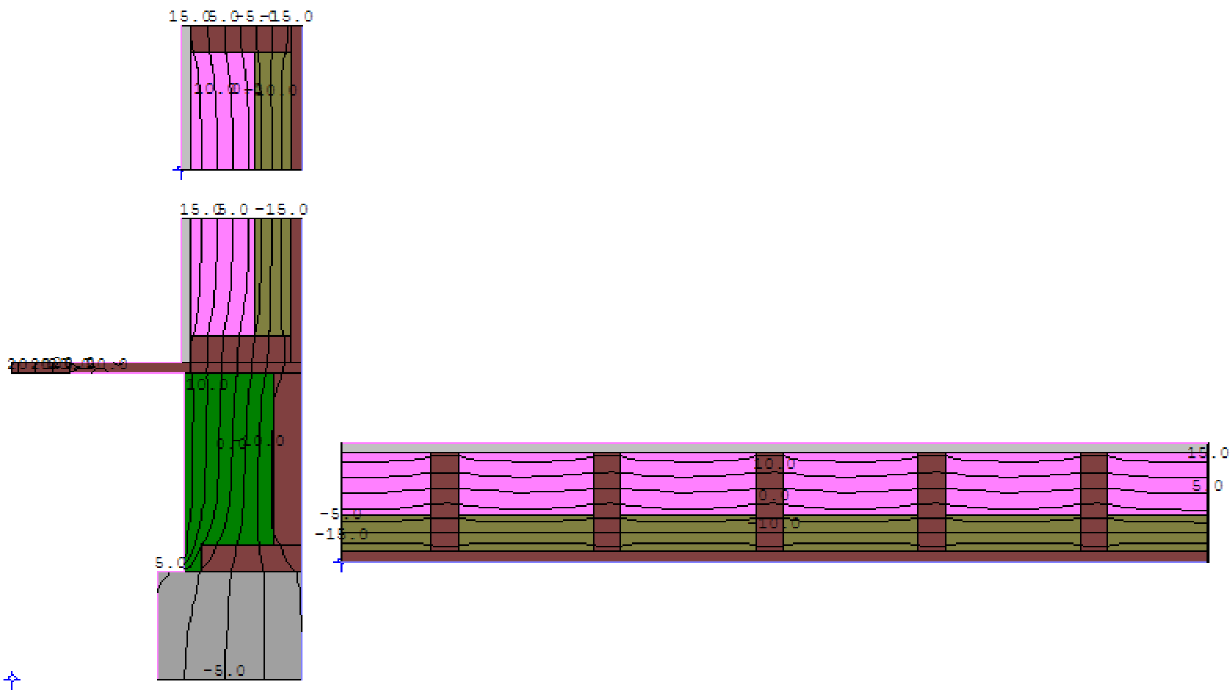

Figure 47 : Therm analysis of hybrid wall system

Table 12 : Calculated R-value for a hybrid wall system

Case	Description	Whole Wall R value	Rim Joist	Clear Wall R value	Top Plate
9	2x6 AF, 24"oc, 2" SPF and 3.5" fibrous fill	**17.5**	13.2	18.4	17.7

1.9.2. Moisture Control

This wall performs very similarly to the Case 2 with 4" of exterior insulation with respect to summer inward vapor drives as shown in Figure 19.

During the winter months, there is a significant improvement in the potential air leakage condensation on the condensation plane in the hybrid wall, from the standard construction wall, as shown in Figure 11 because the condensation plane is kept warmer by the vapor impermeable spray foam insulation.

One disadvantage of this wall system over advanced framing with exterior insulation (Case 2) is that the sheathing is kept much colder in Case 9. Keeping enclosure materials warm and dry with exterior insulation has been known to increase enclosure durability since the 1960s (Hutcheon 1964).

1.9.3. Constructability and Cost

The constructability of this system is as easy as standard construction but the cost of construction is higher than using exclusively fiberglass insulation. This wall system is not as prone to air leakage moisture related damage as standard construction walls.

1.9.4. Other Considerations

Adding high density spray foam insulation in the cavity increases the stiffness and strength of the wall systems. This could be particularly helpful in high wind loads or when impact resistance is required as in tornado or hurricane zones. Spray foam is the most reliable method to achieve air tightness in residential construction and comes with the added bonus of thermal insulation. High density foam is easy to transport to remote locations, and increases the moisture related durability of the enclosure.

1.10 Case 10: Double Stud Wall with Spray Foam

Case 10 with spray foam insulation was chosen to try and improve the moisture related durability of the double stud wall in Case 4 which used cellulose insulation in the cavity space. The thermal performance of Case 4 was quite good, but the air leakage condensation potential could lead to premature enclosure failure. Case 10 analysis was conducted with two inches of spray foam since that is usually the maximum thickness that is sprayed in one pass during 2.0 pcf foam installation. This should increase the temperature of the condensation plane, thus increasing the moisture durability of the wall system. Depending on the climate zone for construction, more spray foam could be used to further decrease the risk of moisture related damage. Analyzing different thicknesses of spray foam for this single wall system are beyond the scope of this analysis report, but should be considered before this wall is constructed.

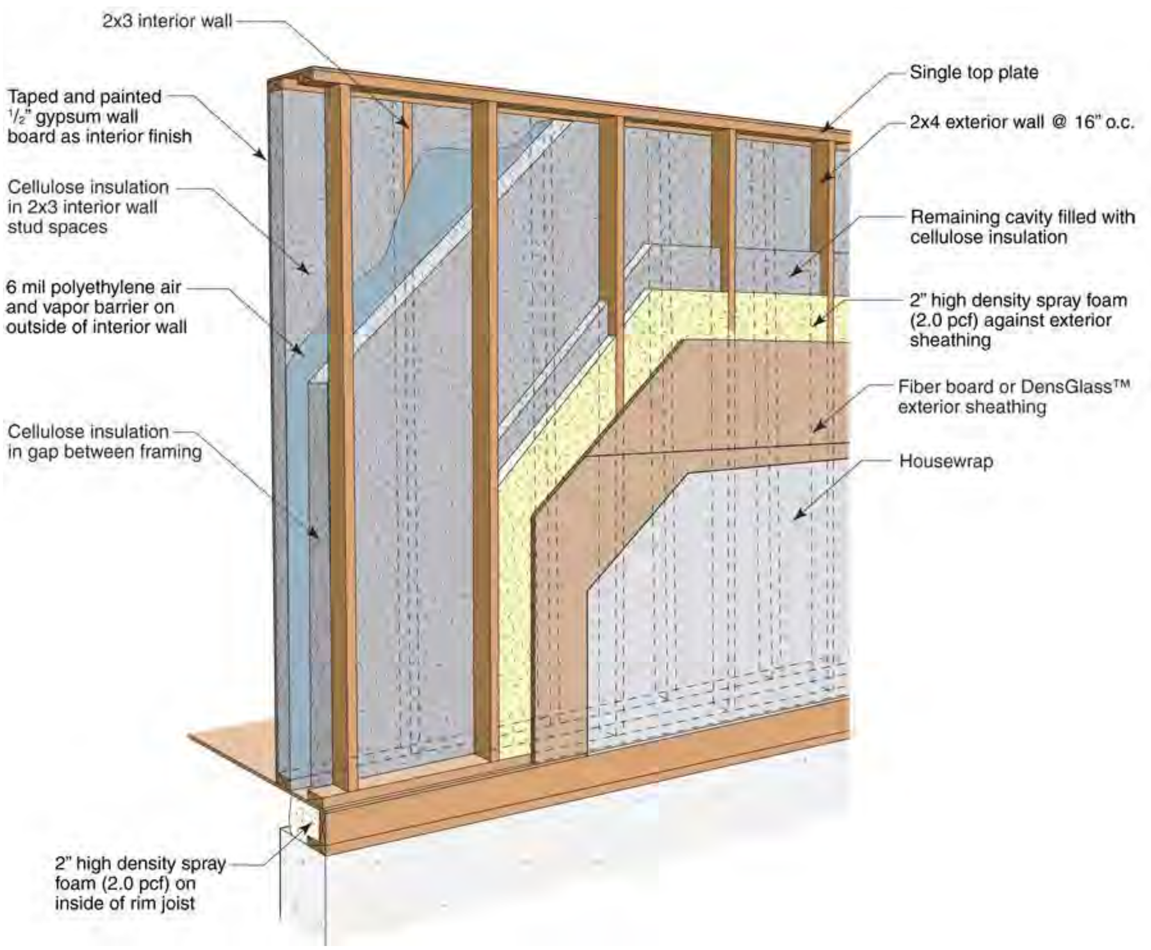

Figure 48 : Double stud wall with 2" of spray foam and cellulose fill

1.10.1. Thermal Control

This wall system has a slight improvement in whole wall R-value over Case 4, without spray foam insulation increasing from R30.1 to R32.4. This is only a minimal increase in the calculated whole wall R-value, but as in all cases with spray foam, there are improvements to the true R-value due to decreasing the air leakage through the wall and rim joist.

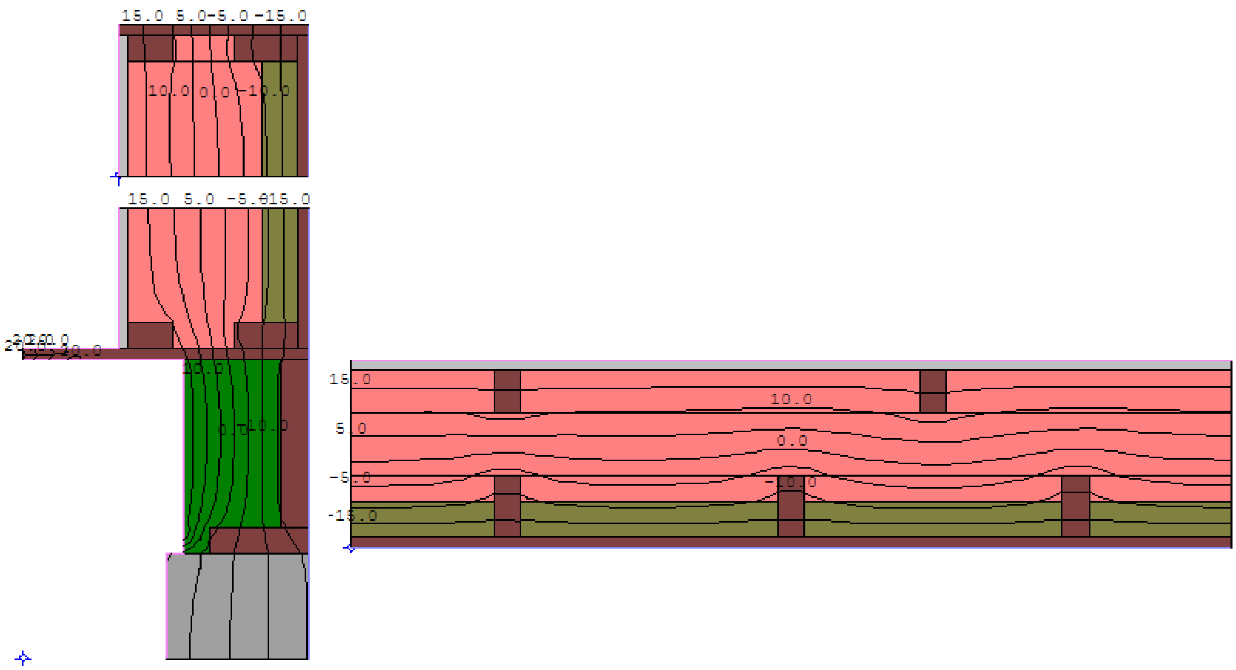

Figure 49 : Therm analysis of double stud wall construction with spray foam

Table 13 : Calculated whole wall R-value for a double stud wall system with 2" spray foam

Case	Description	Whole Wall R value	Rim Joist	Clear Wall R value	Top Plate
10	Double stud with 2" 2.0 pcf foam, 7.5" cell.	**32.4**	15.9	36.2	28.5

1.10.2. Moisture Control

The most evident improvement to adding spray foam was shown in Figure 14 with less wintertime condensation potential. There are still periods of wintertime condensation risk in climate zone 6, the risks have been improved, and more spray foam would decrease the risk even further in climate zone 6 and should likely be required in colder areas. The hours of potential wintertime condensation decreased from approximately 4600 hours for Case 4 to approximately 2300 for Case 10 with spray foam insulation.

There is very little change to the drying results when comparing the double stud wall with and without spray foam insulation. The sheathing retains its moisture longer in Case 10 because the moisture can only dry to the exterior and is not buffered at all on the interior surface by the cellulose insulation (Figure 27). There are no significant changes to the summertime inward vapor drive by adding 2" of high density spray foam to the sheathing of the double stud wall (Figure 21). If a moisture storage cladding was used for simulations, adding the spray foam may reduce the inward vapor drive because of the vapor resistance of the spray foam.

1.10.3. Constructability and Cost

This wall system uses more framing material than most of the other test wall assemblies. The cost of this wall system is high relative to most of the other options, but does provide very high thermal resistance.

1.10.4. Other Considerations

The majority of the insulation is cellulose which is the lowest embodied energy insulation and readily available. The ratio of cellulose to spray foam insulation can be changed depending on the climate zone for construction to limit the potential winter time condensation.

Spray foam will burn, and therefore should always be protected by fire rated material, which in this case is the cellulose insulation.

1.11 Case 11: Offset Frame Wall with Exterior Spray Foam

Case 11 was included because of the increasing need for a retrofit solution that saves energy, increases durability and does not affect the interior space. This strategy also has several advantages as a new construction strategy as well, especially in extreme climates with a short construction season.

Standing lumber off of the sheathing using plywood trusses allows the cladding to be directly attached without requiring more exterior sheathing. High density foam acts as the drainage plane, air barrier, vapor barrier, and thermal control layer. Using plywood gusseted trusses can be a little work intensive since they all need to be made to identical dimensions.

An alternative solution to the traditional truss wall is shown in Figure 15. This method is less energy intensive in preparation. It uses large nails or spikes to support the framing lumber for the cladding installation. A spacer was used between the sheathing and the framing lumber to ensure even spacing and then was removed after the nails were installed. Even though this method does not appear to be strong enough to support cladding, it has supported approximately 200 lbs on a single truss prior to installing the foam, and is considerably stronger following the installation of the spray foam. An alternative method proposed for spacing the lumber off of the sheathing is to use plastic sleeves (possibly PVC pipe) which are cut to a constant length and used to set the depth of the nails that attach the lumber by driving the nails through the centre of them.

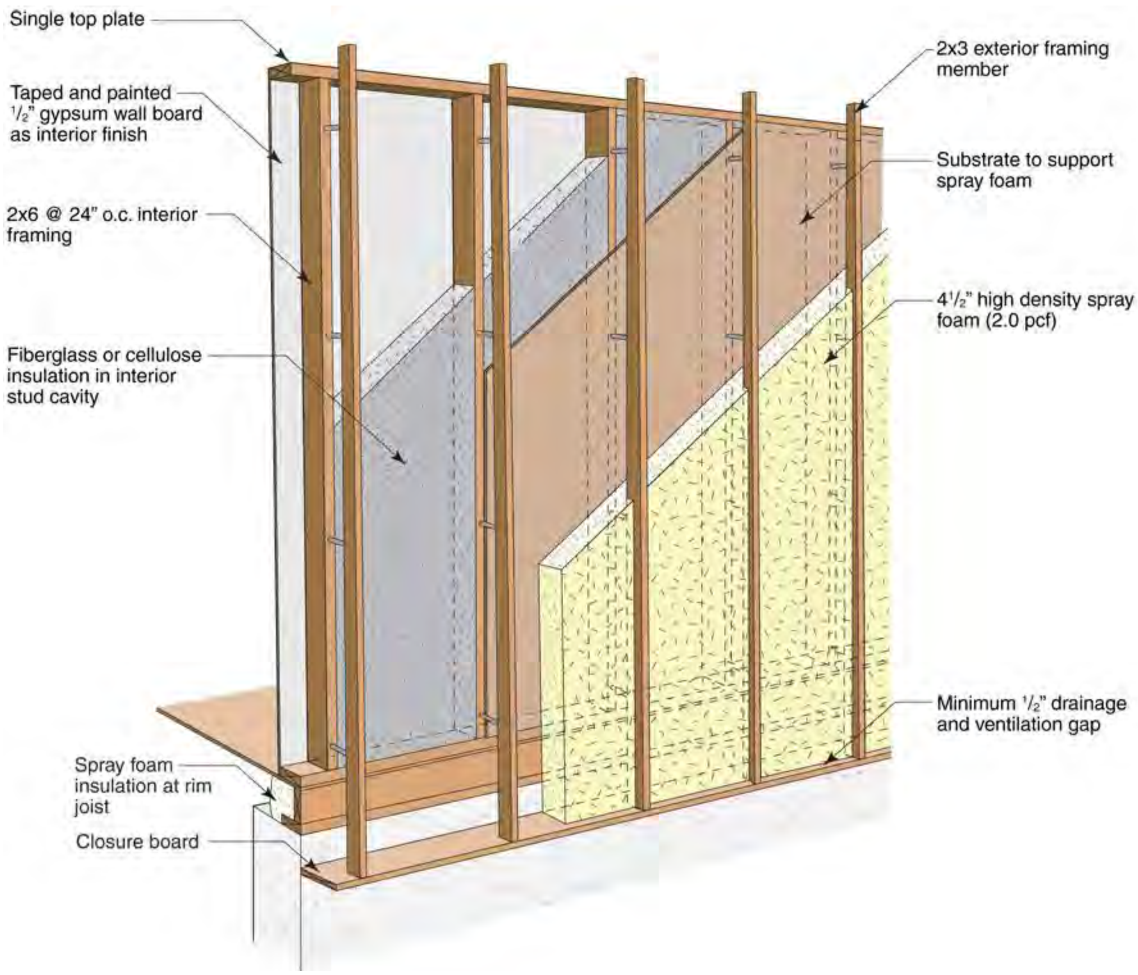

Figure 50 : Offset frame wall construction with exterior spray foam

1.11.1. Thermal Control

This wall with 4.5 inches of high density spray foam and 5.5 inches of fibrous insulation has a whole wall R-value of approximately R37, the highest total wall R-value of all walls analyzed which is, in part, because of the lack of thermal bridges through the entire system. Spray foam is installed over the rim joist, over the exterior of the wall, and up to the soffit, where ideally, it meets with the spray foam in the attic.

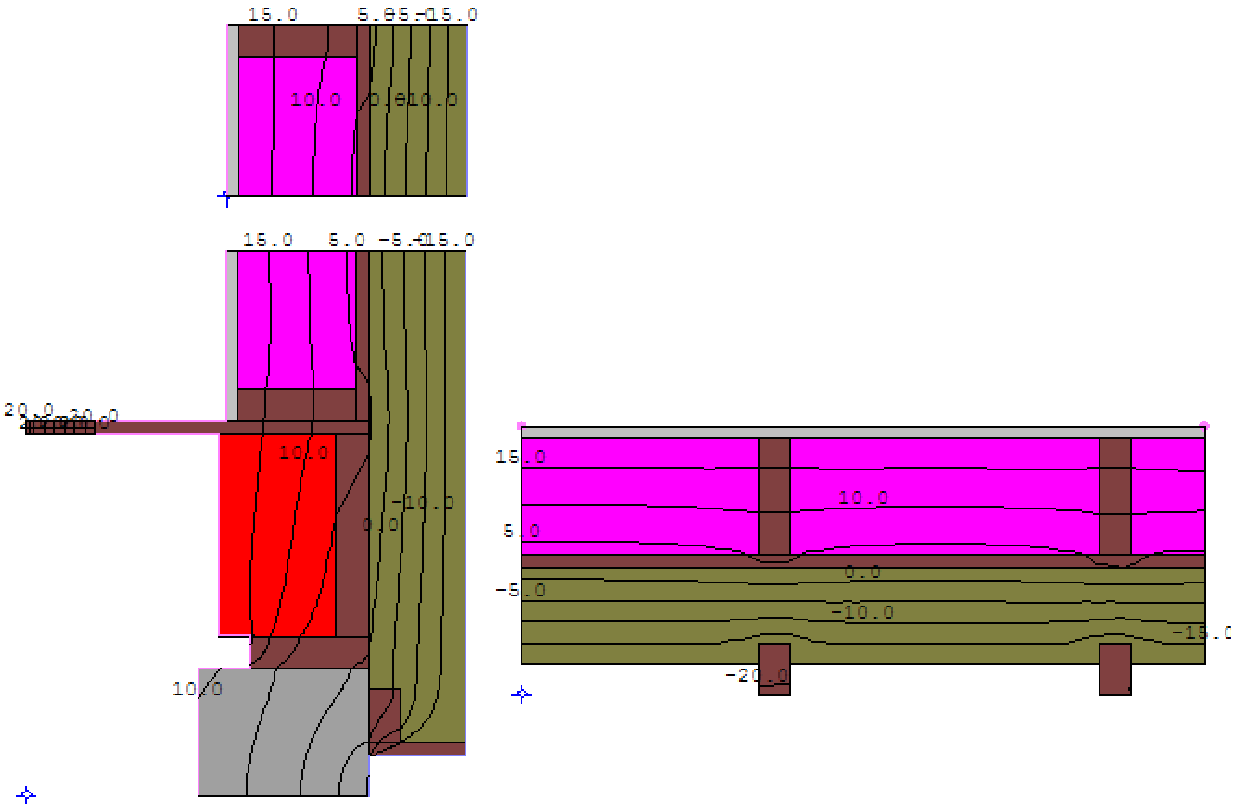

Figure 51 : Therm analysis of an offset truss wall with exterior spray foam

Table 14 : Calculated whole wall R-value for an offset framed wall with exterior spray foam

Case	Description	Whole Wall R value	Rim Joist	Clear Wall R value	Top Plate
11	Offset frame wall with ext. spray foam	**37.1**	18.8	40.6	41.9

1.11.2. Moisture Control

Because of the high level of vapor control in the exterior spray foam insulation, a vapor barrier is not required on the interior of the wall assembly. This allows any necessary drying to occur to the interior. In Minneapolis, (climate zone 6) there is no risk of winter time condensation on the interior of the exterior sheathing (Figure 16).

The summer time inward vapor drive sheathing relative humidity does not change significantly with the addition of the exterior foam (Figure 23). The relative humidity increases slightly in Case 11 because of the higher interior relative humidity, the low solar inward vapor drive load, and the inability for the exterior spray foam wall to dry to the outside.

The sheathing remains wet during the drying test significantly longer with exterior insulation than without since there is no moisture buffering capacity in the fiberglass batt in Case 11, and there is significant moisture buffering capacity of the cellulose insulation in Case 5 (Figure 28).

1.11.3. Constructability and Cost

High density spray foam is a relatively expensive choice for an insulation strategy. In this case, it provides great thermal resistance, reduced thermal bridging, and minimal air leakage. Some of these benefits will result into operating energy costs savings, but other benefits can not be easily quantified such as greater occupant comfort, and quite possibly higher resale value in an uncertain energy future.

1.11.4. Other Considerations

This method could be used as a retrofit without greatly affecting the interior, or for new construction. It is a very quick, high quality method of sealing the exterior and drying in the interior during construction, so that care can be taken with the interior work including wiring, plumbing and HVAC. This is ideal for locations with short construction seasons. Since the foam is transported in liquid phase, more board feet of foam (and R-value) can be transported on a transport truck than any other type of insulation

1.12 Case 12: Exterior Insulation Finish System (EIFS)

Using an exterior insulation finish system (EIFS) is a valid option for cladding in almost every climate zone. The thickness of the exterior insulation can be varied to provide the thermal resistance required in combination with the stud space insulation. EIFs was one of the cladding strategies used on the CCHRC head office in Fairbanks AK (13980 HDD65 or 7767 HDD18) which is considered to be an extremely cold climate.

There is a stigma attached to EIFS because of the large number of failures in various climates in the past. Field and laboratory observations and testing have shown that this cladding technique is an effective and durable wall assembly, if drainage and water management details are constructed correctly. In most cases, during failures, water was trapped behind the EIFS due to poor water management details which eventually rotted the sheathing, causing corrosion and rot of the wall assembly. A properly detailed continuous drainage plane will ensure that this is a successful cladding technique in any climate zone.

Fiberglass-faced gypsum board exterior sheathing was used instead of OSB in the simulation because it is generally used underneath EIFS cladding systems due to its moisture tolerance.

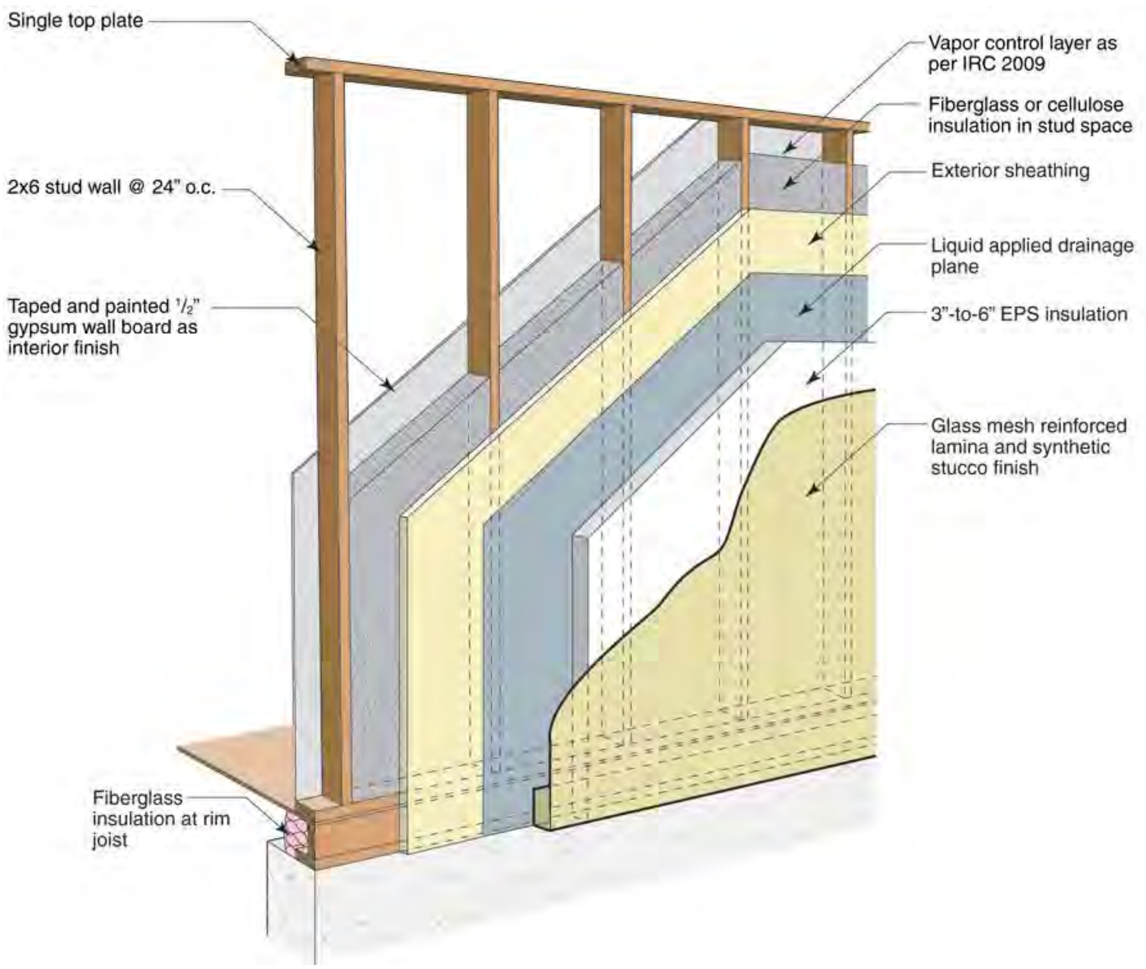

Figure 52 : Wall construction using the EIFS cladding system

1.12.1. Thermal Control

The amount of insulation installed on the exterior of the advanced framing will determine the thermal control of the assembly. In this analysis we used four inches of EPS board foam insulation, and achieved a whole wall R-value of R30. This strategy addresses the thermal bridging of both the framing and the rim joist and is very similar to advanced framing with four inches of XPS insulation in Case 2.

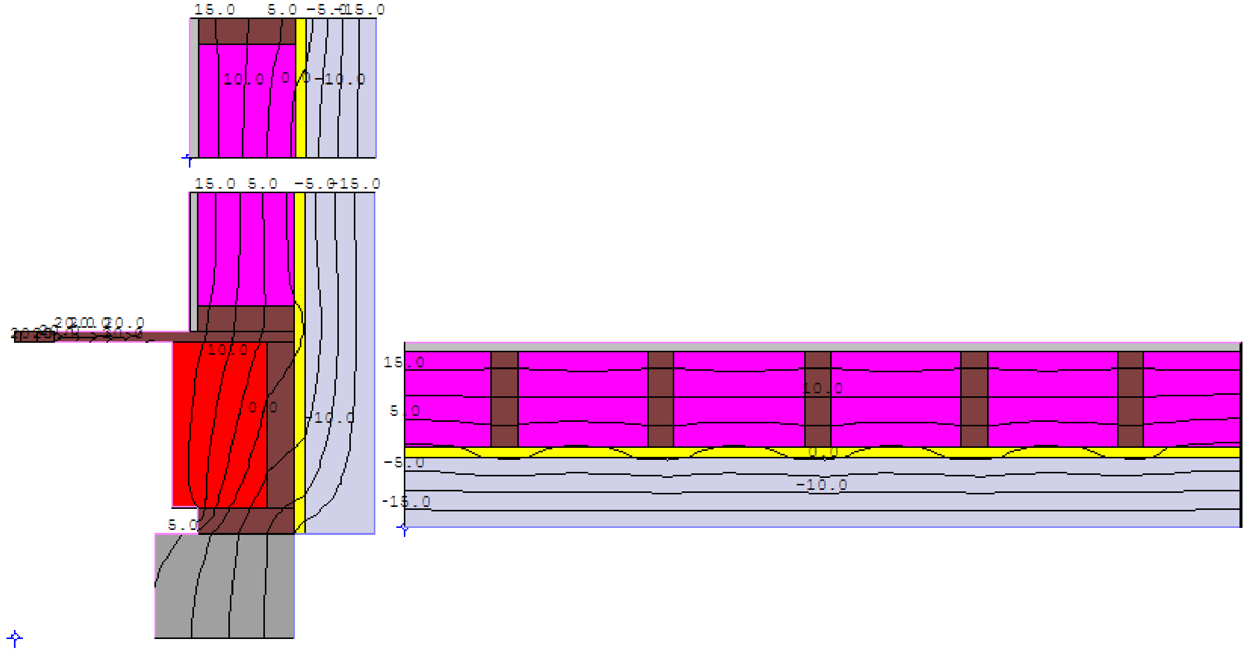

Figure 53 : Thermal analysis of an EIFS wall system

Table 15 : Calculated whole wall R-value for a EIFS wall system with 4" of EPS

Case	Description	Whole Wall R value	Rim Joist	Clear Wall R value	Top Plate
12	2x6 AF, 24"oc, EIFS - 4" EPS	**30.1**	23.8	31.4	31.1

1.12.2. Moisture Control

The moisture management details for this cladding type can be challenging but EIFS companies generally provide good documentation and design details with their product. For example, both Sto Corp and Dryvit Systems provide many details for all of their products on their websites to help builders and designers with moisture management details.

The performance of this wall system was nearly identical in winter time condensation, drying and summer time inward vapor drives to Case 2 with 4" of XPS insulation. EPS is more vapor permeable than XPS insulation, but laminate coating applied to the EPS insulation is usually less than 1 US perm.

1.12.3. Constructability and Cost

Because of the stucco appearance of this cladding system, it can be more expensive depending on the architectural detailing. EIFS is generally only done if the appearance of stucco is specifically desired. It is approximately the same performance and cost to use advanced framing with four inches of XPS insulation and cladding.

1.12.4. Other Considerations

EIFS are generally chosen when the owner or architect wants a stucco finish on a building. There are no significant performance differences between EIFS and the advanced framing with exterior insulation shown in Case 2. Both strategies minimize thermal bridging, and increase the temperature of the potential wintertime air leakage condensation plane. The main differences are the appearance of the finished cladding surface and water drainage details.

D. Conclusions

Whole wall R-values for all of the assemblies were calculated using Therm and the summary is shown in Table 16 below. In some of the analyzed cases, different types or thicknesses of insulation may be used depending on climate zone and local building practice. An attempt was made to choose the most common strategies and list all assumptions made for wall construction.

Table 16 : Summary of all calculated R-values

Case	Description	Whole Wall R-value	Rim Joist	Clear Wall R-value	Top Plate
1bii	2x4, 16"oc, R13FG + OSB (25%ff)	**10.0**	9.8	10.1	9.8
1b	2x4 AF, 24"oc, R13FG + OSB	**11.1**	9.8	11.5	9.8
1aii	2x6, 16"oc, R19FG + OSB (25%ff)	**13.7**	12.3	14.1	12.5
6a	SIPs (3.5" EPS)	**14.1**	12.3	14.5	10.6
1a	2x6 AF, 24"oc, R19FG + OSB	**15.2**	12.3	16.1	12.5
7a	ICF - 8" foam ICF (4" EPS)	**16.4**		16.4	
8b	2x6 AF, 24" o.c., 5.5" R21 0.5 pcf SPF, OSB	**16.5**	13.1	17.2	16.6
7c	ICF - 14" cement woodfiber ICF with Rockwool	**17.4**		17.4	
9	2x6 AF, 24"oc, 2" SPF and 3.5" cellulose	**17.5**	13.2	18.4	17.7
8a	2x6 AF, 24" o.c., 5" 2 pcf R29 SPF, OSB	**19.1**	13.6	20.3	19.5
2a	2x6 AF, 24"oc R19FG + 1" R5 XPS	**20.2**	18.5	20.6	20.3
7b	ICF - 15" foam ICF (5" EPS)	**20.6**		20.6	
3	2x6 AF, 24"oc, 2x3 R19+R8 FG	**21.5**	13.4	23.5	18.4
4	Double stud wall 9.5" R34 cellulose	**30.1**	14.4	33.5	28.8
12	2x6 AF, 24"oc, EIFS - 4" EPS	**30.1**	23.8	31.4	31.1
10	Double stud with 2" 2.0 pcf foam, 7.5" cell.	**32.4**	15.9	36.2	28.5
2b	2x6 AF, 24"oc R19FG + 4" R20 XPS	**34.5**	29.0	35.6	35.4
6b	SIPs (11.25" EPS)	**36.2**	14	41.6	28.2
5	Truss wall 12" R43 cellulose	**36.5**	18.6	40.5	34.4
11	Offset frame wall with ext. spray foam	**37.1**	18.8	40.6	41.9

*AF - Advanced Framing

The walls analyzed in this report can be grouped into three groups based on their calculated whole wall R-values. The first group have whole wall R-values less than approximately R20. These walls are not considered High-R wall systems for cold climates.

The second group of walls have whole wall R-values of approximately R-20. According to the IECC, the requirement for climate zones 7 and 8 is an installed R-value of R21. This report has shown that the whole R-value is less than the installed insulation R-value in almost every case, which means that often, the walls that the IECC allow in extremely cold climates are actually performing at a whole wall R-value of between R15 and R20. This is unacceptable in the future of uncertain oil reserves, increasing energy costs, and decreasing environmental health.

The third group of walls have whole wall R-values greater than R30. This is what the construction industry has been achieving in very small numbers, such as Building America prototype homes, and small custom home builders. The R-value of walls in the category can be modified easily by either decreasing or increasing the amount of insulation depending on the specific construction conditions. All of the walls in category three have minimized thermal bridging which increases the effectiveness of insulation.

The potential for wintertime air leakage was compared for all test walls, and the summary of the results are shown in Table 17. The walls were ranked from the least hours of potential condensation to the greatest. This potential condensation is only an issue if the airtightness details aren't constructed properly, but should still be used to assess the potential risk of a wall system, considering that field observations show the air barrier detailing is rarely perfect.

Table 17 : Hours of potential winter time air leakage condensation

Case	Description	Hours of Potential Condensation
8b	2x6 AF, 24" o.c., 5.5" R21 0.5 pcf SPF, OSB	0
8a	2x6 AF, 24" o.c., 5" 2 pcf R29 SPF, OSB	0
11	Offset frame wall with ext. spray foam	0
9	2x6 AF, 24"oc, 2" SPF and 3.5" cell or FG	934
2b	2x6 AF, 24"oc R19FG + 4" R20 XPS	1189
12	2x6 AF, 24"oc, EIFS - 4" EPS	1532
10	Double stud with 2" 2.0 pcf foam, 7.5" cell.	2284
2a	2x6 AF, 24"oc R19FG + 1" R5 XPS	3813
1a	2x6 AF, 24"oc, R19FG + OSB	4379
1b	2x4 AF, 24"oc, R13FG + OSB	4503
4	Double stud wall 9.5" R34 cellulose	4576
3	2x6 AF, 24"oc, 2x3 R19+R8 FG	4594
5	Truss wall 12" R43 cellulose	4622

*AF - Advanced Framing

The comparison matrix explained in the introduction was completed according to the analysis of each wall section in this report (Table 18), and it was found that three walls achieved the highest score of 20 out of a possible 25 points. The advanced framing wall (Case 2), sprayfoam insulation wall (Case 8) and EIFS wall (Case 12) achieved scores of 20 using an even weighting system of all selection criteria.

The main issue with most of the wood framed walls without exterior insulation is the probability of wintertime air leakage condensation depending on the quality of workmanship and the attention to detail. Inspections of production builder construction quality leads to skepticism regarding the quality of the air barrier in most wall systems. It is always good building practice to design enclosures that will perform as well as possible regardless of the human construction factor.

Table 18 : Wall Comparison Chart

	Thermal Control	Durability (wetting/drying)	Buildability	Cost	Material Use	Total
Criteria Weighting	1	1	1	1	1	
Case 1: Standard Construction	1	3	5	5	3	17
Case 2: Advanced Framing with Insulated Shtg	4	4	4	4	4	20
Case 3: Interior Strapping	3	3	3	4	4	17
Case 4: Double Stud	4	3	3	3	2	15
Case 5: Truss Wall	4	3	2	3	3	15
Case 6: SIPs	4	4	3	3	3	17
Case 7: ICF	4	5	4	2	3	18
Case 8: Sprayfoam	5	5	4	2	4	20
Case 9: Flash and Fill (2" spuf and cell.)	4	4	4	3	4	19
Case10: Double stud with 2" spray foam and cell.	5	4	3	3	3	18
Case 11: Offset Framing (ext. Spray foam insul.)	5	5	4	3	2	19
Case 12: EIFS with fibrous fill in space	5	5	4	3	3	20

Adding exterior insulation to most wall systems has many durability and energy benefits. Two dimensional heat flow modeling has shown that exterior insulation is very effective at minimizing the thermal bridging losses of wall framing, and hygrothermal modeling showed reduced condensation potential in the wall from vapor diffusion and air leakage, as well as increased drying potential to the interior with reasonable interior relative humidities. Adding exterior insulation was shown to increase the effectiveness of the fiberglass batt insulation in the stud space and increase the clear wall R-value greater than the amount of insulation added. This becomes even more important with higher thermal bridging such as a high framing factor or steel studs. Adding exterior insulation greater than approximately R5, the installed insulation R-value can be added directly to the clear wall R-value and is approximately equal to the increase in whole wall R-value since most of the thermal bridging is addressed.

Hygrothermal modeling showed that traditional double stud walls, truss walls and interior strapped walls, are at a greater risk of air leakage condensation because of the air permeable insulation, and cold exterior surface. Hybrid walls are a good strategy to help overcome this problem by using vapor impermeable spray foam insulation against the exterior, which increases the temperature of the condensation plane. The amount of spray foam required in a hybrid system is dependent on the climate zone for construction, but it may be difficult to get a high enough R value or thermal bridge control in cold climates for net zero housing.

ICF and SIPS walls both have insulation integral to the system, but require more insulation for a High R value wall assembly. Experience and modeling indicate that both of these techniques are susceptible to moisture issues if the details are not done correctly. SIPS are particularly susceptible to air leakage at the panel joints, and ICF walls need well designed penetrations, to avoid water ingress.

In extreme cold climates, and remote areas, high density spray foam appears to address most of the concerns that have been reported by NRC during visits and interviews with local residents. High density spray foam is easy to ship and install, not subject to damage during transit, and allows some variations in construction quality levels since it is both an air and vapor barrier. High density spray foam can be used in different wall construction strategies as demonstrated in this report, either on its own or as part of an insulation strategy with other insulations types. An offset frame wall with high density spray foam has the added advantage of drying in a house very quickly in the short construction season so that work can be done on the interior during inclement weather.

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About this Report

This report was prepared with the cooperation of the U.S. Department of Energy's, Building America Program.

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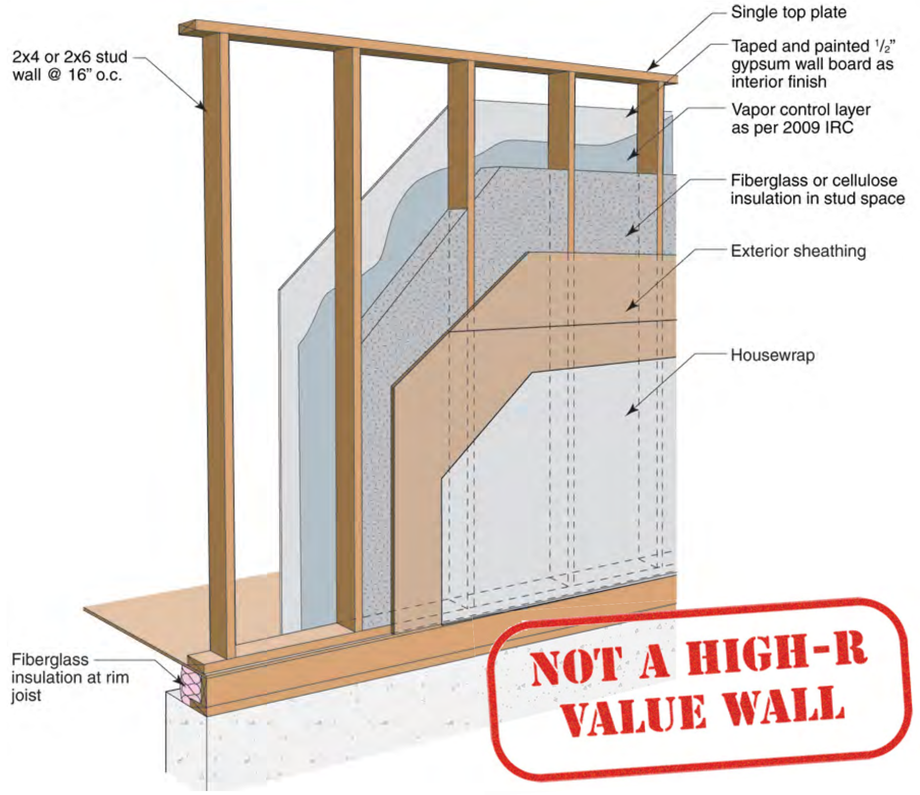
Limits of Liability and Disclaimer of Warranty:

Standard Wall Construction

Standard Wall Construction Details (*Walls 1A and 1B*)[1]

- 2x4 or 2x6 framing
- Fiberglass or cellulose cavity insulation in stud space
- Exterior sheathing
- Housewrap



Scoring: How It Rates

The scoring of each wall system is based on the following five categories. A score of 1 is the lowest score in each category and represents the worst possible technology for each category or highest possible relative cost. A score of 5 is the highest score available in each category, and is representative of the best available technology available on the market or lowest relative cost.

Thermal Control	1
Durability	3
Buildability	5
Cost	5
Material Use	4
Total	**18**

This wall has been the standard of construction for many years in many places but no longer meets the energy code requirements for insulation in some climates. Many higher performance designs exist.

Introduction

This two page summary briefly summarizes standard wall construction including the advantages and disadvantages of this construction strategy. A more detailed analysis and direct comparison to several other walls can be found online.[1] The scoring system is somewhat subjective based on the relative performance and specifications between different wall systems. Complex two dimensional heat flow analysis and one dimensional hygrothermal modeling were used to determine moisture related durability risks for analysis.

For a more complete analysis of this and other wall constructions, go to www.buildingscience.com.

Thermal Control

Installed Insulation R-value: There is a range of installed insulation R-values in commercially available fiberglass batts. The installed insulation R-value for 2x4 fiberglass batt ranges between R-11 and R-15 and for 2x6 the range is between R-19 and R-22. When blown or sprayed cellulose insulation is used, the R-values are typically R-13 for 2x4 and R-20 for 2x6 walls.

Whole-wall R-value: Using two dimensional heat flow analysis with thermal bridging effects and average framing factors, a 2x4 wall with R-14 studspace insulation has a whole-wall R-value of R-9. Similarly a 2x6 wall with R-19 stud space insulation has a whole wall R-value of R-11.[1] The framing factor used for standard construction framing 16 inches on center is 25%.[2] These whole wall R-values could decrease even further if there is significant air leakage or convective looping, or increased framing factor.

Air Leakage Control: Fiberglass batt, and both blown and sprayed cellulose are air permeable materials allowing possible air paths between the interior and exterior as well as convective looping in the insulation. Although densepack cellulose has less air permeance it does not control air leakage.

This summary has been prepared by Building Science Corporation for the Department of Energy's Building America Program, a private/public partnership that develops energy solutions for new and existing homes. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof.

For more information about Building America go to www.buildingamerica.gov.

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Typical Insulation Products: Fiberglass batt, blown fiberglass, blown cellulose, sprayed cellulose

Durability

Rain Control: Rain leakage into the enclosure is the leading cause of premature building enclosure failure. Rain control is typically addressed using a shingle lapped and/or taped drainage plane such as building paper or a synthetic WRB (i.e. homewrap). Intersections, windows, doors and other penetrations must be drained and/or detailed to prevent the penetration of rain water beyond the drainage plane.[3]

Air Leakage Control: Air leakage condensation is the second largest cause of premature building enclosure failure with this type of wall construction. It is very important to control air leakage to minimize air leakage condensation durability issues. An air barrier is required in this wall system to ensure that through-wall air leakage is eliminated (ideally) or at least minimized. An air barrier should be stiff and strong enough to resist wind forces, continuous, durable, and air impermeable.[4]

Air need not leak straight through an assembly to cause moisture problems; it can also leak from the inside, through the wall, and back to the inside; or it can leak from the outside, through the wall, and back to the outside. Condensation within the studspace is possible if this type of airflow occurs, depending on the weather conditions. Hence, wall designs should control airflow into the studspace.[5]

Vapor Control: Fiberglass and cellulose are highly vapor permeable materials, so a separate vapor control strategy must be employed to ensure that vapor diffusion does not result in condensation on, or damaging moisture accumulation in, moisture sensitive materials. The permeance and location of vapor control is dependent on the climate zone. Installing the vapor control layer in the incorrect location can lead to building enclosure failure.[6] The IRC building code should be consulted.

Drying: Cellulose and fiberglass insulation allow drying to occur relatively easily, so drying is controlled by other more vapor impermeable enclosure components such as the vapor barrier and OSB sheathing. Installing vapor control on both sides will seal any moisture into the stud space, resulting in low drying potential, and possibly resulting in moisture-related durability risks. Ventilation behind vapor impermeable claddings and interior components (e.g. kitchen cabinets) can encourage drying.

Built- in Moisture: Care should always be taken to build with dry materials where possible, and allow drying of wet materials before close in. Cellulose is often sprayed in damp, and manufacturers recommend drying before close in and moisture content limits. Because of the polyethylene vapor barrier required in many climates, and relatively vapor impermeable OSB sheathing, drying could be slow if built-in moisture is present.

Durability Summary: The primary durability risks associated with these wall assemblies involve moisture damage related to rain water penetration or condensation (most likely the result of air leakage, but also potentially the result of vapor diffusion).

Cellulose insulated walls are slightly more durable because cellulose insulation is capable of storing and redistributing small amounts of moisture. Cellulose insulation is typically treated with borates that have been shown to protect itself and neighboring wood material from mold growth and decay. Cellulose insulation also has decreased flame spread potential relative to other insulation materials.

Buildability

Wood-framed walls with OSB exterior sheathing and fiberglass or cellulose insulation represent the most common wall assembly used in the construction of low-rise residential buildings in North America. Designers, trades and supply chains are well equipped to produce these walls and education is primarily needed to improve durability through better rainwater control and thermal performance through better air tightness and insulating practices.

Cost

The cost to build this type of wall is well accepted, and is used as a baseline. Costs vary tremendously from region to region.

Material Use

This wall design contains redundant wood framing and wood sheathing. Framing lumber could be minimized further if advanced framing was used. In most of America, much of the sheathing could be removed. Cellulose has a significantly lower embodied energy than fiberglass or rockwool.

Total Score

This wall has been the standard of construction for many years in many places. This wall no longer meets the energy code requirements for insulation in many climates, and thermal control requirements will only continue to increase. This wall system is difficult to air seal adequately and prone to air leakage related condensation and energy losses. Using advanced framing will reduce framing materials, and the cost of framing. Although this construction technique is usually allowed by code, many higher performance designs exist.

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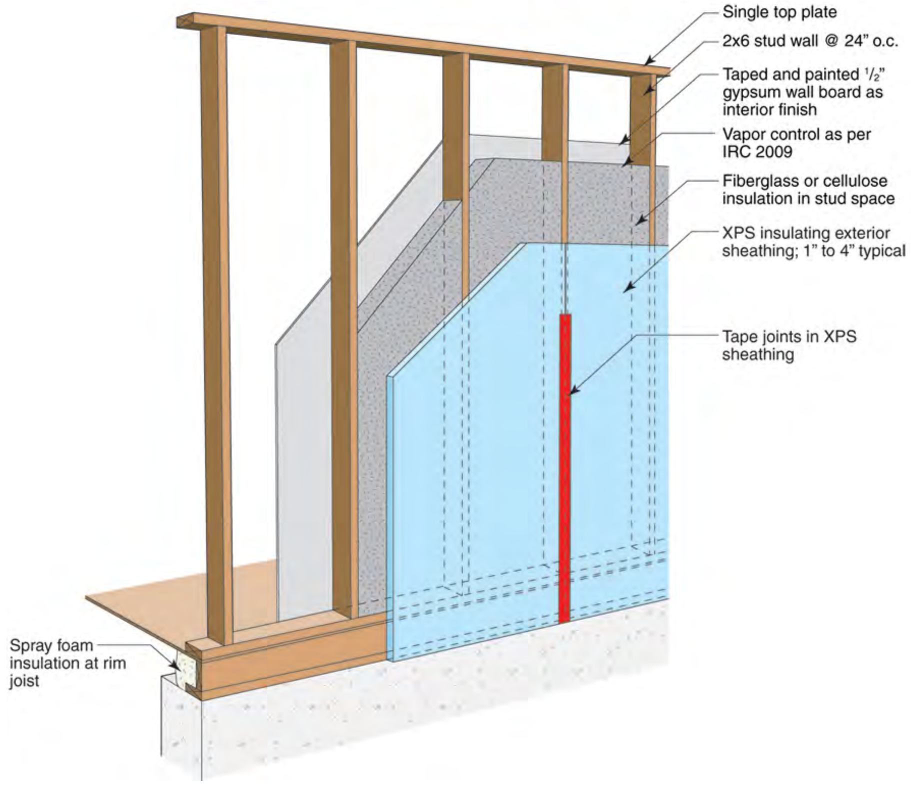
2x6 Advanced Frame Wall Construction

2x6 Advanced Frame Wall Construction Details

(*Walls 2A and 2B*)[1]

- 2x6 framing
- XPS insulating sheathing
- Fiberglass or cellulose cavity insulation in stud space



Scoring: How It Rates

The scoring of each wall system is based on the following five categories. A score of 1 is the lowest score in each category and represents the worst possible technology for each category or highest possible relative cost. A score of 5 is the highest score available in each category, and is representative of the best available technology available on the market or lowest relative cost.

Thermal Control	4
Durability	4
Buildability	4
Cost	4
Material Use	4
Total	**20**

Advanced framing with insulated sheathing significantly reduces the thermal bridging through the enclosure and improves the thermal efficiency of the fiberglass batt in the stud space. Using insulated sheathing decreases the potential for both wintertime condensation, and summer inward vapor drives, and helps mitigate issues caused by poor construction practices.

Introduction

This two page summary briefly summarizes 2x6 advanced frame wall construction including the advantages and disadvantages of this construction strategy. A more detailed analysis and direct comparison to several other walls can be found online.[1] The scoring system is somewhat subjective based on the relative performance and specifications between different wall systems. Complex two dimensional heat flow analysis and one dimensional hygrothermal modeling were used to determine moisture related durability risks for analysis.

For a more complete analysis of this and other wall constructions, go to www.buildingscience.com.

Thermal Control

Installed Insulation R-value: There is a range of installed insulation R-values in commercially available fiberglass batts for the stud space insulation in this wall system. The installed insulation R-value for 2x4 fiberglass batt ranges between R-11 and R-15 and for 2x6 the range is R-19 and R-22. When blown or sprayed cellulose insulation is used, the R-values are typically R-13 for 2x4 walls and R-20 for 2x6 walls.

Exterior insulating sheathing is typically added as expanded Ppolystyrene (EPS) at R-4/inch, extruded polystyrene (XPS) at R-5/inch or foil-faced polyisocyanurate at R-6.5/inch.

Whole-wall R-value: Two-dimensional heat flow analysis with thermal bridging effects and average framing factors (16%) shows increases the R-value of the assembly and improvements to the efficiency of the fiberglass batt in the stud space by decreasing the thermal bridging effects. Advanced framing walls with 1" and 4" of XPS insulated sheathing have whole wall R-values of R-20 and R-34 respectively.[1]

Air Leakage Control: Fiberglass, blown and sprayed cellulose are air permeable materials used in the stud space of the wall allowing possible air paths between the interior and exterior as well as convective looping in the insulation. Densepack cellulose has less air permeance but does not control air leakage. Insulating sheathing (EPS, XPS and foil-faced polyisocyanurate board foam) products are air impermeable. When joints between panels of insulation and the insulation and framing are properly sealed with tape, mastic, caulk, etc., an effective air barrier system can be created at the exterior sheathing.

Typical Insulation Products: Fiberglass batt, blown cellulose, sprayed cellulose, and sprayed fiberglass are typically used to insulate the stud space. Expanded polystyrene (EPS), extruded polystyrene (XPS) and foil-faced polyisocyanurate (PIC) board foam are used as the exterior insulating sheathing. Spray foam is used at the rim joist to control air leaks.

Durability

Rain Control: Rain leakage into the enclosure is the leading cause of premature building enclosure failure. Rain control is typically addressed using a shingle lapped and/or taped drainage plane such as building paper or a synthetic WRB (i.e. homewrap). It is possible to use insulated sheathing as the drainage plane if all the intersections, windows, doors and other penetrations are connected to the surface of the insulated sheathing in a watertight manner, and the seams of the insulation are taped or flashed to avoid water penetration.[2]

Air Leakage Control: Air leakage condensation is the second largest cause of premature building enclosure failure with this type of wall construction. It is very important to control air leakage to minimize air leakage condensation durability issues. Using insulating sheathing decreases the risk of air leakage condensation by increasing the temperature of the condensation plane, but condensation is still possible with insulated sheathing in cold climates. An air barrier is required in this wall system to ensure that through-wall air leakage is eliminated (ideally) or at least minimized.[3] An air barrier should be stiff and strong enough to resist wind forces, continuous, durable, and air impermeable.[4]

Vapor Control: Fiberglass or cellulose in the stud cavity are vapor permeable, while EPS, XPS and PIR are moderately permeable, moderately impermeable and completely impermeable respectively.

Insulated sheathing reduces the risk of wintertime condensation by increasing the temperature of the condensation plane, and reduces the risk of summer time inward vapor drives by slowing the vapor movement into the enclosure from storage claddings such as masonry or stucco. The level of vapor control in insulated sheathing walls is determined in the IRC and should be consulted as installing the incorrect vapor control layer or installing the vapor control layer in the incorrect location can lead to building enclosure failure.[5]

Drying: Insulating sheathing limits the drying to the exterior, and the wall must be able to dry to the interior. Poly vapor barriers are typically avoided so that this drying can occur. The minimum level of vapor control on the interior surface is determined by the IRC. Installing vapor control on both sides of the enclosure will seal any moisture into the stud space, resulting in low drying potential, and possibly resulting in moisture-related durability risks. Ventilation behind vapor impermeable claddings and interior components (e.g. kitchen cabinets) can encourage drying.

Built- in Moisture: Care should always be taken to build with dry materials where possible, and allow drying of wet materials before close in. Cellulose is often sprayed in damp, and manufacturers recommend drying before close in and moisture content limits.

Durability Summary: The primary durability risks associated with these wall assemblies involve moisture damage related to rain water penetration. Condensation (most likely the result of air leakage, but also potentially the result of vapor diffusion) is decreased with insulated sheathing but may still occur, although the insulating sheathing is less susceptible to moisture related risks than structural OSB sheathing.

Buildability

Exterior insulation up to 1.5" requires minimal changes to standard enclosure construction practices. Exterior insulation in excess of 1.5" requires changes to window and wall construction and detailing which requires training and monitoring during the initial implementation.

Cladding can be easily attached to the studs directly through 1" of insulated sheathing. Thicker levels of insulation (>2") require strapping or furring strips)anchored to the framing with long fasteners. Some cladding manufacturers allow their cladding to be fastened to the strapping directly.

Cost

Advanced framing wall construction decreases the cost required for framing. There is a slight increase in cost for the insulating sheathing to replace most of the structural wood sheathing, but there are measureable cost benefits of saving energy, as well as improvements to comfort, which is difficult to quantify.

Material Use

If advanced framing is applied correctly (single top plates, correctly sized headers, two stud corners, etc.) the redundant wood framing from standard construction is removed, and the amount of framing will decrease. Using insulated sheathing instead of structural wood sheathing may require using structural panels or bracing in some locations.

Total Score

Advanced framing with insulating sheathing is a logical choice as the minimum level of construction in most climates considering the more demanding insulation levels required for new construction in many climates. Using insulated sheathing can decrease the potential for both wintertime condensation, and summer inward vapor drives, and help mitigate issues caused by poor construction practices.

References

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Interior Strapping Wall Construction

Interior Strapping Wall Construction Details (*Wall 3*)[1]

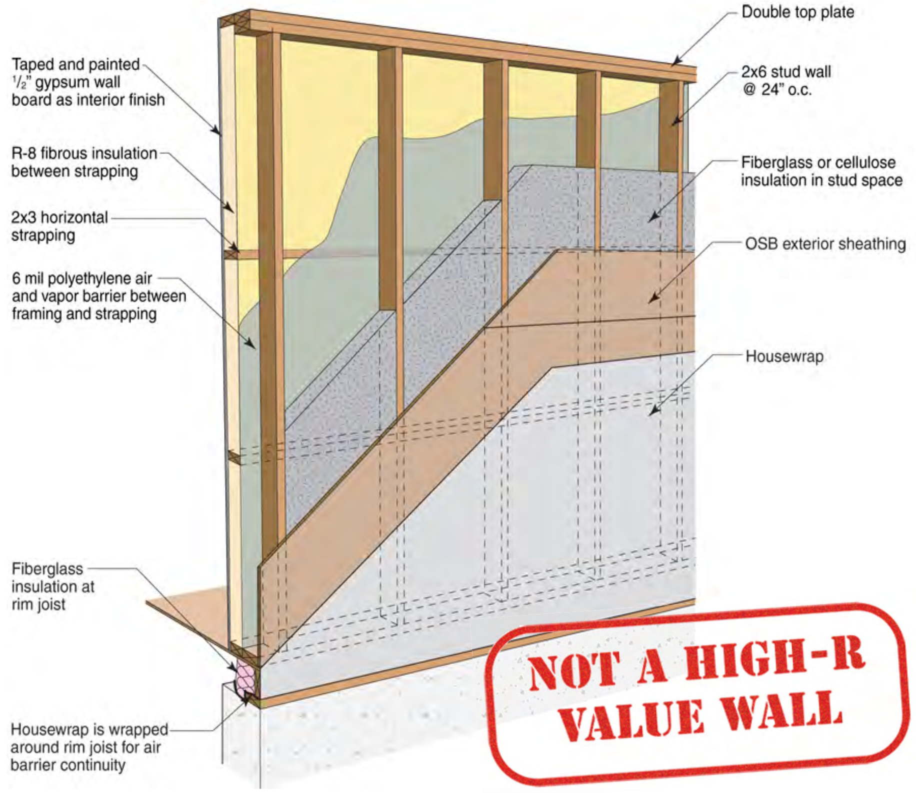
- 2x6 advanced framing
- 2x3 horizontal strapping
- Fibrous insulation between strapping
- 6 mil polyethylene air & vapor barrier
- Fiberglass or cellulose cavity insulation in stud space
- OSB exterior sheathing
- Housewrap

Scoring: How It Rates

The scoring of each wall system is based on the following five categories. A score of 1 is the lowest score in each category and represents the worst possible technology for each category or highest possible relative cost. A score of 5 is the highest score available in each category, and is representative of the best available technology available on the market or lowest relative cost.

Thermal Control	3
Durability	3
Buildability	3
Cost	4
Material Use	3
Total	**16**

Interior strapping in wall construction does increase the R-value over standard construction, but does not address thermal bridges at the rim joist, top plate or bottom plate. The minimal increases in whole wall R-value over standard construction may not be justified by the increased materials, cost and complexity of this wall system.



Introduction

This two page summary briefly summarizes interior strapping wall construction including the advantages and disadvantages of this construction strategy. A more detailed analysis and direct comparison to several other walls can be found online.[1] The scoring system is somewhat subjective based on the relative performance and specifications between different wall systems. Complex two dimensional heat flow analysis and one dimensional hygrothermal modeling were used to determine moisture related durability risks for analysis.

For a more complete analysis of this and other wall constructions, go to www.buildingscience.com.

Thermal Control

Installed Insulation R-value: There is a range of installed insulation R-values in commercially available fiberglass batts. The installed insulation R-value for 2x6 fiberglass batt ranges between R-19 and R-22 for the framed portion of this wall, the strapped interior section is typically R-8 fiberglass insulation, and for 2x6 the range is between R-19 and R-22. When blown or sprayed cellulose insulation is used, the R-value is typically R-20 for 2x6 walls.

Whole-wall R-value: Using two dimensional heat flow analysis with thermal bridging effects and average framing factors, this wall construction achieves a whole wall R-value of approximately R-21.5.[1] Adding horizontal strapping to the interior surface helps minimize the thermal bridges through the stud wall, but there are still thermal bridges at the top plate, bottom plate and rim joist that decrease the installed insulation R-value.

Air Leakage Control: Fiberglass batt, and both blown and sprayed cellulose are air permeable materials allowing possible air paths between the interior and exterior as well as convective looping in the insulation. Although densepack cellulose has less air permeance it does not control air leakage.[2]

This summary has been prepared by Building Science Corporation for the Department of Energy's Building America Program, a private/public partnership that develops energy solutions for new and existing homes. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof.
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Typical Insulation Products: Fiberglass batt, blown fiberglass, blown cellulose, sprayed cellulose.

Durability

Rain Control: Rain leakage into the enclosure is the leading cause of premature building enclosure failure. Rain control is typically addressed using a shingle lapped and/or taped drainage plane such as building paper or a synthetic WRB (i.e. homewrap). Intersections, windows, doors and other penetrations must be drained and/or detailed to prevent the penetration of rain water beyond the drainage plane.[3]

Air Leakage Control: Air leakage condensation is the second largest cause of premature building enclosure failure with this type of wall construction. It is very important to control air leakage to minimize air leakage condensation durability issues. An air barrier is required in this wall system to ensure that through-wall air leakage is eliminated (ideally) or at least minimized. An air barrier should be stiff and strong enough to resist wind forces, continuous, durable, and air impermeable.[4]

Often the polyethylene vapor barrier will be constructed as the air barrier even though it is not stiff or strong enough to resist wind forces. If the polyethylene is installed between the stud wall and the interior strapping, there will be fewer holes made for electrical and plumbing services, and can be made more airtight than in standard construction.

Air need not leak straight through an assembly to cause moisture problems; it can also leak from the inside, through the wall, and back to the inside; or it can leak from the outside, through the wall, and back to the outside. Condensation within the studspace is possible if this type of airflow occurs, depending on the weather conditions. Hence, wall designs should control airflow into the studspace.[5]

Vapor Control: Fiberglass and cellulose are highly vapor permeable materials, so a separate vapor control strategy must be employed to ensure that vapor diffusion does not result in condensation on, or damaging moisture accumulation in, moisture sensitive materials. The permeance and location of vapor control is dependent on the climate zone. Installing the vapor control layer in the incorrect location can lead to building enclosure failure.[6] The IRC building code should be consulted.

Drying: Cellulose and fiberglass insulation allow drying to occur relatively easily, so drying is controlled by other more vapor impermeable enclosure components such as the vapor barrier and OSB sheathing. Installing vapor control on both sides will seal any moisture into the stud space, resulting in low drying potential, and possibly resulting in moisture-related durability risks. Ventilation behind vapor impermeable claddings and interior components (e.g. kitchen cabinets) can encourage drying.

Built- in Moisture: Care should always be taken to build with dry materials where possible, and allow drying of wet materials before close in. Cellulose is often sprayed in damp, and manufacturers recommend drying before close in and moisture content limits. Because of the polyethylene vapor barrier required in many climates, and relatively vapor impermeable OSB sheathing, drying could be slow if built-in moisture is present.

Durability Summary: The primary durability risks associated with these wall assemblies involve moisture damage related to rain water penetration or condensation (most likely the result of air leakage, but also potentially the result of vapor diffusion).

Cellulose insulated walls are slightly more durable because cellulose insulation is capable of storing and redistributing small amounts of moisture. Cellulose insulation is typically treated with borates which have been shown to protect itself and neighbouring wood material from mold growth and decay. Cellulose insulation also has decreased flame spread potential relative to other insulation materials.

Buildability

This type of construction is a modification of standard construction, but is not common, and construction trades may have difficulty with some of the detailing. All window and door penetrations will require plywood box frames to pass through both the interior strapping and exterior framing. If the poly is installed properly between the stud wall and interior strapping, there is decreased risk of moisture related durability issues often caused by penetrations such as electrical and plumbing.

Cost

There will be increased costs over standard construction due to an increase in framing material, and complexity for construction, since this is not a standard construction technique. Costs vary tremendously from region to region.

Material Use

Using sdvanced framing will reduce redundant wood framing in the wall, but overall framing still increases for the interior strapping. Cellulose has a significantly lower embodied energy than fiberglass or rockwool.

Total Score

Interior strapping in wall construction does increase the R-value over standard construction, but does not address thermal bridges at the rim joist, top plate or bottom plate. The minimal increases in whole wall R-value over standard construction may not be justified by the increased materials, cost and complexity of this wall system. Many higher performance designs for wall construction exist.

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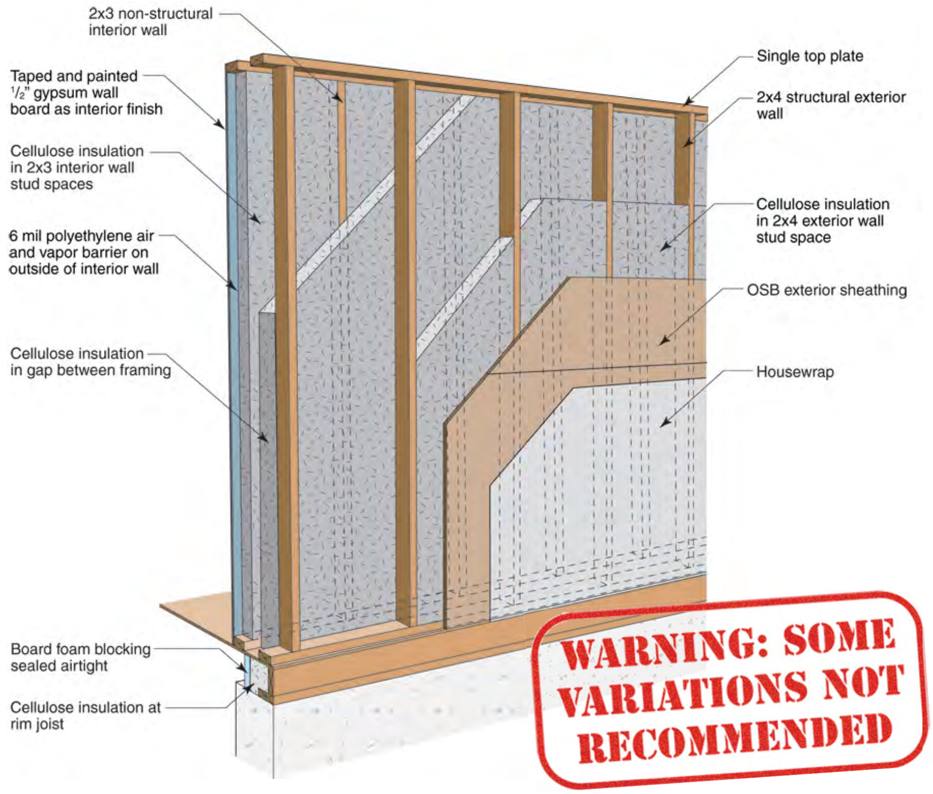
Double Stud Wall Construction

Double Stud Wall Construction Details (*Wall 4*)[1]

- 2x4 structural exterior wall with cellulose cavity insulation
- 2x3 non-structural interior wall with cellulose cavity insulation
- 6 mil polyethylene vapor barrier
- Cellulose insulation in gap
- OSB exterior sheathing
- Housewrap



Scoring: How It Rates

The scoring of each wall system is based on the following five categories. A score of 1 is the lowest score in each category and represents the worst possible technology for each category or highest possible relative cost. A score of 5 is the highest score available in each category, and is representative of the best available technology available on the market or lowest relative cost.

Thermal Control	4
Durability	3
Buildability	3
Cost	3
Material Use	2
Total	**15**

This is a highly insulated wall system that will work in extreme climates, but still has significant risks to moisture related durability issues and premature enclosure failure. This wall system decreases the interior floor area of a fixed floorplan and may experience thermal and moisture issues at the rim joist unless it's detailed correctly.

Introduction

This two page summary briefly summarizes double stud wall construction including the advantages and disadvantages of this construction strategy. A more detailed analysis and direct comparison to several other walls can be found online.[1] The scoring system is somewhat subjective based on the relative performance and specifications between different wall systems. Complex two dimensional heat flow analysis and one dimensional hygrothermal modeling were used to determine moisture related durability risks for analysis.

For a more complete analysis of this and other wall constructions, go to www.buildingscience.com.

Thermal Control

Installed Insulation R-value: The thickness of double stud walls varies, however, walls with overall insulation thickness of 9.5" appear to be most common. The insulation can be of either fiberglass batt (R-3.5/inch) or blown cellulose insulation (R-3.7/inch) resulting in overall installed insulation R-values of R-33 and 35 respectively.

Whole-wall R-value: Using two dimensional heat flow analysis with thermal bridging effects and average framing factors demonstrates that adding an interior framed wall with a insulation filled gap greatly reduces the thermal breaks through the stud wall and can increases the Clear wall R-value to R-34 depending on the thickness of insulation. However, because of the significant thermal losses at the rim joist, the whole-wall R-value is closer to R-30.[1]

Air Leakage Control: Fiberglass batt, and both blown and sprayed cellulose are air permeable materials allowing possible air paths between the interior and exterior as well as convective looping in the insulation. Although densepack cellulose has less air permeance it does not control air leakage.

Typical Insulation Products: Fiberglass batt, or blown cellulose; blown fiberglass is another option, but not too common.

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Durability

Rain Control: Rain leakage into the enclosure is the leading cause of premature building enclosure failure. Rain control is typically addressed using a shingle lapped and/or taped drainage plane such as building paper or a synthetic WRB (i.e. homewrap). Intersections, windows, doors and other penetrations must be drained and/or detailed to prevent the penetration of rain water beyond the drainage plane.[2]

Air Leakage Control: Air leakage condensation is the second largest cause of premature building enclosure failure with this type of wall construction. It is very important to control air leakage to minimize air leakage condensation durability issues. An air barrier is required in this wall system to ensure that through-wall air leakage is eliminated (ideally) or at least minimized. An air barrier should be stiff and strong enough to resist wind forces, continuous, durable, and air impermeable.[3]

Air need not leak straight through an assembly to cause moisture problems; it can also leak from the inside, through the wall, and back to the inside; or it can leak from the outside, through the wall, and back to the outside. Condensation within the stud space is possible if this type of airflow occurs, depending on the weather conditions. Hence, wall designs should control airflow into the studspace.[4]

Vapor Control: Fiberglass and cellulose are highly vapor permeable materials, so a separate vapor control strategy must be employed to ensure that vapor diffusion does not result in condensation on, or damaging moisture accumulation in, moisture sensitive materials. The permeance and location of vapor control is dependent on the climate zone. Installing the vapor control layer in the incorrect location can lead to building enclosure failure.[5] The IRC building code should be consulted.

Drying: Cellulose and fiberglass insulation allow drying to occur relatively easily, so drying is controlled by other more vapor impermeable enclosure components such as the vapor barrier and OSB sheathing. Installing vapor control on both sides will seal any moisture into the stud space, resulting in low drying potential, and possibly resulting in moisture-related durability risks. Ventilation behind vapor impermeable claddings and interior components (e.g. kitchen cabinets) can encourage drying.

Built- in Moisture: Care should always be taken to build with dry materials where possible, and allow drying of wet materials before close in. Cellulose is often sprayed in damp, and manufacturers recommend drying before close in and moisture content limits. Because of the polyethylene vapor barrier required in many climates, and relatively vapor impermeable OSB sheathing, drying could be slow if built-in moisture is present.

Durability Summary: The primary durability risks associated with these wall assemblies involve moisture damage related to rain water penetration or condensation (most likely the result of air leakage, but also potentially the result of vapor diffusion).

Cellulose insulated walls are slightly more durable because cellulose insulation is capable of storing and redistributing small amounts of moisture. Cellulose insulation is typically treated with borates that have been shown to protect itself and neighboring wood material from mold growth and decay. Cellulose insulation also has decreased flame spread potential relative to other insulation materials.

Buildability

This type of wall construction is more typically found in party walls of multi unit residential because of its superior sound suppression and fire resistance. This wall construction is not very complicated, but does require custom frames around penetrations such as windows and doors. If polyethylene is used as the air barrier, it is critical to seal it perfectly to avoid wintertime air leakage condensation against the sheathing. This construction generally does not address the thermal losses or air leakage at the rim joist. Because the second framed wall is constructed on the interior of the structural wall, the interior floor space is decreased. This wall is quite susceptible to construction deficiencies in the air and vapor barrier.

Cost

The cost of this wall is higher than standard construction, but with a significant increase in thermal performance. This wall construction requires more time and materials for construction.

Material Use

The wall framing material is increased significantly by building a secondary interior wall. This wall is often not structural, which means the stud spacing can be wider, and smaller framing lumber can be used provided an even surface is constructed to install the gypsum board. There is also an increase in insulation, but the embodied energy of cellulose is relatively small, and results in large increases in R-value.

Total Score

This is a highly insulated wall system that will work in extreme climates as part of a high-R enclosure, if the air barrier details are perfect, and the thermal losses at the rim joist are minimized. This construction technique does cost the occupant interior floor space with the thick insulated wall. There is significant risk to moisture related durability issues from wintertime condensation, however, the large amount of cellulose in this wall system will be able to buffer some moisture in the enclosure as long as the safe moisture capacity of the cellulose is not exceeded.

References

1 Straube, J., & Smegal, J. (2009). *Building America Special Research Project - High-R Walls Case Study Analysis*. Retrieved from buildingscience.com.

2 Lstiburek, J. W. (2006). *Water Management Guide*. Westford: Building Science Press Inc.

3 Lstiburek, J. (2008, 08 20). *BSD-104: Understanding Air Barriers*. Retrieved from buildingscience.com.

4 Straube, J. (2009, 04 22). *BSD-014 Air Flow Control in Buildings*. Retrieved from buildingscience.com.

5 Lstiburek, J. (2008, 10 17). *BSD-106 Understanding Vapor Barriers*. Retrieved from buildingscience.com.

Truss Wall Construction

Truss Wall Construction Details (*Wall 5*)[1]

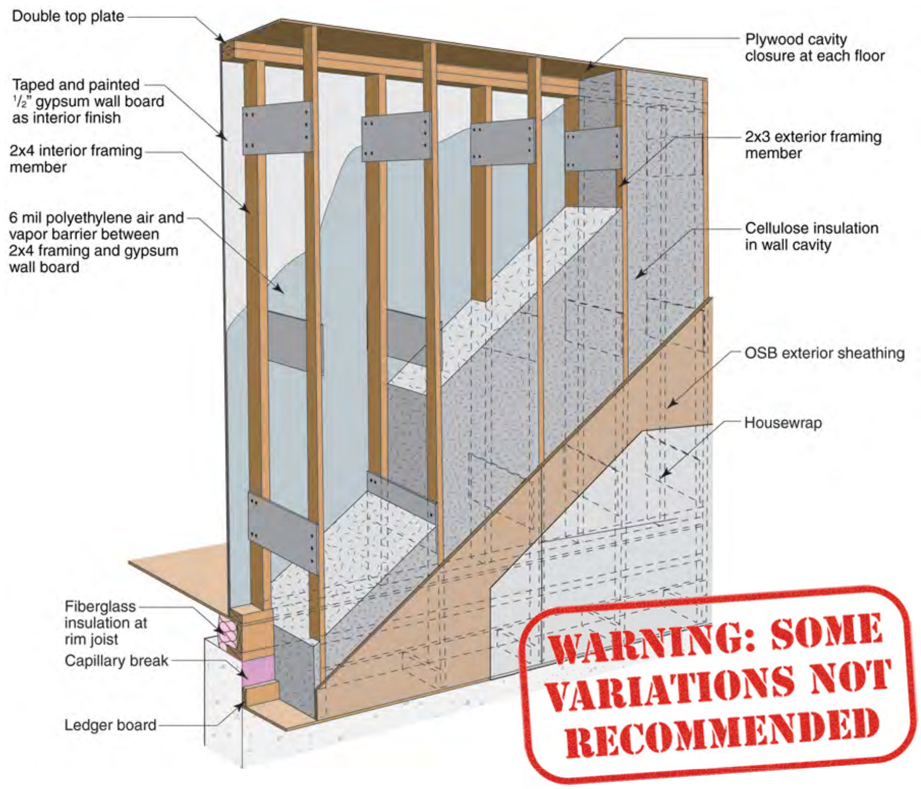
- 2x4 interior framing member
- 2x3 exterior framing member
- 6 mil polyethylene vapor barrier to interior
- Cellulose cavity insulation
- OSB exterior sheathing
- Housewrap

Scoring: How It Rates

The scoring of each wall system is based on the following five categories. A score of 1 is the lowest score in each category and represents the worst possible technology for each category or highest possible relative cost. A score of 5 is the highest score available in each category, and is representative of the best available technology available on the market or lowest relative cost.

Thermal Control	4
Durability	3
Buildability	2
Cost	3
Material Use	2
Total	**14**

The truss wall system can achieve a very high whole wall R-value with minimal thermal bridging and would be perform well in extreme climates provided the air barrier was detailed perfectly minimizing the high risk of air leakage condensation durability issues. It is time consuming to construct and susceptible to premature enclosure failures resulting from poor construction and detailing.



Introduction

This two page summary briefly summarizes the truss wall construction including the advantages and disadvantages of this construction strategy. A more detailed analysis and direct comparison to several other walls can be found online.[1] The scoring system is somewhat subjective based on the relative performance and specifications between different wall systems. Complex two dimensional heat flow analysis and one dimensional hygrothermal modeling were used to determine moisture related durability risks for analysis.

For a more complete analysis of this and other wall constructions, go to www.buildingscience.com.

Thermal Control

Installed Insulation R-value: The thickness of truss walls varies greatly and because it is not a common wall construction, there does not appear to be a established standard construction insulation thickness. These walls are typically insulated with blown cellulose insulation (R-3.7/inch) or fiberglass batt insulation (R-3.5/inch), and overall installed insulation R-values in excess of 50 are possible.

Whole-wall R-value: Using two dimensional heat flow analysis with thermal bridging effects and average framing factors shows that adding the insulation to the exterior of the framing addresses the thermal bridge at the rim joist, studs and top plate. There is a large range of R-values possible with this type of construction, but 12" of cellulose provides a whole-wall R-value of approximately R-36.[1]

Air Leakage Control: Cellulose insulation is an air permeable material allowing possible air paths between the interior and exterior as well as convective looping in the insulation. Although densepack cellulose has less air permeance than some other air permeable insulations, it does not control air leakage.

Typical Insulation Products: Blown cellulose.

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Durability

Rain Control: Rain leakage into the enclosure is the leading cause of premature building enclosure failure. Rain control is typically addressed using a shingle lapped and/or taped drainage plane such as building paper or a synthetic WRB (i.e. homewrap). Intersections, windows, doors and other penetrations must be drained and/or detailed to prevent the penetration of rainwater beyond the drainage plane.[2]

Air Leakage Control: Air leakage condensation is the second largest cause of premature building enclosure failure with this type of wall construction. It is very important to control air leakage to minimize air leakage condensation durability issues. An air barrier is required in this wall system to ensure that through-wall air leakage is eliminated (ideally) or at least minimized. An air barrier should be stiff and strong enough to resist wind forces, continuous, durable, and air impermeable.[3]

Air need not leak straight through an assembly to cause moisture problems; it can also leak from the inside, through the wall, and back to the inside; or it can leak from the outside, through the wall, and back to the outside. Condensation within the stud space is possible if this type of airflow occurs, depending on the weather conditions. Hence, wall designs should control airflow into the stud space.[4]

The truss wall has a much higher R-value that standard construction, and the exterior sheathing is well insulated from the interior conditions. This wall system has greater risk for severe air leakage condensation since the sheathing is considerably colder than standard construction.

Vapor Control: Fiberglass and cellulose are highly vapor permeable materials, so a separate vapor control strategy must be employed to ensure that vapor diffusion does not result in condensation on, or damaging moisture accumulation in, moisture sensitive materials. The permeance and location of vapor control is dependent on the climate zone. Installing the vapor control layer in the incorrect location can lead to building enclosure failure.[5] The IRC building code should be consulted.

There is a higher risk of vapor diffusion condensation if the vapor barrier is not detailed correctly due to the lower wintertime temperature of the sheathing in the truss wall relative to standard construction.

Drying: Cellulose and fiberglass insulation allow drying to occur relatively easily, so drying is controlled by other more vapor impermeable enclosure components such as the vapor barrier and OSB sheathing. Installing vapor control on both sides will seal any moisture into the stud space, resulting in low drying potential, and possibly resulting in moisture-related durability risks. Ventilation behind vapor impermeable claddings and interior components (e.g. kitchen cabinets) can encourage drying.

Built- in Moisture: Care should always be taken to build with dry materials where possible, and allow drying of wet materials before close in. Because of the polyethylene vapor barrier required in many climates, and relatively vapor impermeable OSB sheathing, drying could be slow if built-in moisture is present.

Durability Summary: The primary durability risks associated with these wall assemblies involve moisture damage related to rain water penetration or condensation (most likely the result of air leakage, but also potentially the result of vapor diffusion).

Cellulose insulated walls are slightly more durable than fiberglass insulated walls because cellulose insulation is capable of storing and redistributing small amounts of moisture. Cellulose insulation is typically treated with borates that have been shown to protect itself and neighboring wood material from mold growth and decay. Cellulose insulation also has decreased flame spread potential relative to other insulation materials.

Buildability

This wall construction is not a standard construction practice. The gussets used to space the exterior framed wall off the structure are time consuming to construct, and require tight tolerances to ensure smooth sheathing and cladding. This wall is highly susceptible to construction workmanship and requires a perfect air barrier in cold climates since the potential for wintertime condensation is high. Penetrations such as windows and doors require plywood boxes be installed through the wall.

Cost

This construction requires increases in both time and materials for the enclosure. The wall framing material is essentially doubled, and constructing the exterior wall with gussets is time consuming. The increased thermal performance and decreased thermal bridges may be worth the extra time and money in specific cases.

Material Use

There is a significant increase to framing since every framing member in the structural wall has a corresponding exterior framing member attached with wood gussets.

Total Score

The truss wall system can achieve a very high whole wall R-value with minimal thermal bridging and would be perform well in extreme climates provided the air barrier was detailed perfectly minimizing air leakage condensation durability risks. It is possible to reduce the risk of condensation by using a combination of the truss wall in combination with an air impermeable insulation. One advantage of the truss wall is that it is used in both new construction and retrofit situations to decrease energy consumption, and improve occupant comfort. The truss wall allows the extra insulation to be placed on the exterior of the structural wall that does not affect the interior space, unlike the double stud wall.

References

1 Straube, J., & Smegal, J. (2009). *Building America Special Research Project - High-R Walls Case Study Analysis.* Retrieved from buildingscience.com.

2 Lstiburek, J. W. (2006). *Water Management Guide.* Westford: Building Science Press Inc.

3 Lstiburek, J. (2008, 08 20). *BSD-104: Understanding Air Barriers.* Retrieved from buildingscience.com.

4 Straube, J. (2009, 04 22). *BSD-014 Air Flow Control in Buildings.* Retrieved from buildingscience.com.

5 Lstiburek, J. (2008, 10 17). *BSD-106 Understanding Vapor Barriers.* Retrieved from buildingscience.com.

SIPs Wall Construction

SIPs Wall Construction Details (*Wall 6*)[1]

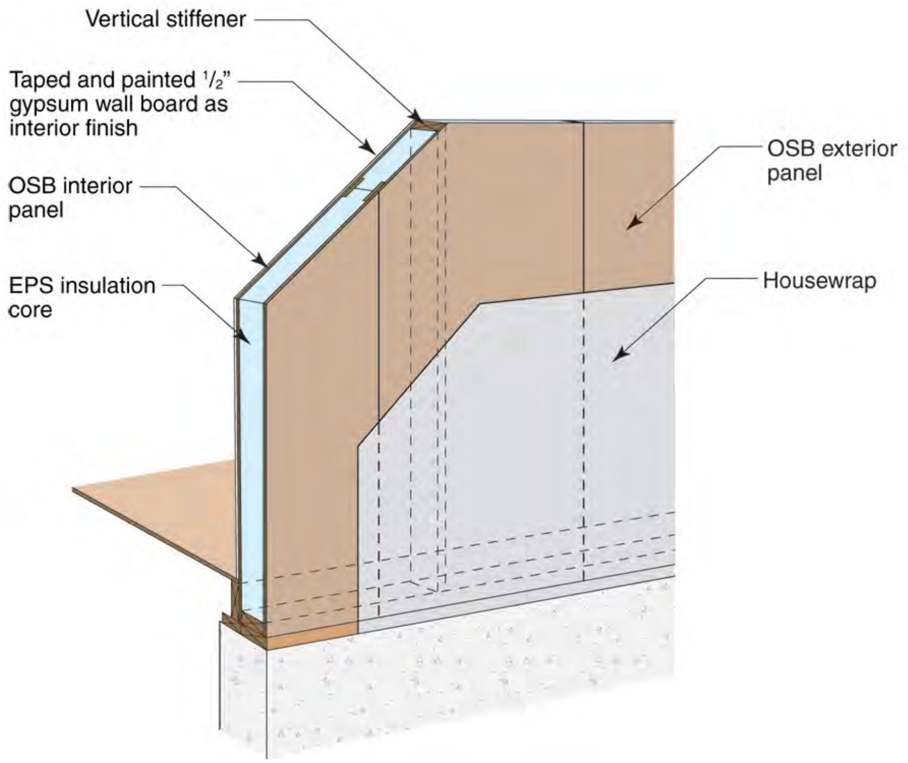
- OSB interior and exterior panels
- EPS insulation core typical
- Housewrap

Scoring: How It Rates

The scoring of each wall system is based on the following five categories. A score of 1 is the lowest score in each category and represents the worst possible technology for each category or highest possible relative cost. A score of 5 is the highest score available in each category, and is representative of the best available technology available on the market or lowest relative cost.

Thermal Control	4
Durability	4
Buildability	3
Cost	3
Material Use	3
Total	**17**

The typical SIPs panels are not constructed with enough insulation to be considered high-R assemblies in heating climates. SIPs installation requires specialized training but is quicker and easier than wood framed construction following training. Historical moisture related durability issues with SIPs have been solved with a better understanding of building science, and airtightness details.



Introduction

This two page summary briefly summarizes SIPs wall construction including the advantages and disadvantages of this construction strategy. A more detailed analysis and direct comparison to several other walls can be found online.[1] The scoring system is somewhat subjective based on the relative performance and specifications between different wall systems. Complex two dimensional heat flow analysis and one dimensional hygrothermal modeling were used to determine moisture related durability risks for analysis.

For a more complete analysis of this and other wall constructions, go to www.buildingscience.com.

Thermal Control

Installed Insulation R-value: Structural Insulated Panels (SIPs) are typically constructed using OSB panels adhered to both sides of an expanded polystyrene (EPS) foam insulation core. The most common SIP insulation thicknesses are 3.5" and 5.5" and are equivalent to R-14 and R-22. It is possible, although not as common, to use different insulation types, and thicker panels to achieve high R wall values.

Whole-wall R-value: Using two dimensional heat flow analysis with thermal bridging effects and average framing factors, the clear wall R-value with the OSB layers, drywall, cladding, and surface films often has an R-value higher than the installed insulation R-value because of fewer thermal bridges in the wall system. The whole-wall R-value depends on thermal bridging through vertical stiffeners, top and bottom plate, as well as the wood bucks for windows and doors.[1]

Air Leakage Control: Both OSB and EPS foam are air impermeable so there is no air leakage through the centre of the SIPS panels; however it is important to address the air tightness of joints between the panels as well as interfaces with other structural elements (i.e. foundation walls or roofs) and penetrations such as windows, doors and services.[2] It is relatively easy to achieve a high level of airtightness on a SIPs enclosure.

Typical Insulation Products: EPS foam is the most common, but SIPs have also been constructed with XPS and polyisocyanurate foam cores.

Durability

Rain Control: Rain leakage into the enclosure is the leading cause of premature building enclosure failure. Rain control is typically addressed using a shingle lapped and/or taped drainage plane such as building paper or a synthetic WRB (i.e. homewrap). Intersections, windows, doors and other penetrations must be drained and/or detailed to prevent the penetration of rainwater beyond the drainage plane.[3]

Air Leakage Control: There is no air leakage through the centre of the panel but there is risk of air leakage at the joints between panels if not detailed correctly. Historically, there were design detail issues with the air tightness of the joints between the panels allowing warm moist interior air to condense on the exterior cold OSB layer.[4] Standards of SIPs construction have improved and following the recommended construction guidelines mitigates nearly all of the risk of moisture related durability issues from air leakage.

Vapor Control: A SIPs panel controls vapor well. There is very minimal risk to vapor related moisture damage in SIPs construction.

Drying: Water on either the interior or exterior of the SIPs will dry easily to the interior or exterior in most climates. In very humid or wet climates with minimal drying potential, the OSB may remain wet for an extended period and could result in moisture related durability issues. If moisture accumulates between the interior and exterior OSB faces, it will be difficult to dry.

Built- in Moisture: Water on the surfaces of the panel during construction should dry easily following completion, any water trapped in the panel joints will dry much more slowly.

Durability Summary: If the SIPs are installed according to best practice, with proper air seals and flashed penetrations, the system is very durable in all climates.

Buildability

Using SIPs is relatively easy and quick once the training has been completed. Panels are ordered and shipped to site and assembled with a crane. More specific info can be found at www.sips.org. Generally, most of the services are run on interior partition walls, but there are methods of installing services on the interior of a SIPs panel. A SIPs house can be assembled and dried in more quickly than a wood framed house once the panels are on site.

Cost

SIPs panels range considerably in price depending on the project details and the required thickness of wall panels. It is more expensive than standard construction and can generally only be used on simple geometries.

Material Use

SIPs panels require minimal framing lumber but an increase in structural sheathing panels.

Total Score

SIPs wall panels are generally not constructed with enough insulation to be considered a high R enclosure system on its own in heating climates. It is possible to use thicker insulation panels or to combine SIPs with another insulation strategy in cold climates. It is relatively quick and easy to build with SIPs following training, and refined standard practice techniques have removed nearly all of the historical risks of air leakage condensation. The cost and simple geometries of SIPs houses are two of the main reasons why this technology is not used more often.

References

1 Straube, J., & Smegal, J. (2009). *Building America Special Research Project - High-R Walls Case Study Analysis.* Retrieved from buildingscience.com.

2 Lstiburek, J. W. (2008). *Builder's Guide to Structural Insulated Panels (SIPs) for all Climates.* Westford: Building Science Press Inc.

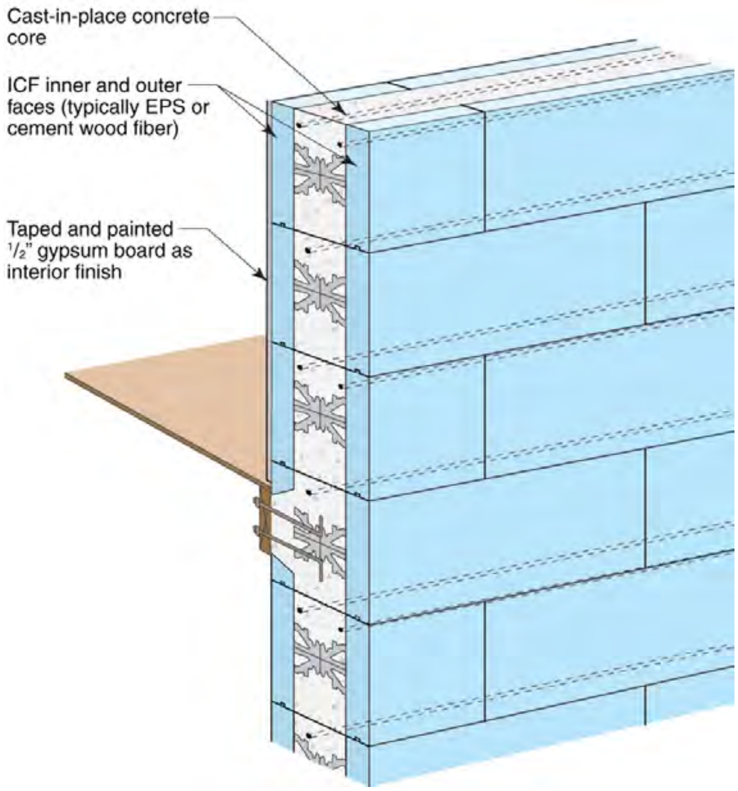
3 Lstiburek, J. W. (2006). *Water Management Guide.* Westford: Building Science Press Inc.

4 SIPA (n.d.). *Report on the Juneau, Alaska Roof Issue.* Retrieved May 2009 from Structural Insulated panel Association: http://www.sips.org/content/technical/index.cfm?PageId=161.

ICF Wall Construction

ICF Wall Construction Details (*Wall 7*)[1]

- ICF inner and outer faces; typically EPS or cement wood fiber
- Cast-in-place concrete core



Scoring: How It Rates

The scoring of each wall system is based on the following five categories. A score of 1 is the lowest score in each category and represents the worst possible technology for each category or highest possible relative cost. A score of 5 is the highest score available in each category, and is representative of the best available technology available on the market or lowest relative cost.

Thermal Control	4
Durability	5
Buildability	4
Cost	2
Material Use	3
Total	**18**

ICF construction is a very durable construction strategy provided the rainwater management details are constructed correctly. Generally, ICF construction alone cannot achieve a high R-value and will require other insulation strategies in combination for cold climates, which is commonly done in practice.

Introduction

This two page summary briefly summarizes ICF wall construction including the advantages and disadvantages of this construction strategy. A more detailed analysis and direct comparison to several other walls can be found online.[1] The scoring system is somewhat subjective based on the relative performance and specifications between different wall systems. Complex two dimensional heat flow analysis and one dimensional hygrothermal modeling were used to determine moisture related durability risks for analysis.

For a more complete analysis of this and other wall constructions, go to www.buildingscience.com.

Thermal Control

Installed Insulation R-value: R-values of Insulated Concrete Form construction vary considerably with the type, and thickness of form. The most common ICF form is constructed of EPS insulation in the range of 2" thick on the interior and exterior. Other ICF materials include cementitious wood based forms, some of which are constructed with an extra layer of insulation (e.g. Rockwool) in the form.

Whole-wall R-value: Using two dimensional heat flow analysis with thermal bridging effects and average framing factors shows that there are few thermal breaks from the interior to the exterior on an ICF wall. An 8" foam ICF form with 4" of EPS has a whole-wall R-value of approximately R-16.[1]

Air Leakage Control: Many ICF construction strategies form air barriers in the field of the wall. Air leakage will occur at penetrations through the wall if they are not detailed correctly.[2]

Typical Insulation Products: EPS foam insulation forms, or cementitious wood based forms.

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Durability

Rain Control: Rain leakage into the enclosure is the leading cause of premature building enclosure failure. Rain control is typically addressed using a shingle lapped and/or taped drainage plane such as building paper or a synthetic WRB (i.e. homewrap). Intersections, windows, doors and other penetrations must be drained and/or detailed to prevent the penetration of rainwater beyond the drainage plane.[3] There is little to no moisture buffering capacity of and ICF wall so even a minimal amount of water, undetectable in standard construction, will have durability issues in ICF construction.

Air Leakage Control: ICF construction strategies form air barriers in the field of the wall. All through wall penetrations require air sealing details.[4]

Vapor Control: There are no significant risks to moisture durability from vapor drive in ICF construction.

Drying: ICFs will dry both to the interior and exterior depending on climate and time of year.

Built- in Moisture: Since ICFs are poured concrete walls in forms with relatively low vapor permeance surfaces, the concrete will dry very slowly, and should be allowed to dry to both sides following the completion of the wall system.

Durability Summary: There are very few risks associated with air leakage and vapor condensation of ICF construction. The most common durability issue is from rainwater leakage into the enclosure. ICF forms typically do not have any buffering capacity of leakage, so even a small leak, that may occur undetected with no durability risks in a wood framed wall, may affect the interior of and ICF building. The ICF wall itself is not susceptible to moisture related issues but interior finishes are generally sensitive to moisture.

Buildability

Generally, building with ICFs is quite easy and straightforward following initial training. Care should be taken to line the surfaces of the forms up to ensure even drywall if it is directly attached. Problems in the past have occurred with air pockets in the forms, as well as bulging and breaking of forms due to the hydrostatic pressure of concrete. These problems are well documented and there are strategies to address these issues.

Cost

The cost of ICF construction varies considerably depending on the type of forms chosen, geometry of construction and location. ICF construction is more expensive that standard construction and is usually prohibitively expensive in residential housing.

Material Use

ICF walls use less concrete than an alternative wall built entirely with concrete, and concrete is very high in embodied energy. The wood framing can be minimized by attaching the drywall directly to the ICF block on the interior.

Total Score

ICF construction is a very durable construction strategy provided the rainwater management details are constructed correctly. Generally, ICF construction alone cannot achieve a high R-value and will require other insulation strategies in combination for cold climates, which is commonly done in practice. ICF is generally only used in multifamily and mid rise buildings, and not in residential housing.

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1 Straube, J., & Smegal, J. (2009). *Building America Special Research Project - High-R Walls Case Study Analysis.* Retrieved from buildingscience.com.

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4 Lstiburek, J. (2008, 08 20). *BSD-104: Understanding Air Barriers.* Retrieved from buildingscience.com.

Spray Foam Wall Construction

Spray Foam Wall Construction Details *(Wall 8a and 8b)*[1]

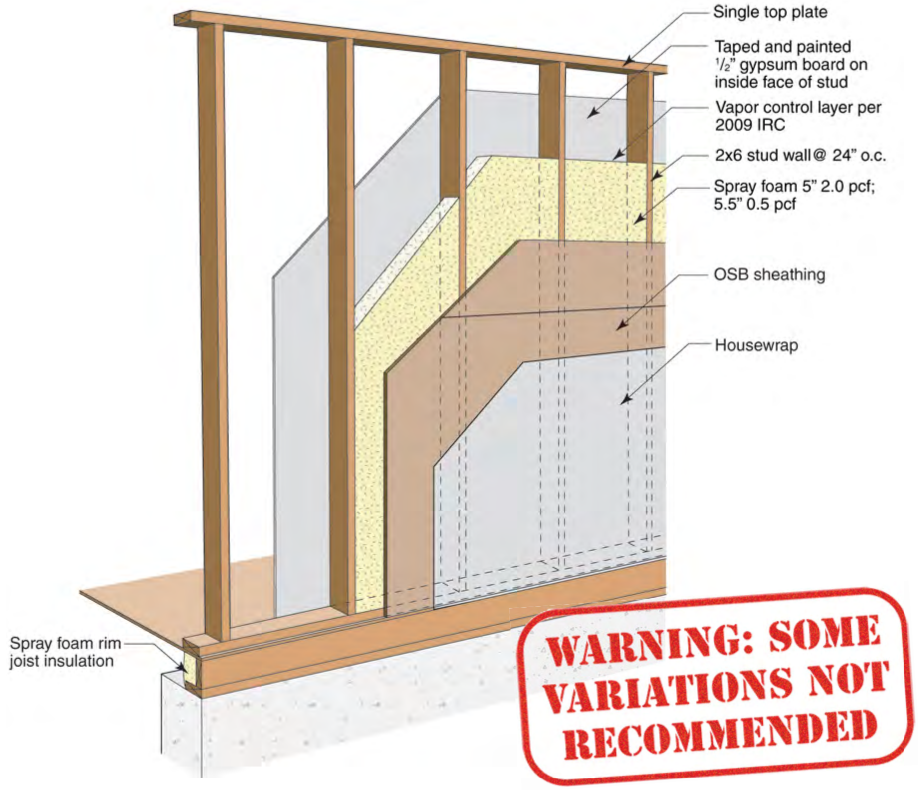
- 2x6 wood frame wall at 24" o.c.
- Spray foam cavity insulation
- OSB sheathing
- Housewrap

Scoring: How It Rates

The scoring of each wall system is based on the following five categories. A score of 1 is the lowest score in each category and represents the worst possible technology for each category or highest possible relative cost. A score of 5 is the highest score available in each category, and is representative of the best available technology available on the market or lowest relative cost.

Thermal Control	5
Durability	5
Buildability	4
Cost	2
Material Use	4
Total	**20**

Both low and high density foam increase the air tightness of the enclosure and reduce the risks to air leakage related durability risks. The R-values of both the low and high density spray foam are significantly reduced by thermal bridging of the wall framing and rim joist, demonstrating the value of insulated sheathing.



Introduction

This two page summary briefly summarizes spray foam wall construction including the advantages and disadvantages of this construction strategy. A more detailed analysis and direct comparison to several other walls can be found online.[1] The scoring system is somewhat subjective based on the relative performance and specifications between different wall systems. Complex two dimensional heat flow analysis and one dimensional hygrothermal modeling were used to determine moisture related durability risks for analysis.

For a more complete analysis of this and other wall constructions, go to www.buildingscience.com.

Thermal Control

Installed Insulation R-value: The installed insulation R-value depends somewhat on the company and but generally speaking, high density foam (2.0 pcf) ranges between R-5.5 and R-6.5 per inch for the aged R-value, and low density foam (0.5pcf) has an R-value of approximately R-3.6/inch. Since high density foam is generally installed short of the cavity to avoid trimming, the installed insulation R-value is approximately R-30 (using R-6/inch). Low density is generally installed deliberately overflowing the cavity and trimmed off resulting in an R-value of approximately R-21.

Whole-wall R-value: Using two dimensional heat flow analysis with thermal bridging effects and average framing factors, it is clear that the thermal bridging through the framing, bottom plate, and top plate reduces the effectiveness of the spray foam insulation.[1] The R-value of the high density spray foam wall decreases from an installed R-value of R-30 to approximately R-20, a decrease of R-10 because of thermal bridging. The low density spray foam wall decreases from an installed insulation R-value of 21 to a whole wall R-value of approximately R-16.

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Air Leakage Control: Both low density and high density foam form an air barrier decreasing thermal losses through air leakage. Air leakage is still common under the bottom plate and at the rim joist if these areas are not detailed correctly.[2]

Typical Insulation Products: Low density 0.5 pcf foam, or high density 2.0 pcf foam.

Durability

Rain Control: Rain control is typically addressed using a shingle lapped and/or taped drainage plane such as building paper or a synthetic WRB (i.e. homewrap). Intersections, windows, doors and other penetrations must be detailed to prevent the penetration of rain water.[3]

Air Leakage Control: Air leakage is significantly minimized by installing spray foam insulation in the stud space since both low density and high density spray foam act as an air barrier. This increases the durability of the wall system considerably over standard construction.[4]

Vapor Control: High density (2.0 pcf) foam forms a vapor control layer reducing vapor movement through the enclosure, minimizing the potential for wintertime vapor condensation and summertime inward vapor drive. Low density foam allows moisture vapor movement through the foam so other methods of vapor control such as poly, kraft paper, or vapor barrier paint may be required based on the geographic location.[5] The IRC building code should be consulted.

Drying: Both of the spray foam walls dry relatively slowly if water enters the enclosure, since they do not experience convective looping and air movement similar to air permeable insulations. Spray foam does not provide any buffering capacity or redistribution. Foam is relatively moisture tolerant and will be able to dry given enough time. Ventilation behind vapor impermeable claddings and interior components (e.g. kitchen cabinets) can encourage drying.

Built- in Moisture: Care should always be taken to build with dry materials where possible, and allow drying of wet materials before close in. High density foam will inhibit the drying of wet building materials more than low density vapor permeable foam.

Durability Summary: The primary durability risks associated with these wall assemblies involve moisture damage related to rain water penetration. Both air leakage and vapor diffusion durability is significantly increased with spray foam but some vapor control may be necessary with low density spray foam in cold climates.

Buildability

Using spray foam as the stud space insulation is a very simple modification to the construction technique. Generally, the wall construction is the same as standard or advanced framing construction, and spray foam is sprayed into the cavity. Spray foam significantly reduces risks of poor air tightness detailing of the exterior sheathing or interior drywall.

Cost

Using spray foam will increase construction costs considerably but these increased costs may be outweighed by the benefits to energy efficiency, and occupancy comfort from reduced drafts.

Material Use

Wood framing required for spray foam insulation is the same required for the standard construction, or advanced framed wall depending on the framing strategy used.

Total Score

Both low and high density foam increase the air tightness of the enclosure and reduce the risks to air leakage related durability risks. A vapor control (ie. polyethylene, kraft paper, SVR) with high density foam is generally not required and vapor control with low density spray foam will be climate specific. The R-values of both the low and high density spray foam are significantly reduced by thermal bridging of the wall framing and rim joist, demonstrating the value of insulated sheathing. It may be possible to use spray foam insulation in combination with another insulation strategy to maximize the R-value gained with the spray foam insulation.

References

1 Straube, J., & Smegal, J. (2009). *Building America Special Research Project - High-R Walls Case Study Analysis*. Retrieved from buildingscience.com.

2 Straube, J. (2009, 04 22). *BSD-014 Air Flow Control in Buildings.* Retrieved from buildingscience.com.

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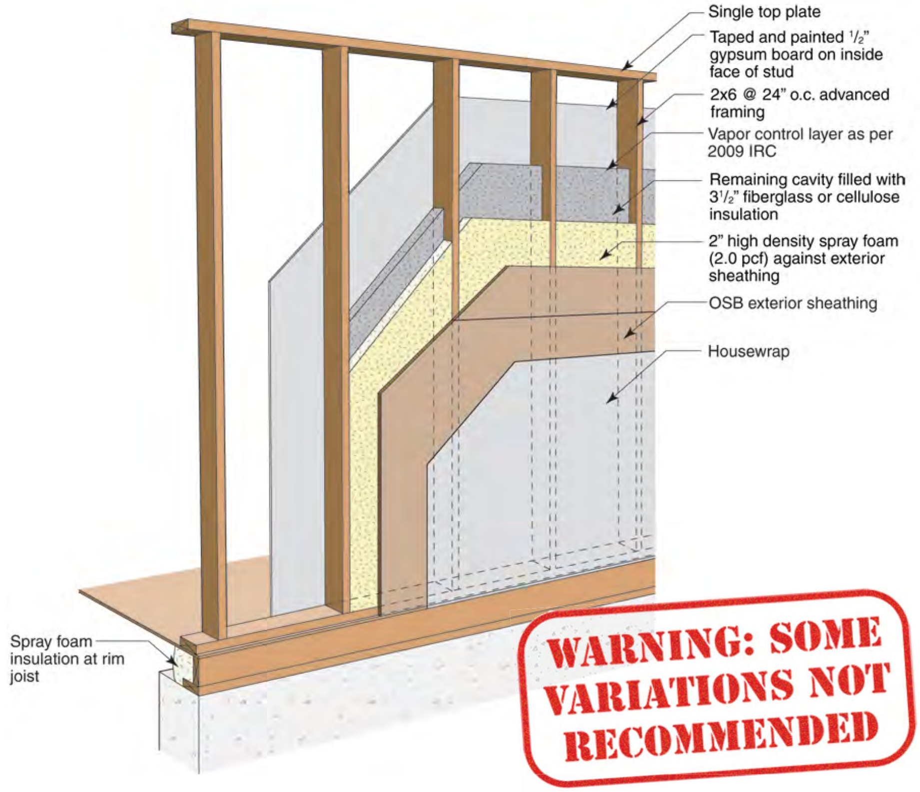
Flash-and-Fill Hybrid Wall Construction

Flash-and-Fill Hybrid Wall Construction Details *(Wall 9)*[1]

- 2x6 wood frame wall at 24" o.c.
- 2" high density spray foam
- Fiberglass or cellulose cavity insulation
- OSB sheathing
- Housewrap



Scoring: How It Rates

The scoring of each wall system is based on the following five categories. A score of 1 is the lowest score in each category and represents the worst possible technology for each category or highest possible relative cost. A score of 5 is the highest score available in each category, and is representative of the best available technology available on the market or lowest relative cost.

Thermal Control	4
Durability	4
Buildability	4
Cost	3
Material Use	4
Total	**19**

The hybrid wall system significantly reduces air leakage over standard construction or advanced framing, which conserves energy, and reduces the potential for both air leakage and vapor condensation durability issues. Unfortunately, the added cost of the spray foam insulation only adds a minimal amount to the R-value since the thermal bridging of the wall is not addressed. Addressing the thermal bridges would improve this wall construction.

Introduction

This two page summary briefly summarizes flash-and-fill hybrid wall construction including the advantages and disadvantages of this construction strategy. A more detailed analysis and direct comparison to several other walls can be found online.[1] The scoring system is somewhat subjective based on the relative performance and specifications between different wall systems. Complex two dimensional heat flow analysis and one dimensional hygrothermal modeling were used to determine moisture related durability risks for analysis.

For a more complete analysis of this and other wall constructions, go to www.buildingscience.com.

Thermal Control

Installed Insulation R-value: The installed R-value is approximately R-12 for two inches of high density spray foam (2.0 pcf) and R-13 for three and a half inches of fiberglass batt, totaling R-25.

Whole-wall R-value: Using two dimensional heat flow analysis with thermal bridging effects and average framing factors, the R-value decreases from an installed insulation R-value of R-25 to whole wall R-value of approximately R-17 for a the hybrid wall construction in this case.[1] The decrease in R-value is due to the thermal bridging of the wall framing, top and bottom plates.

Air Leakage Control: Fiberglass batt, and both blown and sprayed cellulose are air permeable materials allowing possible air paths between the interior and exterior as well as convective looping in the insulation. Although densepack cellulose has less air permeance it does not control air leakage. In the case of the hybrid wall system, the spray foam is used as an air barrier in the stud space to limit the air movement between the interior and exterior so there are fewer energy losses due to air leakage. It is still possible and common to get air leakage

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below the bottom plate if is not sealed.[2] When spray foam is used in the wall system, it is beneficial to also use it in the rim joist which has a high potential for air leakage.

Typical Insulation Products: Spray foam insulation and fiberglass batt, blown fiberglass, blown cellulose, or sprayed cellulose.

Durability

Rain Control: Rain leakage into the enclosure is the leading cause of premature building enclosure failure. Rain control is typically addressed using a shingle lapped and/or taped drainage plane such as building paper or a synthetic WRB (i.e. homewrap). Intersections, windows, doors and other penetrations must be drained and/or detailed to prevent the penetration of rainwater beyond the drainage plane.[3]

Air Leakage Control: Air leakage condensation is the second largest cause of premature building enclosure failure with wood framed wall construction. It is very important to control air leakage to minimize air leakage condensation durability issues. An air barrier is required in this wall system to ensure that through-wall air leakage is eliminated (ideally) or at least minimized. An air barrier should be stiff and strong enough to resist wind forces, continuous, durable, and air impermeable.[4]

In the hybrid wall system, two inches of spray foam is used as an air barrier to reduce the air leakage. This also reduces the air leakage condensation against the sheathing in the winter as it significantly warms the condensation plane. Since air leakage from the interior, into the studspace and back into the interior can also cause condensation in some climates, it is still important to detail the interior surface as an air barrier as well.

Vapor Control: Fiberglass and cellulose are vapor permeable materials, but including two inches of high density spray foam acts as a vapor barrier limiting vapor movement to the cold exterior sheathing, and significantly reduces the risk of vapor condensation durability issues. High density spray foam also decreases the summer inward vapor drives. If low density spray foam is used, it is not a vapor barrier, and other vapor control may be required depending on the climate. Calculations should be done to ensure a minimum risk to vapor condensation durability issues.[5] The IRC building code should be consulted.

Drying: Using high density spray foam will slow the movement of moisture across the enclosure. and there is no moisture buffering capacity or redistribution within the spray foam. Some vapor control may still be required at the interior surface in cold climates which slows drying. Proper flashing of all penetrations should help minimize moisture in the enclosure. Ventilation behind vapor impermeable claddings and interior components (e.g. kitchen cabinets) can encourage drying.

Built- in Moisture: Care should always be taken to build with dry materials where possible, and allow drying of wet materials before close in. High density spray foam may slow drying across the enclosure since it is a vapor barrier. In geographic regions with reduced drying potential, the moisture content of the sheathing may stay elevated for an extended period due to the inability to dry or redistribute moisture into the wall.

Durability Summary: Hybrid wall construction has a greater resistance to both air leakage condensation and vapor diffusion condensation because of the high density spray foam increasing the dew point of the condensation surface. The primary durability risks associated with these wall assemblies involve moisture damage related to rain water penetration.

Buildability

Hybrid wall construction is not very different from standard wall construction or advanced framing. By filling the stud space with two inches of spray foam, an R-13 batt can still easily be installed against the foam, or cellulose could be sprayed in the remaining stud space. All other aspects of the construction are the same as standard construction or advanced framing. Using high density spray foam reduces the risks from poor workmanship during construction.

Cost

Using spray foam insulation can be costly, and while it reduces the risks of moisture related durability issues, the minimal increase in R-value due to the thermal bridging may not be worth the increased cost of the spray foam insulation.

Material Use

There is no increase in framing materials from standard construction, but the embodied energy of the system increases with the addition of high density spray foam insulation.

Total Score

The hybrid wall system significantly reduces air leakage over standard construction, which conserves energy, and reduces the potential for both air leakage and vapor condensation durability issues. Reducing the air leakage may also increase occupancy comfort by reducing drafts. Unfortunately, the added cost of the spray foam insulation only adds a minimal amount to the R-value since the thermal bridging of the wall is not addressed. This wall is very similar to build as standard construction and less susceptible to poor workmanship during construction. Addressing the thermal bridges would improve this wall construction.

References

1. Straube, J., & Smegal, J. (2009). *Building America Special Research Project - High-R Walls Case Study Analysis*. Retrieved from buildingscience.com.
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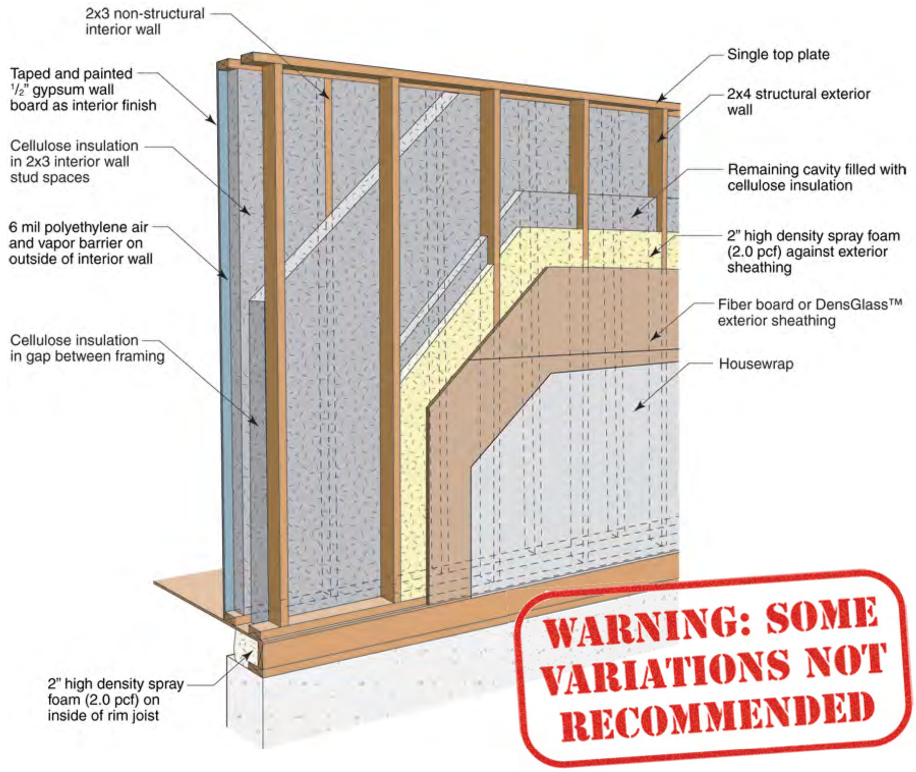
Double Stud with Spray Foam Wall Construction

Double Stud with Spray Foam Wall Construction Details *(Wall 10)*[1]

- 2x4 exterior wall framing
- 2” high density spray foam
- Fiberglass or cellulose cavity insulation
- 2x3 interior wall framing
- Fiber board or DensGlass™ sheathing
- Housewrap



Scoring: How It Rates

The scoring of each wall system is based on the following five categories. A score of 1 is the lowest score in each category and represents the worst possible technology for each category or highest possible relative cost. A score of 5 is the highest score available in each category, and is representative of the best available technology available on the market or lowest relative cost.

Thermal Control	5
Durability	4
Buildability	3
Cost	3
Material Use	3
Total	**18**

This is truly a high-R wall assembly, and with the addition of spray foam, there is a reduction in moisture related durability issues. In some extreme climates, two inches of spray foam may not be enough to sufficiently reduce the risk, which means that more spray foam is required, or an interior air barrier and some form of vapor control, likely a Class II or Class II would be sufficient.

Introduction

This two page summary briefly summarizes double stud with spray foam wall construction including the advantages and disadvantages of this construction strategy. A more detailed analysis and direct comparison to several other walls can be found online.[1] The scoring system is somewhat subjective based on the relative performance and specifications between different wall systems. Complex two dimensional heat flow analysis and one dimensional hygrothermal modeling were used to determine moisture related durability risks for analysis.

For a more complete analysis of this and other wall constructions, go to www.buildingscience.com.

Thermal Control

Installed Insulation R-value: The thickness of double stud walls varies, however walls with overall insulation thickness of 9.5” appear to be most common. The insulation is most commonly cellulose insulation but could also be sprayed fiberglass. In this system with two inches of high density spray foam (R-6/inch) the installed insulation R-value is approximately R-40. This is an increase of R-5 over the same double stud construction insulated only with cellulose.

Whole-wall R-value: Using two dimensional heat flow analysis with thermal bridging effects and average framing factors shows that adding an interior framed wall with a insulation filled gap greatly reduces the thermal breaks through the stud wall and can increases the Clear wall R-value to R-36 depending on the thickness of insulation. However, because of the thermal losses at the rim joist, the Whole-wall R-value is closer to R-33.[1]

Air Leakage Control: Fiberglass batt, blown and sprayed cellulose are all air permeable materials allowing possible air paths between the interior and exterior as well as convective looping through the material. In this case, the spray foam is used as an air barrier in the stud space to limit the air movement between the interior and exterior so there are fewer energy losses due to air leakage. It is still possible and common to get air leakage below the bottom plate if is not sealed.[2] When spray foam is used in the wall system, it is beneficial to also use it in the rim joist that has a high potential for air leakage. Reducing the air leakage with spray foam may also increase occupancy comfort by reducing drafts.

Typical Insulation Products: High density spray foam, blown cellulose, sprayed fiberglass.

Durability

Rain Control: Rain Control – Rain leakage into the enclosure is the leading cause of premature building enclosure failure. Rain control is typically addressed using a shingle lapped and/or taped drainage plane such as building paper or a synthetic WRB (i.e. homewrap). Intersections, windows, doors and other penetrations must be drained and/or detailed to prevent the penetration of rainwater beyond the drainage plane.[3]

Air Leakage Control: Since fibrous insulations are air permeable, air leakage condensation may occur if air moves into the stud space from the interior, or the exterior, depending on the climate. An air barrier is required in this wall system to ensure that air leakage is ideally eliminated, but at least minimized. Air leakage condensation is one of the greatest causes of premature building enclosure failure. An air barrier should be stiff, continuous, durable, strong, and impermeable.[4]

Air need not leak straight through an assembly to cause moisture problems; it can also leak from the inside, through the wall, and back to the inside. Condensation within the stud space is possible if this type of airflow occurs, depending on the weather conditions. Hence, wall designs should control airflow into the stud space.

Vapor Control: Fiberglass and cellulose are vapor permeable materials, so a separate vapor control strategy must be employed to ensure that vapor diffusion from does not result in condensation on or damaging moisture accumulation in moisture sensitive materials. In this case, the high density foam acts as a vapor control layer in the assembly. The permeance and location of vapor control is dependent on the climate zone and in cold climates, further vapor control may be required due to the ratio of insulation interior of the vapor control layer. Some level of vapor control may be needed on the interior surface or the amount of spray foam insulation could be increased. Installing the vapor control layer in the incorrect location can lead to building enclosure failure.[5] The IRC building code should be consulted.

Drying: Cellulose and fiberglass insulation allow drying easily, so drying is controlled by other enclosure components such as the high density spray foam and OSB sheathing. Installing vapor control on both sides will seal any moisture into the stud space, resulting in low drying potential, and possibly resulting in moisture-related durability risks. Ventilation behind vapor impermeable claddings and interior components (e.g. kitchen cabinets) can encourage drying.

Built- in Moisture: Care should always be taken to build with dry materials where possible, and allow drying of wet materials before close in. Cellulose is often sprayed in damp, and manufacturers recommend drying before close in and moisture content limits. Interior vapor control may be required depending on the climate zone, and with the combination of vapor semi-impermeable foam and OSB, will increase the time required for adequate drying.

Durability Summary: The primary durability risks associated with these wall assemblies involve moisture damage related to rain water penetration or condensation (most likely the result of air leakage, but also potentially the result of vapor diffusion). In some extreme cold climates, two inches of spray foam may not be enough insulation to minimize the risk of air leakage and vapor condensation durability issues because of the ratio of insulation to the interior and exterior of the surface of the spray foam. Increasing the amount of spray foam (the amount of insulation exterior of the condensation plane) will further decrease the risk.

An airtight drywall construction approach will also reduce risks associated with air leakage condensation, and some form of vapor control may be needed (poly, kraft paper or vapor barrier paint depending on climate).

Cellulose insulated walls are slightly more durable because cellulose insulation is capable of storing and redistributing small amounts of moisture. Cellulose insulation is typically treated with borates that have been shown to protect itself and neighboring wood material from mold growth and decay. Cellulose insulation also has decreased flame spread potential relative to other insulation materials.

Buildability

A double stud wall requires more effort and time to construct properly compared to standard construction practices. The thickness of the wall requires plywood boxes to install all windows and doors in the enclosure. Installing spray foam reduces the risks from poor workmanship but in some climates more than two inches of high density spray foam may be required to completely avoid the risk of air leakage and vapor condensation. Double stud wall construction reduces the interior living space of the building by adding insulation to the interior of the structural framed wall.

Cost

There are increased costs in the addition of a secondary interior wall, and spray foam insulation. The benefits of reduced condensation potential may not be worth the cost of adding spray foam since there are only minimal benefits to the R-value of the wall assembly.

Material Use

A secondary interior framed wall increases the amount of framing material required for wall construction. Spray foam insulation significantly increases the embodied energy over using cellulose insulation with minimal returns in R-value.

Total Score

This is truly a high-R wall assembly, and with the addition of spray foam, there is a reduction in moisture related durability issues. In some extreme climates, two inches of spray foam may not be enough to sufficiently reduce the risk, which means that more spray foam is required, or an interior air barrier and some form of vapor control, likely a Class II or Class II would be sufficient. The other disadvantage to this wall system is that it reduces the living space of the building.

References

1 Straube, J., & Smegal, J. (2009). *Building America Special Research Project - High-R Walls Case Study Analysis.* Retrieved from buildingscience.com.

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Offset Frame Wall Construction

Offset Frame Wall Construction Details *(Wall 11)*[1]

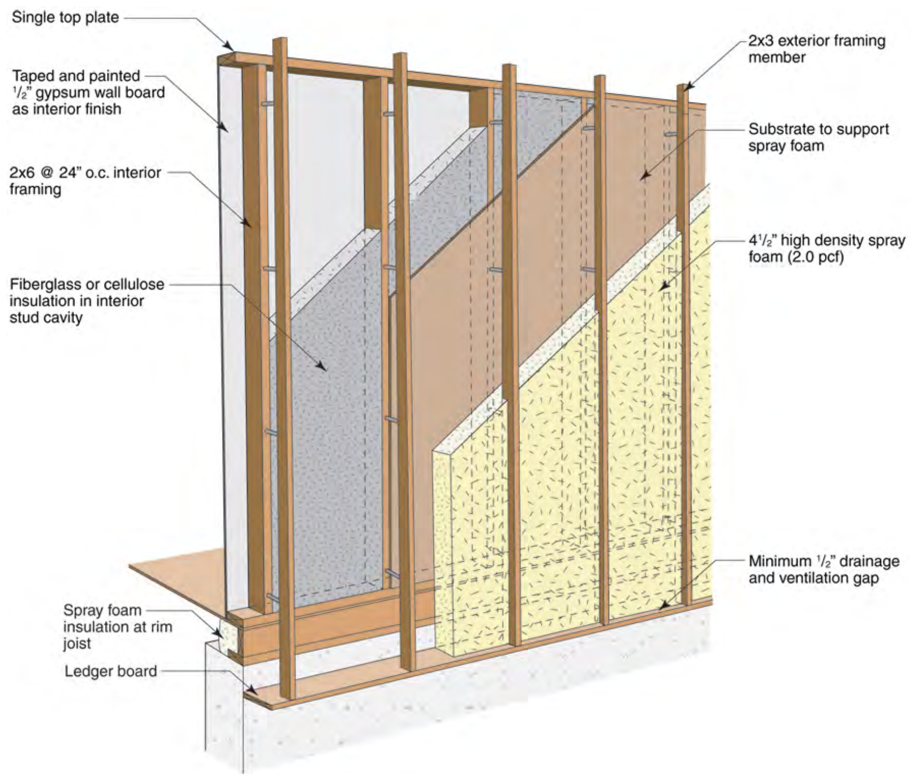
- 2x6 structural framing wall
- 2x3 cantilevered wall
- 4.5" high density spray foam
- Fiberglass or cellulose cavity insulation
- OSB sheathing

Scoring: How It Rates

The scoring of each wall system is based on the following five categories. A score of 1 is the lowest score in each category and represents the worst possible technology for each category or highest possible relative cost. A score of 5 is the highest score available in each category, and is representative of the best available technology available on the market or lowest relative cost.

Thermal Control	5
Durability	5
Buildability	4
Cost	3
Material Use	2
Total	**19**

The offset frame wall system is ideal in many situations where the cost of high density spray foam is justified. There is very minimal risk to moisture related durability issues from rain penetration or condensation because off the continuous exterior spray foam insulation if the penetrations are detailed correctly. This is a very durable wall system for all climates, and can be built as new construction or a deep retrofit.



Introduction

This two page summary briefly summarizes the offset frame wall construction including the advantages and disadvantages of this construction strategy. A more detailed analysis and direct comparison to several other walls can be found online.[1] The scoring system is somewhat subjective based on the relative performance and specifications between different wall systems. Complex two dimensional heat flow analysis and one dimensional hygrothermal modeling were used to determine moisture related durability risks for analysis.

For a more complete analysis of this and other wall constructions, go to www.buildingscience.com.

Thermal Control

Installed Insulation R-value: The amount of insulation installed in this wall system can be modified quite easily but in this case, 4.5" of high density spray foam (R-6/inch) was used on the exterior, and 5.5" of cellulose (R-3.7/inch) was installed in the stud space for a total installed insulation R-value of R-47. It is possible to install as much or as little spray foam insulation on the exterior as practical in specific cases.

Whole-wall R-value: Using two dimensional heat flow analysis with thermal bridging effects and average framing factors, the thermal bridging in this wall system is significantly reduced by the uniform layer of spray foam over the exterior covering the rim joist and wall framing. The whole wall R-value for this assembly is approximately R-37.[1]

Air Leakage Control: The exterior spray foam insulation is a perfect air barrier for this enclosure eliminating heat losses by air leakage through the wall. Air still could leak around penetrations such as windows, doors, and services if not detailed correctly.[2]

Typical Insulation Products: High density spray foam and fiberglass batt, blown cellulose, sprayed cellulose, or sprayed fiberglass.

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Durability

Rain Control: For this wall system, the continuous drainage plane will be the exterior surface of the high density foam. Rain screen cladding will be installed directly on the exterior framing, and any moisture that passes through the cladding will drain against the high density spray foam. Intersections, windows, doors and other penetrations must be detailed to prevent the penetration of rainwater.[3]

Air Leakage Control: The continuous layer of high density spray foam prevents all air leakage through the enclosure system. Care should be taken to make sure that penetrations through the enclosure (windows, doors, services) are airtight. There should be no risk of air leakage condensation against the sheathing in most climates with 4.5" of exterior spray foam. In climate zone 8, more spray foam may be required, or the stud space insulation can be removed to ensure that there is no condensation.[4]

Vapor Control: The continuous layer of high density spray foam prevents vapor movement through the enclosure system. There should be no risk of vapor condensation against the sheathing in most climates with 4.5" of exterior spray foam. In climate zone 8, more spray foam may be required, or the stud space insulation can be removed to ensure that there is no condensation.[5]

Drying: This enclosure system will dry both to the interior, if the moisture is in the stud space, and to the exterior, if the moisture is in the cladding. Proper flashing of all penetrations should help minimize moisture in the enclosure. Ventilation behind vapor impermeable claddings and interior components (e.g. kitchen cabinets) can encourage drying.

Built- in Moisture: Care should always be taken to build with dry materials where possible, and allow drying of wet materials before closing in. Cellulose is often sprayed in wet, and manufacturer's recommendation is to allow drying before closing in. Because no polyethylene vapor barrier is required, moisture in the stud space will be able to dry quite easily to the interior.

Durability Summary: Provided the minimum amount of spray foam insulation is exceeded for a given climate to keep the condensation plane above the dew point, there is virtually no risk to moisture condensation in the enclosure, and any small amounts of moisture in the enclosure will dry easily.

Cellulose insulation is typically treated with borates that have been shown to protect itself and neighboring wood material from mould and decay. Cellulose insulation also has decreased flame-spread potential.

Buildability

This wall system does require some attention to detailing, and likely some initial training to install the exterior framing material1, but the risks from poor construction are very minimal. Spray foam insulation is shipped as a liquid in two components and only mixed as it is installed, so shipping is much more efficient and reliable than board foam, which has been reported to arrive on the job site damaged, especially in remote areas. It is very quick and easy to dry in a structure with spray foam insulation to weatherproof it, which is critical in environments with short construction seasons. Interior finishing can be done even in inclement weather. This enclosure system has been used both in new construction and in retrofit situations in cold climates.

Cost

In most regions high density spray foam is a relatively expensive method of insulating the enclosure, however the benefits, of a complete air and vapor barrier, occupancy comfort, reduced energy consumption, and reduced risks to contractor errors may be worth the increased cost in some locations and situations.

Material Use

More framing materials are required for this enclosure assembly, as well as the higher embodied energy high density spray foam. Cellulose in the stud space has very low embodied energy.

Total Score

This wall system is ideal in many situations where the cost of high density spray foam is justified. One of the locations where the cost is justified is the extremely cold climates and short construction seasons of the north. Most of the durability related issues are caused by air leakage and vapor condensation on the sheathing causing rot and mold in the enclosure. The common complaints in the remote locations is that the board foam arrives on trucks badly damaged, but with spray foam, the foam is shipped in two liquid components, and more board feet of foam could be shipped on the same truck. The construction season is very short but houses can be dried in during the best weather, and the interior finished later if necessary.

References

1 Straube, J., & Smegal, J. (2009). *Building America Special Research Project - High-R Walls Case Study Analysis.* Retrieved from buildingscience.com.

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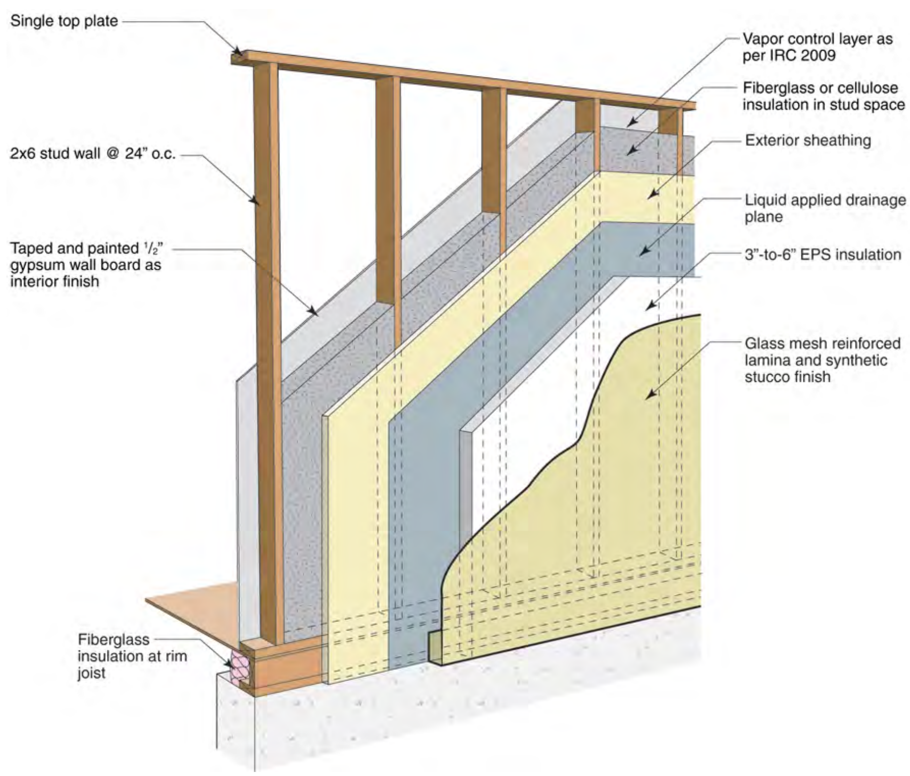
Exterior Insulation Finish Systems (EIFS) Wall Construction

Exterior Insulation Finish Systems (EIFS) Wall Construction Details

(Wall 12)[1]

- 2x6 structural framing wall
- Fiberglass or cellulose cavity insulation
- Glass-faced gypsum sheathing
- Exterior EPS insulation
- Stucco finish



Scoring: How It Rates

The scoring of each wall system is based on the following five categories. A score of 1 is the lowest score in each category and represents the worst possible technology for each category or highest possible relative cost. A score of 5 is the highest score available in each category, and is representative of the best available technology available on the market or lowest relative cost.

Thermal Control	5
Durability	5
Buildability	4
Cost	3
Material Use	3
Total	**20**

This wall system is a durable and reliable choice regardless of the historical failures of this construction strategy. A better understanding of enclosure design and building science with drained and ventilated claddings and better design details have nearly eliminated the historical moisture related issues. This wall system has the appearance of a stucco finish, but with significant energy improvements, which is often the reason for using this construction strategy.

Introduction

This two page summary briefly summarizes EIFS wall construction including the advantages and disadvantages of this construction strategy. A more detailed analysis and direct comparison to several other walls can be found online.[1] The scoring system is somewhat subjective based on the relative performance and specifications between different wall systems. Complex two dimensional heat flow analysis and one dimensional hygrothermal modeling were used to determine moisture related durability risks for analysis.

For a more complete analysis of this and other wall constructions, go to www.buildingscience.com.

Thermal Control

Installed Insulation R-value: The framed portion of this wall assembly typically has an R-value of R-19-20 when insulated with fiberglass batt or cellulose. Exterior insulation for EIFS is typically EPS at R-4/inch.

Whole-wall R-value: Using two dimensional heat flow analysis with thermal bridging effects and average framing factors demonstrates improvements in the efficiency of the fiberglass batt or cellulose in the stud space by decreasing the thermal bridging effects of the framing and the rim joist. Adding 4" of EPS insulation for a total an increase of R-16 increases the Clear-wall R-value of standard construction by slightly more than R-16 because of thermal bridging of the framing and rim joist. The whole-wall R-value for this system is approximately R-30.[1]

Air Leakage Control: Fiberglass batt, blown and sprayed cellulose are all air permeable materials allowing possible air paths between the interior and exterior as well as convective looping through the material. The air tightness of an EIFS system is typically at the surface of the exterior sheathing (usually glass-faced exterior gypsum) because it is the drainage plane.

Typical Insulation Products: EPS exterior insulation, fiberglass batt, blown cellulose, sprayed cellulose.

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Durability

Rain Control: In the EIFS system, it is critical to correctly detail the drainage plane to adequately handle rain. Historically EIFS were constructed using a face-sealed approach, but this lead to many moisture related durability issues. EIFS can be used as part of a very durable and reliable enclosure system, provided it is drained and ventilated. Intersections, windows, doors and other penetrations must be detailed to prevent the penetration of rain water.[2]

Air Leakage Control: By adding exterior insulation as part of the EIFS construction, the temperature of the sheathing (condensation plane) increases, and the risk of air leakage condensation is reduced. It is always good practice to build airtight enclosure systems, often with both an interior and exterior air barrier to avoid air leakage condensation and windwashing. Air leakage condensation is one of the greatest causes of premature building enclosure failure. An air barrier should be stiff, continuous, durable, strong, and impermeable.[3]

Air need not leak straight through an assembly to cause moisture problems; it can also leak from the inside, through the wall, and back to the inside. Condensation within the stud space is possible if this type of airflow occurs, depending on the weather conditions. Hence, wall designs should control airflow into the studspace.[4]

Vapor Control: By adding exterior insulation as part of the EIFS construction, the temperature of the sheathing (condensation plane) increases, and the risk of moisture vapor condensation is reduced. It may be possible to avoid the use of an interior vapor control layer, or use a higher permeance vapor control layer (Class II or III) depending on the amount of insulation on the exterior and regional building codes. Installing the incorrect vapor control layer or installation in the incorrect location can lead to building enclosure failure.[5] The IRC building code should be consulted.

Drying: Insulating sheathing limits the drying to the exterior, and the wall must be able to dry to the interior. Poly vapor barriers are typically avoided so that this drying can occur. The minimum level of vapor control on the interior surface is determined by the IRC. Installing vapor control on both sides of the enclosure will seal any moisture into the stud space, resulting in low drying potential, and possibly resulting in moisture-related durability risks. Ventilation behind vapor impermeable claddings and interior components (e.g. kitchen cabinets) can encourage drying.

Built- in Moisture: Care should always be taken to build with dry materials where possible, and allow drying of wet materials before close in. Cellulose is often sprayed in damp, and manufacturers recommend drying before close in and moisture content limits.

Durability Summary: The primary durability risks associated with these wall assemblies involve moisture damage related to rain water penetration. Insulating sheathings keep the condensation plane temperature elevated so there is less risk of condensation due to air leakage or vapor diffusion. Framing members are also kept warmer so they are exposed to lower relative humidity levels and generally have lower equilibrium moisture contents. Board foam products are typically less moisture sensitive than wood-based structural sheathing products.

Cellulose insulated walls are somewhat more durable because cellulose insulation is capable of storing and redistributing small amounts of moisture. Cellulose insulation is typically treated with borates that have been argued to protect adjacent wood members from mold and decay.

Buildability

Exterior insulation up to 1.5” requires minimal changes to standard construction practices. Exterior insulation in excess of 1.5” requires minor changes to window and wall construction and detailing which requires training and monitoring during the initial implementation. The EIFS finish system is directly applied to the exterior foam, and requires skilled trades to install. Some EIFS companies produce detail drawings for their products to reduce the risk of construction issues resulting in premature enclosure failure. www.stocorp.com and www.dryvit .ca are two examples that provide detailed drawings on their websites.

Cost

There is an increased cost to EIFS wall construction because of the specialized stucco like finish. It is possible to add exterior insulation with a rain screen cladding as an alternative to the stucco appearance finish that may be more cost effective.

Material Use

Typically, in EIFS construction, structural wood sheathing is exchanged for a more moisture tolerant sheathing such as glass mesh reinforced exterior gypsum board. The addition of EPS foam can usually be sourced locally, and has relatively low embodied energy relative to other board foam insulations.

Total Score

This wall system is a durable and reliable choice regardless of the historical failures of this construction strategy. A better understanding of enclosure design and building science with drained and ventilated claddings and better design details have nearly eliminated the historical moisture related issues. This wall system has the appearance of a stucco finish, but with significant energy improvements, which is often the reason for using this construction strategy. It is possible to use exterior insulation with many different cladding options if a stucco appearance is not the desired architectural result.

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Building America Special Research Project: High-R Walls Case Study Analysis

Research Report - 0903

March 11, 2009 (rev. 8/7/09)

John Straube and Jonathan Smegal

Abstract:

Many concerns, including the rising cost of energy, climate change concerns, and demands for increased comfort, have lead to the desire for increased insulation levels in many new and existing buildings. More building codes are being modified to require higher levels of thermal control than ever before. This report considers a number of promising wall systems that can meet the requirement for better thermal control. Unlike previous studies, this one considers performance in a more realistic matter, including some true three-dimensional heat flow and the relative risk of moisture damage.

Building America Special Research Project
High-R Walls Case Study Analysis

2009 08 07

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A. Introduction

Many concerns, including the rising cost of energy, climate change concerns, and demands for increased comfort, have lead to the desire for increased insulation levels in many new and existing buildings. More building codes are being modified to require higher levels of thermal control than ever before. This report considers a number of promising wall systems that can meet the requirement for better thermal control. Unlike previous studies, this one considers performance in a more realistic matter, including some true three-dimensional heat flow and the relative risk of moisture damage.

In some cases, increasing the quantity of insulation may result in an increased risk of moisture-related issues when the exterior surfaces of the enclosure are kept colder in cold weather, and the interior surfaces are kept cooler in warm weather. This may result in increased condensation, and increased freeze thaw potential or decay potential of the assembly in different situations. Analysis is required to predict the potential hygrothermal risks due to increasing the amount of insulation (R-value) in the enclosure.

High R-values for framed wall assemblies are defined here as ranging from approximately R18 to R40 and above depending on the geographic location and climate conditions. A high R-value wall in the south will be considerably less than a high R-value in a cold climate. The analysis in this report includes a summary of historical wall construction types and R-values, current construction strategies, as well as walls that will likely become popular in the future based on considerations such as energy and material availability.

Previous work, largely stemming from research in the 1970's and 1980's, involved postulating newer assemblies with improved R-values. R-value was, and often still is, defined as the "clear wall" R-value (no framing effects accounted for) or the total amount of insulation installed in the assembly. The increased moisture risks were rarely considered.

A study currently being conducted by the National Research Council of Canada (NRC) is investigating and developing durable and energy efficient wall assemblies for Northern Canada. In the first stage of the NRC study, meetings with the northern communities and investigations of the houses were conducted. A literature review covering selection criteria for possible envelope assemblies in Northern Canada, current wall systems and systems to consider was written (Saïd 2006). Walls are currently undergoing extreme temperature testing in the NRC laboratory in Ottawa, Canada. All of the walls being tested by the NRC are constructed with a polyethylene air and vapor barrier and none of the walls are constructed with exterior insulation (Rousseau, et al. 2008).

The Cold Climate Housing Research Center (CCHRC) of Alaska has conducted field monitoring tests on different wall systems, specifically to assess the moisture-related performance of high performance wall systems. Several tests were conducted on a test hut at the University of Alaska Southeast, in Juneau AK (8574 HDD65 or 4763 HDD18) (Smegal and Straube 2006), and others were conducted on the CCHRC main office building in Fairbanks Alaska (13980 HDD65 or 7767 HDD18) constructed in 2007. Streaming data and wall drawings can be viewed on the CCHRC website showing the thermal performance of the wall systems (CCHRC 2007). CCHRC also successfully completed construction of a high R-value house as part of the Building American program in Haida, AK, and the report can be found online (BSC 2008).

Some of the walls for this high R-value study were chosen based on the literature review of the NRC report, and references to construction techniques from both the NRC and CCHRC will be made throughout this report. Some walls have been built by niche builders since the early 1980's.

1. OBJECTIVE

The objective of this study is to identify highly-insulated building enclosure wall systems based on selected criteria, resulting in a durable affordable, and resource efficient enclosure that provides a comfortable living environment in different climate zones. This report will present the analysis of different enclosure wall strategies and present their advantages and disadvantages according to several comparison criteria.

2. SCOPE

This study is limited to wall systems for cold climates. Further studies should be conducted to address other components of the building enclosure such as roofs and foundations. In general, only cold climates are considered in this report since enclosures in cold climates benefit the greatest from a highly insulated building enclosure, but important conclusions can also be drawn for other climate zones.

3. APPROACH

This study examines thermal and moisture control, durability, buildability, cost and material use. The quantitative analysis for each wall system is based on a two-dimensional steady-state heat flow modeling program and a one-dimensional dynamic heat and moisture (hygrothermal) model. Minneapolis, MN in IECC climate Zone 6 was used as the representative cold climate for most of the modeling, because of the cold winter weather, and fairly warm and humid summer months. In cold climates, a building's enclosure is often the most important factor limiting heat loss, both in terms of insulation and air tightness.

B. Analysis

1. WALL ASSEMBLIES REVIEWED

Because there are a number of variables possible for each possible wall system depending on the local practices, climate, and architect or general contractor preferences, an attempt was made to choose the most common wall systems and make notes and comments about other alternatives during analysis. This list of chosen systems is explained in more detail in the analysis section for each wall system.

- Case 1a : Standard Construction Practice with 2x6 framing
- Case 1b : Standard Construction Practice with 2x4 framing
- Case 2a : Advanced Framing with 1" of XPS insulated sheathing
- Case 2b : Advanced Framing with 4" of XPS insulated sheathing
- Case 3 : Interior 2x3 horizontal strapping
- Case 4 : Double Stud
- Case 5 : Truss Wall
- Case 6 : Structural Insulated Panel Systems (SIPs)
- Case 7 : Insulated Concrete Forms (ICFs)
- Case 8a : Advanced Framing with low density (0.5 pcf) spray foam
- Case 8b : Advanced Framing with high density (2.0 pcf) spray foam
- Case 9: Hybrid system with high density (2.0 pcf) (Flash and Fill) spray foam and fibrous insulation
- Case 10: Double Stud wall with 2" of high density (2.0 pcf) spray foam and fibrous insulation
- Case 11: Exterior high density (2.0 pcf) (Offset Frame Wall) spray foam with fibrous cavity insulation
- Case 12: Exterior Insulation Finish System (EIFS)

2. ANALYSIS CRITERIA

A comparison matrix will be used to quantitatively compare all of the different wall system strategies. A value between 1 (poor performance) and 5 (excellent performance) will be assigned, upon review of the analysis, to each of the comparison criteria for each wall. An empty comparison matrix is shown below in Table 1 as an example.

Table 1: Criteria comparison matrix

	Thermal Control	Durability (wetting/drying)	Buildability	Cost	Material Use	Total
Criteria Weighting	1	1	1	1	1	
Case 1: Standard Construction						
Case 2: Advanced Framing with Insulated Shtg						
Case 3: Interior Strapping						
Case 4: Double Stud						
Case 5: Truss Wall						
Case 6: SIPs						
Case 7: ICF						
Case 8: Sprayfoam						
Case 9: Flash and Fill (2" spuf and cell.)						
Case10: Double stud with 2" spray foam and cell.						
Case 11: Offset Framing (ext. Spray foam insul.)						
Case 12: EIFS with fibrous fill in space						

The criteria scores will be summed for each test wall, and the walls with the highest scores are the preferred options assuming all of the comparison criteria are weighted equally. It is also possible to weight the different comparison criteria asymmetrically depending on the circumstances surrounding a particular wall design. The weightings for each wall will fall between 1 (least important) and 5 (most important). The weighting is multiplied by the comparison criteria score and added to other weighted values. An example of the weighted conclusion matrix will be shown in the Conclusions section.

One of the benefits of using a comparison matrix is that it allows a quantitative comparison when some of the criteria, such as cost may be poorly defined or highly variable. For example, even though the exact costs of different insulations may be uncertain, fiberglass batt insulation is always less expensive than low density (0.5 pcf) spray foam which is less expensive than high density (2.0 pcf) spray foam, so these systems can be ranked accordingly regardless of the actual costs.

2.1 Heat flow analysis

Two dimensional heat flow analysis was conducted for each test wall using Therm 5.2, a two-dimensional steady-state finite element software package developed by the Lawrence Berkeley National Laboratory at the University of California. Therm was used to calculate the thermal performance of each of the different proposed assemblies including thermal bridging effects.

In many cases, it is generally assumed that installing an R13 fiberglass batt into a 2x4 stud wall leads to wall performance of R13. This does not take into account thermal bridging of the wall framing including the studs, rim joist and top and bottom plates which allows heat to bypass the insulation decreasing the whole wall R-value. Therm can predict the impact of thermal bridging and determine a whole wall R-value that considers the rim joist, wall framing and top plate(s).

The effect of thermal bridging and different framing details requires a metric more complex than just a single R-value to allow for meaningful comparisons. Five R-values have been and are used in the building industry. Oak Ridge National Labs (ORNL) proposed a number of definitions in (Christian and Kosny 1995). We have found it useful to add some and extend their definitions.

1. **Installed Insulation R-value**

   This R-value is commonly referenced in building codes and used by industry. This is simply the R-value labeled on the product installed in the assembly.

2. **Center-of-Cavity R-value**

   The R-value at a line through an assembly that contains the most insulation, and the least framing, typically, the middle of a stud-bay in framed construction.

3. **Clear wall R-value**

   R-value of an assembly containing only insulation and minimum necessary framing materials at a clear section with no windows, corners, columns, architectural details, or interfaces with roofs, foundations or other walls.

4. **Whole-wall R-value**

   R-value for the whole opaque assembly including all additional structural elements (such as double studs), and typical enclosure interface details, including wall/wall (corners), wall /roof, wall/floor, wall/door, and wall/window connections.

5. **True R-value**

   The R-value of an enclosure assembly that includes all thermal bridging, air leakage, wind washing, convective loops, radiation enhancements, thermal and hygric mass, and installation defects.

Each of these measures is progressively more realistic. The True R-value is very difficult to measure without field samples.

The whole-wall R-value will be approximated in this analysis. To accurately calculate this whole-wall R-value, the wall in question was divided into three sections, modeled individually, and then the results were combined with a weighted average.

The R-value of the wall section was simulated in plan view to best represent the thermal bridging effects of wall studs as shown in Figure 1. This section is similar to a clear-wall R-value except that the studs are placed closer together to more accurately represent actual numbers of wood framing elements used in real wall systems. The height of the wall section for simulation purposes is 92 inches.

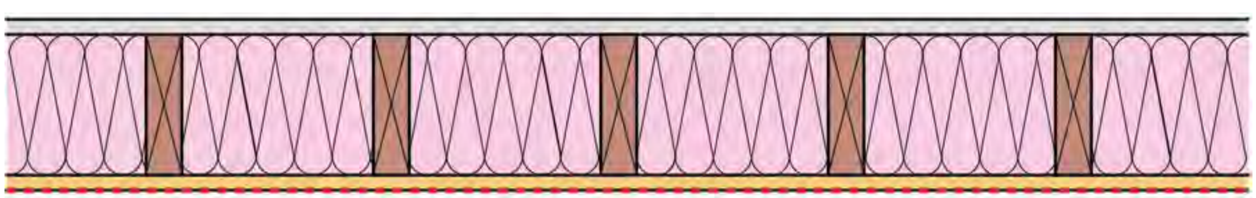

Figure 1 : Plan view of wall section for Therm simulation

The top plate was simulated in section view to assess the importance of the thermal bridging of the top plate(s). This section was eight inches in height since the thermal effect of the top plate will influence the effectiveness of the cavity insulation in its vicinity. The R-value of this detail was calculated over the entire height as indicated by the red dashed line in Figure 2.

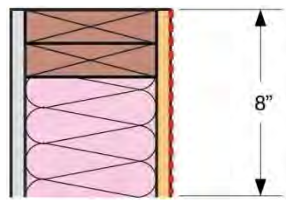

Figure 2: Top plate simulation with 8” of wall

The rim joist was also simulated in a vertical section to take into account the thermal bridging effects of the bottom plate, sill plate, floor sheathing and rim joist. It was simulated with eight inches of wall above the floor sheathing to take into account any changes in the insulation caused by thermal bridging effects.

The concrete foundation was included beneath the rim joist to determine the effects of the interface between the foundation and wood framing, but the concrete was not included in the R-value calculation as indicated by the red dashed line in Figure 3.

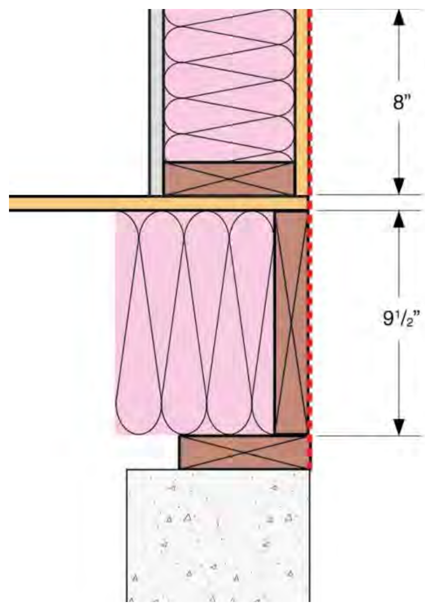

Figure 3 : Rim joist simulation with 8" of wall

Although Therm is a two-dimensional modeling software it was used to model three-dimensional geometries. For example, at the rim joist, there are floor joists connected to the rim joist alternating with pockets of insulation. When this is drawn and modeled in plan view (Figure 4), the effective R-value of just this section through the assembly can be determined.

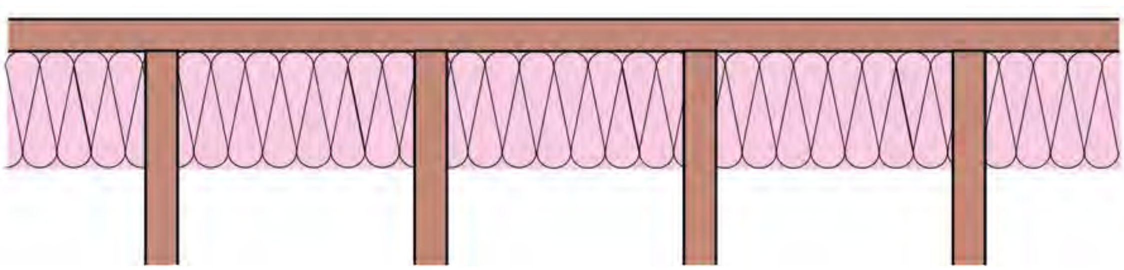

Figure 4 : Plan section of rim joist, floor joists, and fiberglass batt insulation

A fictitious material is then made in the Therm library that has the effective thermal properties of the insulation and floor joists and used in the section profile for modeling of the rim joist system (shown in red in Figure 3).

Once the R-values are calculated for all three sections of a wall system, The Whole Wall R-value is calculated by taking the weighted average of the individual components as shown in the equation below. The total wall height from the bottom plate to the top plate is nine feet.

$$\text{Total wall R-value} = \text{R-value top plate x } \frac{\text{height of top plate}}{\text{overall wall height}} + \text{R-value of rim joist x } \frac{\text{height of rim joist}}{\text{overall wall height}} +$$

$$\text{R-value of wall section x } \frac{\hbar eig\hbar t\ of\ wall\ section}{\text{overall wall height}}$$

One drawback of Therm is that it cannot accurately represent air leakage and insulation installation defects, both of which can significantly lower the effective R-value of the assembly by bypassing the insulation in the wall system. There are four main ways in which air leakage affects interact with the enclosure as shown in Figure 5.

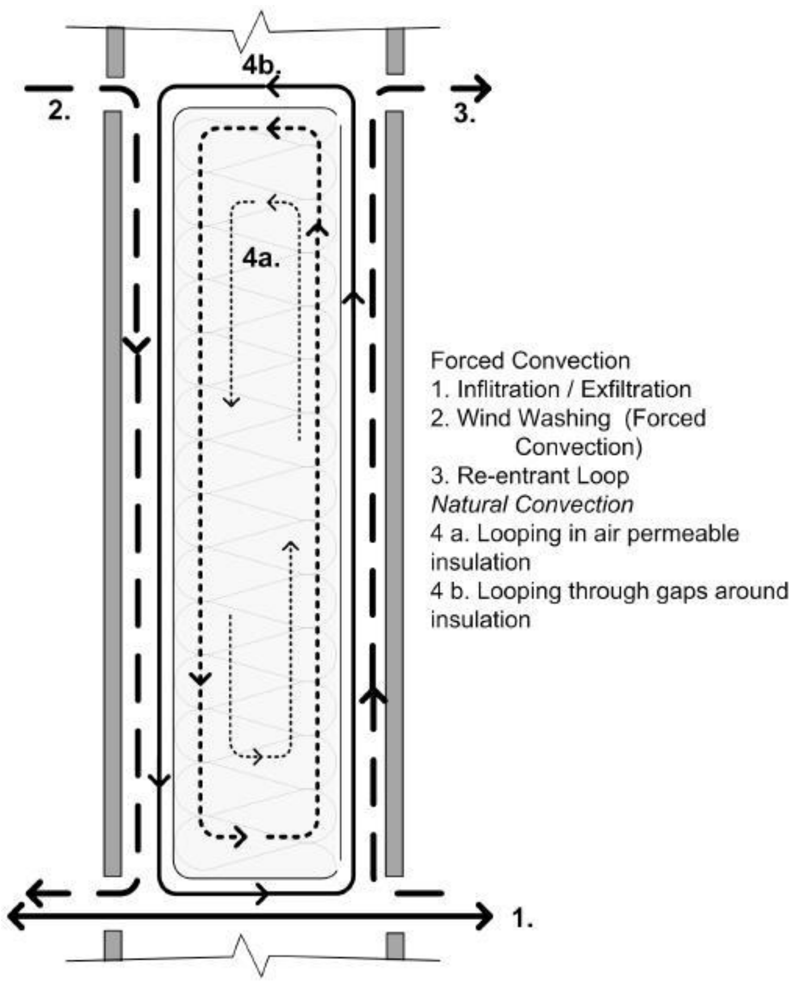

Figure 5 : Common Convective Heat Flow Paths in Enclosures

One of the most common areas for air leakage is at the rim joist where fiberglass batts are often stuffed into the cavities between the ceiling joists. In houses that are constructed using this method it is quite common to feel air leakage through the assembly at the rim joist bypassing the insulation even without imposing a pressure difference across the enclosure. Air tightness of the building enclosure has begun to improve in cold climates for the most part to address occupancy comfort issues and contractor call-backs.

Both cellulose and fiberglass batt insulation have similar R-values per inch according to ASTM testing standards, but in practice, standard installation for both fiberglass batt and cellulose generally result in higher installed R-values for cellulose compared to fiberglass batt. Fiberglass batts are almost always installed with air gaps against either the drywall or exterior sheathing and fiberglass installers are generally not careful installing fiberglass batts, leading to air gaps around plumbing, electrical and other obstacles in the stud space. These air gaps can lead to convective looping in the stud space as well as poorly insulated locations resulting in cold spots around obstacles that could increase the risk of moisture condensation.

Cellulose installation is blown into place, and fills the entire stud space between the exterior sheathing and drywall, around all obstacles without leaving air gaps. Cellulose has also been shown to have better convection suppression resulting in less convective looping and, in some studies, tighter building enclosures. Neither cellulose nor fiberglass batt is an air barrier, so an air barrier should always be used with either insulation.

Since air leakage cannot be simulated using Therm, the increased convective looping and air movement around poorly installed batt insulation relative to cellulose insulation, and to a lesser extent blown-in or sprayed fiberglass cannot be captured numerically in this study. Also, the convection suppression through the cellulose insulation relative the fiberglass batt insulation cannot be fully appreciated using this analysis.

All of the Therm analysis were conducted with an interior temperature of 20°C (68°F) and an exterior temperature of -20°C (-4°F) so the results could be compared. Because the R-value is a weak function of the temperature difference across the enclosure, the results may vary slightly for different temperatures.

A list of some of the most common materials and their respective conductivities used in the two dimensional Therm analysis are shown in Table 2. Where there was some discrepancy in the choice of conductivity that should be used for modeling, values from the ASHRAE Handbook of Fundamentals were selected.

Film conductance values of 8.3 W/m^{2}K for the interior surface and 34.0 W/m^{2}K for the exterior surface were used for all Therm simulations

Table 2 : Conductivity values used for two dimensional heat flow analysis

Enclosure Component	Thermal Conductivity k [W/mK]	R-value per inch [hr·°F·ft^2/Btu]
R8 Fiberglass Batt (2.5")	0.045	3.1
R13 Fiberglass Batt (3.5")	0.039	3.7
R19 Fiberglass Batt (5.5")	0.042	3.4
Extruded Polystyrene (XPS)	0.029	4.9
Expanded Polystyrene (EPS)	0.038	3.7
Framing lumber	0.140	1.0
Cellulose Insulation	0.040	3.5
0.5 pcf spray foam	0.037	3.8
2.0 pcf spray foam	0.025	5.7
OSB	0.140	1.0

One of the considerations for thermal modeling was the number of framing components in the wall system. This is usually measured as using the "framing factor", or percentage of a wall cross-sectional area that is comprised of framing elements. For example, a 2x4 stud spacing in a typical wall system is sixteen inches (405 mm) on centre. Modeling the wall with a stud spacing of 16 inches o.c. (Figure 6) results in a framing factor of approximately 9%. This method of analysis ignores many of the framing members present in real walls including double studs at windows, partition walls, corners, etc.

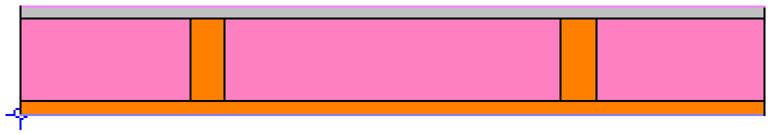

Figure 6 : Typical framing 16" o.c. - 9% framing factor

Field studies have shown that the actual average framing factor, using 16" o.c. framing, including studs, bottom plate and top plates throughout an entire house are closer to 23-25% (Carpenter and Schumacher 2003). Modeling was conducted to investigate the impact on effective R-value for a wall system with 23% (Figure 7) framing factor and with 9% framing factor. It was found that the Clear Wall R-value of a wall section insulated with R13 fiberglass batt decreased from R12.6 to R10.1 when a more realistic 25% framing factor was used. This results in a Whole Wall R-value decrease from R12 to R10 when the more realistic 25% framing factor was used. The reason that neither wall section achieved a Clear wall or Whole Wall R13 is because of the thermal bridging effects of the studs, one of the underlying issues in using Installed Insulation R-values to describe enclosure systems.

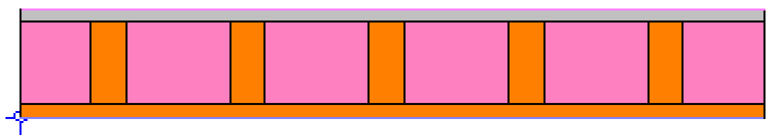

Figure 7 : Actual average framing factor of 23% in standard construction

Most of the framed walls in this analysis were proposed with advanced framing techniques (also described as Optimum Value Engineering, OVE) that include 2x6 framing, 24" o.c., and single top plates. Field studies have also been conducted on advanced framed walls, and it was found that the average framing factor is approximately 16%. For comparison purposes, all of the standard wood framed wall sections were simulated with a framing factor of 25% and advanced framed walls were modeled with 16% framing factor.

Table 3 shows all of the Whole Wall R-values calculated using Therm simulations. The thermal performance is further discussed for each wall system in the following sections.

Table 3 : R-values for analyzed wall systems

Case	Description	Whole Wall R-value	Rim Joist	Clear Wall R-value	Top Plate	Framing Fraction
1a	2x6 AF, 24"oc, R19FG + OSB	**15.2**	12.3	16.1	12.5	16%
1aii	2x6, 16"oc, R19FG + OSB (25%ff)	**13.7**	12.3	14.1	12.5	25%
1b	2x4 AF, 24"oc, R13FG + OSB	**11.1**	9.8	11.5	9.8	16%
1bii	2x4, 16"oc, R13FG + OSB (25%ff)	**10.0**	9.8	10.1	9.8	25%
2a	2x6 AF, 24"oc R19FG + 1" R5 XPS	**20.2**	18.5	20.6	20.3	16%
2b	2x6 AF, 24"oc R19FG + 4" R20 XPS	**34.5**	29.0	35.6	35.4	16%
3	2x6 AF, 24"oc, 2x3 R19+R8 FG	**21.5**	13.4	23.5	18.4	16%
4	Double stud wall 9.5" R34 cellulose	**30.1**	14.4	33.5	28.8	
5	Truss wall 12" R43 cellulose	**36.5**	18.6	40.5	34.4	
6a	SIPs (3.5" EPS)	**14.1**	12.3	14.5	10.6	
6b	SIPs (11.25" EPS)	**36.2**	14	41.6	28.2	
7a	ICF - 8" foam ICF (4" EPS)	**16.4**		16.4		
7b	ICF - 15" foam ICF (5" EPS)	**20.6**		20.6		
7c	ICF - 14" cement woodfiber ICF with Rockwool	**17.4**		17.4		
8a	2x6 AF, 24" o.c., 5" 2 pcf R29 SPF, OSB	**19.1**	13.6	20.3	19.5	16%
8b	2x6 AF, 24" o.c., 5.5" R21 0.5 pcf SPF, OSB	**16.5**	13.1	17.2	16.6	16%
9	2x6 AF, 24"oc, 2" SPF and 3.5" cellulose	**17.5**	13.2	18.4	17.7	16%
10	Double stud with 2" 2.0 pcf foam, 7.5" cell.	**32.4**	15.9	36.2	28.5	
11	Offset frame wall with ext. spray foam	**37.1**	18.8	40.6	41.9	16%
12	2x6 AF, 24"oc, EIFS - 4" EPS	**30.1**	23.8	31.4	31.1	16%

*AF - Advanced Framing

2.2 Hygrothermal Analysis

Hygrothermal analysis is the combined analysis of heat and moisture movement. For this research, WUFI® from the Fraunhofer Institut Bauphysik was used to determine the hygrothermal performance of the chosen wall systems.

WUFI® was used only to investigate wood framed walls. ICF and SIPs walls are not subject to the same moisture-related failure mechanisms as wood framed walls and hence, to model with WUFI® would provide little useful information.

Vinyl siding was chosen as the cladding system for the analysis as it is the most widely used residential cladding system in North America, and it can be found in almost any geographic area.

Minneapolis MN was chosen as the climate to compare all of the chosen wall systems. Minneapolis is in DOE climate zone 6, which experiences cold wintertime temperatures as well as some warm humid summer temperatures.

A Class I or II vapor retarder is required according to the International Residential Building Code (IRC) on the interior of the framing in zones 5,6,7,8 and marine 4. This will control vapor condensation on the sheathing in the winter months as shown in Figure 9. The RH at the sheathing did not reach elevated levels in Case 1 (framed walls with OSB sheathing) with the Class I vapor retarder in WUFI®. There are some exceptions to the interior vapor control layer if a sufficient amount of insulation and vapor control is installed on the exterior.

Often times, the 6-mil polyethylene vapor barrier is also used as the air barrier. This is very difficult to detail correctly, and because it may not be air tight, there is a considerable risk to air leakage condensation on the sheathing should interior air leak into the enclosure.

WUFI® was used to simulate three different scenarios which can cause performance problems for wall systems; wintertime condensation, summer inward vapor drives, and simulated drying following a wetting event.

2.2.1. Moisture Balance

Assessing moisture related durability risks involves three different moisture processes; wetting, drying and moisture redistribution. These three processes in combination with the safe storage capacity will determine the risk of moisture damage to a building enclosure assembly (Figure 8).

Wetting of the enclosure is most often caused by rain, air leakage condensation, vapour condensation, plumbing leaks and built in construction moisture. Minimizing these sources with good design details for shedding rain, air tightness, and vapour control will help decrease the risk of moisture related durability failure.

Drying is important since nearly all building enclosures will experience wetting at some point. Assemblies that can dry to both the interior and exterior generally have an advantage and can manage more frequent wettings.

The safe storage capacity of an individual material or enclosure system is fundamental to good building design. Over the last 50 years, there have been changes to buildings that decrease the safe storage capacity and increase the risk of moisture related durability. Four of these changes are listed below (Lstiburek 2007).

1. Increasing the thermal resistance of the building enclosure
2. Decreasing the permeability of the linings that we put on the interior and exterior of the enclosure
3. Increasing the mould and water sensitivity of the building materials
4. Decreasing the buildings ability to store and redistribute moisture.

These changes to building enclosures and materials increase the need for good enclosure design with water management details and maximizing the drying potential. It is rarely economical to build an enclosure with no risk of wetting but managing the risk is important. In any building enclosure, building materials should be chosen based on moisture tolerance that correlate to the risk of moisture in the enclosure. In all cases drying should be maximized, and attention to good design details should be used.

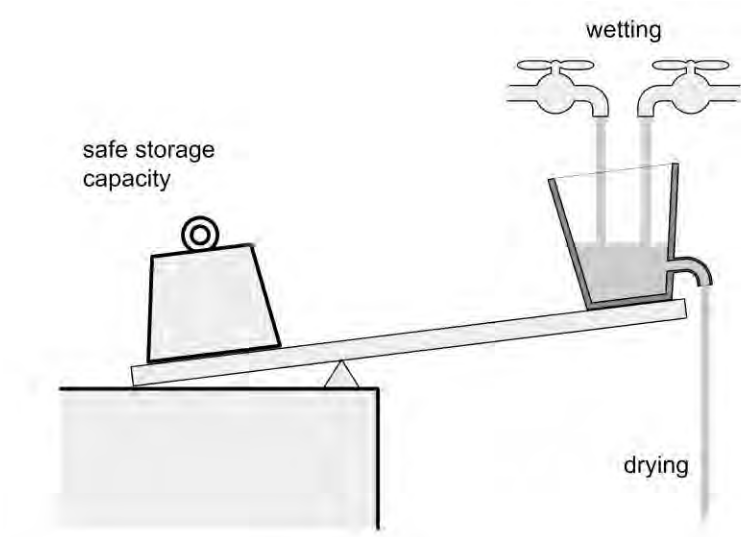

Figure 8 : Moisture balance

2.2.2. Wintertime Condensation

Wintertime diffusion and air leakage condensation potential was determined for each case. The diffusion condensation potential was determined by analyzing the relative humidity at the interior surface of the sheathing (or other condensation plane) during the cold winter months. The interior relative humidity for these simulations was sinusoidal condition varying from a minimum of 30% in the winter to a maximum of 60% in the summer. The interior relative humidity is strongly correlated to occupancy behavior and ventilation strategies. Typically, the relative humidity in a cold climate will decrease to between 20% and 30% in the winter months. In extremely cold climates this could decrease even further. If humidification is used, or there is inadequate ventilation in a relatively airtight enclosure, the RH could increase to 40 or 50% which increases the risks significantly.

In the 2007 supplement to the International residential code, three classes of vapor control were defined for enclosure systems (1 US perm = 57.4 ng/(s·m²·Pa))

- Class I: 0.1 perm or less (eg. sheet polyethylene)
- Class II: 0.1 < perm ≤ 1.0 perm (eg. kraft faced fiberglass batts , some vapor barrier paints)
- Class III: 1.0 < perm ≤ 10 perm (latex paint)

Class I or II vapor retarders are required on the interior side of framed walls in Zones 5, 6, 7, 8 and marine 4 (IRC N1102.5). Under some conditions, such as vented claddings or insulated sheathings, a Class III vapor retarder is allowed by the code (IRC Table N1102.5.1).

Figure 9 shows a comparison of the relative humidity caused by vapor diffusion at the sheathing for Case 1, standard construction, and Case 2, advanced framing with insulated sheathing. A polyethylene vapor barrier is installed on the interior of the framing in Case 1, vapor barrier paint is used for Case 2 with 1" of XPS insulated sheathing, and latex paint is used for Case 2 with 4" of XPS insulated sheathing. Table 4 shows the vapor control strategies and permeance values for all four walls compared in Figure 9.

Table 4 : Vapor control strategies and permeance values for Case 1 and 2

Case	Description	Vapor Control	Permeance	
			[US perms]	[ng/(s•m²•Pa)
1a	2x6 AF, 24"oc, R19FG + OSB	poly	0.07	4.0
1b	2x4, 16"oc, R13FG + OSB	poly	0.07	4.0
2a	2x6 AF, 24"oc R19FG + 1" R5 XPS	vapor retarder paint	1.0	57.8
2b	2x6 AF, 24"oc R19FG + 4" R20 XPS	latex paint	10.7	616.7

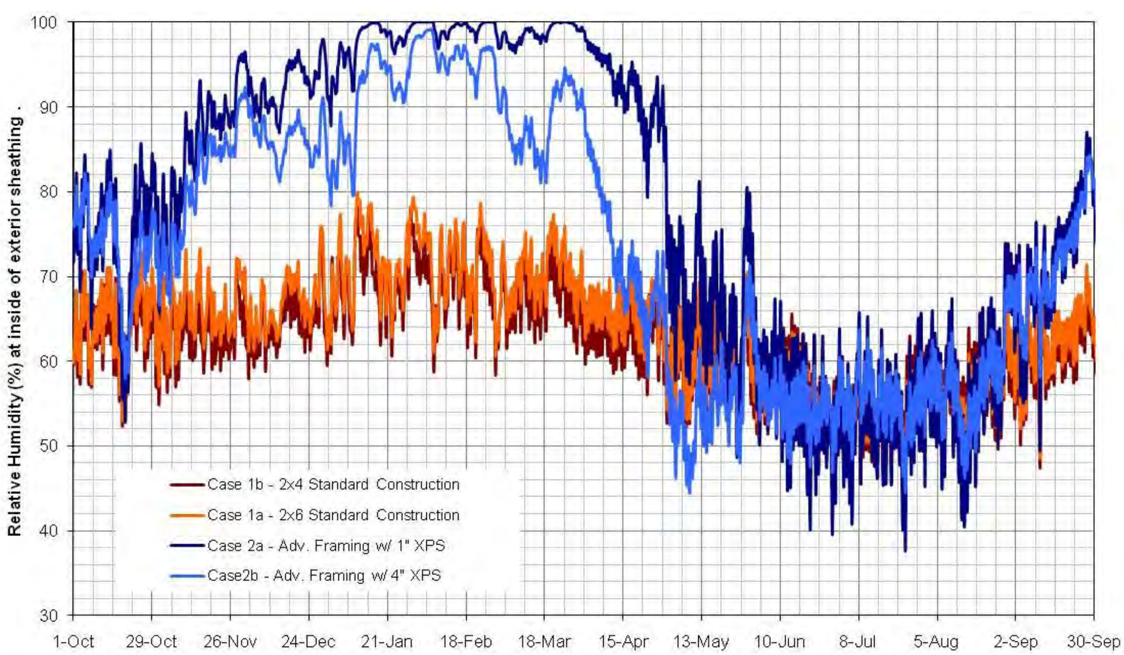

Figure 9 : Winter time sheathing relative humidity for Case 1 and Case 2

The advanced framing wall (Case 2) with 1" of XPS was modeled with the minimum amount of vapor control required (Class II vapor retarder - 1 perm or 57 ng/Pa•s•m2) according to the IRC. The elevated moisture levels during the winter months are only a small concern, since the XPS is not moisture sensitive, and temperatures are quite low in the winter months, minimizing moisture related risks. The advanced framing wall with 4" of XPS insulated sheathing does not require any extra vapor control layers according to the IRC because it qualifies as having more than R-11.25 insulated exterior sheathing over 2x6 wood framing.

Figure 10 shows the potential for air leakage condensation for Case 1 and Case 2. This analysis shows the dewpoint of the interior air and the temperature of the sheathing for both Case 1 and Case 2. When the temperature of the sheathing falls below the interior dewpoint line (black line) the potential for air leakage condensation exists. The severity of condensation increases the further below the dewpoint line the sheathing temperature falls and the length of time the sheathing temperature is below the interior air dewpoint line, since drying is minimal during periods of condensation.

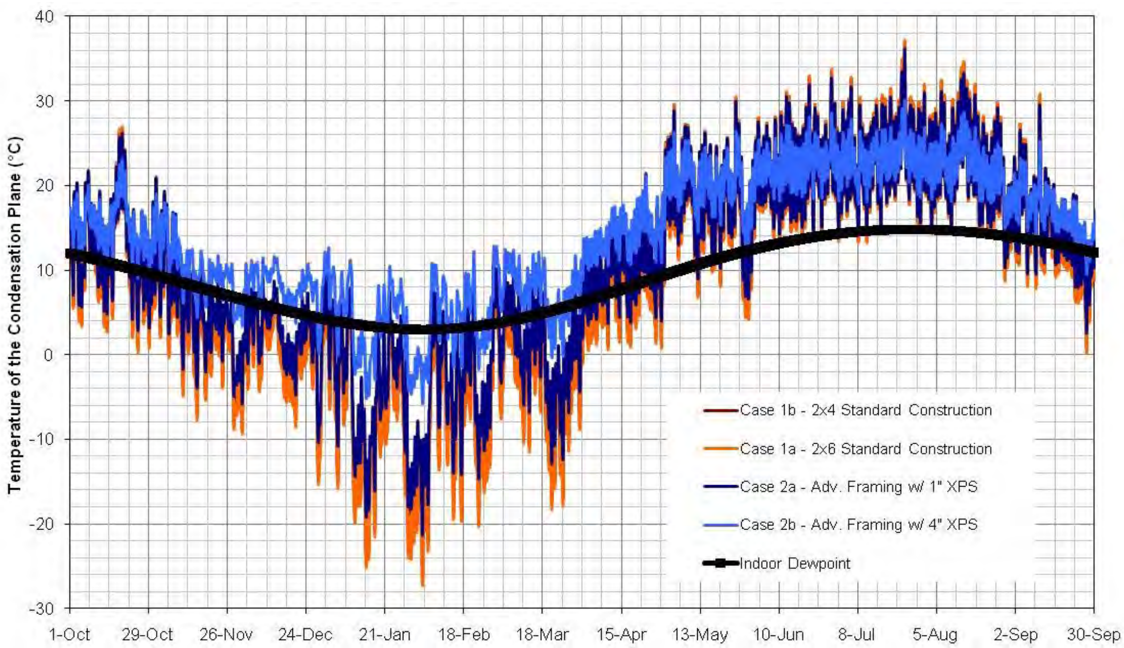

Figure 10 : Winter air leakage condensation potential for Case 1 and Case 2

The risk of air leakage condensation is greatest on the standard construction walls, and slightly improved on the advanced framing wall with 1" of XPS. The wall with 4" of insulated sheathing has the least risk of moisture related durability issues from air leakage condensation because of the short periods of time the interior face of the sheathing is below the dewpoint. When the hours of potential condensation are added together over the entire year, Case 1 with 2x4 construction and 2x6 construction have approximately 4400 and 4500 hours respectively of potential condensation. Case 2 with 1" of insulated sheathing experiences approximately 3800 hours of potential condensation and Case 2 with 4" of insulated sheathing only experiences 1200 hours of potential air leakage condensation.

One method of improving the risk of air leakage condensation in standard construction is by using a hybrid wall system (Case 9). In our analysis a hybrid wall system consists of advanced framing (2x6 24"oc) with OSB sheathing and 2" of high density (2.0 pcf) spray foam installed against the interior of the sheathing. This spray foam can be an excellent air barrier if installed properly and because it is vapor semi-impermeable, the temperature of the condensation plane increases (Figure 11). Two inches of high density spray foam was chosen because it is reported as being the maximum thickness that can be sprayed in one pass on any surface. This hybrid wall has approximately the same amount of condensation potential as Case 2 with 4" of exterior XPS and will be significantly less expensive than Case 8 with 5" of high density spray foam. Unfortunately, it also has much less R-value, and still suffers from thermal bridging.

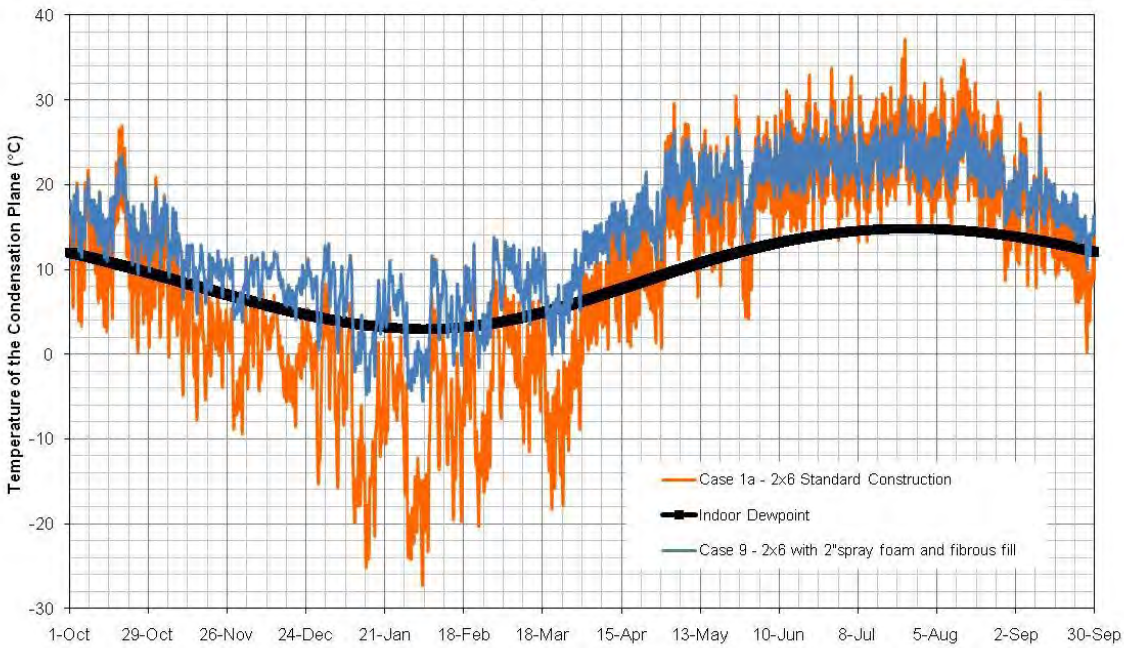

Figure 11 : Winter air leakage condensation potential for Case 1 and Case 9

The winter time sheathing relative humidities for Cases 3, 4, and 5 without air leakage are shown in Figure 12. Constructing these walls with a Class I - 6-mil polyethylene vapor control layer, there is no risk to moisture related issues on the sheathing from vapor diffusion in the winter.

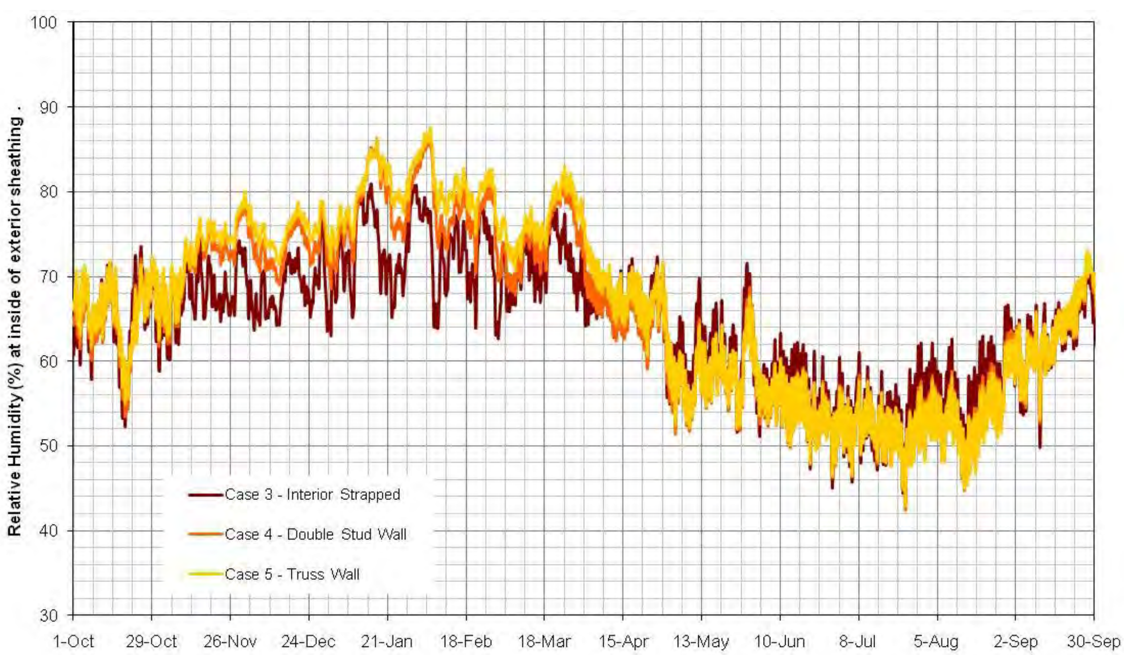

Figure 12 : Winter time sheathing relative humidity for Case 3, Case 4, and Case 5

Winter time air leakage condensation potential for Cases 3, 4, and 5 are shown in Figure 13. The sheathing temperatures of all three of the walls spend a significant portion of the year below the dew point of the interior air because of the increased thermal resistance of the wall system. This means that considerable care must be given to all air tightness details, or there will be a high risk of moisture related durability issues from air leakage.

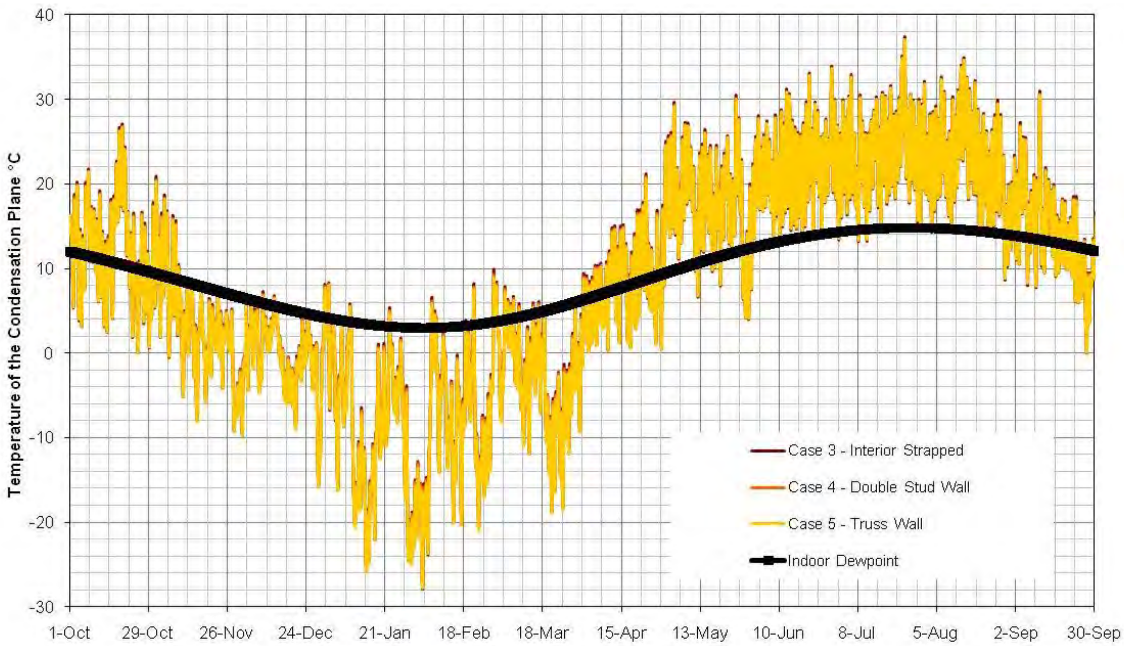

Figure 13 : Winter air leakage condensation potential for Case 3, Case 4, and Case 5

Increasing the temperature of the condensation plane can be done by adding spray foam to the interior surface of the exterior sheathing. Case 10 is a double stud wall with 2" of high density foam sprayed against the sheathing from the interior. Increased vapor resistant insulation raises the temperature of both the diffusion and air leakage condensation planes. Analysis showed that the condensation plane temperature was increased throughout the winter months but that there was still a risk of condensation related damage to the enclosure if air leakage occurs. Figure 14 shows that in Minneapolis (DOE climate zone 6) 2" of high density spray foam may not be enough to reduce the potential condensation risk to a satisfactory level.

Case 10 with 2" of spray foam spends considerably more time below the interior dewpoint compared to Case 9 (hybrid wall) which also has 2" of high density spray foam. The difference in condensation potential is caused by the ratio of the insulation amounts on the interior and exterior of the condensation plane. The remaining 3.5" of the stud space can be filled with an R19 FG batt or cellulose. The increased convection suppression of cellulose insulation is not as critical to this enclosure assembly because of the air tightness of the two inches of spray foam insulation, but will still do a better job of reducing gaps around services, and other places that fiberglass batt is prone to convective looping. The increased thermal resistance of the double stud wall ensures that the condensation plane is kept much cooler. This is a critical consideration to designing a wall enclosure for a specific climate. The double stud walls with 2" of high density spray foam would likely work successfully with little risk in a Climate zone 6 or lower. Alternately, open cell foam could be used to fill the double stud wall although a vapour retarding coating would be needed in cold climates. A mid-density foam, with moderate vapor permeance could also be used as a full fill.

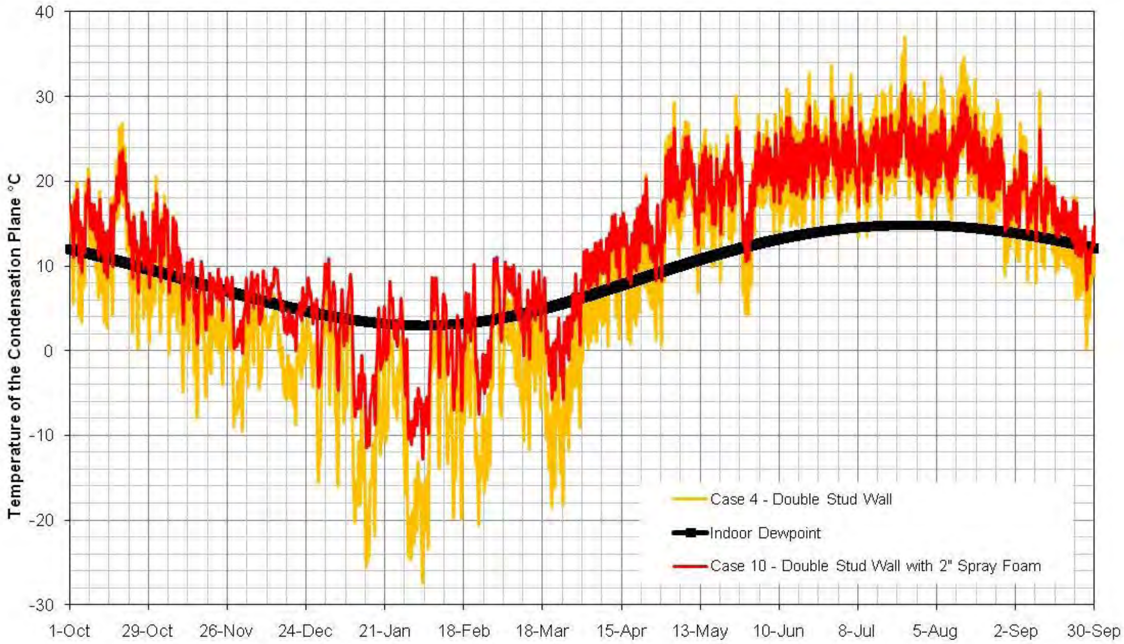

Figure 14 : Winter air leakage condensation potential for Case 4 and Case 10

One wall system becoming more popular in cold climates is a wall constructed with exterior foam insulation, sometimes referred to as an Offset frame wall. This has many advantages over traditional wall construction techniques, and can be used for both new construction and retrofits. Figure 15 shows high density spray foam being installed over the existing exterior sheathing during a retrofit. The surface of the foam becomes the drainage plane, air barrier and vapor barrier of the enclosure. Cladding can be attached directly to the exterior framing that tie back to the framing of the house, and are very stiff and supportive once the foam has been installed.

In this case, the exterior framing was attached with 8" spikes using a spacer to ensure that the exterior framing was the correct distance from the sheathing. Because of the strength and rigidity of the high density spray foam insulation, no additional support is needed for fiber cement siding.

Figure 15 : Installation of high density spray foam in an Offset Framed Wall in a cold climate

In the case of new construction, wood sheathing may not be necessary on the exterior of the structural wall framing to support the spray foam. Removing the sheathing would decrease the cost and work considerably. Other membranes, such as housewraps may be used to support the foam during installation, but more analysis and research may be required before installing spray foam directly on housewraps.

Analysis of the possible wintertime condensation for a Truss Wall constructed with 12" cellulose insulation (Case 5) and constructed with 4.5" of exterior high density foam and 5.5" of fibrous fill in the stud cavity (Case 11) is shown in Figure 16. The sheathing (or foam supporting membrane) never reaches the interior dew point temperature in DOE climate zone 6. In a very extreme cold climate, more foam could be added to the outside or the stud space insulation could be removed which would also decrease the condensation potential.

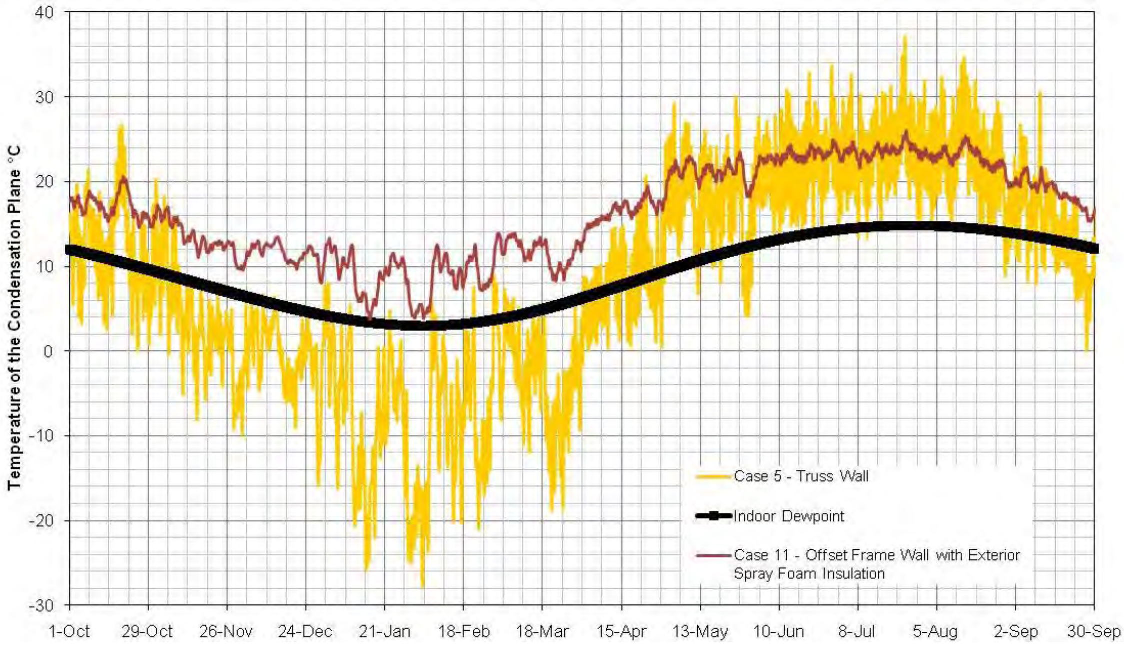

Figure 16 : Winter time air leakage condensation potential for Case 5 and Case 11

There are other advantages to an offset frame wall with exterior foam besides the decreased risk for condensation potential in the enclosure. A house can be dried in very quickly with exterior spray foam insulation, which means that the house is weather proof against rain and snow. This is very important in arctic regions with a very short construction season. Once the foam is installed on the exterior, interior work such as insulation, drywall and finishes can be finished as desired.

There were complaints from the remote areas of Northern Canada (according to the NRC) that when foam board was shipped to be used as exterior insulation, it always arrived broken, which is why they preferred not to use it. High density spray foam is shipped as two liquid components that are combined during the foam installation process. Many more board feet of spray foam can be shipped on the same truck than the equivalent board feet of EPS or XPS board foam insulation. This application is ideal for remote climates.

The sheathing relative humidities for Case 8, the spray foam wall, is shown below in Figure 17. The sheathing relative humidities with high density foam, and low density foam with a vapor barrier show no risks of moisture related issues caused by vapor diffusion. The wall system with low density foam and no vapor control layer may experience some risk to moisture related durability issues depending on the climate.

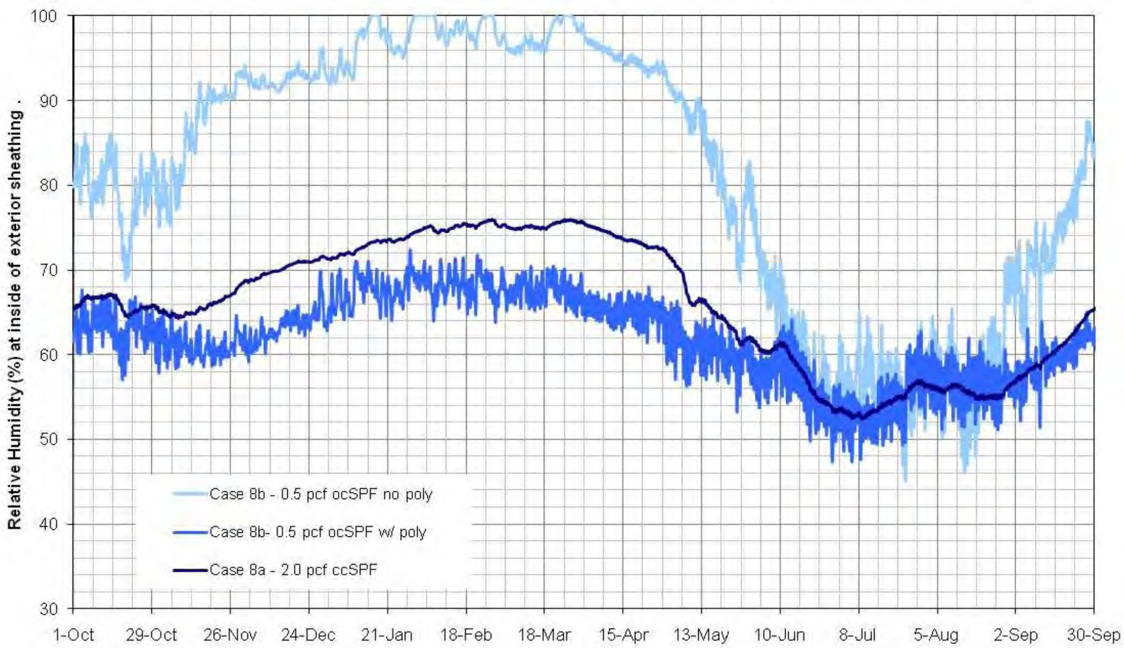

Figure 17 : Winter time sheathing relative humidity for Case 8

A vapor control layer should be used with low-density foam in climate zone 6 based on this hygrothermal analysis. More analysis is required to determine what level of vapor control is required to minimize risk. It may be possible to use a Class II vapor barrier (IBC 2007 supplement). In climate zones warmer than climate zone 6, it may be possible to use 0.5 pcf spray foam with much less risk of moisture related durability issues. More analysis should be conducted on this specific case in different climate zones before design recommendations can be made.

Air leakage condensation potential of Case 8 is shown in Figure 18. Because both low and high density spray foams form an air barrier when installed properly, interior air will not pass the interior surface of the foam. There is no risk of any moisture related durability issues in the walls insulated with spray foam in this analysis.

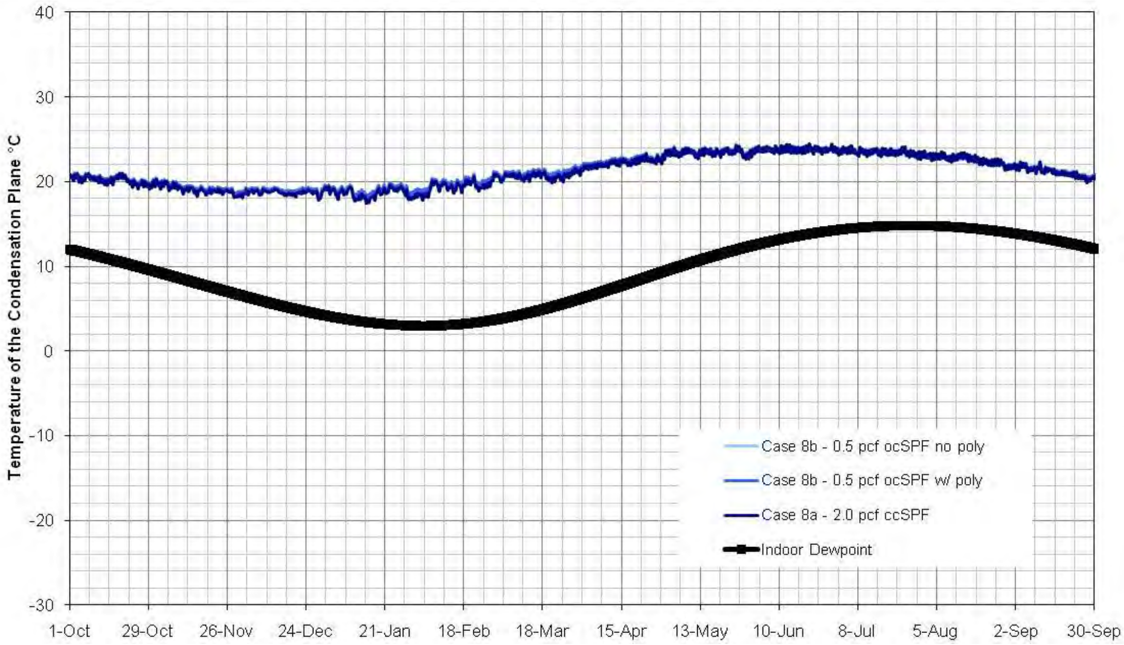

Figure 18 : Winter air leakage condensation potential for Case 8

2.2.3. Summer Inward Vapor Drives

Summer inward vapor drives occur when moisture stored in the cladding is heated and driven into the enclosure by a large vapor pressure gradient. Both field testing, and modeling have shown that assemblies that have reservoir claddings such as stucco, adhered stone veneer and concrete, that absorb and store water, are much more susceptible to summer inward vapor drives. During field testing, moisture has been observed condensing on the interior polyethylene vapor barrier and may run down the polyethylene to the bottom plate if enough water condenses.

Inward vapor drives were compared in this analysis using vinyl siding as the cladding. This type of cladding does not stress the wall systems from an inward vapor drive perspective but still gives a basis for comparison of the different wall systems. More analysis should be done in the future to more accurately predict the amount of inward vapor drive in cold climates using reservoir claddings (masonry, stucco, adhered stone etc.).

Analysis was conducted by graphing the relative humidity at the vapor barrier, or drywall surface in the absence of a vapor barrier, between the months of May and September.

Figure 19 shows the comparison of Case 1, standard construction, Case 2, advanced framing with insulated sheathing, and Case 9 hybrid wall. Standard construction experiences higher relative humidities at peak times because of the polyethylene vapor barrier, and lack of vapor control on the exterior. The advanced framing with insulated sheathing walls have some vapor control at the exterior surface of the wall system, and no polyethylene vapor barrier to limit drying to the interior. The advanced framing wall with 1" of XPS has a slightly elevated relative humidity when compared to the wall with 4" of XPS because of the 1 perm (57 ng/Pa•s•m2) paint layer on the drywall slowing drying to the interior, and less vapor control at the exterior surface. The hybrid wall performs very similarly to the advanced framing with 4" of XPS

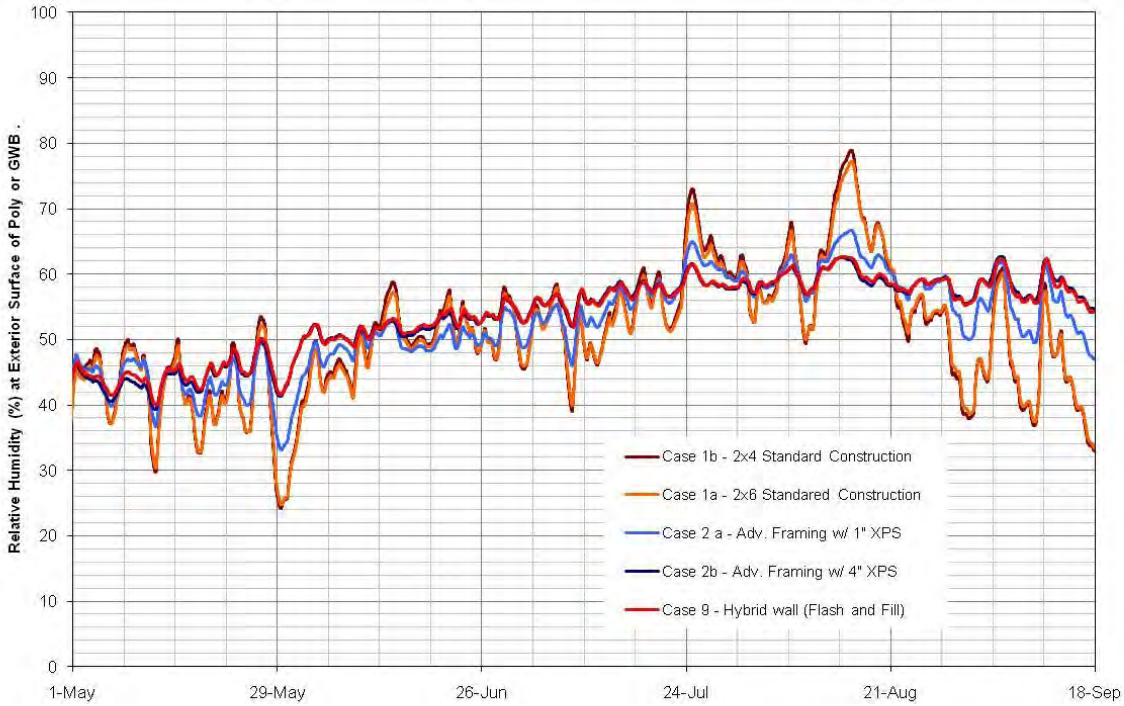

Figure 19 : Inward vapor drive relative humidity of poly or GWB for Case 1, Case 2, and Case 9

Inward vapor drives of Cases 3, 4, and 5(Figure 20) show there is very little performance difference between the test walls, and none of the walls experience any moisture related durability issues caused by inward vapor drives. Case 4, double stud construction, and Case 5, truss wall, experience slightly lower relative humidities because of the moisture buffering effect of the cellulose insulation.

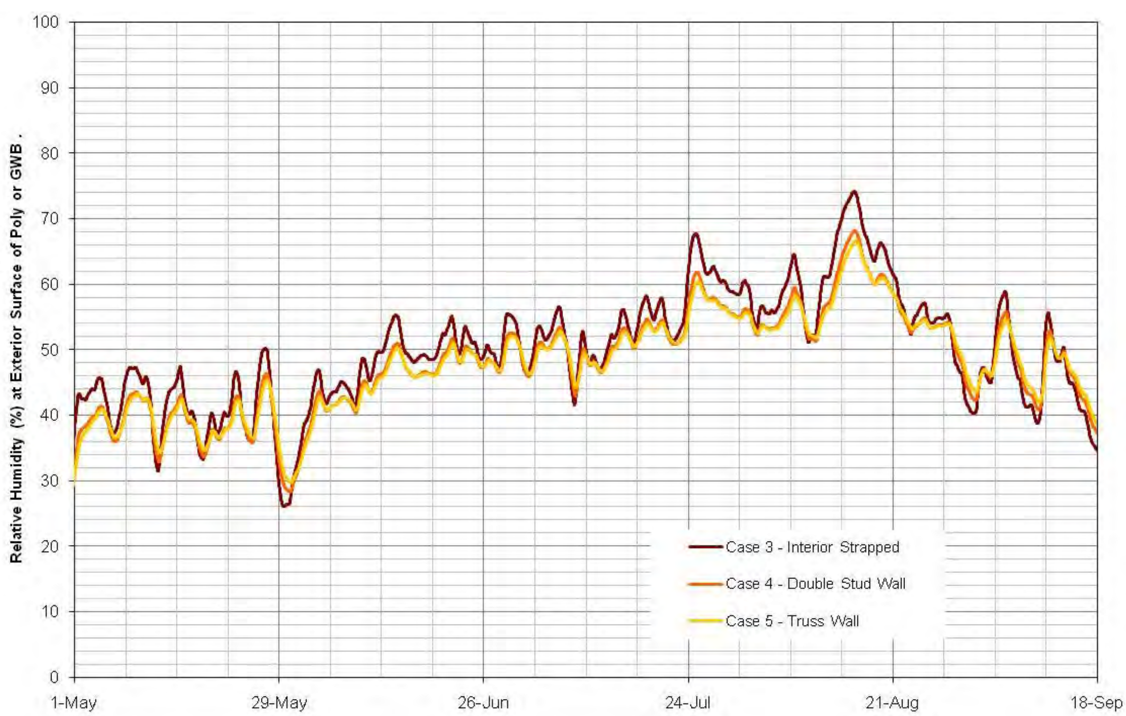

Figure 20 : Inward vapor drive relative humidity of poly or GWB for Case 3, Case 4, and Case 5

A double stud wall with 2" of high density foam (Case 10) with and without an interior vapor barrier was compared to Case 4, a double stud wall filled with cellulose in Figure 21. There was an improvement in performance when two inches of foam were used on the exterior and an interior vapor barrier was installed. The foam restricted the inward vapor drive, and the poly controlled vapor from the interior environment. Although this wall showed lower relative humidities with respect to summer inward vapor drives, it is never recommended to have a high level of vapor control on both sides of the wall system. This substantially increases the risk of moisture related durability issues, should any water get into the wall cavity. This could be improved by adding more foam to the exterior surface, and less vapor control to the interior, with a Class II or III vapor control layer depending on climate. More specific analysis is required before design recommendations can be determined.

Case 10 without an interior vapor barrier experiences slightly elevated relative humidity levels, likely due to the interior relative humidity. In a more severe testing condition for summer inward vapor drives, this wall would likely have lower relative humidity to Case 4, the standard double stud wall.

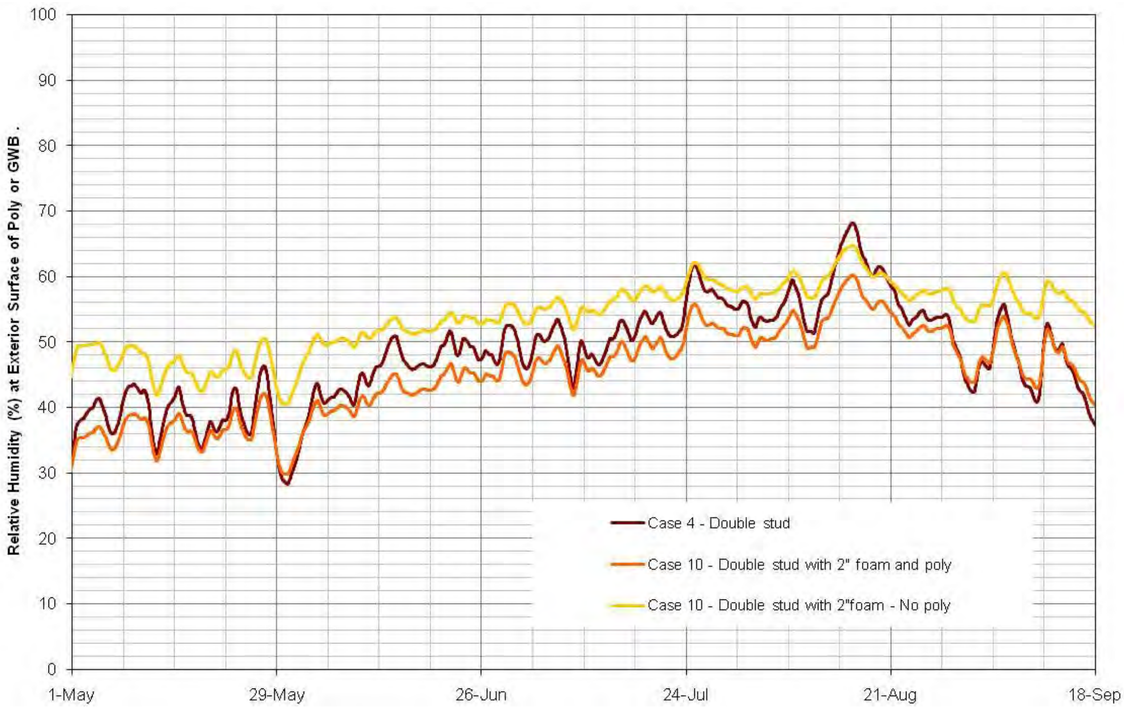

Figure 21 : Inward vapor drive relative humidity of poly or GWB for Case 4, and Case 10

Analysis of inward vapor drives on the spray foam walls shows that the walls without polyethylene vapor barrier dry adequately to the interior, but the low density spray foam wall with poly has elevated relative humidities because of the vapor control layer (Figure 22).

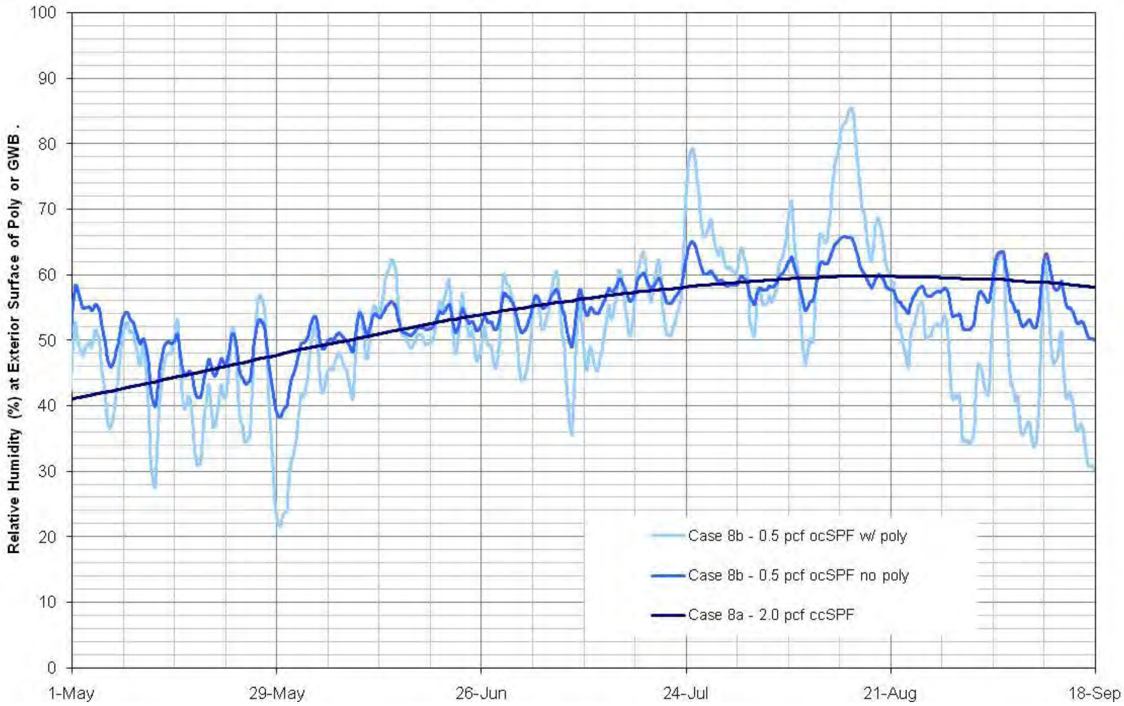

Figure 22 : Inward vapor drive relative humidity of poly or GWB for Case 8

The inward vapor drive for the offset frame wall (Case 11) with exterior foam insulation was compared to Case 3, a truss wall with only cellulose insulation, and Case 8 with 5 ½" of high density spray foam in the cavity space in Figure 23.

Both Case 8 and Case 11 perform very similarly, with slightly higher relative humidities than Case 4, although there is no risk of moisture related damage from inward vapor drives in of the walls (Figure 23). Had the cladding been a moisture storage cladding, it is suspected that both Case 8 with spray foam in the stud space, and Case 11 with exterior foam would have much lower relative humidities than Case 5 because of the vapor control of the high density spray foam.

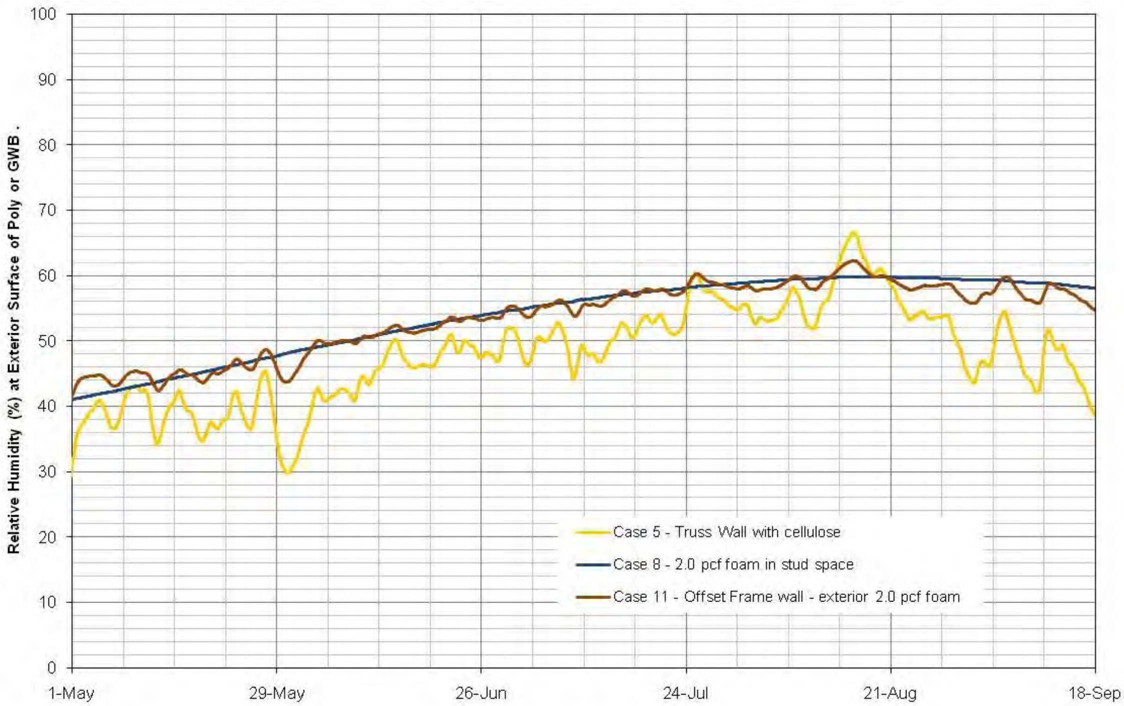

Figure 23 : Inward vapor drive relative humidity of poly or GWB for Cases 5, 8, and 11

2.2.4. Wall Drying

The third analysis conducted by using WUFI® hygrothermal modeling is the drying ability of the different wall systems. Drying was quantified by beginning the simulation with elevated sheathing moisture content (250 kg/m3) in the wall systems and observing the drying curve of the wetted layer. In walls without OSB sheathing a wetting layer was applied between the insulated sheathing and fiberglass batt insulation with similar physical properties to fiberglass insulation. Drying is a very important aspect of durability since there are many sources of possible wetting including rain leakage, air leakage condensation and vapor diffusion condensation. If a wall is able to try adequately, it can experience some wetting without any long-term durability risks.

The drying curves of Case 1 (standard construction), and Case 2 (advanced framing with insulated sheathing) are shown in Figure 24. The slowest drying wall is the advanced framing with 1" of exterior insulation and interior vapor control paint because there are lower permeance layers on both the interior and exterior of the enclosure. The OSB in the standard construction walls dry only marginally quicker than advanced framing with insulated sheathing, which is likely insignificant in the field. In the advanced framing wall, the wetting layer is immediately interior of the XPS sheathing, and drying is predominantly to the interior.

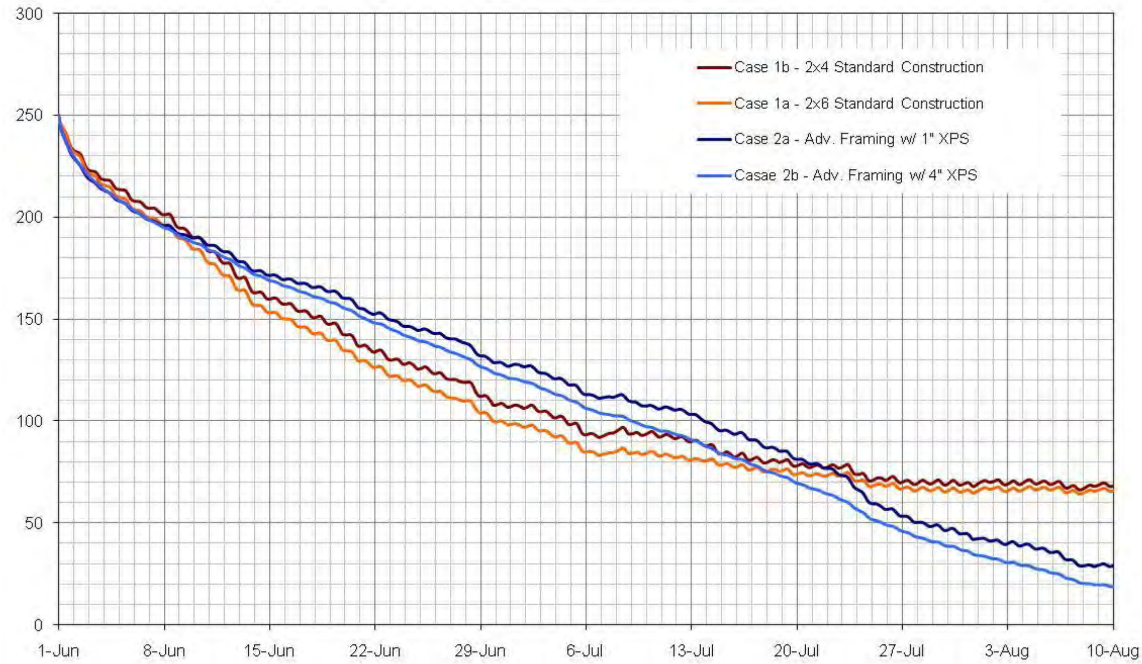

Figure 24 : Drying Curves for Case 1 and Case 2

Figure 25 shows that the drying curves of the interior strapped wall, the double stud wall, and the truss wall are all very similar, with no significant differences. These three walls perform very similarly to the standard construction walls in Figure 24.

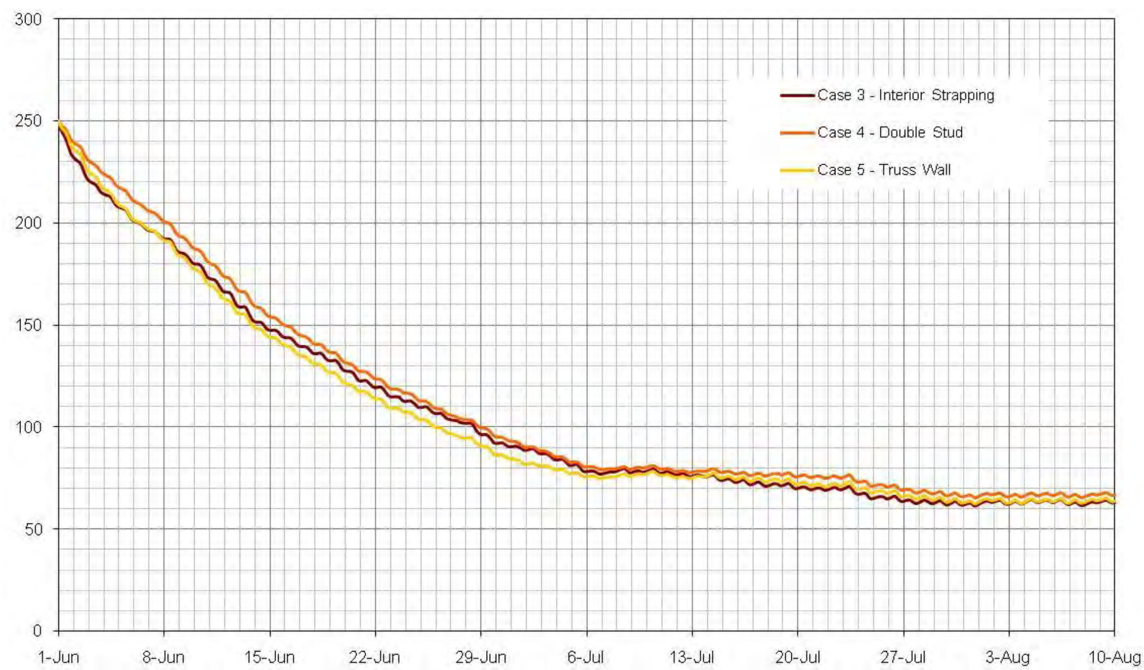

Figure 25 : Drying curves for Case 3, Case 4, and Case 5

The drying curves for spray foam insulated walls, Case 8, are shown in Figure 26. The quickest drying wall is the low density spray foam without a poly vapor barrier. Both the high density spray foam and the low density spray form with poly both dry more slowly because of the decreased permeance of the building enclosure and inhibited drying

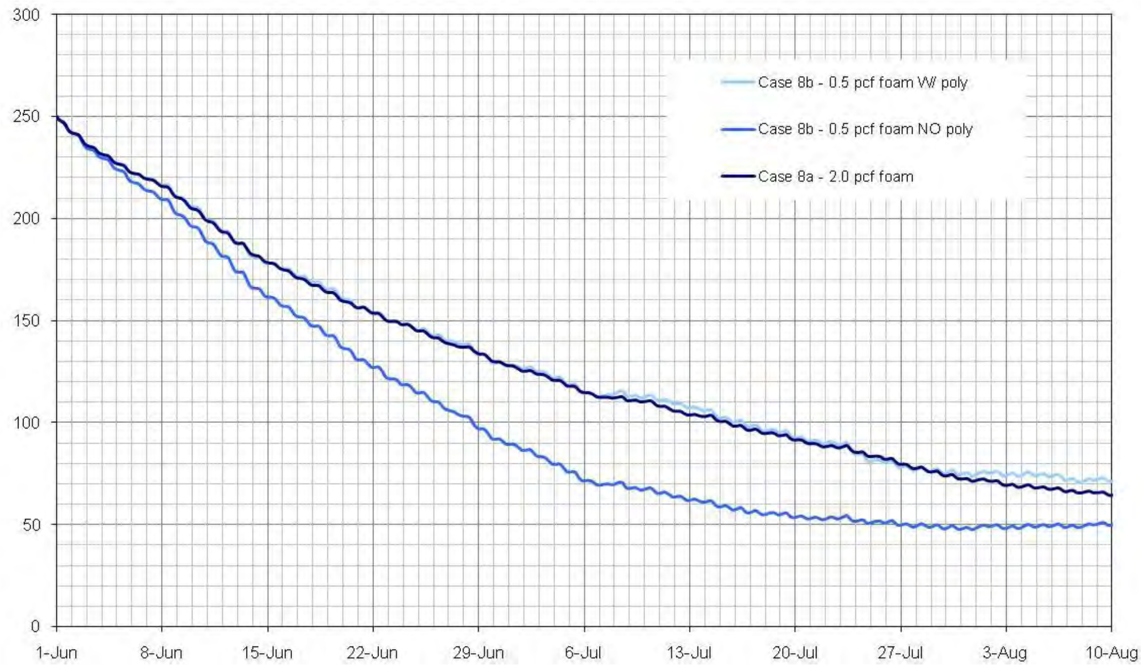

Figure 26 : Drying curves for Case 8

Comparing the double stud wall with cellulose insulation (Case 4) with the double stud wall with spray foam and cellulose (Case 10), Case 4 dried more quickly than Case 10 both with and without a interior polyethylene vapor barrier. With 12" of moisture buffering cellulose insulation in Case 4, it appears that the wall is able to quickly buffer and redistribute the moisture of a single wetting event and then release it slowly, mostly to the exterior of the OSB. Neither wall would suffer moisture related durability issues following a single wetting event but repeated wetting events to the OSB will increase the risk of moisture related durability issues.

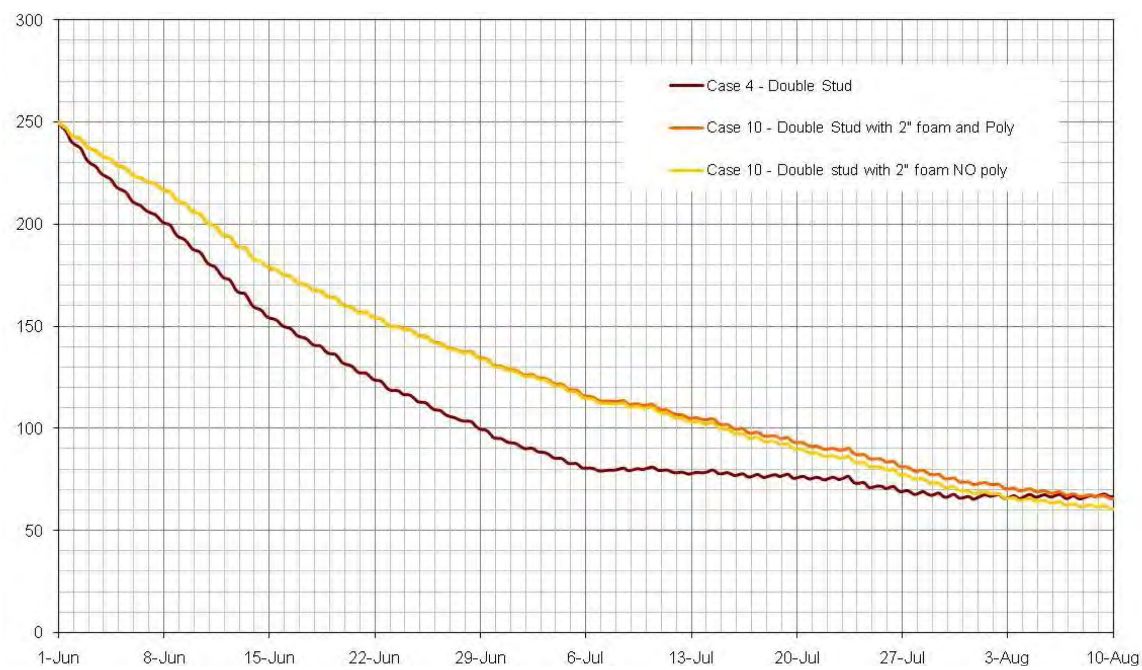

Figure 27 : Drying Curves for Case 4, and Case 10 with and without a poly vapor barrier

The offset wall enclosure with exterior spray foam dried very slowly compared to the truss wall of Case 5 with cellulose insulation. The wall system with exterior high density spray foam is unable to dry to the exterior due to the vapor control of the spray foam. The interior relative humidity is elevated in the spring and summer months which would also affect the vapor pressure gradient and drying potential. The sheathing in Case 11 is not significantly affected by the solar energy of the sun and the warm summer temperatures, nor is it in contact with cellulose insulation to buffer the wetting event.

In Case 5, with cellulose insulation against the wet OSB sheathing, the cellulose absorbed and redistributed the moisture, helping the OSB dry more quickly. Installing fiberglass batt insulation against the sheathing does not redistribute moisture and the OSB will stay wetter longer. Cellulose insulation is more susceptible to repeated wetting events because of its organic nature than fiberglass batt. Both of these wall systems would be at risk for moisture related damage if they were wetted repeatability and both walls are able to handle rare wetting events.

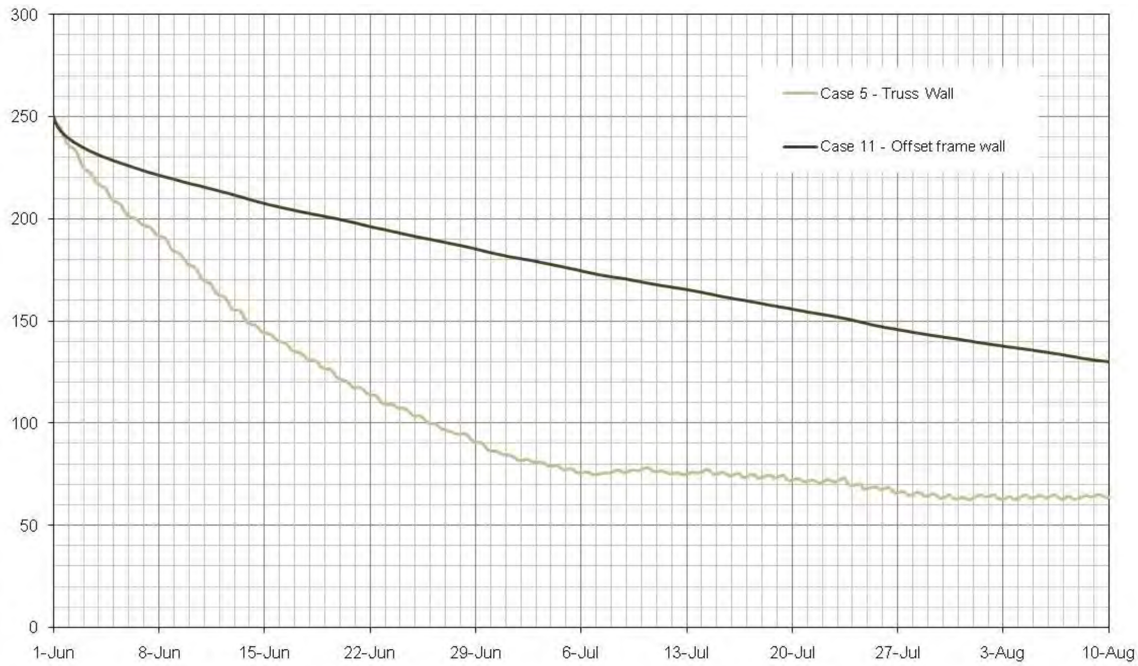

Figure 28 : Drying Curves for Case 5 and Case 11

2.3 Enclosure Durability

Durability of the building enclosure system was also used to classify the different wall construction scenarios. Durability is used in this report to group together multiple durability related criteria such as rain control, drying of water leakage events, air leakage condensation, built in moisture, and susceptibility of different building materials to moisture related issues. The durability assessment will be determined from hygrothermal modeling, as well as qualitatively based on the knowledge and experience of building material characteristics such as vapor permeability, and hygric buffering capacity, and susceptibility to moisture related damage..

2.4 Buildability

Buildability is a key comparison criteria for practical purposes. Often the general contractor and trades will influence design decisions based on the perceived complexity of different construction techniques or deviation from their standard practice. Any enclosure system and detailing should be buildable on a production level to achieve the greatest benefit even though the trades are often resistant to changes in construction practices. The susceptibility of the enclosure system to poorly constructed water management details and poor workmanship is also considered in buildability.

2.5 Material Use

Material use is becoming a critical design issue with the increasing concerns of depleting resources, and increasing costs of materials and energy. Some construction strategies use more construction materials such as the double stud wall, and the advantages of increased thermal control should be balanced against the disadvantages of increasing the building materials and embodied energy. In some cases, materials that have less embodied energy, or recycled material, such as cellulose insulation could be used instead of the more energy intensive fiberglass batt insulation.

2.6 Cost

The factor which generally has the greatest influence on implementation of a building enclosure strategy, particularly for production builders, is cost. Because the cost of some materials varies significantly depending on location and case-specific relationships between builders and suppliers, the cost of a building enclosure system will be perceived relative to other systems. For example, it's accepted that R19 fiberglass batt is less expensive than low-density (0.5 pcf) spray foam, which is less expensive than high density (2.0 pcf) spray foam. The strategy of a comparison matrix for the test wall assemblies is able to use relative values for cost rather than exact costs.

C. Results

1. CASE 1: STANDARD CONSTRUCTION PRACTICE

For this analysis, standard construction practice includes OSB sheathing, 2x4 or 2x6 framing 16" oc, fiberglass batt insulation, a 6-mil polyethylene vapor barrier and taped and painted ½" drywall. (Figure 29) Historically, this has been used for residential wall construction in most areas of North America.

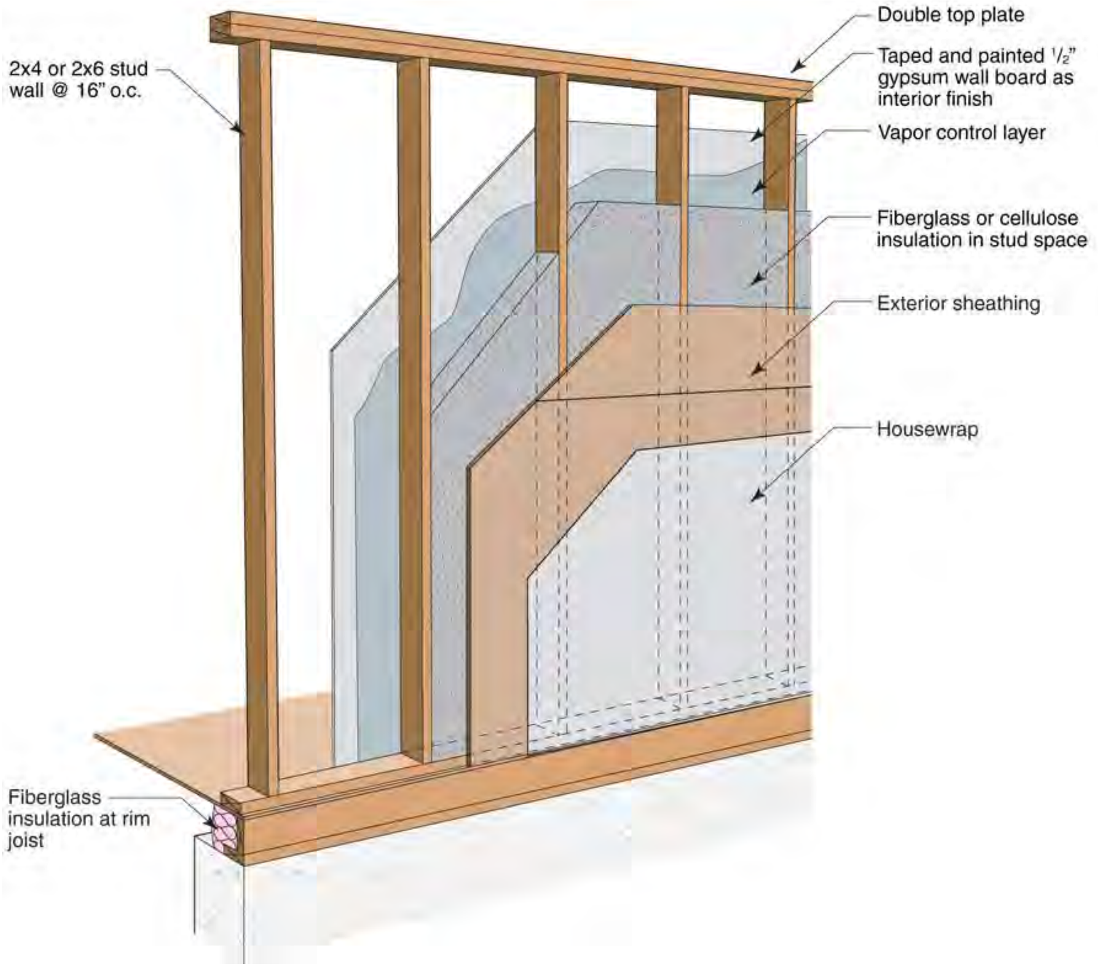

Figure 29 : Standard construction practice

1.1.1. Thermal Control

Fiberglass batt installed in a 2x4 wall system has an installed insulation value of R13, and fiberglass batt in a 2x6 wall system has an installed insulation value of R19. There are several different densities that can be used to provide slightly different R-values (e.g., 3.5" thick batts are available in R11, R12, R13 and R15 ratings). Other insulations that could be used in this assembly include densepack or spray applied cellulose, spray applied fiberglass, and spray foam (Case 8). Regardless of the insulation used in the cavity space, the framing components of the wall act as thermal bridges between the interior drywall and the exterior sheathing and this affects the whole wall R-value of the assembly. Figure 30 shows the vertical and horizontal wall sections used in Therm to determine the whole wall R-values for standard construction practices.

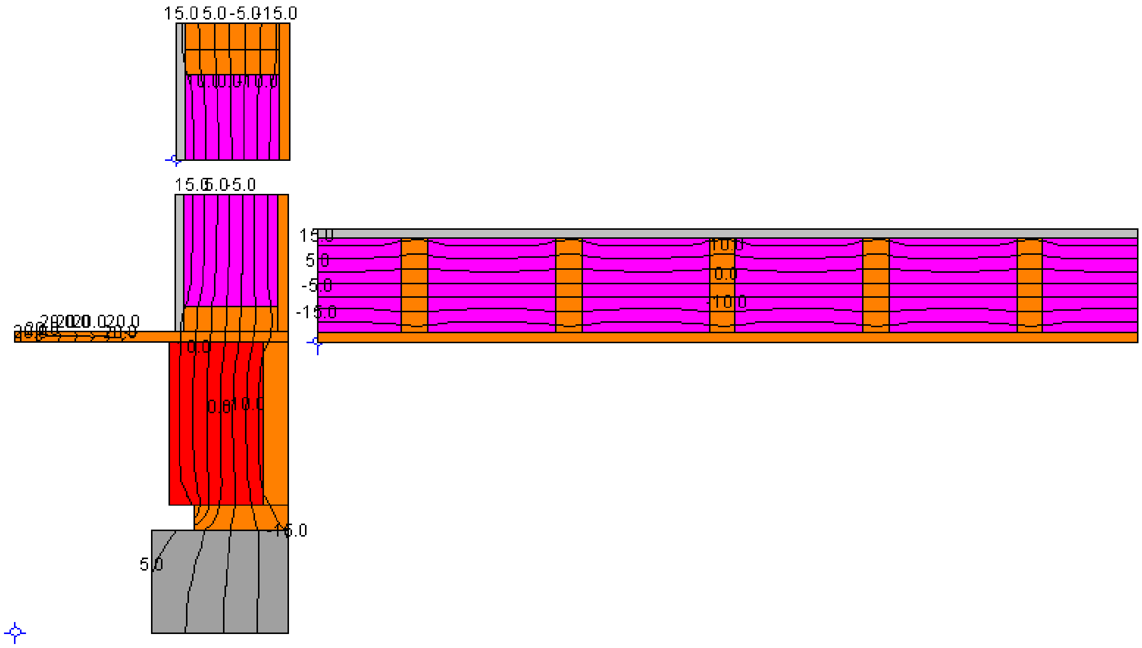

Figure 30 : Therm modeling of Case 1 - 2x6 construction

As stated previously, studies have shown that even when using a stud spacing of 16"o.c., which corresponds to a framing factor of approximately 9%, the actual average framing factor can be considerably higher, between 23 and 25%. For comparison between the different cases, framing factors of 16% were used to limit the variables and determine the effects of other variables.

Table 5 shows a summary of the R-values calculated for the three different components of both the 2x4 and the 2x6 standard construction practice. These insulation values are not considered high-R wall systems in cold climates.

Table 5 : Summary of R-value results from Therm modeling for Case 1

Case	Description	Whole Wall R value	Rim Joist	Clear Wall R value	Top Plate
1a	2x6 AF, 24"oc, R19FG + OSB	**15.2**	12.3	16.1	12.5
1aii	2x6, 16"oc, R19FG + OSB (25%ff)	**13.7**	12.3	14.1	12.5
1b	2x4 AF, 24"oc, R13FG + OSB	**11.1**	9.8	11.5	9.8
1bii	2x4, 16"oc, R13FG + OSB (25%ff)	**10.0**	9.8	10.1	9.8

Neither of the two most common insulations, fiberglass or cellulose, control air flow. Cellulose does a better job of suppressing convection because it fills the gaps that are typically left during typical fiberglass batt installation. Blown-in fiberglass also helps address the gaps left during fiberglass batt installation but is relatively new, and not as widely used as cellulose.

Air tightness can be significantly improved by using an airtight insulation such as sprayfoam at the rim joist.

1.1.2. Moisture Control

Analysis of the air leakage condensation potential from a poorly detailed air barrier results in approximately 4400 and 4500 hours of potential condensation for the 2x4 and 2x6 standard construction walls respectively when the temperature of the exterior sheathing is less than the dew point of the interior air. (Figure 10)

These walls are unable to dry to the interior, but generally are able to dry fairly well to the exterior depending on the cladding type. WUFI® showed that with a ventilated cladding like vinyl siding, the sheathing in both of the standard construction walls decreased from 250 kg/m3 to 100 kg/m3 in 29-34 days (Figure 24).

1.1.3. Constructability and Cost

Generally speaking, all of the trades and construction industry are very familiar with building the Case 1 wall system. Cladding attachment is straightforward, and the only education necessary may be air tightness details to increase the overall building performance.

1.1.4. Other Considerations

The amount of material used in this type of construction is the standard against what other walls will be compared since it has been the standard of construction in many places of many years. Standard construction uses less framing and wood sheathing than a double stud wall construction (Case 4), but more than advanced framing material. Using cellulose insulation instead of fiberglass not only increases the fire resistance for the enclosure wall, it also decreases the embodied energy used in construction.

1.2 Case 2: Advanced framing with insulated sheathing

Advanced framing techniques are becoming more popular for residential construction because of several advantages. These practices have been adopted by some smaller builders, but not on many large scale production developments. The main difference with advanced framing is 2x6 framing lumber on 24" o.c. with a single top plate. The idea of advanced framing is to reduce the framing factor of the wall system in the areas by good design, such as corners and penetrations. A single top plate is structurally possible if stack framing is used, which means the framing from one floor is lined up directly with the framing above and below it to create a continuous load path. In many cases of advanced framing, insulated sheathing is used either in place of or in combination with wood sheathing. This is important for thermal performance to minimize thermal bridging effects.

For this analysis, 1" and 4" insulated sheathing is considered (Figure 31). Insulating sheathing up to 1.5" thick does not change any of the other details such as windows installation and cladding attachment, but insulating sheathing at thicknesses of 2" and greater requires some slightly different design details for window and door installation as well as cladding attachment. Most of these details have already been designed and can be found in building science resources.

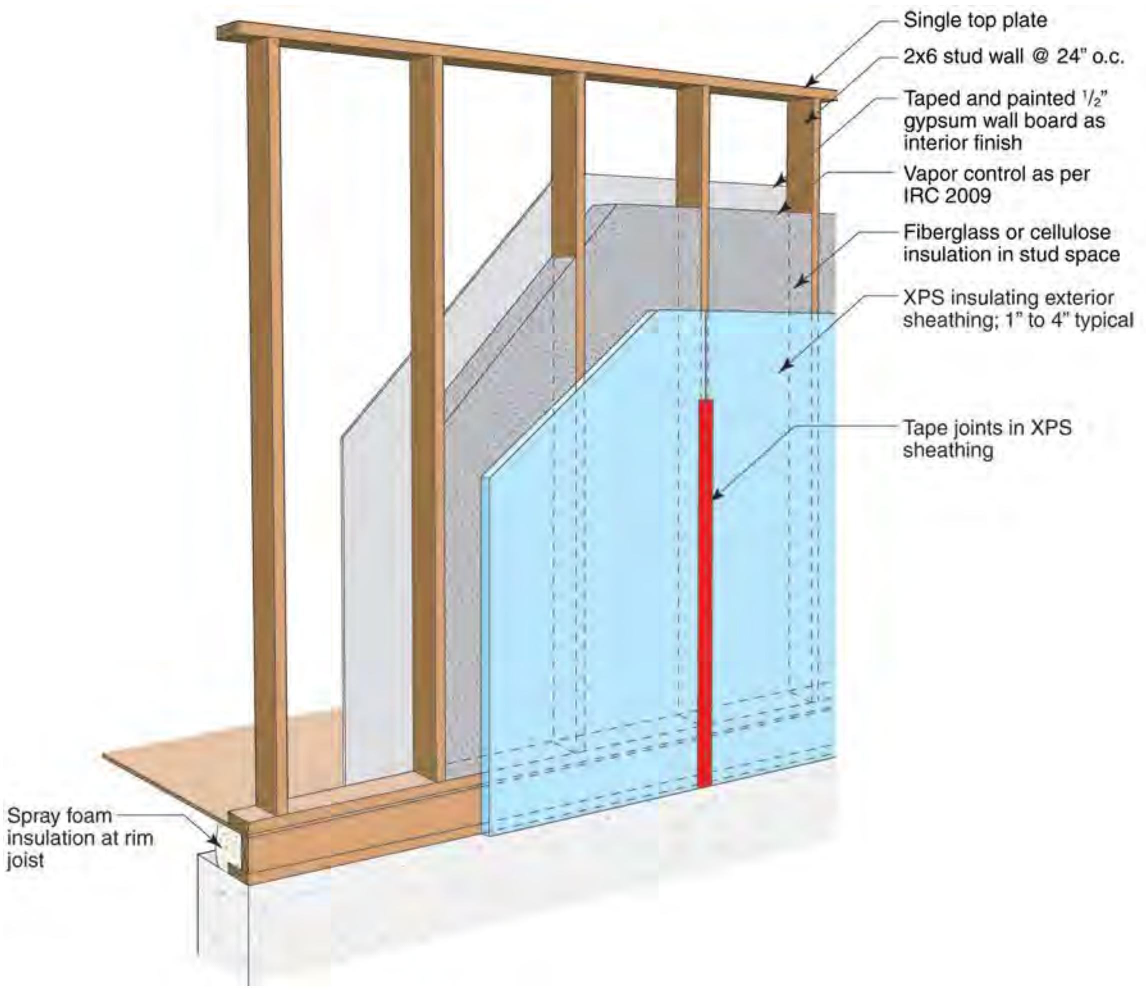

Figure 31 : Advanced framing construction

1.2.1. Thermal Control

Thermal control is improved over standard construction practices by adding insulating sheathing to the exterior of the framing in place of OSB. This insulation is typically board foam which includes expanded polystyrene (EPS), extruded polystyrene (XPS) and polyisocyanurate (PIC). PIC is often reflective aluminum foil faced which also helps control radiation losses in some cases. Thicknesses of insulation have been installed that range from ¾" to 4" on wall systems. Often times, when 4" of insulation is added, it will be done with two 2" layers with the joints offset both horizontally and vertically. Fiberglass batt, blown fiberglass or cellulose could be used in the stud space. The biggest thermal advantage of the insulating sheathing is decreasing the thermal bridging of the framing members through the thermal barrier.

Drawings from Therm show the vertical and horizontal sections which indicate increased thermal protection at both the rim joist and top plate, decreasing heat flow through the thermal bridges.

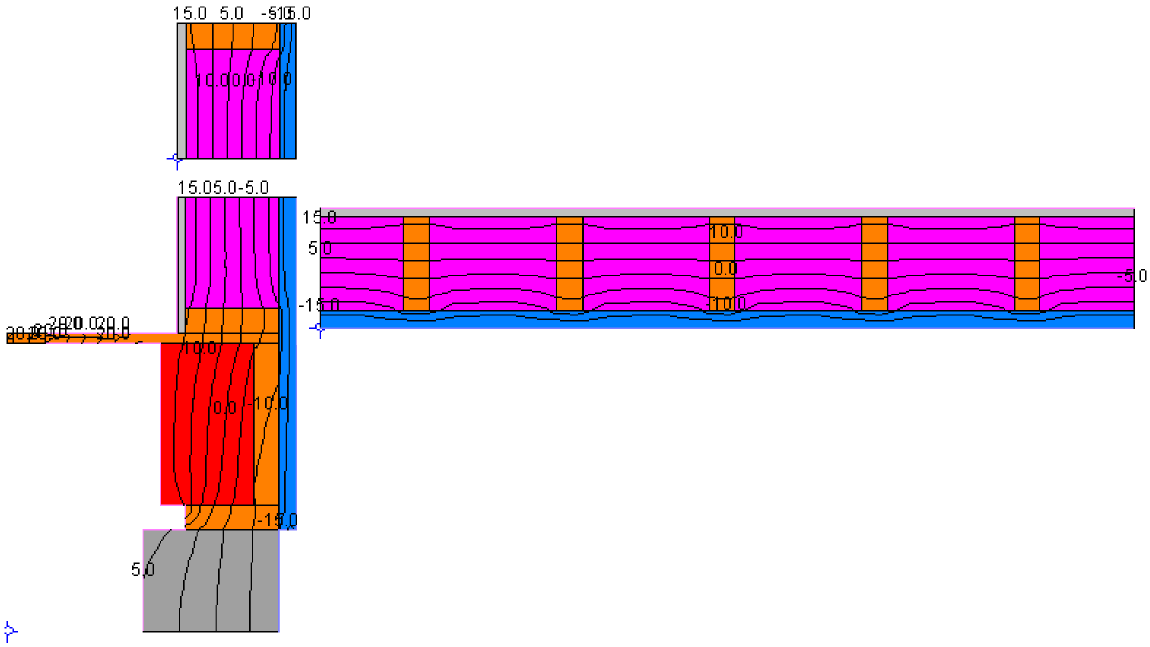

Figure 32 : Therm modeling of Case 2 advanced framing with 1" XPS insulated sheathing

Analysis shows that when substituting 1" of XPS (R5) for the OSB in a standard 2x6 wall with a 16% framing factor, the clear wall R-value increases from R16.1 to R20.6, an increase of R4.5. Since the OSB was removed from the standard construction wall, this is actually a difference of R5.1, which is greater than the R-value of the insulation that was added. If the framing factor was higher, or metal studs were used, an even greater increase in the R-value for 1" of XPS can be seen. For example, increasing the conductivity of the studs by an order of magnitude results in an increase of R6.5 for 1" of R5 XPS sheathing over standard construction. This is an example of the importance of reducing the thermal bridging through the enclosure.

The calculated R-values for both of the advanced framing walls are shown in Table 6.

Table 6 : Summary of R-value results from Therm modeling for Case 2

Case	Description	Whole Wall R value	Rim Joist	Clear Wall R value	Top Plate
2a	2x6 AF, 24"oc R19FG + 1" R5 XPS	**20.2**	18.5	20.6	20.3
2b	2x6 AF, 24"oc R19FG + 4" R20 XPS	**34.5**	29.0	35.6	35.4

1.2.2. Moisture Control

The Therm results show that the interior surface of the foam is at a higher temperature than the standard construction wall which will decrease the potential for both vapor diffusion condensation and air leakage condensation. According to the IRC, a Class I or II vapor retarder is still required depending on the R- value of the insulated sheathing and the wall framing used. Table N1102.5.1 from the IRC shows that for climate Zone 6, with insulating sheathing R>= 11.25 on a 2x6 wall, only a Class III vapor retarder is required.

There is some risk of winter time condensation from vapor diffusion depending on the level of vapor retarder and the interior temperature and relative humidity conditions. Figure 9 shows that with 1" of XPS some condensation is possible on the surface of the insulated sheathing. Since the XPS is not moisture sensitive, some condensation will not affect the durability of the wall system.

Air leakage condensation may still be a concern, although not as great as with standard construction. There are approximately 3800 hours and 1200 hours of potential air leakage condensation when the temperature of the insulated sheathing is below the dew point of the interior air for 1" of XPS and 4" of XPS respectively.

Both of the advanced framing walls dry slower than the standard construction walls because drying to the exterior is throttled by the low vapor permeance XPS (Figure 24).

There is less inward vapor drives in the advanced framing walls with insulated sheathing than the standard construction since vapor is slowed at the sheathing, and allowed to dry more readily to the interior (Figure 19). The relative humidity peaks are considerably higher in the standard construction walls than the advanced framing walls.

1.2.3. Constructability and Cost

There is some education and training required for the successful construction of advanced framing walls with insulated sheathing. The changes are very minimal for insulated sheathing thicknesses of 1.5" and less, but for insulating sheathing thicknesses of 2" and greater, special details are required for cladding attachment and window and door installation.

Some solutions have been found for cladding attachment directly to 3/4" strapping anchored to the framing members, but in some areas, building code officials require letters from the specific building materials companies before allowing construction.

1.2.4. Other Considerations

The R-value of a wall system can be increased more than the added value of insulation by minimizing the thermal bridging with exterior insulating sheathing. Advanced framing techniques use less framing lumber than traditional construction, which is a savings of both money and embodied energy while reducing the framing fraction. Similar to traditional construction, using cellulose in the stud space will decrease the embodied energy of the insulation and increase the fire resistance of the wall system.

1.3 Case 3: Interior 2x3 horizontal strapping

Horizontal interior strapping is a method of reducing the thermal bridging through the wall framing, protecting the vapor barrier against penetrations, and adding more insulation.

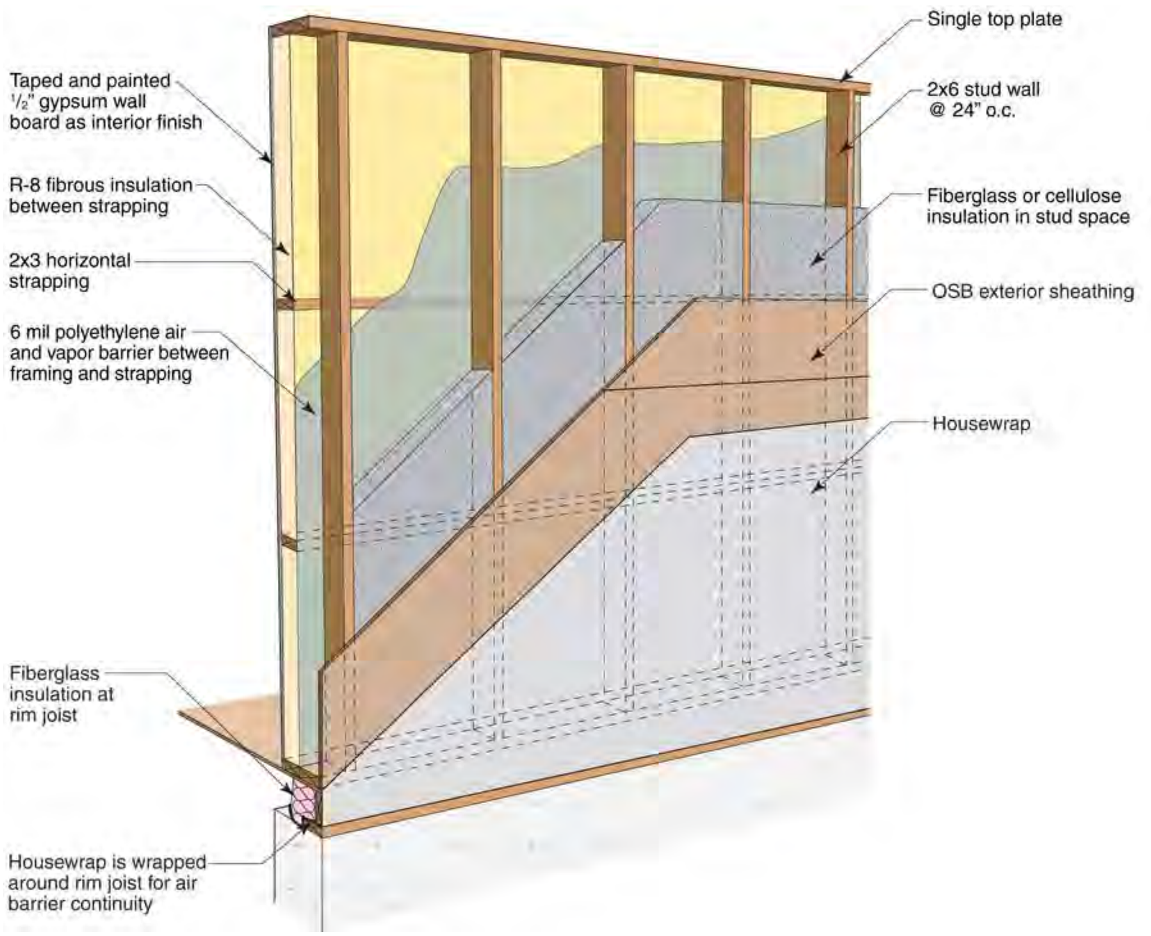

Figure 33 : 2x6 wall construction with interior strapping

1.3.1. Thermal Control

The horizontal strapping added to the wall allows for an extra 2.5" of insulation. This is commonly in the form of R8 fiberglass, which totals an installed insulation R-value of R27 for the wall assembly. For the Therm simulation four interior strapping elements were used as shown in the drawing.

Thermal bridging is decreased through the vertical studs but there is still thermal bridging at the top and bottom plates. Thermal losses due to air leakage are likely been minimized by installing the polyethylene vapor barrier against the wall framing. This means fewer penetrations are required for services and wiring resulting in greater air tightness than standard construction.

Therm was used to determine the whole wall R-value of the interior strapping wall. Figure 34 shows the horizontal and vertical sections from the Therm analysis.

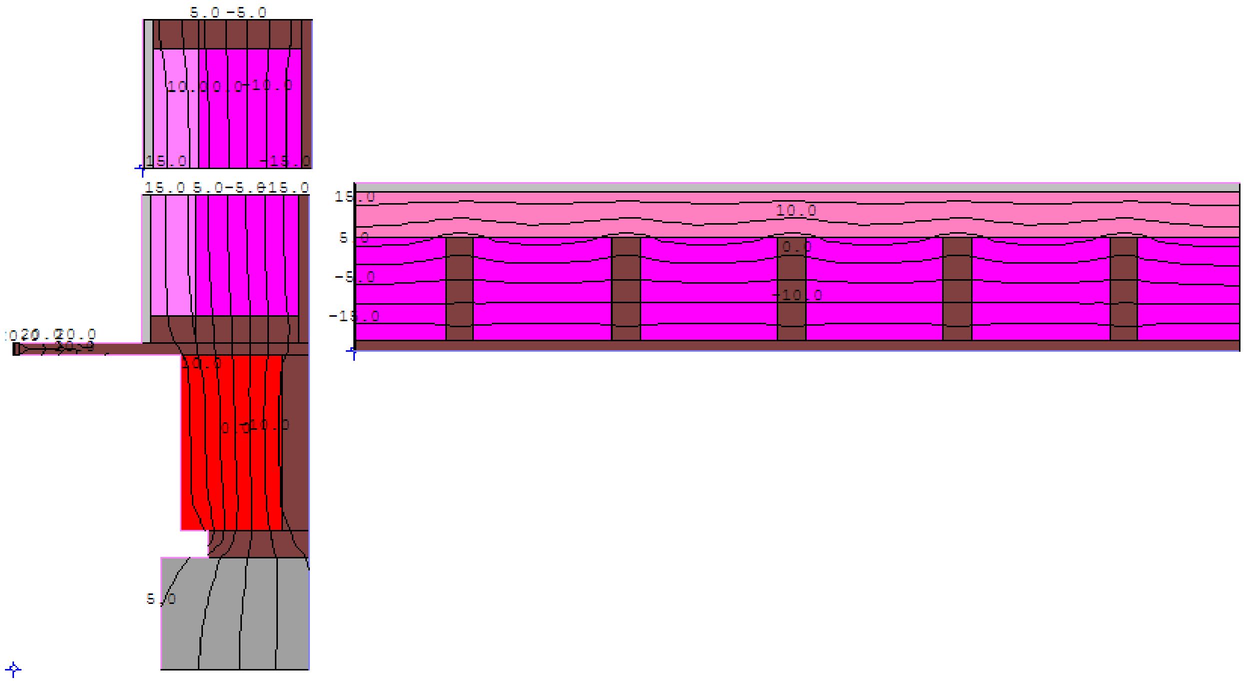

Figure 34 : Therm analysis of horizontally strapped wall

The Whole wall R-value of the wall assembly was determined to be R21.5 (Table 7). This means that even by adding R8 to the standard 2x6 wall, this results in an increase of R6.3 because of the thermal bridging that is not addressed. The rim joist R-value can be improved with more insulation, and better airtightness.

Table 7 : Calculated R-value of an interior horizontal strapped wall

Case	Description	Whole Wall R value	Rim Joist	Clear Wall R value	Top Plate
3	2x6 AF, 24"oc, 2x3 R19+R8 FG	**21.5**	13.4	23.5	18.4

1.3.2. Moisture Control

The control of both vapor diffusion condensation and air leakage condensation is increased since there are fewer penetrations in the air/vapor barrier of the wall assembly.

The potential for vapor diffusion condensation is very similar to the standard construction assemblies (Figure 12). The temperature of the sheathing is kept only slightly colder because of the increased insulation beyond standard construction which results in a small increase in the potential intensity of air leakage condensation. There does not appear to be any risk of moisture related durability from vapor diffusion assuming the vapor barrier is adequately installed.

Air leakage condensation potential is slightly increased from the standard construction walls with a total of approximately 4600 hours of potential condensation through the winter.

Analysis of the summertime inward vapor drives shows very similar results between the standard construction practices in Case 1 and the interior strapped wall.

Drying of the interior strapped wall shows slightly improved performance over the standard construction practice, by a few days for the OSB to reach 100 kg/m3.

The interior strapped wall performed very similarly to the standard construction practice in terms of moisture control.

1.3.3. Constructability and Cost

Constructing a wall with interior horizontal strapping is not a normal construction technique in most places. It would require some education and training in the design details, such as window installation, but cladding attachment is the same, and the wall system would be less susceptible to workmanship issues on the vapor barrier, since there are far fewer penetrations required through the air/vapor barrier. Additional costs would be incurred due to the addition of both horizontal strapping and the installation of additional batt insulation as well as some more installation time. The mechanical and electrical services should see a reduction in cost since that the horizontal framing does not require as much drilling or modification to distribute the services. The mechanical and electrical trades would also not have to take the time to seal as many locations as in standard vapor and air barrier practices.

1.3.4. Other Considerations

It would be possible to use cellulose insulation between the polyethylene vapor barrier and the exterior sheathing, which would increase the fire resistance, and decrease the embodied energy. There is more framing required to construct these walls, and the tradeoff in adding insulation is not quite made up in the overall R-value of the assembly.

1.4 Case 4: Double Stud

Double stud walls are most commonly used as interior partition walls in multifamily construction because of their noise reducing effect and increased fire resistance. They can also be used as a highly insulated exterior enclosure wall in cold climates.

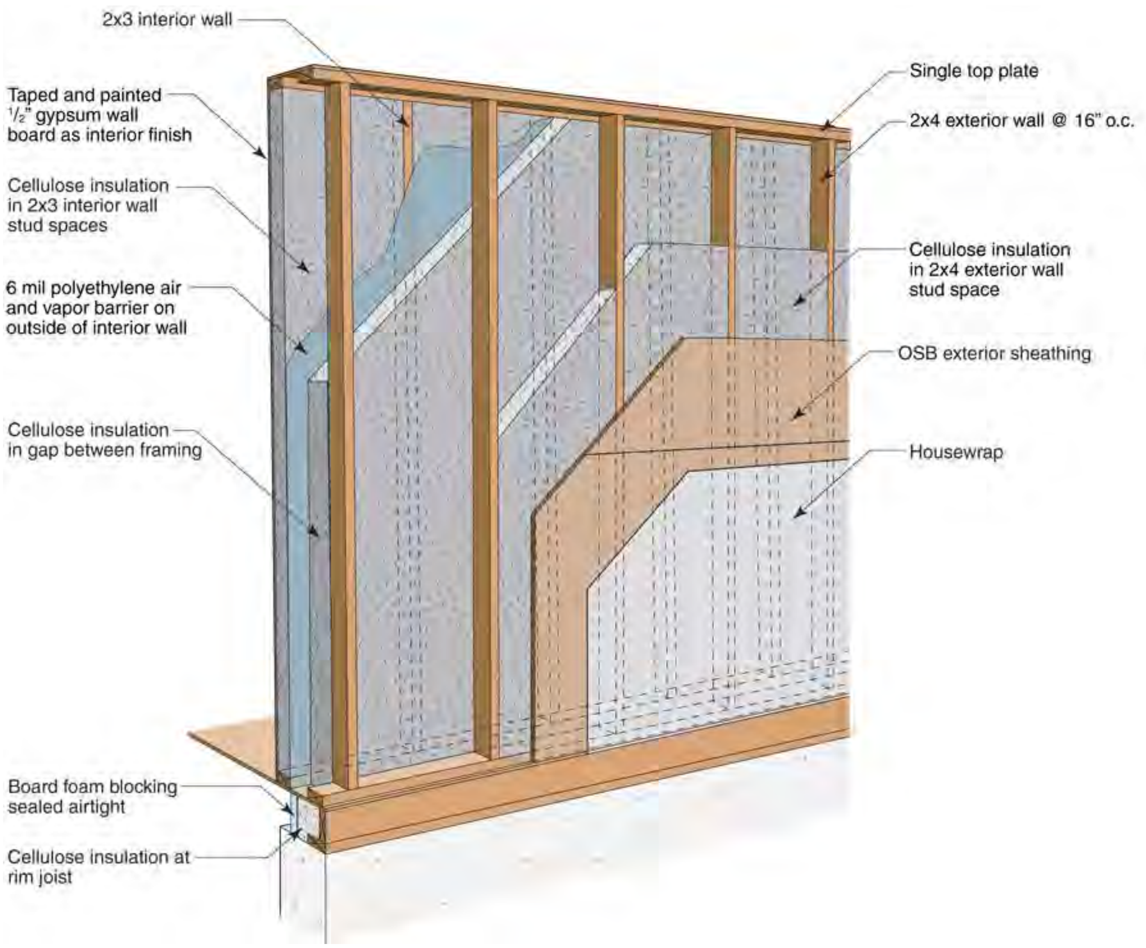

Figure 35 : Double stud wall

1.4.1. Thermal Control

This wall is typically built with an exterior structural wall using standard construction practices, a gap on the interior filled with insulation, and a second wall that is non-structural, used to support services and drywall. The interior wall studs are often installed further than 16" o.c. since it is not used for structural purposes. For the Therm simulation the exterior structural members were spaced 16"o.c. and the interior framed wall used to support the drywall and insulation was spaced at 24"o.c. The framing spacing becomes less important for simulations, and field installation, when there is a significant thermal break between the exterior and interior environments. The actual placement and alignment of interior and exterior framing members will depend on many variables such as windows, doors, corners, and the building practices of the framing crew. It is also common to use a double top plate on the exterior structural wall but for this analysis a single top plate was simulated. As with the framing members, a single or double top plate has less impact on the thermal performance for walls with significant thermal breaks between the interior and exterior. It is possible to install the 6-mil polyethylene Class I vapor barrier on the back of the interior wall by installing the plastic when the wall is on the floor, and then lifting the wall into place and securing, making sure to seal the plastic at the top and bottom. This produces a more continuous air/vapor barrier since fewer penetrations are needed for services when compared to the standard framing methods although this may increase the perceived complexity to an unsatisfactory level for some builders.

One advantage observed in the field of installing the air/vapor barrier on the interior framing is one large cavity space that is easier and quicker to insulate with cellulose insulation.

The gap between the two walls can be varied, and produces a much more effective thermal bridge between the two rows of framing than the horizontal interior strapping in Case 3. Often the insulation of choice is cellulose because it is easy to install in wide wall cavities, and will not have the spaces that can occur if fiberglass batt were installed incorrectly (as it commonly is).

The Therm model (Figure 36) shows the space between the two separate walls that helps act as thermal break. Since the gap between the walls can be changed, the R-value will depend on the designed wall thickness. In this analysis, 9.5" of cellulose was used which has an installed insulation R-value of approximately R34. Therm analysis shows that with the existing thermal bridging and rim joist, the whole wall R-value of the system is approximately R30 which is only a slight reduction from the clear wall R-value. The R-value can be improved by improving the rim joist detail: more insulation, better airtightness, and better insulation of the concrete foundation.

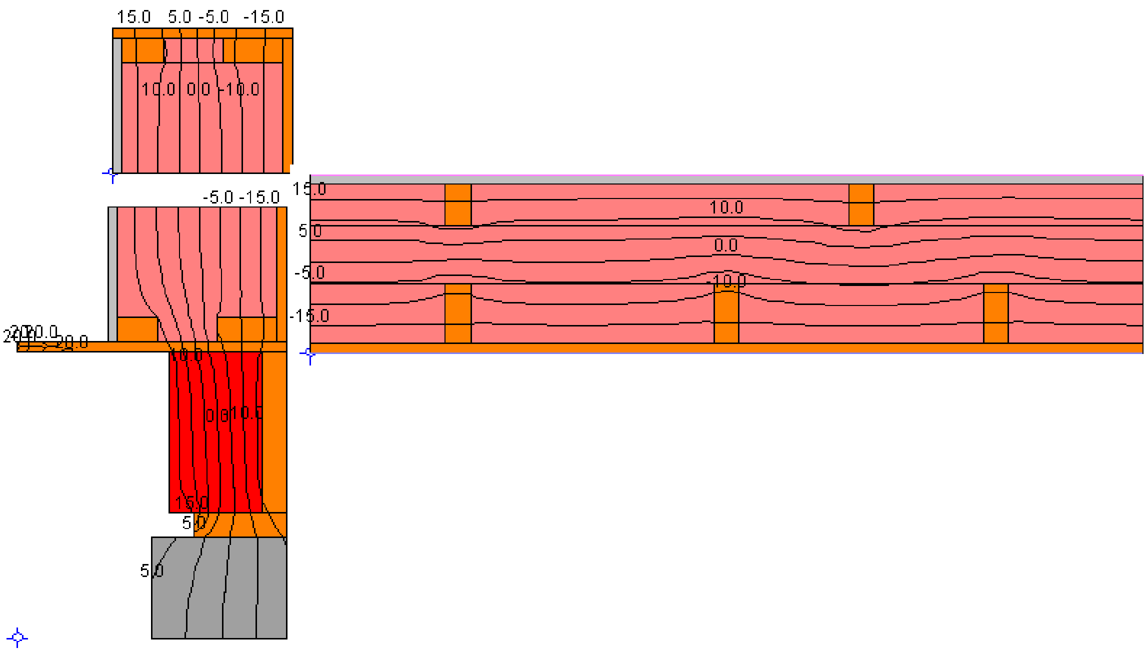

Figure 36 : Therm model of the double stud wall

Table 8 : Calculated R-value of a double stud wall

Case	Description	Whole Wall R value	Rim Joist	Clear Wall R value	Top Plate
4	Double stud wall 9.5" R34 cellulose	**30.1**	14.4	33.5	28.8

1.4.2. Moisture Control

Moisture control in the form of air leakage condensation and vapor diffusion condensation is controlled with a 6-mil polyethylene vapor barrier that can be installed on the back side of the interior wall or directly behind the drywall. Installing the poly on the back side of the interior wall, if possible, helps reduce the amount of air leakage condensation because fewer penetrations are needed and the air barrier can be more continuous.

Because of the greatly increased thermal performance, the sheathing is kept colder than standard construction and therefore the probability and intensity of vapor diffusion and air leakage condensation increases. There are approximately 4600 hours of potential wintertime condensation hours, similar to Case 3 with interior horizontal strapping but because the temperature of the sheathing is colder, the amount of condensation would increase for the same amount of air leakage (Figure 13).

In the summer time the potential inward driven moisture condensation is slightly less than the standard construction walls (Figure 20). This is because the cellulose in the insulation cavity has some buffering effect of moisture, so with a non-reservoir cladding such as vinyl siding, the buffering capacity is not overcome. The outcome may be different with a cladding such as stucco or adhered stone veneer.

In the drying analysis, the double stud wall performs very similarly to the standard construction practice as well as the interior strapped wall drying to 100 kg/m3 in 28 days (Figure 25).

1.4.3. Constructability and Cost

There is some education and training required with this construction technique, mostly with the window boxes and window installation. In any construction where the wall is much thicker than standard construction, window bucks (plywood boxes) are required for window installation. The cladding attachment is the same as normal construction practices.

1.4.4. Other Considerations

There is considerable extra framing required for the double stud wall which should be considered during design. If the exterior dimensions of the building are fixed, there is also a significant reduction in the interior floor area because of the thickness of the walls. Cellulose increases the fire resistance of the wall system, and allows for buffering and redistribution of enclosure moisture as long as the buffering capacity is not overwhelmed.

1.5 Case 5: Truss Wall

The truss wall is a construction technology that is not as widely known as the other cases being considered. It provides a great deal of insulation space, minimizes thermal bridging through the wall by using plywood gusset plates, and covers the rim joist with insulation (the rim joist is generally a location of significant air leakage and thermal bridging). Also, unlike the double stud wall, the increased wall width is to the exterior of the structural wall, which does not compromise indoor floor area.

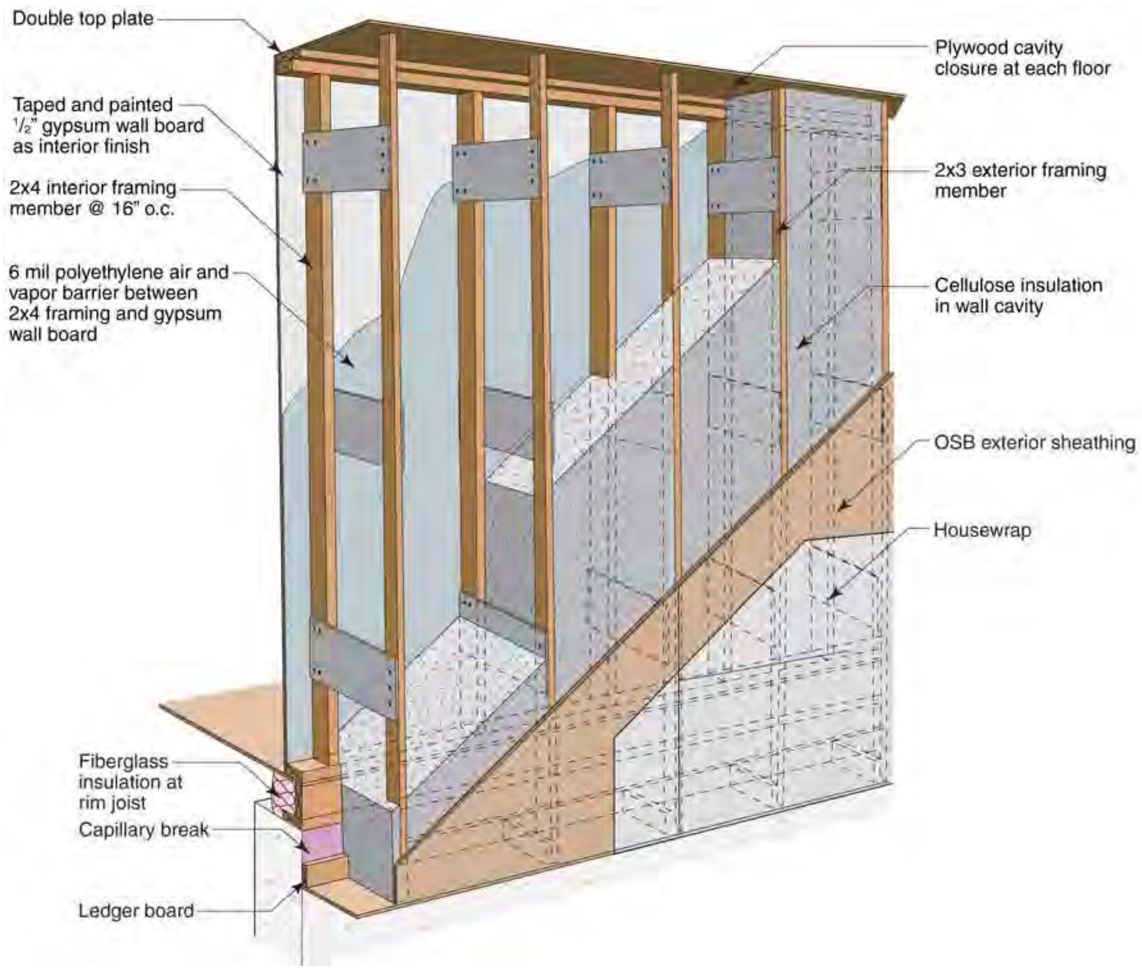

Figure 37 : Truss wall construction

1.5.1. Thermal Control

The goal of this wall is to provide as much space as possible for insulation to increase the thermal performance. In this analysis, an insulation cavity of 12 inches was constructed through the wall system. This was filled with cellulose to achieve a nominal R-value of R43, the highest R-value of any of the walls analyzed.

Therm was used to predict the whole wall R-value of this high-R assembly (Figure 38), and a value of R36.5 was calculated. Looking at the three individual components, the clear wall R-value is R40, but both the top plate and rim joist exhibited lower values. It is likely that a high heel truss with wide overhangs would be utilized for the attic and the attic space insulation would extend out over the top plate creating continuous insulation over the plates reducing the thermal bridging. This is not a commonly constructed wall but it was felt that a double top plate is more likely to be used than a single top plate for construction. It is possible to construct the same wall with a single top plate instead.

The wall schematic in Figure 37 shows that every structural wall stud has a corresponding exterior framing member for cladding attachment. In practice this is unlikely to happen because of extra framing studs commonly used for construction. It is more likely that there will be some structural wall members without a corresponding exterior framing member as was simulated in Therm (Figure 38). Similar to the double stud wall, the actual number and spacing of structural members has little influence on the whole wall R-value because of the significant thermal break of the insulation between the interior and exterior framing members.

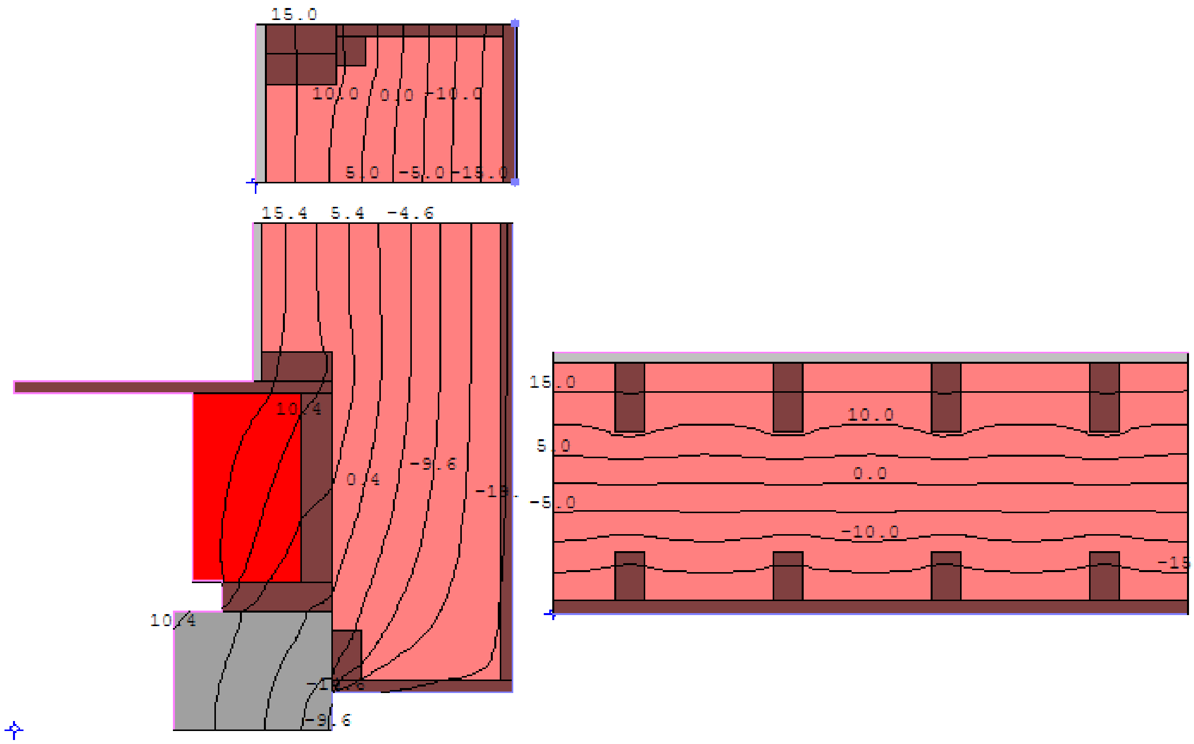

Figure 38 : Therm results of the truss wall

Table 9 : Calculated R-value for truss wall

Case	Description	Whole Wall R value	Rim Joist	Clear Wall R value	Top Plate
5	Truss wall 12" R43 cellulose	**36.5**	18.6	40.5	34.4

1.5.2. Moisture Control

Vapor diffusion control and air leakage control are particularly important in this assembly since it has the greatest insulation value and the coldest winter sheathing temperatures. The truss wall has similar winter sheathing relative humidities to the double stud wall, but the relative humidities are slightly higher because of the lower sheathing temperature. There are approximately 4600 hours of potential winter time condensation, but the intensity of condensation is slightly greater than the double stud wall, again, because of the lower sheathing temperature (Figure 13).

The truss wall is very similar to the double stud wall although slightly lower in summertime inward vapor drive relative humidity at the vapor barrier (Figure 20). This is likely because of the increased moisture distribution and buffering from the increased amount of cellulose insulation in the truss wall.

Analysis of the drying results shows that the truss wall dries two or three days faster than both the double stud wall and the interior strapping wall (Figure 25) which is also because of the greater redistribution and buffering of moisture.

There is an increased risk of problems with the vapor control layer in the truss wall than both the double stud wall and the interior strapping wall, since the polyethylene vapor barrier will have penetrations for services and wiring. If the polyethylene sheet is also being relied on as the air barrier, which is common, this could lead to the highest risk of moisture related durability issues in all three similar test walls.

1.5.3. Constructability and Cost

The truss wall appears to require more time and energy to construct than the double stud wall. This strategy would likely not be considered by a production builder under normal conditions. Cladding attachment will be the same as the traditional construction. This wall appears to be highly dependent on good workmanship (even more so than the double stud Case 4 and interior strapping Case 3), as holes in the air barrier could result in serious moisture related durability issues from air leakage condensation. If a proper airtight drywall approach is used, this could help resolve any issues with holes in the polyethylene air and vapor barrier.

1.5.4. Other Considerations

This system seems both energy and work intensive, constructing gussets, and installing the exterior framing wall and is unlikely to be used except possibly in the coldest of locations where extremely high R-values are required. There are other alternatives that may have more appeal and less risk such as Cases 10 and 11 further in this report.

1.6 Case 6: Structural Insulated Panel Systems (SIPs)

SIPs are constructed by sandwiching foam board on both sides with OSB. The foam most commonly used is EPS because of its low cost and availability, but SIPs have also been produced with XPS and even PIC in some cases to increase the R-value per inch.

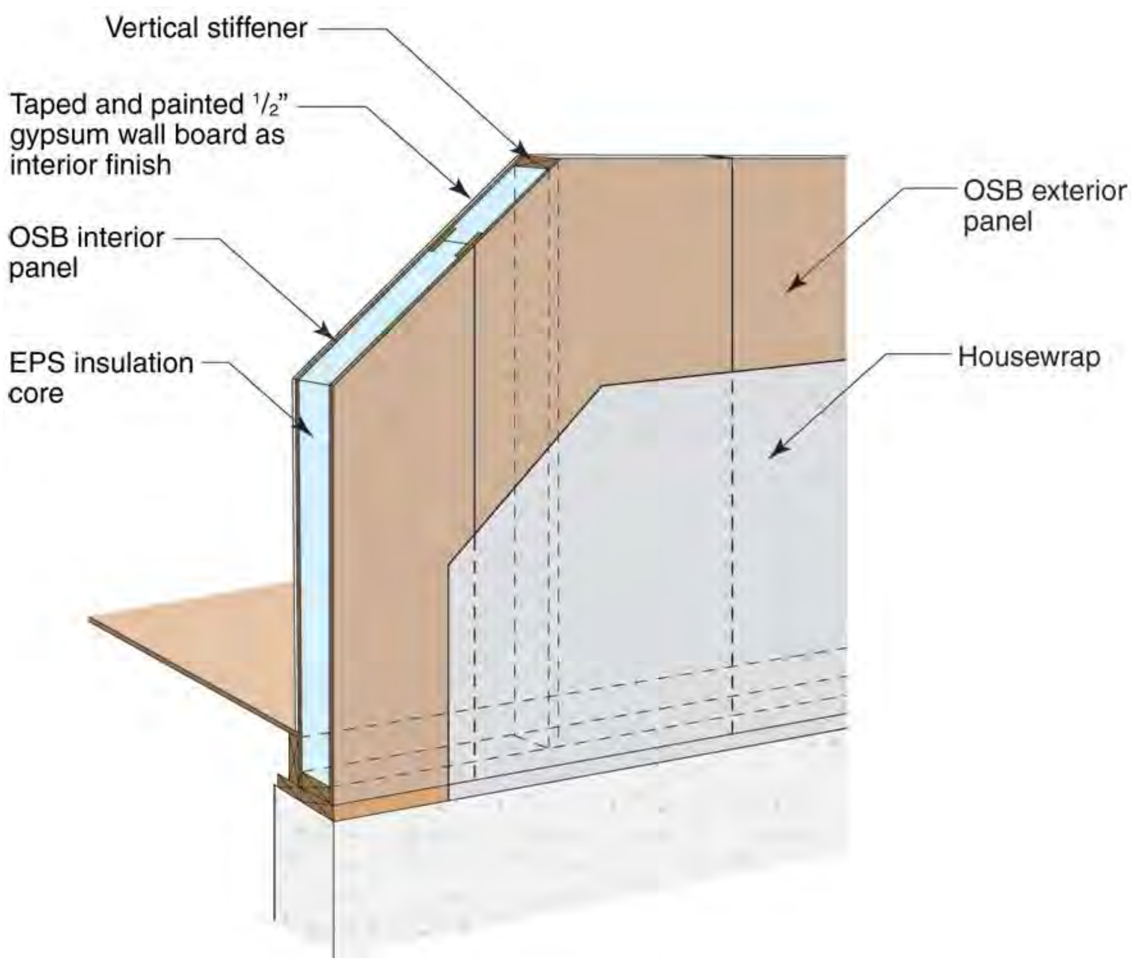

Figure 39 : SIPs wall construction

1.6.1. Thermal Control

SIPs are generally constructed with a thickness of EPS foam that matches the thickness of standard framing lumber (ie. 3.5", 5.5", 7.5"). This allows framing lumber to be inserted between the sheets of OSB in places where it is structurally required. EPS has a range of conductivity values but was modeled for this report using an R-value of R3.7/inch.

SIPs panels provide a fairly continuous plane of insulation, but quite often there are considerable thermal bridges around punched openings, the top and bottom of the panels, and sometimes through vertical reinforcement between panels.

The nominal value of this SIPs panel is R13, but because of a lack of thermal bridging through the wall (Figure 39), the calculated clear wall R-value of the wall is approximately R14.5 when the OSB and air films are taken into account. The whole wall R-value is approximately 13.6 when the top and bottom plate thermal bridges are accounted for (Table 10), which is actually higher than the installed insulation R-value.

Generally the cladding is applied directly to the exterior over a sheathing membrane, and possibly a drainage cavity, and the drywall is applied directly to the inside face. It is possible to increase the R-value of the assembly by adding insulation to the interior or exterior of the SIPs panel but it may not be cost effective.

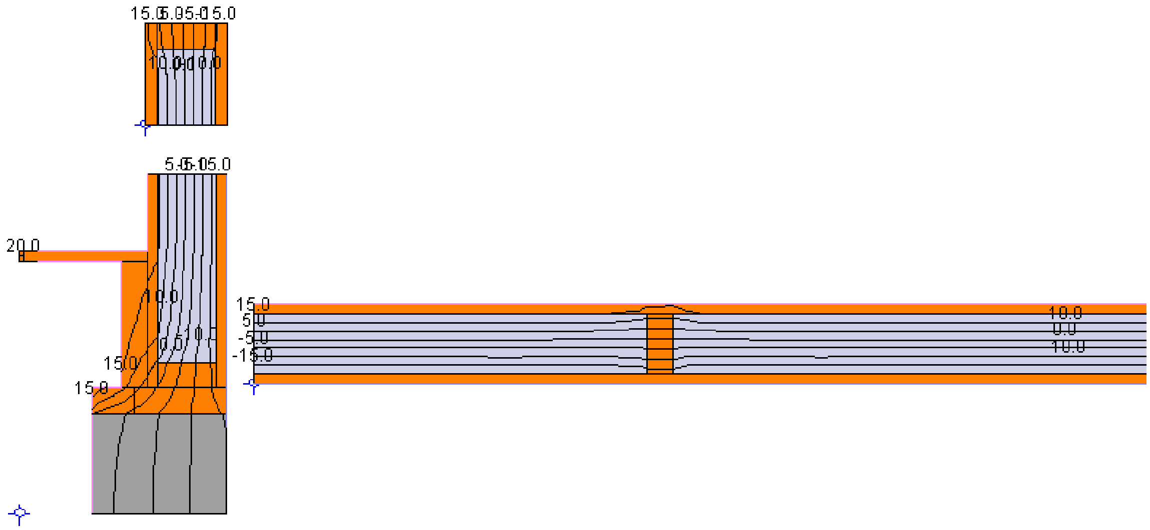

Figure 40 : Therm results of SIPs panel analysis

Table 10 : Calculated R-value for a Sips wall system

Case	Description	Whole Wall R value	Rim Joist	Clear Wall R value	Top Plate
6a	SIPs (3.5" EPS)	**14.1**	12.3	14.5	10.6
6b	SIPs (11.25" EPS)	**36.2**	14	41.6	28.2

1.6.2. Moisture Control

The plane of the SIPs wall provides a good air and vapor barrier between the interior and exterior environments. Historically, there were problems at the joints between SIPs panels where air would leak from the interior space to the exterior surface and condense against the back of the sheathing during the heating season in cold climates (SIPA 2002). Many SIPs failures have been reported to be caused by this air leakage condensation mechanism.

Currently there are better practice guides and standards applied to the installation and construction of SIPs panels and in new buildings these moisture-related durability issues are rare.

1.6.3. Constructability and Cost

Construction with SIPs panels requires training and education about construction techniques and design details. Generally, houses built from SIPs panels have very simple layouts and roof designs to help simplify the design of details at SIPs joints and roof-wall interfaces.

1.6.4. Other Considerations

This is a fairly simple, yet durable solution if constructed properly. EPS foam is the least energy intensive to produce of all the board foams, and this technique requires far less framing lumber than other standard techniques, but twice as much OSB as normal framing with a single layer of exterior sheathing. During field installation it has been observed that there are often significant thermal bridges around penetrations, and depending on the structural loading of the SIPS panel, there may be multiple vertical stiffeners which also act as thermal bridges. As with all cases, the whole wall R-value makes assumptions regarding the occurrence of framing member thermal bridging, and in the field it is likely that the whole wall R-value is slightly lower than simulations indicate.

The 3.5" SIPs panel is not considered a High-R wall system, but as the thickness level, and insulation are increased, this system could be considered for more extreme cold climates.

1.7 Case 7: Insulated Concrete Forms (ICFs)

The most common type of ICF consists of two sides of EPS of varying thickness and a poured in place concrete core. This combination of insulation and concrete provides both the thermal component and the structural component of the enclosure. Some ICFs are constructed of a cement wood fiber instead of EPS, and have varying amounts of insulation.

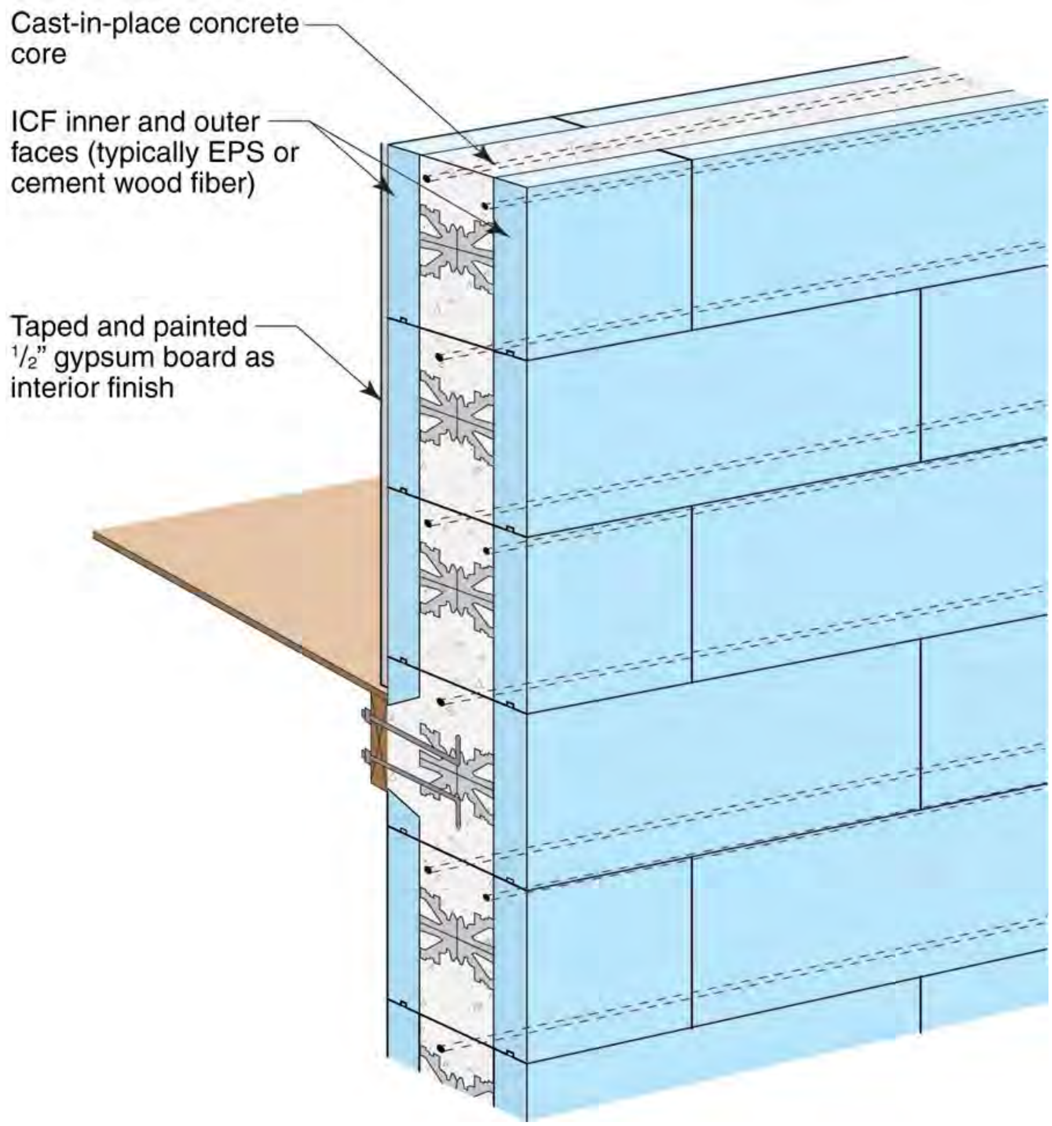

Figure 41 : ICF wall construction

1.7.1. Thermal Control

The ICF wall provides a barrier to both vapor and air flow across the enclosure. Care must still be taken at the penetrations for windows, doors and services to prevent air from moving through the enclosure, reducing the effectiveness of the insulation.

Therm analysis was used to determine the whole wall R-value of two different ICF systems. Figure 42 shows an 8" ICF with 2" of EPS on both the interior and exterior, and 4" of concrete. This has an R-value of 16.4. In comparison a 15" foam ICF with 5 total inches of EPS has an R-value of 20.6

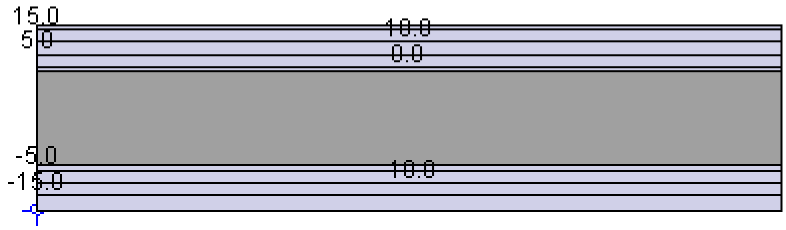

Figure 42 : Eight inch foam ICF with four inches of EPS

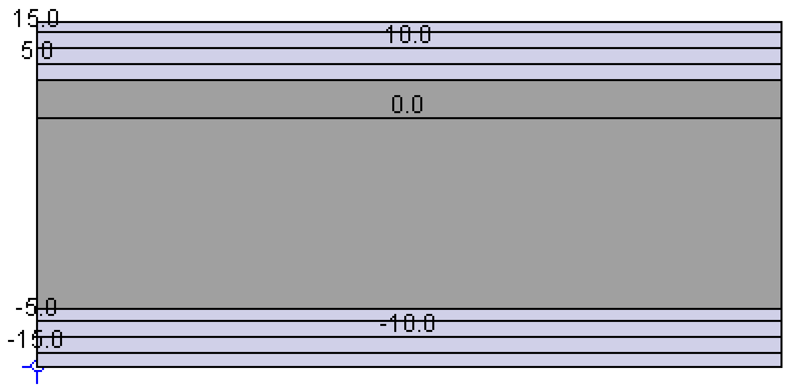

Figure 43 : Fifteen inch foam ICF with five inches of EPS

Neither of these ICF strategies would be considered a high-R enclosure in a cold climate, but these could be combined with an interior insulated framed wall or a layer of spray foam on the exterior to increase the thermal performance. The good airtightness, and the use of convection-immune rigid foam insulation means that the thermal performance is reliably delivered.

1.7.2. Moisture Control

Most ICF walls are vapor barriers that do not allow vapor to pass through easily. This also means that the wet concrete in the ICF form will retain an elevated moisture content for an extended period of time. The ICF wall system should be designed to allow to dry as easily as possible, in both directions if possible.

One of the failure mechanisms of ICF walls is improperly flashed openings that allow water to drain into the enclosure through windows, and doors, and service penetrations. Since there is no storage component to the enclosure materials, all of the water will pass through, affecting the interior finishes.

1.7.3. Constructability and Cost

ICFs are generally easy to use with some training on where and how to use steel reinforcement if necessary and installing services. Blocks are simply stacked on top of each other and concrete is poured into the centre. There have been reported issues with gaps left in the concrete or blocks breaking under the internal pressure of the concrete, and there may be issues with lining up the interior edges of the ICF blocks to provide a perfectly flat substrate for drywall installation, but all of these problems can be dealt with by better training and quality control.

1.7.4. Other Considerations

An ICF wall uses less concrete than the comparison structural wall made of only concrete, but concrete requires significantly more embodied energy than some other alternative building materials such as wood framing. ICFs appear to be ideally suited to use in areas where there is a risk of flooding or severe moisture damage, since it is much more tolerant of severe wetting events. The resistance to hurricane wind loads and debris damage is also very high.

There are many different design possibilities for ICF construction with regards to design details, which may have an effect on both the durability and thermal performance. Field investigations have shown that this construction strategy is not immune to serious moisture related risks such as bulk water leakage, window leakage, and mould if installed incorrectly.

1.8 Case 8: Advanced framing with spray foam

Polyurethane spray foam can be used in the stud cavity instead of fiberglass or cellulose insulation. Spray foam forms a very good air barrier when installed correctly and can be installed as low density (0.5 pcf) or high density (2.0 pcf) foam.

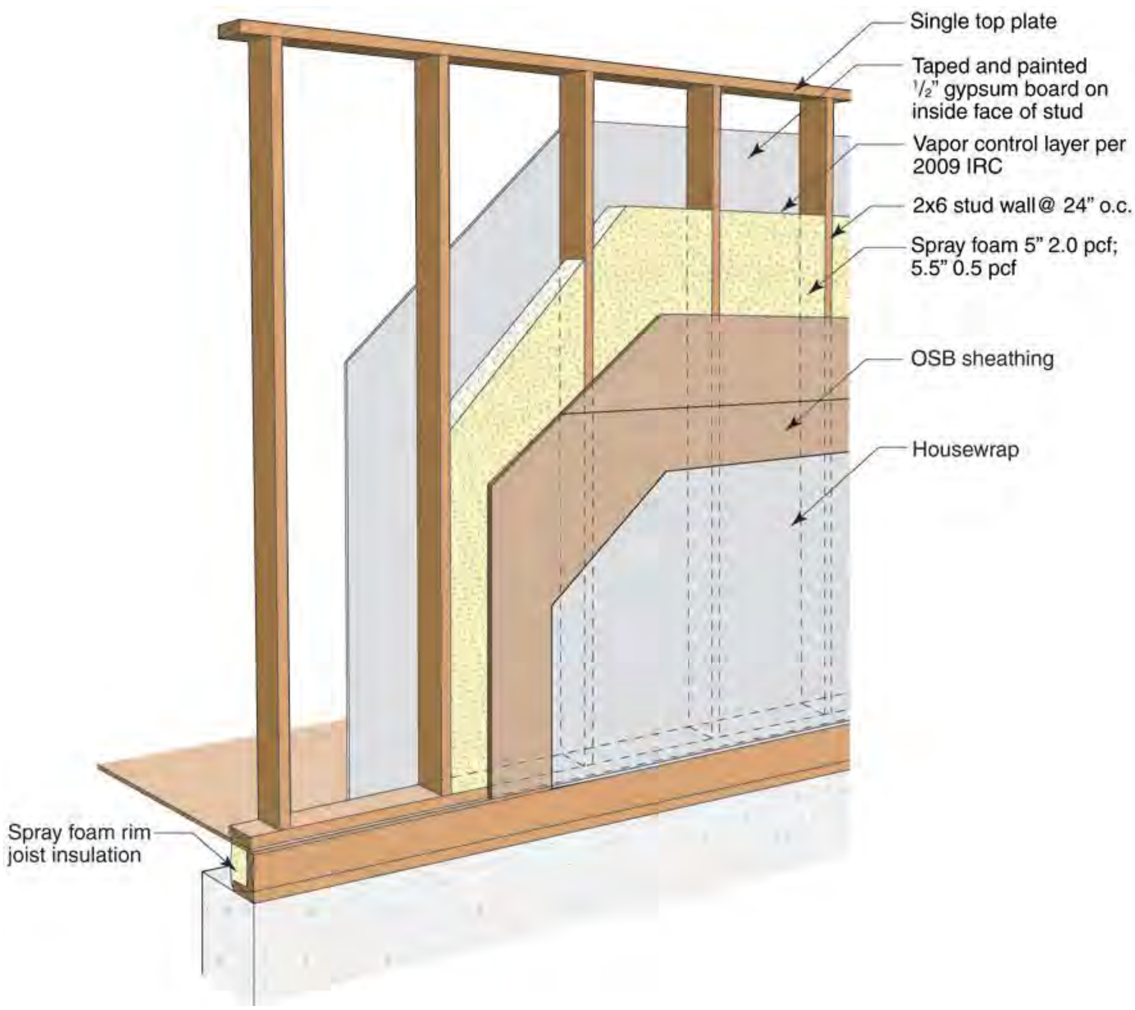

Figure 44 : 2x6 wall construction with spray foam insulation

1.8.1. Thermal Control

Using Therm to model different wall enclosure strategies does not accurate represent the benefits of spray foam insulation. Properly installed spray foam insulation completely stops air flow movement through and around the insulation so decreases in R-value associated with air leakage do not occur, either in the stud space or at the rim joist. There are different published R-values for both low and high density insulation but in this analysis for Case 8, 5.5” of R21 low density foam, and 5” of R28 high density foam were used. High density foam is installed short of the edge of the cavity to minimize trimming of the foam, while low density foam is softer, and installed to the edge of the cavity so that the excess can be trimmed flush with the stud wall framing.

Similar to standard construction practices, using spray foam does not address the concern of thermal bridging through the framing material as can be seen in Figure 45.

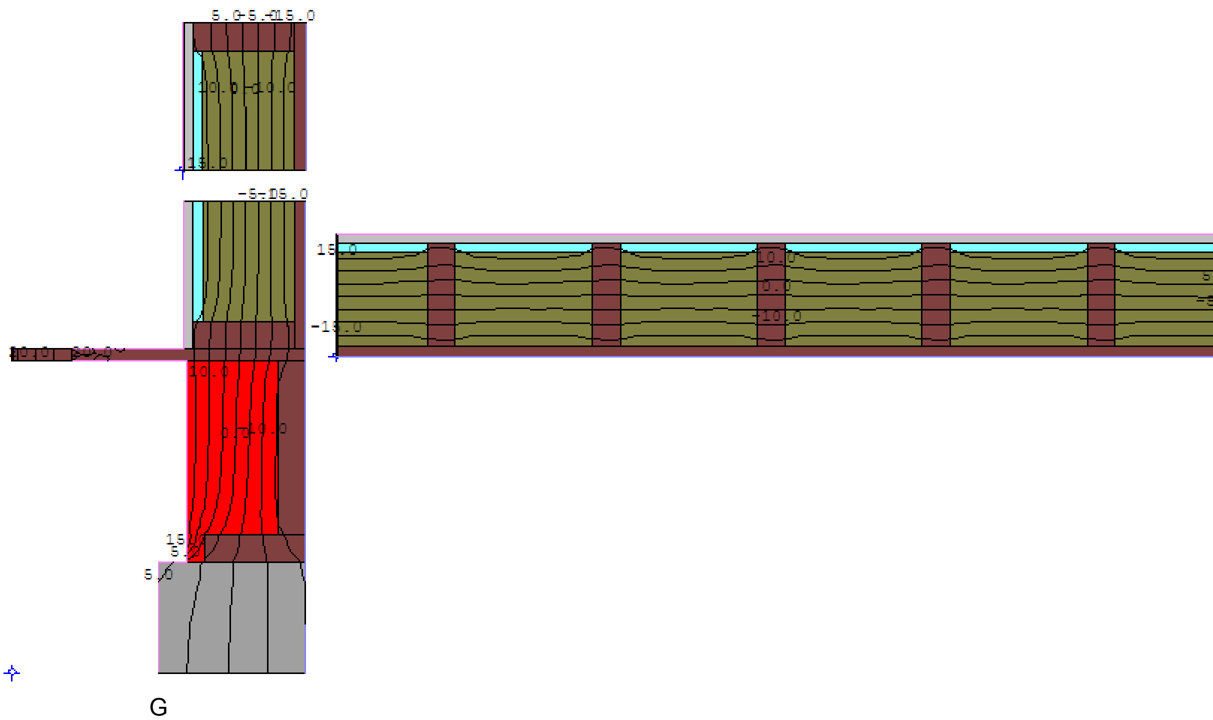

Figure 45 : Therm modeling of spray foam wall and rim joist

Calculating the whole wall R-values for the two spray foam assemblies results in R-values of R19.1 for high density spray foam, and R16.5 for the low density spray foam. The whole wall R-value of low density foam decreased by almost R4.5 versus the installed insulation R-value (from R20.9 to R16.5) because of thermal bridging. The whole wall R-value of the high density foam insulated wall decreased R9 from the installed insulation R-value due to the thermal bridging.

Table 11 : Therm results of spray foam insulation analysis

Case	Description	Whole Wall R value	Rim Joist	Clear Wall R value	Top Plate
8a	2x6 AF, 24" o.c., 5" 2 pcf R29 SPF, OSB	**19.1**	13.6	20.3	19.5
8b	2x6 AF, 24" o.c., 5.5" R21 0.5 pcf SPF, OSB	**16.5**	13.1	17.2	16.6

1.8.2. Moisture Control

High density spray foam is both an air and vapor barrier. This limits the movement of moisture vapor and air leakage condensation. Low density foam is an air barrier, but it is permeable to water vapor and is susceptible to vapor diffusion condensation. Low density foam was modeled both with and without a class I vapor retarder to determine the performance differences of a class I vapor barrier with low density foam in climate Zone 6.

Both the high density foam and the low density foam with a vapor barrier had some of the lowest sheathing relative humidities in the winter months of all of the tested wall cases. The low density foam without a vapor barrier experienced high sheathing relative humidities sustained above 95% through the winter months (Figure 13).

Analysis of air leakage condensation shows that because the spray foam is an air barrier, there would be no condensation caused by air leakage, since the surface temperature of the interior face of the foam was always warmer than the dew point of the interior air (Figure 14).

Analysis of the summertime inward vapor drive shows that the low density sprayfoam with a poly vapor barrier experienced the highest relative humidity peaks of any of the test walls, approximately 5% higher than standard construction practice.

The high density foam and the low density foam without a vapor barrier experienced some of the lowest relative humidities of test walls because they were allowed to dry very easily to the interior.

Drying results (Figure 21) showed that the low density foam without poly dried to 100 kg/m3 in approximately 28 days similar to some of the other test walls, but the high density foam and low density foam with a vapor barrier took approximately 43 days to dry to 100 kg/m3.

1.8.3. Constructability and Cost

This wall is easier to build than a standard construction wall, since no care is required at installing fiberglass batts. The costs can be perceived as prohibitively expensive which is why sprayfoam is often only used where a perfect air barrier is required, and may be difficult to install, such as garage-house interface and rim joists.

1.8.4. Other Considerations

With the new era of environmentally friendly products, many spray foam companies are marketing green spray foams that are less or harmful to the environment. In most cases, spray foam may need to be protected with a fire rated material according to the code.

1.9 Case 9: Hybrid Wall Insulation – Flash and Fill

In this analysis, hybrid walls consist of two inches of 2.0 pcf closed cell foam sprayed against the interior surface of the exterior sheathing, and three and a half inches of fiberglass. Instead of fiberglass batt, cellulose or sprayed fiberglass could also be used. Flash and Fill or Flash and Batt is often used to describe the combination of spray foam and cellulose, or spray foam and fiberglass batt respectively. The framing strategy used is advanced framing with 2x6s 24" on centre with a single top plate. Spray foam insulation helps considerably with the air tightness of the wall assembly and will increase the temperature of the potential wintertime condensation plane. Two inches of high density spray foam in the cavity also decreases the need for an interior vapor control layer which simplifies construction.

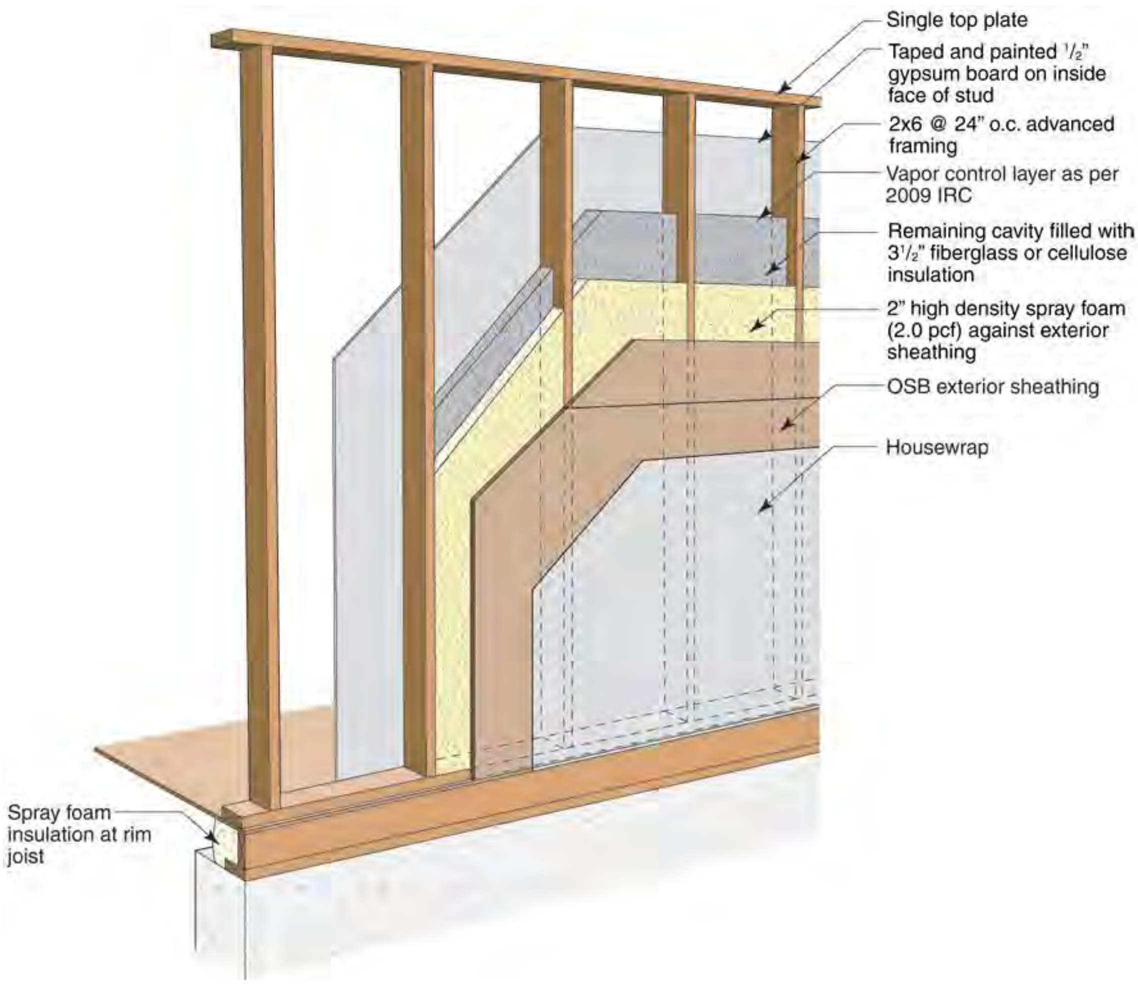

Figure 46 : Hybrid wall construction with 2" spray foam and fibrous fill

1.9.1. Thermal Control

The hybrid wall provides an increase in thermal control over the standard wall construction. Unfortunately, adding a high quality, air tight insulation between the framing does not address the issue of thermal bridging of the framing materials. Heat lost by air leakage can be greatly reduced by using the spray foam insulation, thus increases the true R-value. The whole wall R-value increases from R15.2 to R17.5 when comparing the same framing strategy with only fiberglass insulation (Case 1a) to Case 9. This improvement alone may not be enough to justify the added cost, but the heat lost from air leakage would also be greatly reduced through the wall and rim joist improving energy efficiency and human comfort.

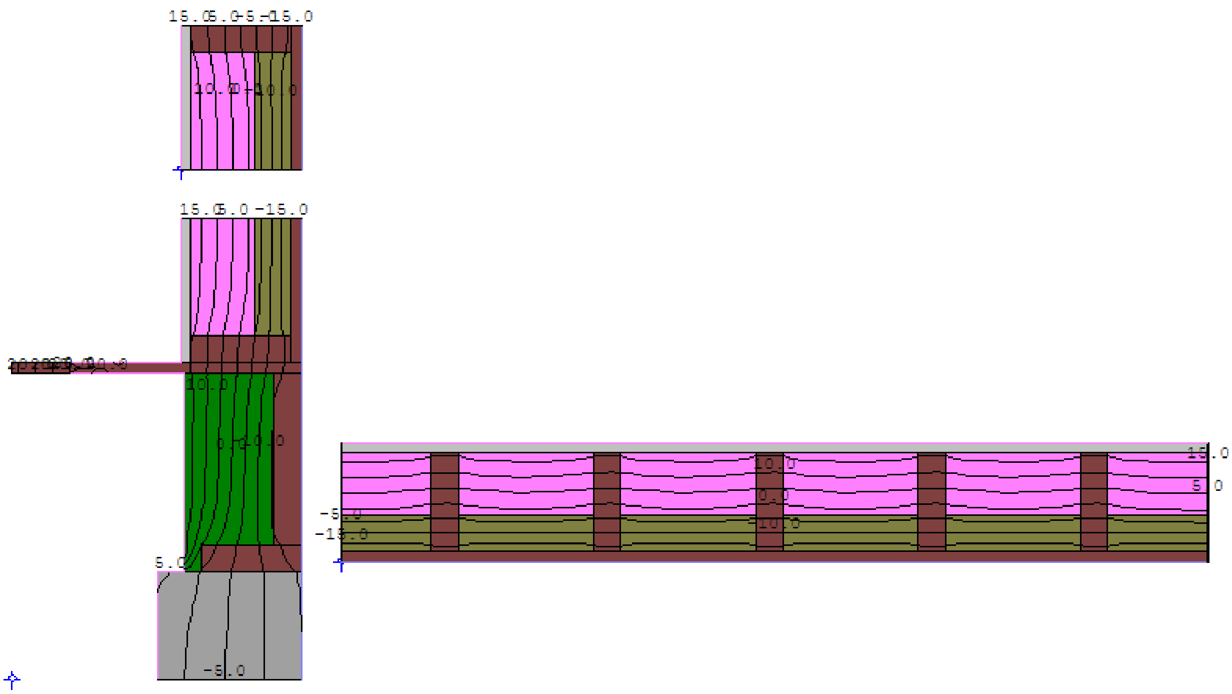

Figure 47 : Therm analysis of hybrid wall system

Table 12 : Calculated R-value for a hybrid wall system

Case	Description	Whole Wall R value	Rim Joist	Clear Wall R value	Top Plate
9	2x6 AF, 24"oc, 2" SPF and 3.5" fibrous fill	**17.5**	13.2	18.4	17.7

1.9.2. Moisture Control

This wall performs very similarly to the Case 2 with 4" of exterior insulation with respect to summer inward vapor drives as shown in Figure 19.

During the winter months, there is a significant improvement in the potential air leakage condensation on the condensation plane in the hybrid wall, from the standard construction wall, as shown in Figure 11 because the condensation plane is kept warmer by the vapor impermeable spray foam insulation.

One disadvantage of this wall system over advanced framing with exterior insulation (Case 2) is that the sheathing is kept much colder in Case 9. Keeping enclosure materials warm and dry with exterior insulation has been known to increase enclosure durability since the 1960s (Hutcheon 1964).

1.9.3. Constructability and Cost

The constructability of this system is as easy as standard construction but the cost of construction is higher than using exclusively fiberglass insulation. This wall system is not as prone to air leakage moisture related damage as standard construction walls.

1.9.4. Other Considerations

Adding high density spray foam insulation in the cavity increases the stiffness and strength of the wall systems. This could be particularly helpful in high wind loads or when impact resistance is required as in tornado or hurricane zones. Spray foam is the most reliable method to achieve air tightness in residential construction and comes with the added bonus of thermal insulation. High density foam is easy to transport to remote locations, and increases the moisture related durability of the enclosure.

1.10 Case 10: Double Stud Wall with Spray Foam

Case 10 with spray foam insulation was chosen to try and improve the moisture related durability of the double stud wall in Case 4 which used cellulose insulation in the cavity space. The thermal performance of Case 4 was quite good, but the air leakage condensation potential could lead to premature enclosure failure. Case 10 analysis was conducted with two inches of spray foam since that is usually the maximum thickness that is sprayed in one pass during 2.0 pcf foam installation. This should increase the temperature of the condensation plane, thus increasing the moisture durability of the wall system. Depending on the climate zone for construction, more spray foam could be used to further decrease the risk of moisture related damage. Analyzing different thicknesses of spray foam for this single wall system are beyond the scope of this analysis report, but should be considered before this wall is constructed.

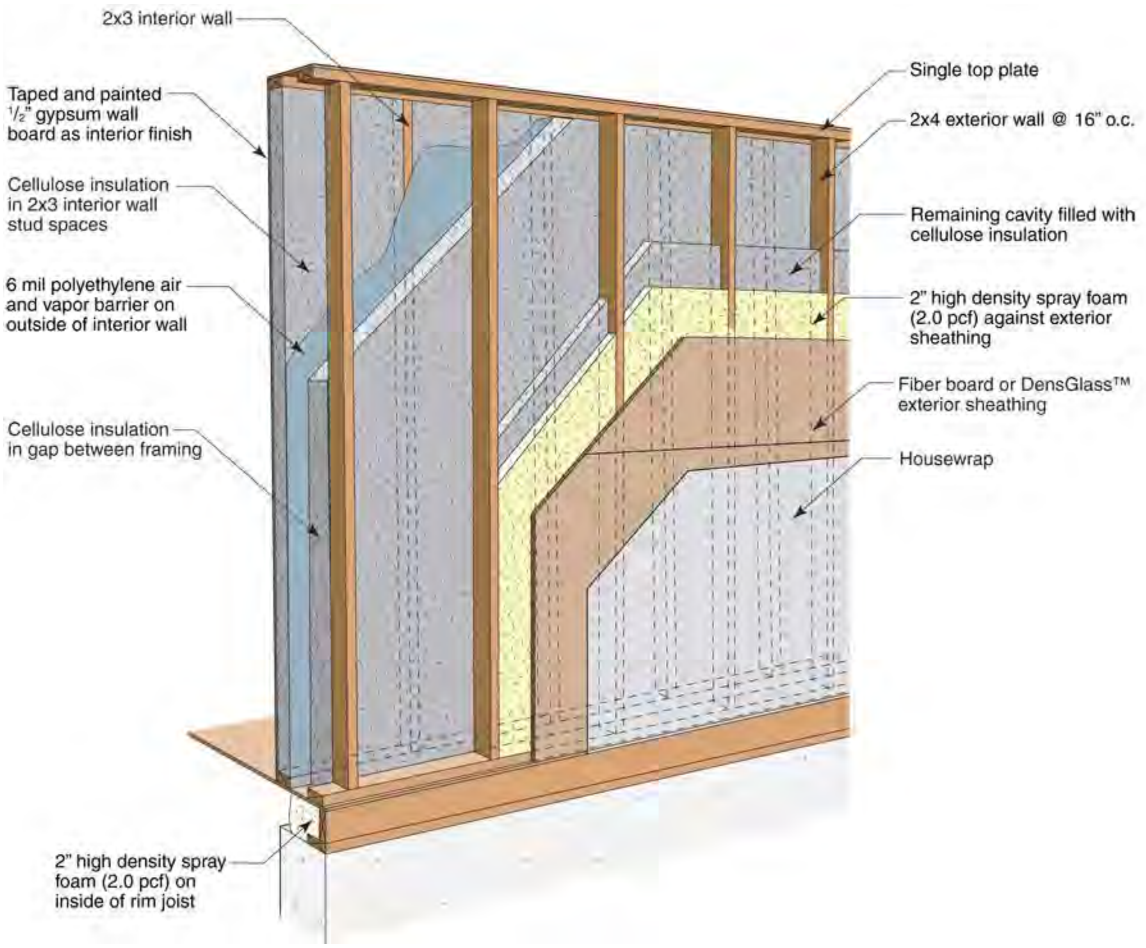

Figure 48 : Double stud wall with 2" of spray foam and cellulose fill

1.10.1. Thermal Control

This wall system has a slight improvement in whole wall R-value over Case 4, without spray foam insulation increasing from R30.1 to R32.4. This is only a minimal increase in the calculated whole wall R-value, but as in all cases with spray foam, there are improvements to the true R-value due to decreasing the air leakage through the wall and rim joist.

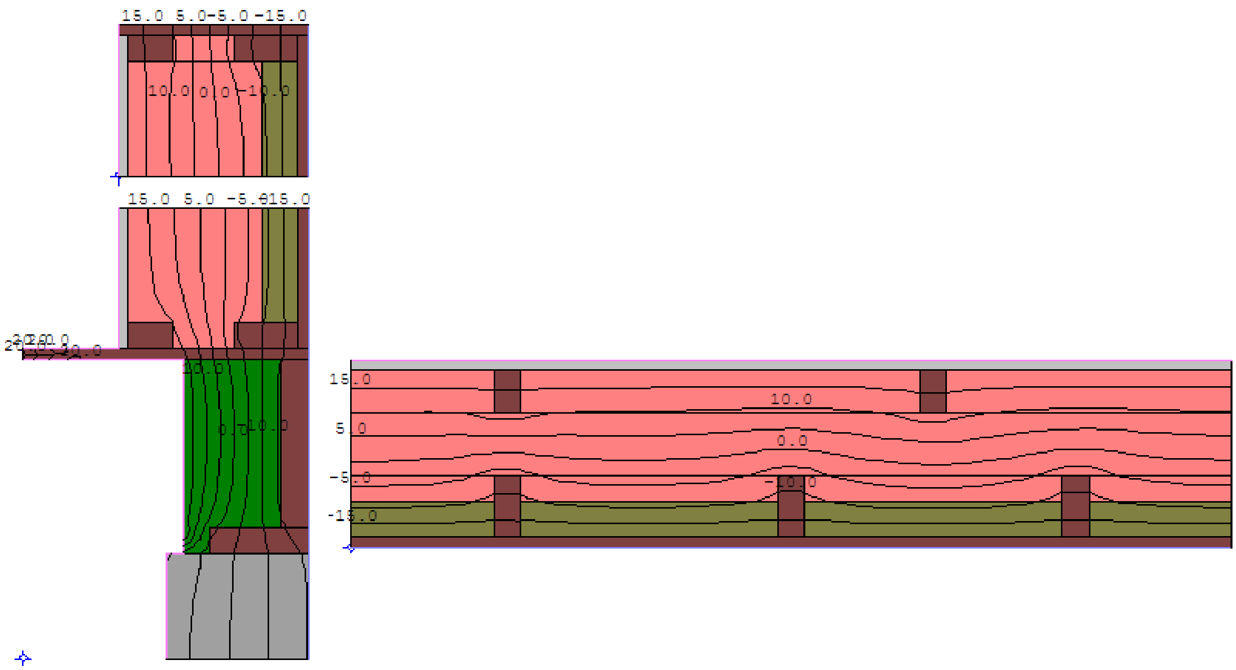

Figure 49 : Therm analysis of double stud wall construction with spray foam

Table 13 : Calculated whole wall R-value for a double stud wall system with 2" spray foam

Case	Description	Whole Wall R value	Rim Joist	Clear Wall R value	Top Plate
10	Double stud with 2" 2.0 pcf foam, 7.5" cell.	**32.4**	15.9	36.2	28.5

1.10.2. Moisture Control

The most evident improvement to adding spray foam was shown in Figure 14 with less wintertime condensation potential. There are still periods of wintertime condensation risk in climate zone 6, the risks have been improved, and more spray foam would decrease the risk even further in climate zone 6 and should likely be required in colder areas. The hours of potential wintertime condensation decreased from approximately 4600 hours for Case 4 to approximately 2300 for Case 10 with spray foam insulation.

There is very little change to the drying results when comparing the double stud wall with and without spray foam insulation. The sheathing retains its moisture longer in Case 10 because the moisture can only dry to the exterior and is not buffered at all on the interior surface by the cellulose insulation (Figure 27). There are no significant changes to the summertime inward vapor drive by adding 2" of high density spray foam to the sheathing of the double stud wall (Figure 21). If a moisture storage cladding was used for simulations, adding the spray foam may reduce the inward vapor drive because of the vapor resistance of the spray foam.

1.10.3. Constructability and Cost

This wall system uses more framing material than most of the other test wall assemblies. The cost of this wall system is high relative to most of the other options, but does provide very high thermal resistance.

1.10.4. Other Considerations

The majority of the insulation is cellulose which is the lowest embodied energy insulation and readily available. The ratio of cellulose to spray foam insulation can be changed depending on the climate zone for construction to limit the potential winter time condensation.

Spray foam will burn, and therefore should always be protected by fire rated material, which in this case is the cellulose insulation.

1.11 Case 11: Offset Frame Wall with Exterior Spray Foam

Case 11 was included because of the increasing need for a retrofit solution that saves energy, increases durability and does not affect the interior space. This strategy also has several advantages as a new construction strategy as well, especially in extreme climates with a short construction season.

Standing lumber off of the sheathing using plywood trusses allows the cladding to be directly attached without requiring more exterior sheathing. High density foam acts as the drainage plane, air barrier, vapor barrier, and thermal control layer. Using plywood gusseted trusses can be a little work intensive since they all need to be made to identical dimensions.

An alternative solution to the traditional truss wall is shown in Figure 15. This method is less energy intensive in preparation. It uses large nails or spikes to support the framing lumber for the cladding installation. A spacer was used between the sheathing and the framing lumber to ensure even spacing and then was removed after the nails were installed. Even though this method does not appear to be strong enough to support cladding, it has supported approximately 200 lbs on a single truss prior to installing the foam, and is considerably stronger following the installation of the spray foam. An alternative method proposed for spacing the lumber off of the sheathing is to use plastic sleeves (possibly PVC pipe) which are cut to a constant length and used to set the depth of the nails that attach the lumber by driving the nails through the centre of them.

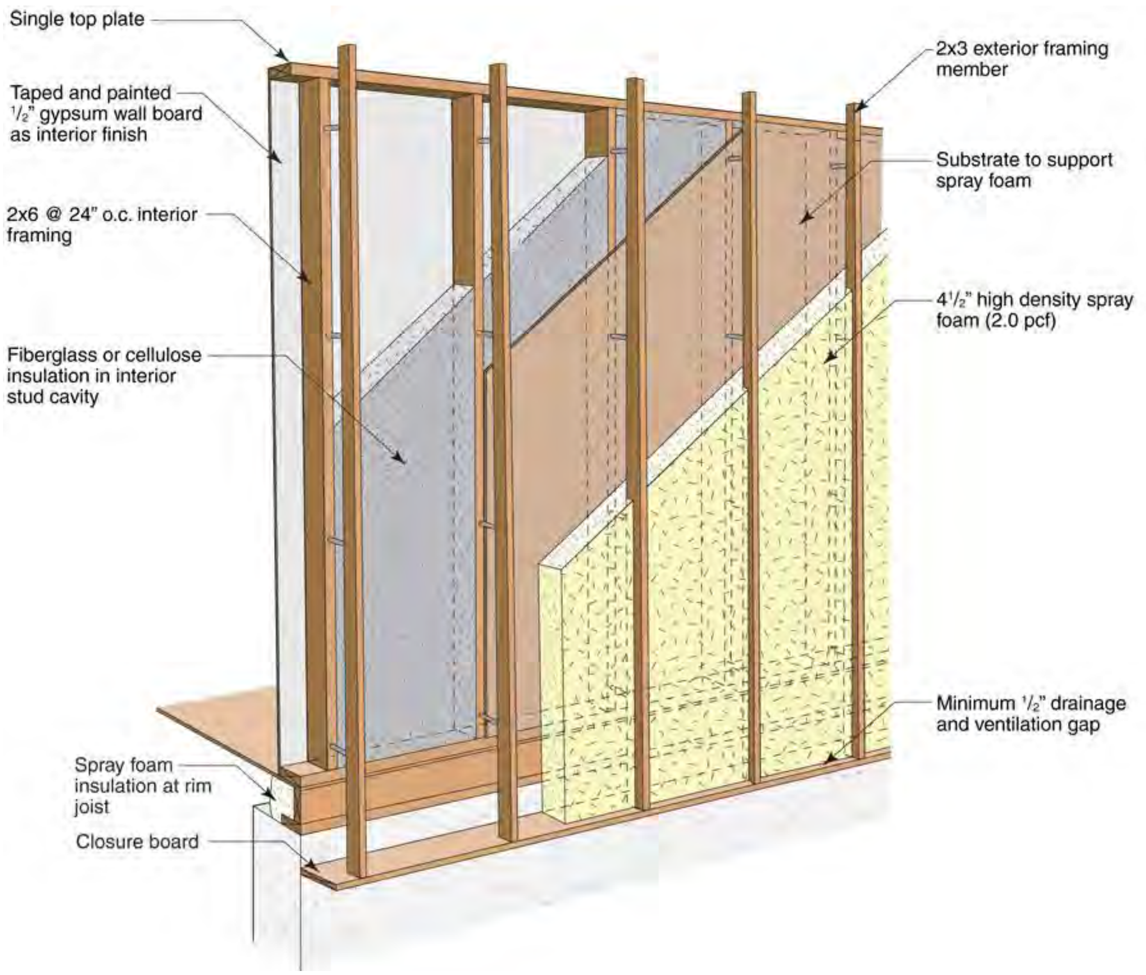

Figure 50 : Offset frame wall construction with exterior spray foam

1.11.1. Thermal Control

This wall with 4.5 inches of high density spray foam and 5.5 inches of fibrous insulation has a whole wall R-value of approximately R37, the highest total wall R-value of all walls analyzed which is, in part, because of the lack of thermal bridges through the entire system. Spray foam is installed over the rim joist, over the exterior of the wall, and up to the soffit, where ideally, it meets with the spray foam in the attic.

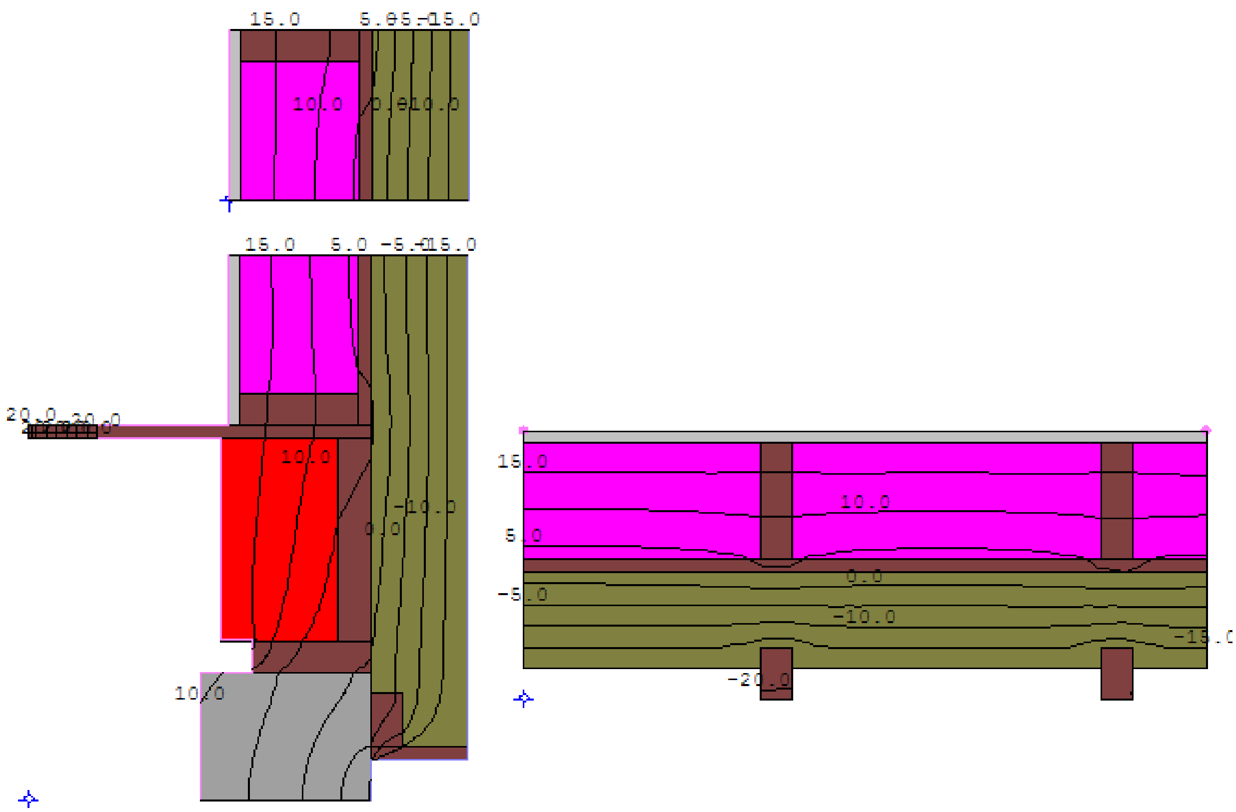

Figure 51 : Therm analysis of an offset truss wall with exterior spray foam

Table 14 : Calculated whole wall R-value for an offset framed wall with exterior spray foam

Case	Description	Whole Wall R value	Rim Joist	Clear Wall R value	Top Plate
11	Offset frame wall with ext. spray foam	**37.1**	18.8	40.6	41.9

1.11.2. Moisture Control

Because of the high level of vapor control in the exterior spray foam insulation, a vapor barrier is not required on the interior of the wall assembly. This allows any necessary drying to occur to the interior. In Minneapolis, (climate zone 6) there is no risk of winter time condensation on the interior of the exterior sheathing (Figure 16).

The summer time inward vapor drive sheathing relative humidity does not change significantly with the addition of the exterior foam (Figure 23). The relative humidity increases slightly in Case 11 because of the higher interior relative humidity, the low solar inward vapor drive load, and the inability for the exterior spray foam wall to dry to the outside.

The sheathing remains wet during the drying test significantly longer with exterior insulation than without since there is no moisture buffering capacity in the fiberglass batt in Case 11, and there is significant moisture buffering capacity of the cellulose insulation in Case 5 (Figure 28).

1.11.3. Constructability and Cost

High density spray foam is a relatively expensive choice for an insulation strategy. In this case, it provides great thermal resistance, reduced thermal bridging, and minimal air leakage. Some of these benefits will result into operating energy costs savings, but other benefits can not be easily quantified such as greater occupant comfort, and quite possibly higher resale value in an uncertain energy future.

1.11.4. Other Considerations

This method could be used as a retrofit without greatly affecting the interior, or for new construction. It is a very quick, high quality method of sealing the exterior and drying in the interior during construction, so that care can be taken with the interior work including wiring, plumbing and HVAC. This is ideal for locations with short construction seasons. Since the foam is transported in liquid phase, more board feet of foam (and R-value) can be transported on a transport truck than any other type of insulation

1.12 Case 12: Exterior Insulation Finish System (EIFS)

Using an exterior insulation finish system (EIFS) is a valid option for cladding in almost every climate zone. The thickness of the exterior insulation can be varied to provide the thermal resistance required in combination with the stud space insulation. EIFs was one of the cladding strategies used on the CCHRC head office in Fairbanks AK (13980 HDD65 or 7767 HDD18) which is considered to be an extremely cold climate.

There is a stigma attached to EIFS because of the large number of failures in various climates in the past. Field and laboratory observations and testing have shown that this cladding technique is an effective and durable wall assembly, if drainage and water management details are constructed correctly. In most cases, during failures, water was trapped behind the EIFS due to poor water management details which eventually rotted the sheathing, causing corrosion and rot of the wall assembly. A properly detailed continuous drainage plane will ensure that this is a successful cladding technique in any climate zone.

Fiberglass-faced gypsum board exterior sheathing was used instead of OSB in the simulation because it is generally used underneath EIFS cladding systems due to its moisture tolerance.

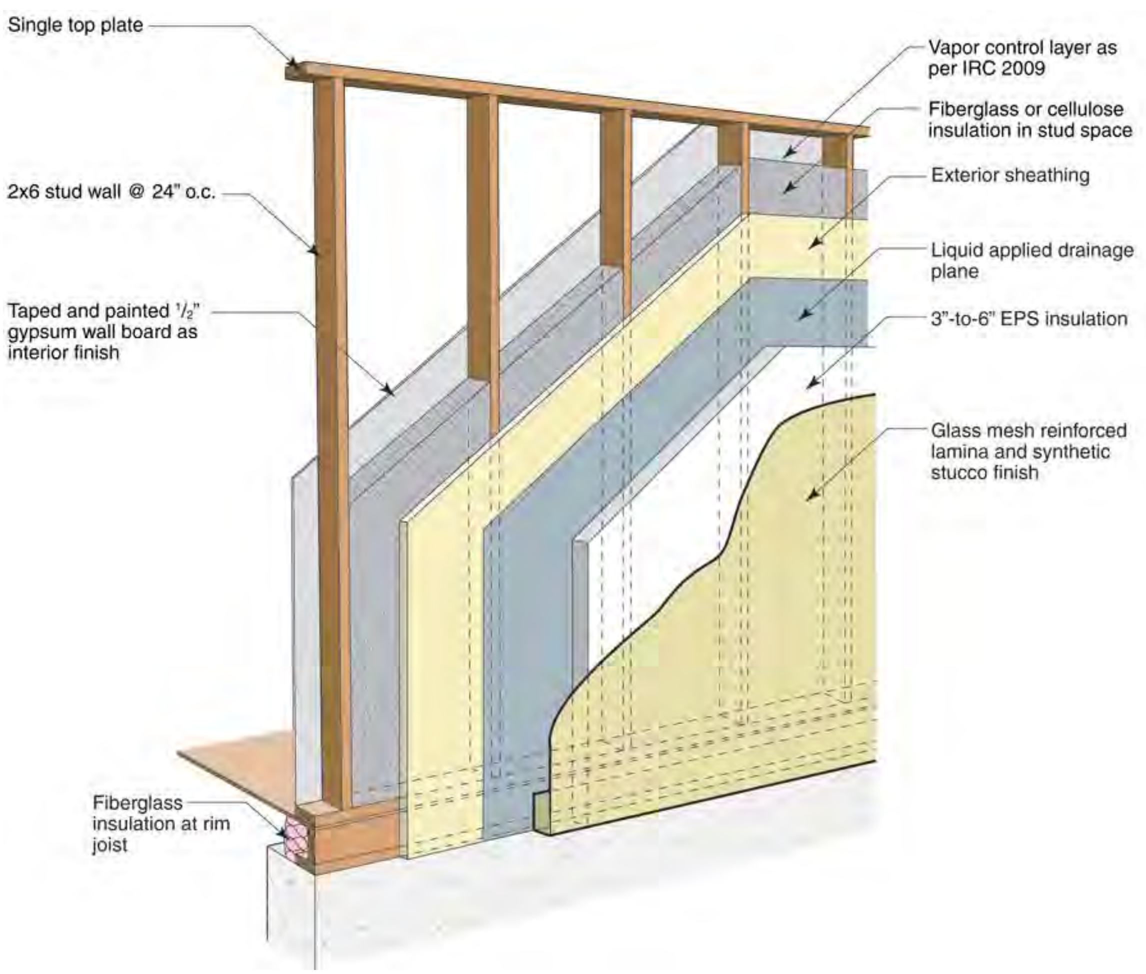

Figure 52 : Wall construction using the EIFS cladding system

1.12.1. Thermal Control

The amount of insulation installed on the exterior of the advanced framing will determine the thermal control of the assembly. In this analysis we used four inches of EPS board foam insulation, and achieved a whole wall R-value of R30. This strategy addresses the thermal bridging of both the framing and the rim joist and is very similar to advanced framing with four inches of XPS insulation in Case 2.

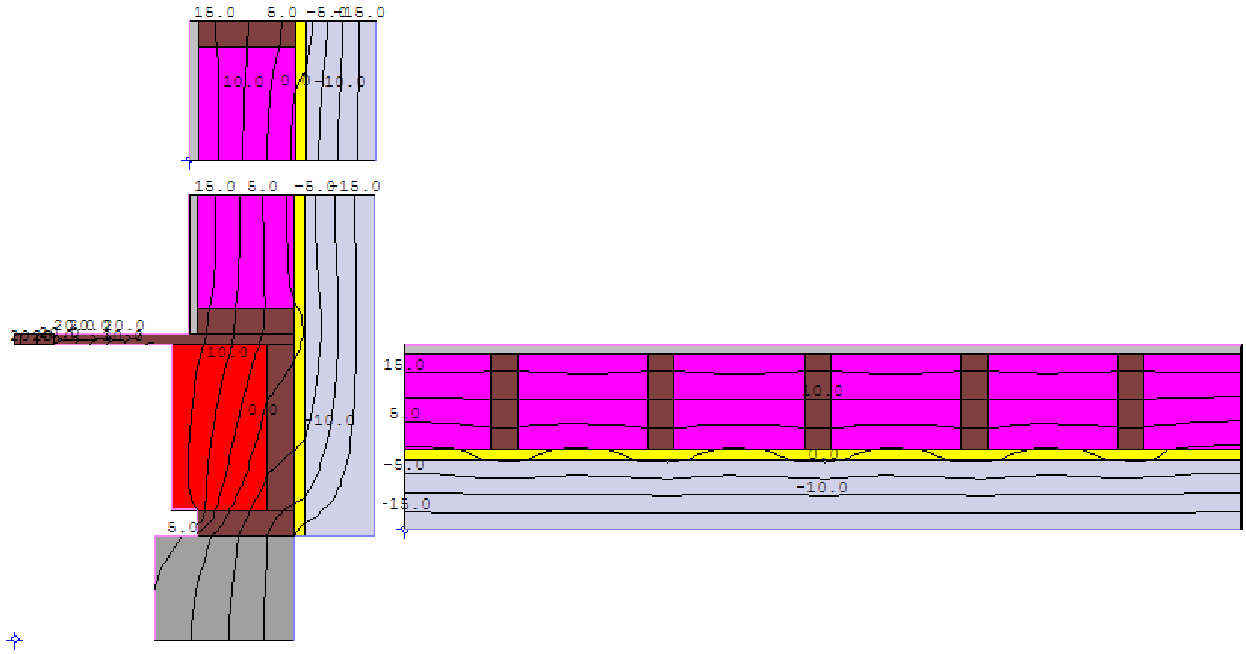

Figure 53 : Thermal analysis of an EIFS wall system

Table 15 : Calculated whole wall R-value for a EIFS wall system with 4" of EPS

Case	Description	Whole Wall R value	Rim Joist	Clear Wall R value	Top Plate
12	2x6 AF, 24"oc, EIFS - 4" EPS	**30.1**	23.8	31.4	31.1

1.12.2. Moisture Control

The moisture management details for this cladding type can be challenging but EIFS companies generally provide good documentation and design details with their product. For example, both Sto Corp and Dryvit Systems provide many details for all of their products on their websites to help builders and designers with moisture management details.

The performance of this wall system was nearly identical in winter time condensation, drying and summer time inward vapor drives to Case 2 with 4" of XPS insulation. EPS is more vapor permeable than XPS insulation, but laminate coating applied to the EPS insulation is usually less than 1 US perm.

1.12.3. Constructability and Cost

Because of the stucco appearance of this cladding system, it can be more expensive depending on the architectural detailing. EIFS is generally only done if the appearance of stucco is specifically desired. It is approximately the same performance and cost to use advanced framing with four inches of XPS insulation and cladding.

1.12.4. Other Considerations

EIFS are generally chosen when the owner or architect wants a stucco finish on a building. There are no significant performance differences between EIFS and the advanced framing with exterior insulation shown in Case 2. Both strategies minimize thermal bridging, and increase the temperature of the potential wintertime air leakage condensation plane. The main differences are the appearance of the finished cladding surface and water drainage details.

D. Conclusions

Whole wall R-values for all of the assemblies were calculated using Therm and the summary is shown in Table 16 below. In some of the analyzed cases, different types or thicknesses of insulation may be used depending on climate zone and local building practice. An attempt was made to choose the most common strategies and list all assumptions made for wall construction.

Table 16 : Summary of all calculated R-values

Case	Description	Whole Wall R-value	Rim Joist	Clear Wall R-value	Top Plate
1bii	2x4, 16"oc, R13FG + OSB (25%ff)	**10.0**	9.8	10.1	9.8
1b	2x4 AF, 24"oc, R13FG + OSB	**11.1**	9.8	11.5	9.8
1aii	2x6, 16"oc, R19FG + OSB (25%ff)	**13.7**	12.3	14.1	12.5
6a	SIPs (3.5" EPS)	**14.1**	12.3	14.5	10.6
1a	2x6 AF, 24"oc, R19FG + OSB	**15.2**	12.3	16.1	12.5
7a	ICF - 8" foam ICF (4" EPS)	**16.4**		16.4	
8b	2x6 AF, 24" o.c., 5.5" R21 0.5 pcf SPF, OSB	**16.5**	13.1	17.2	16.6
7c	ICF - 14" cement woodfiber ICF with Rockwool	**17.4**		17.4	
9	2x6 AF, 24"oc, 2" SPF and 3.5" cellulose	**17.5**	13.2	18.4	17.7
8a	2x6 AF, 24" o.c., 5" 2 pcf R29 SPF, OSB	**19.1**	13.6	20.3	19.5
2a	2x6 AF, 24"oc R19FG + 1" R5 XPS	**20.2**	18.5	20.6	20.3
7b	ICF - 15" foam ICF (5" EPS)	**20.6**		20.6	
3	2x6 AF, 24"oc, 2x3 R19+R8 FG	**21.5**	13.4	23.5	18.4
4	Double stud wall 9.5" R34 cellulose	**30.1**	14.4	33.5	28.8
12	2x6 AF, 24"oc, EIFS - 4" EPS	**30.1**	23.8	31.4	31.1
10	Double stud with 2" 2.0 pcf foam, 7.5" cell.	**32.4**	15.9	36.2	28.5
2b	2x6 AF, 24"oc R19FG + 4" R20 XPS	**34.5**	29.0	35.6	35.4
6b	SIPs (11.25" EPS)	**36.2**	14	41.6	28.2
5	Truss wall 12" R43 cellulose	**36.5**	18.6	40.5	34.4
11	Offset frame wall with ext. spray foam	**37.1**	18.8	40.6	41.9

*AF - Advanced Framing

The walls analyzed in this report can be grouped into three groups based on their calculated whole wall R-values. The first group have whole wall R-values less than approximately R20. These walls are not considered High-R wall systems for cold climates.

The second group of walls have whole wall R-values of approximately R-20. According to the IECC, the requirement for climate zones 7 and 8 is an installed R-value of R21. This report has shown that the whole R-value is less than the installed insulation R-value in almost every case, which means that often, the walls that the IECC allow in extremely cold climates are actually performing at a whole wall R-value of between R15 and R20. This is unacceptable in the future of uncertain oil reserves, increasing energy costs, and decreasing environmental health.

The third group of walls have whole wall R-values greater than R30. This is what the construction industry has been achieving in very small numbers, such as Building America prototype homes, and small custom home builders. The R-value of walls in the category can be modified easily by either decreasing or increasing the amount of insulation depending on the specific construction conditions. All of the walls in category three have minimized thermal bridging which increases the effectiveness of insulation.

The potential for wintertime air leakage was compared for all test walls, and the summary of the results are shown in Table 17. The walls were ranked from the least hours of potential condensation to the greatest. This potential condensation is only an issue if the airtightness details aren't constructed properly, but should still be used to assess the potential risk of a wall system, considering that field observations show the air barrier detailing is rarely perfect.

Table 17 : Hours of potential winter time air leakage condensation

Case	Description	Hours of Potential Condensation
8b	2x6 AF, 24" o.c., 5.5" R21 0.5 pcf SPF, OSB	0
8a	2x6 AF, 24" o.c., 5" 2 pcf R29 SPF, OSB	0
11	Offset frame wall with ext. spray foam	0
9	2x6 AF, 24"oc, 2" SPF and 3.5" cell or FG	934
2b	2x6 AF, 24"oc R19FG + 4" R20 XPS	1189
12	2x6 AF, 24"oc, EIFS - 4" EPS	1532
10	Double stud with 2" 2.0 pcf foam, 7.5" cell.	2284
2a	2x6 AF, 24"oc R19FG + 1" R5 XPS	3813
1a	2x6 AF, 24"oc, R19FG + OSB	4379
1b	2x4 AF, 24"oc, R13FG + OSB	4503
4	Double stud wall 9.5" R34 cellulose	4576
3	2x6 AF, 24"oc, 2x3 R19+R8 FG	4594
5	Truss wall 12" R43 cellulose	4622

*AF - Advanced Framing

The comparison matrix explained in the introduction was completed according to the analysis of each wall section in this report (Table 18), and it was found that three walls achieved the highest score of 20 out of a possible 25 points. The advanced framing wall (Case 2), sprayfoam insulation wall (Case 8) and EIFS wall (Case 12) achieved scores of 20 using an even weighting system of all selection criteria.

The main issue with most of the wood framed walls without exterior insulation is the probability of wintertime air leakage condensation depending on the quality of workmanship and the attention to detail. Inspections of production builder construction quality leads to skepticism regarding the quality of the air barrier in most wall systems. It is always good building practice to design enclosures that will perform as well as possible regardless of the human construction factor.

Table 18 : Wall Comparison Chart

	Thermal Control	Durability (wetting/drying)	Buildability	Cost	Material Use	Total
Criteria Weighting	1	1	1	1	1	
Case 1: Standard Construction	1	3	5	5	3	17
Case 2: Advanced Framing with Insulated Shtg	4	4	4	4	4	20
Case 3: Interior Strapping	3	3	3	4	4	17
Case 4: Double Stud	4	3	3	3	2	15
Case 5: Truss Wall	4	3	2	3	3	15
Case 6: SIPs	4	4	3	3	3	17
Case 7: ICF	4	5	4	2	3	18
Case 8: Sprayfoam	5	5	4	2	4	20
Case 9: Flash and Fill (2" spuf and cell.)	4	4	4	3	4	19
Case10: Double stud with 2" spray foam and cell.	5	4	3	3	3	18
Case 11: Offset Framing (ext. Spray foam insul.)	5	5	4	3	2	19
Case 12: EIFS with fibrous fill in space	5	5	4	3	3	20

Adding exterior insulation to most wall systems has many durability and energy benefits. Two dimensional heat flow modeling has shown that exterior insulation is very effective at minimizing the thermal bridging losses of wall framing, and hygrothermal modeling showed reduced condensation potential in the wall from vapor diffusion and air leakage, as well as increased drying potential to the interior with reasonable interior relative humidities. Adding exterior insulation was shown to increase the effectiveness of the fiberglass batt insulation in the stud space and increase the clear wall R-value greater than the amount of insulation added. This becomes even more important with higher thermal bridging such as a high framing factor or steel studs. Adding exterior insulation greater than approximately R5, the installed insulation R-value can be added directly to the clear wall R-value and is approximately equal to the increase in whole wall R-value since most of the thermal bridging is addressed.

Hygrothermal modeling showed that traditional double stud walls, truss walls and interior strapped walls, are at a greater risk of air leakage condensation because of the air permeable insulation, and cold exterior surface. Hybrid walls are a good strategy to help overcome this problem by using vapor impermeable spray foam insulation against the exterior, which increases the temperature of the condensation plane. The amount of spray foam required in a hybrid system is dependent on the climate zone for construction, but it may be difficult to get a high enough R value or thermal bridge control in cold climates for net zero housing.

ICF and SIPS walls both have insulation integral to the system, but require more insulation for a High R value wall assembly. Experience and modeling indicate that both of these techniques are susceptible to moisture issues if the details are not done correctly. SIPS are particularly susceptible to air leakage at the panel joints, and ICF walls need well designed penetrations, to avoid water ingress.

In extreme cold climates, and remote areas, high density spray foam appears to address most of the concerns that have been reported by NRC during visits and interviews with local residents. High density spray foam is easy to ship and install, not subject to damage during transit, and allows some variations in construction quality levels since it is both an air and vapor barrier. High density spray foam can be used in different wall construction strategies as demonstrated in this report, either on its own or as part of an insulation strategy with other insulations types. An offset frame wall with high density spray foam has the added advantage of drying in a house very quickly in the short construction season so that work can be done on the interior during inclement weather.

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About this Report

This report was prepared with the cooperation of the U.S. Department of Energy's, Building America Program.

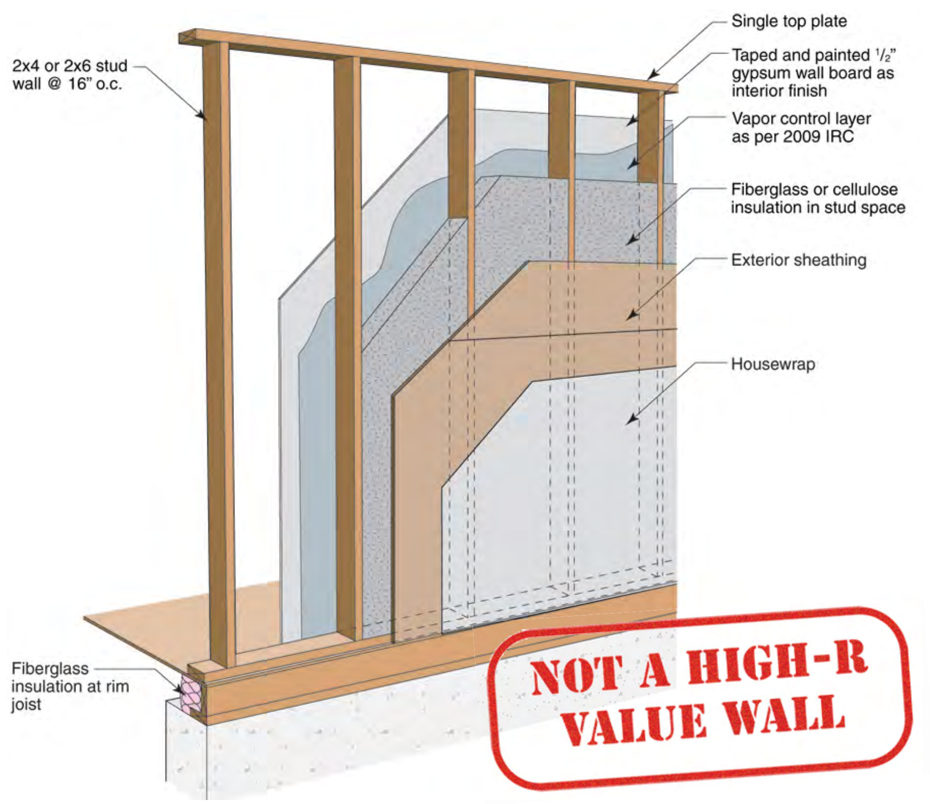
Direct all correspondence to: Building Science Corporation, 30 Forest Street, Somerville, MA 02143.

Limits of Liability and Disclaimer of Warranty:

Standard Wall Construction

Standard Wall Construction Details (*Walls 1A and 1B*)[1]

- 2x4 or 2x6 framing
- Fiberglass or cellulose cavity insulation in stud space
- Exterior sheathing
- Housewrap



Scoring: How It Rates

The scoring of each wall system is based on the following five categories. A score of 1 is the lowest score in each category and represents the worst possible technology for each category or highest possible relative cost. A score of 5 is the highest score available in each category, and is representative of the best available technology available on the market or lowest relative cost.

Thermal Control	1
Durability	3
Buildability	5
Cost	5
Material Use	4
Total	**18**

This wall has been the standard of construction for many years in many places but no longer meets the energy code requirements for insulation in some climates. Many higher performance designs exist.

Introduction

This two page summary briefly summarizes standard wall construction including the advantages and disadvantages of this construction strategy. A more detailed analysis and direct comparison to several other walls can be found online.[1] The scoring system is somewhat subjective based on the relative performance and specifications between different wall systems. Complex two dimensional heat flow analysis and one dimensional hygrothermal modeling were used to determine moisture related durability risks for analysis.

For a more complete analysis of this and other wall constructions, go to www.buildingscience.com.

Thermal Control

Installed Insulation R-value: There is a range of installed insulation R-values in commercially available fiberglass batts. The installed insulation R-value for 2x4 fiberglass batt ranges between R-11 and R-15 and for 2x6 the range is between R-19 and R-22. When blown or sprayed cellulose insulation is used, the R-values are typically R-13 for 2x4 and R-20 for 2x6 walls.

Whole-wall R-value: Using two dimensional heat flow analysis with thermal bridging effects and average framing factors, a 2x4 wall with R-14 studspace insulation has a whole-wall R-value of R-9. Similarly a 2x6 wall with R-19 stud space insulation has a whole wall R-value of R-11.[1] The framing factor used for standard construction framing 16 inches on center is 25%.[2] These whole wall R-values could decrease even further if there is significant air leakage or convective looping, or increased framing factor.

Air Leakage Control: Fiberglass batt, and both blown and sprayed cellulose are air permeable materials allowing possible air paths between the interior and exterior as well as convective looping in the insulation. Although densepack cellulose has less air permeance it does not control air leakage.

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Typical Insulation Products: Fiberglass batt, blown fiberglass, blown cellulose, sprayed cellulose

Durability

Rain Control: Rain leakage into the enclosure is the leading cause of premature building enclosure failure. Rain control is typically addressed using a shingle lapped and/or taped drainage plane such as building paper or a synthetic WRB (i.e. homewrap). Intersections, windows, doors and other penetrations must be drained and/or detailed to prevent the penetration of rain water beyond the drainage plane.[3]

Air Leakage Control: Air leakage condensation is the second largest cause of premature building enclosure failure with this type of wall construction. It is very important to control air leakage to minimize air leakage condensation durability issues. An air barrier is required in this wall system to ensure that through-wall air leakage is eliminated (ideally) or at least minimized. An air barrier should be stiff and strong enough to resist wind forces, continuous, durable, and air impermeable.[4]

Air need not leak straight through an assembly to cause moisture problems; it can also leak from the inside, through the wall, and back to the inside; or it can leak from the outside, through the wall, and back to the outside. Condensation within the studspace is possible if this type of airflow occurs, depending on the weather conditions. Hence, wall designs should control airflow into the studspace.[5]

Vapor Control: Fiberglass and cellulose are highly vapor permeable materials, so a separate vapor control strategy must be employed to ensure that vapor diffusion does not result in condensation on, or damaging moisture accumulation in, moisture sensitive materials. The permeance and location of vapor control is dependent on the climate zone. Installing the vapor control layer in the incorrect location can lead to building enclosure failure.[6] The IRC building code should be consulted.

Drying: Cellulose and fiberglass insulation allow drying to occur relatively easily, so drying is controlled by other more vapor impermeable enclosure components such as the vapor barrier and OSB sheathing. Installing vapor control on both sides will seal any moisture into the stud space, resulting in low drying potential, and possibly resulting in moisture-related durability risks. Ventilation behind vapor impermeable claddings and interior components (e.g. kitchen cabinets) can encourage drying.

Built- in Moisture: Care should always be taken to build with dry materials where possible, and allow drying of wet materials before close in. Cellulose is often sprayed in damp, and manufacturers recommend drying before close in and moisture content limits. Because of the polyethylene vapor barrier required in many climates, and relatively vapor impermeable OSB sheathing, drying could be slow if built-in moisture is present.

Durability Summary: The primary durability risks associated with these wall assemblies involve moisture damage related to rain water penetration or condensation (most likely the result of air leakage, but also potentially the result of vapor diffusion).

Cellulose insulated walls are slightly more durable because cellulose insulation is capable of storing and redistributing small amounts of moisture. Cellulose insulation is typically treated with borates that have been shown to protect itself and neighboring wood material from mold growth and decay. Cellulose insulation also has decreased flame spread potential relative to other insulation materials.

Buildability

Wood-framed walls with OSB exterior sheathing and fiberglass or cellulose insulation represent the most common wall assembly used in the construction of low-rise residential buildings in North America. Designers, trades and supply chains are well equipped to produce these walls and education is primarily needed to improve durability through better rainwater control and thermal performance through better air tightness and insulating practices.

Cost

The cost to build this type of wall is well accepted, and is used as a baseline. Costs vary tremendously from region to region.

Material Use

This wall design contains redundant wood framing and wood sheathing. Framing lumber could be minimized further if advanced framing was used. In most of America, much of the sheathing could be removed. Cellulose has a significantly lower embodied energy than fiberglass or rockwool.

Total Score

This wall has been the standard of construction for many years in many places. This wall no longer meets the energy code requirements for insulation in many climates, and thermal control requirements will only continue to increase. This wall system is difficult to air seal adequately and prone to air leakage related condensation and energy losses. Using advanced framing will reduce framing materials, and the cost of framing. Although this construction technique is usually allowed by code, many higher performance designs exist.

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1. Straube, J., & Smegal, J. (2009). *Building America Special Research Project - High-R Walls Case Study Analysis.* Retrieved from buildingscience.com.
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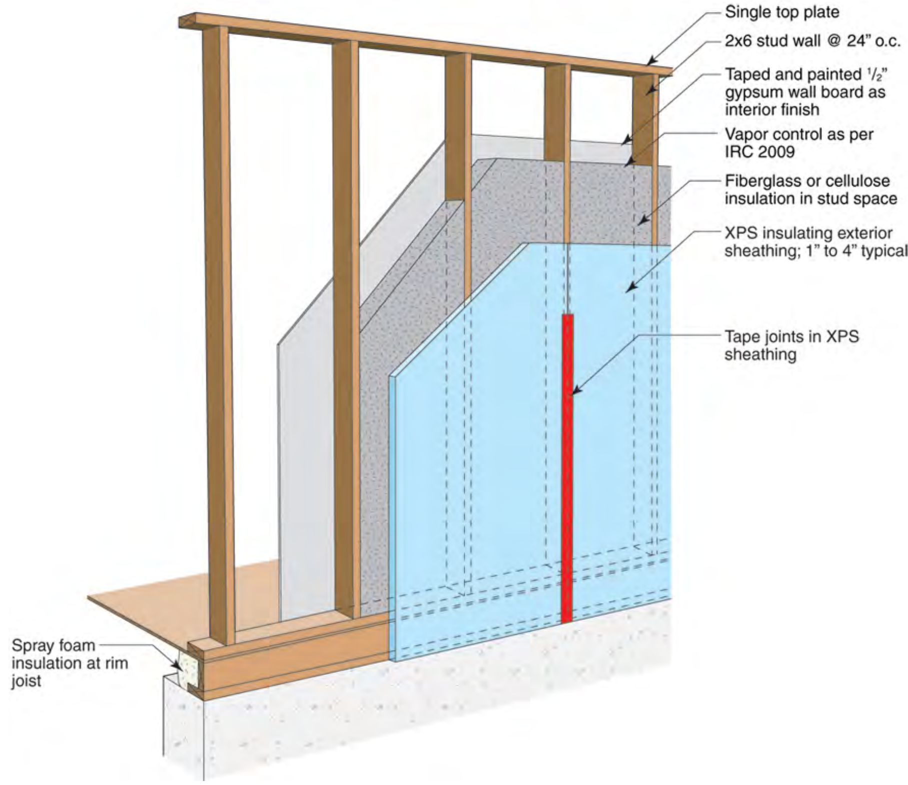
2x6 Advanced Frame Wall Construction

2x6 Advanced Frame Wall Construction Details

(*Walls 2A and 2B*)[1]

- 2x6 framing
- XPS insulating sheathing
- Fiberglass or cellulose cavity insulation in stud space



Scoring: How It Rates

The scoring of each wall system is based on the following five categories. A score of 1 is the lowest score in each category and represents the worst possible technology for each category or highest possible relative cost. A score of 5 is the highest score available in each category, and is representative of the best available technology available on the market or lowest relative cost.

Thermal Control	4
Durability	4
Buildability	4
Cost	4
Material Use	4
Total	**20**

Advanced framing with insulated sheathing significantly reduces the thermal bridging through the enclosure and improves the thermal efficiency of the fiberglass batt in the stud space. Using insulated sheathing decreases the potential for both wintertime condensation, and summer inward vapor drives, and helps mitigate issues caused by poor construction practices.

Introduction

This two page summary briefly summarizes 2x6 advanced frame wall construction including the advantages and disadvantages of this construction strategy. A more detailed analysis and direct comparison to several other walls can be found online.[1] The scoring system is somewhat subjective based on the relative performance and specifications between different wall systems. Complex two dimensional heat flow analysis and one dimensional hygrothermal modeling were used to determine moisture related durability risks for analysis.

For a more complete analysis of this and other wall constructions, go to www.buildingscience.com.

Thermal Control

Installed Insulation R-value: There is a range of installed insulation R-values in commercially available fiberglass batts for the stud space insulation in this wall system. The installed insulation R-value for 2x4 fiberglass batt ranges between R-11 and R-15 and for 2x6 the range is R-19 and R-22. When blown or sprayed cellulose insulation is used, the R-values are typically R-13 for 2x4 walls and R-20 for 2x6 walls.

Exterior insulating sheathing is typically added as expanded Ppolystyrene (EPS) at R-4/inch, extruded polystyrene (XPS) at R-5/inch or foil-faced polyisocyanurate at R-6.5/inch.

Whole-wall R-value: Two-dimensional heat flow analysis with thermal bridging effects and average framing factors (16%) shows increases the R-value of the assembly and improvements to the efficiency of the fiberglass batt in the stud space by decreasing the thermal bridging effects. Advanced framing walls with 1" and 4" of XPS insulated sheathing have whole wall R-values of R-20 and R-34 respectively.[1]

Air Leakage Control: Fiberglass, blown and sprayed cellulose are air permeable materials used in the stud space of the wall allowing possible air paths between the interior and exterior as well as convective looping in the insulation. Densepack cellulose has less air permeance but

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does not control air leakage. Insulating sheathing (EPS, XPS and foil-faced polyisocyanurate board foam) products are air impermeable. When joints between panels of insulation and the insulation and framing are properly sealed with tape, mastic, caulk, etc., an effective air barrier system can be created at the exterior sheathing.

Typical Insulation Products: Fiberglass batt, blown cellulose, sprayed cellulose, and sprayed fiberglass are typically used to insulate the stud space. Expanded polystyrene (EPS), extruded polystyrene (XPS) and foil-faced polyisocyanurate (PIC) board foam are used as the exterior insulating sheathing. Spray foam is used at the rim joist to control air leaks.

Durability

Rain Control: Rain leakage into the enclosure is the leading cause of premature building enclosure failure. Rain control is typically addressed using a shingle lapped and/or taped drainage plane such as building paper or a synthetic WRB (i.e. homewrap). It is possible to use insulated sheathing as the drainage plane if all the intersections, windows, doors and other penetrations are connected to the surface of the insulated sheathing in a watertight manner, and the seams of the insulation are taped or flashed to avoid water penetration.[2]

Air Leakage Control: Air leakage condensation is the second largest cause of premature building enclosure failure with this type of wall construction. It is very important to control air leakage to minimize air leakage condensation durability issues. Using insulating sheathing decreases the risk of air leakage condensation by increasing the temperature of the condensation plane, but condensation is still possible with insulated sheathing in cold climates. An air barrier is required in this wall system to ensure that through-wall air leakage is eliminated (ideally) or at least minimized.[3] An air barrier should be stiff and strong enough to resist wind forces, continuous, durable, and air impermeable.[4]

Vapor Control: Fiberglass or cellulose in the stud cavity are vapor permeable, while EPS, XPS and PIR are moderately permeable, moderately impermeable and completely impermeable respectively.

Insulated sheathing reduces the risk of wintertime condensation by increasing the temperature of the condensation plane, and reduces the risk of summer time inward vapor drives by slowing the vapor movement into the enclosure from storage claddings such as masonry or stucco. The level of vapor control in insulated sheathing walls is determined in the IRC and should be consulted as installing the incorrect vapor control layer or installing the vapor control layer in the incorrect location can lead to building enclosure failure.[5]

Drying: Insulating sheathing limits the drying to the exterior, and the wall must be able to dry to the interior. Poly vapor barriers are typically avoided so that this drying can occur. The minimum level of vapor control on the interior surface is determined by the IRC. Installing vapor control on both sides of the enclosure will seal any moisture into the stud space, resulting in low drying potential, and possibly resulting in moisture-related durability risks. Ventilation behind vapor impermeable claddings and interior components (e.g. kitchen cabinets) can encourage drying.

Built- in Moisture: Care should always be taken to build with dry materials where possible, and allow drying of wet materials before close in. Cellulose is often sprayed in damp, and manufacturers recommend drying before close in and moisture content limits.

Durability Summary: The primary durability risks associated with these wall assemblies involve moisture damage related to rain water penetration. Condensation (most likely the result of air leakage, but also potentially the result of vapor diffusion) is decreased with insulated sheathing but may still occur, although the insulating sheathing is less susceptible to moisture related risks than structural OSB sheathing.

Buildability

Exterior insulation up to 1.5" requires minimal changes to standard enclosure construction practices. Exterior insulation in excess of 1.5" requires changes to window and wall construction and detailing which requires training and monitoring during the initial implementation.

Cladding can be easily attached to the studs directly through 1" of insulated sheathing. Thicker levels of insulation (>2") require strapping or furring strips)anchored to the framing with long fasteners. Some cladding manufacturers allow their cladding to be fastened to the strapping directly.

Cost

Advanced framing wall construction decreases the cost required for framing. There is a slight increase in cost for the insulating sheathing to replace most of the structural wood sheathing, but there are measureable cost benefits of saving energy, as well as improvements to comfort, which is difficult to quantify.

Material Use

If advanced framing is applied correctly (single top plates, correctly sized headers, two stud corners, etc.) the redundant wood framing from standard construction is removed, and the amount of framing will decrease. Using insulated sheathing instead of structural wood sheathing may require using structural panels or bracing in some locations.

Total Score

Advanced framing with insulating sheathing is a logical choice as the minimum level of construction in most climates considering the more demanding insulation levels required for new construction in many climates. Using insulated sheathing can decrease the potential for both wintertime condensation, and summer inward vapor drives, and help mitigate issues caused by poor construction practices.

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1 Straube, J., & Smegal, J. (2009). *Building America Special Research Project - High-R Walls Case Study Analysis*. Retrieved from buildingscience.com.

2 Lstiburek, J. W. (2006). *Water Management Guide.* Westford: Building Science Press Inc.

3 Lstiburek, J. (2008, 08 20). *BSD-104: Understanding Air Barriers*. Retrieved from buildingscience.com.

4 Straube, J. (2009, 04 22). *BSD-014 Air Flow Control in Buildings.* Retrieved from buildingscience.com.

5 Lstiburek, J. (2008, 10 17). *BSD-106 Understanding Vapor Barriers*. Retrieved from buildingscience.com.

Interior Strapping Wall Construction

Interior Strapping Wall Construction Details (*Wall 3*)[1]

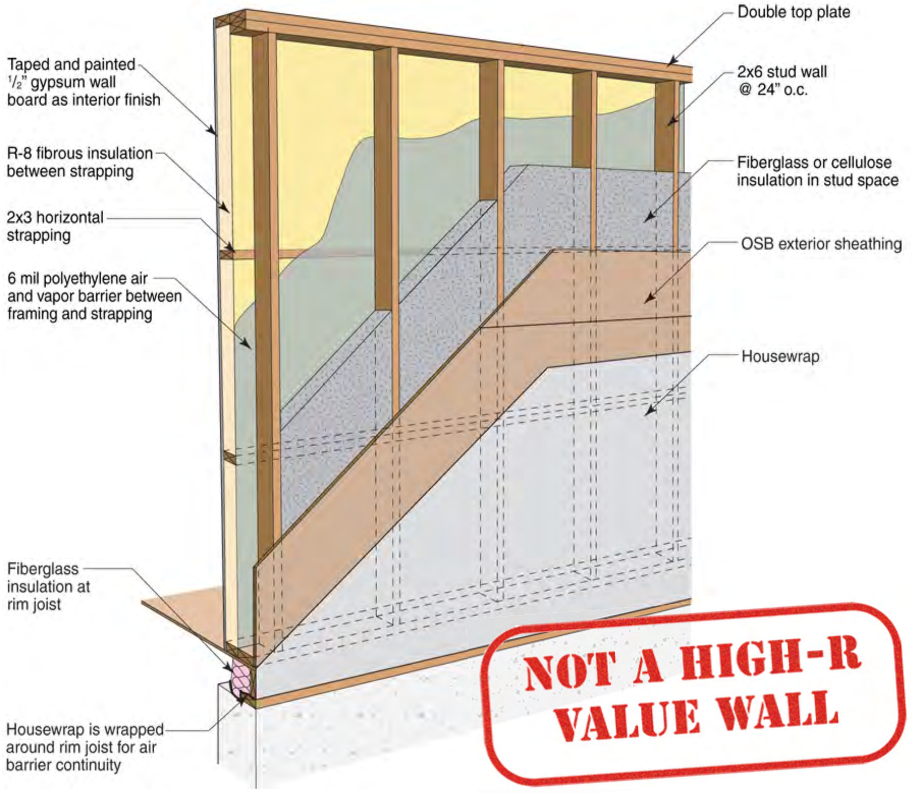
- 2x6 advanced framing
- 2x3 horizontal strapping
- Fibrous insulation between strapping
- 6 mil polyethylene air & vapor barrier
- Fiberglass or cellulose cavity insulation in stud space
- OSB exterior sheathing
- Housewrap

Scoring: How It Rates

The scoring of each wall system is based on the following five categories. A score of 1 is the lowest score in each category and represents the worst possible technology for each category or highest possible relative cost. A score of 5 is the highest score available in each category, and is representative of the best available technology available on the market or lowest relative cost.

Thermal Control	3
Durability	3
Buildability	3
Cost	4
Material Use	3
Total	**16**

Interior strapping in wall construction does increase the R-value over standard construction, but does not address thermal bridges at the rim joist, top plate or bottom plate. The minimal increases in whole wall R-value over standard construction may not be justified by the increased materials, cost and complexity of this wall system.



Introduction

This two page summary briefly summarizes interior strapping wall construction including the advantages and disadvantages of this construction strategy. A more detailed analysis and direct comparison to several other walls can be found online.[1] The scoring system is somewhat subjective based on the relative performance and specifications between different wall systems. Complex two dimensional heat flow analysis and one dimensional hygrothermal modeling were used to determine moisture related durability risks for analysis.

For a more complete analysis of this and other wall constructions, go to www.buildingscience.com.

Thermal Control

Installed Insulation R-value: There is a range of installed insulation R-values in commercially available fiberglass batts. The installed insulation R-value for 2x6 fiberglass batt ranges between R-19 and R-22 for the framed portion of this wall, the strapped interior section is typically R-8 fiberglass insulation, and for 2x6 the range is between R-19 and R-22. When blown or sprayed cellulose insulation is used, the R-value is typically R-20 for 2x6 walls.

Whole-wall R-value: Using two dimensional heat flow analysis with thermal bridging effects and average framing factors, this wall construction achieves a whole wall R-value of approximately R-21.5.[1] Adding horizontal strapping to the interior surface helps minimize the thermal bridges through the stud wall, but there are still thermal bridges at the top plate, bottom plate and rim joist that decrease the installed insulation R-value.

Air Leakage Control: Fiberglass batt, and both blown and sprayed cellulose are air permeable materials allowing possible air paths between the interior and exterior as well as convective looping in the insulation. Although densepack cellulose has less air permeance it does not control air leakage.[2]

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Typical Insulation Products: Fiberglass batt, blown fiberglass, blown cellulose, sprayed cellulose.

Durability

Rain Control: Rain leakage into the enclosure is the leading cause of premature building enclosure failure. Rain control is typically addressed using a shingle lapped and/or taped drainage plane such as building paper or a synthetic WRB (i.e. homewrap). Intersections, windows, doors and other penetrations must be drained and/or detailed to prevent the penetration of rain water beyond the drainage plane.[3]

Air Leakage Control: Air leakage condensation is the second largest cause of premature building enclosure failure with this type of wall construction. It is very important to control air leakage to minimize air leakage condensation durability issues. An air barrier is required in this wall system to ensure that through-wall air leakage is eliminated (ideally) or at least minimized. An air barrier should be stiff and strong enough to resist wind forces, continuous, durable, and air impermeable.[4]

Often the polyethylene vapor barrier will be constructed as the air barrier even though it is not stiff or strong enough to resist wind forces. If the polyethylene is installed between the stud wall and the interior strapping, there will be fewer holes made for electrical and plumbing services, and can be made more airtight than in standard construction.

Air need not leak straight through an assembly to cause moisture problems; it can also leak from the inside, through the wall, and back to the inside; or it can leak from the outside, through the wall, and back to the outside. Condensation within the studspace is possible if this type of airflow occurs, depending on the weather conditions. Hence, wall designs should control airflow into the studspace.[5]

Vapor Control: Fiberglass and cellulose are highly vapor permeable materials, so a separate vapor control strategy must be employed to ensure that vapor diffusion does not result in condensation on, or damaging moisture accumulation in, moisture sensitive materials. The permeance and location of vapor control is dependent on the climate zone. Installing the vapor control layer in the incorrect location can lead to building enclosure failure.[6] The IRC building code should be consulted.

Drying: Cellulose and fiberglass insulation allow drying to occur relatively easily, so drying is controlled by other more vapor impermeable enclosure components such as the vapor barrier and OSB sheathing. Installing vapor control on both sides will seal any moisture into the stud space, resulting in low drying potential, and possibly resulting in moisture-related durability risks. Ventilation behind vapor impermeable claddings and interior components (e.g. kitchen cabinets) can encourage drying.

Built- in Moisture: Care should always be taken to build with dry materials where possible, and allow drying of wet materials before close in. Cellulose is often sprayed in damp, and manufacturers recommend drying before close in and moisture content limits. Because of the polyethylene vapor barrier required in many climates, and relatively vapor impermeable OSB sheathing, drying could be slow if built-in moisture is present.

Durability Summary: The primary durability risks associated with these wall assemblies involve moisture damage related to rain water penetration or condensation (most likely the result of air leakage, but also potentially the result of vapor diffusion).

Cellulose insulated walls are slightly more durable because cellulose insulation is capable of storing and redistributing small amounts of moisture. Cellulose insulation is typically treated with borates which have been shown to protect itself and neighbouring wood material from mold growth and decay. Cellulose insulation also has decreased flame spread potential relative to other insulation materials.

Buildability

This type of construction is a modification of standard construction, but is not common, and construction trades may have difficulty with some of the detailing. All window and door penetrations will require plywood box frames to pass through both the interior strapping and exterior framing. If the poly is installed properly between the stud wall and interior strapping, there is decreased risk of moisture related durability issues often caused by penetrations such as electrical and plumbing.

Cost

There will be increased costs over standard construction due to an increase in framing material, and complexity for construction, since this is not a standard construction technique. Costs vary tremendously from region to region.

Material Use

Using sdvanced framing will reduce redundant wood framing in the wall, but overall framing still increases for the interior strapping. Cellulose has a significantly lower embodied energy than fiberglass or rockwool.

Total Score

Interior strapping in wall construction does increase the R-value over standard construction, but does not address thermal bridges at the rim joist, top plate or bottom plate. The minimal increases in whole wall R-value over standard construction may not be justified by the increased materials, cost and complexity of this wall system. Many higher performance designs for wall construction exist.

References

1 Straube, J., & Smegal, J. (2009). *Building America Special Research Project - High-R Walls Case Study Analysis*. Retrieved from buildingscience.com.

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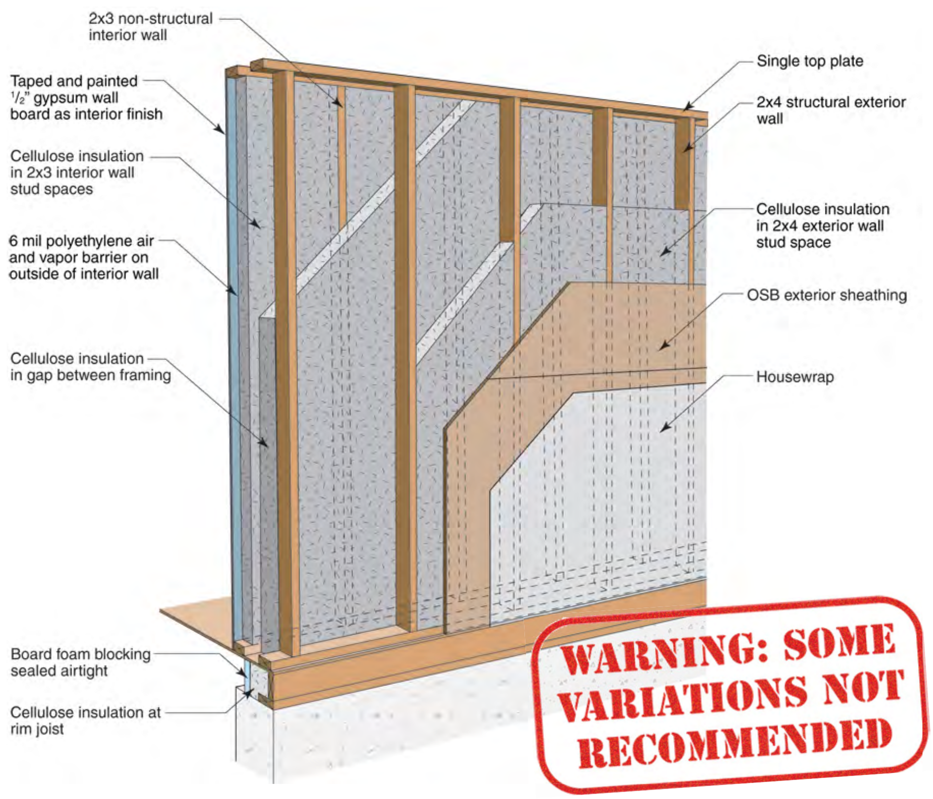
5 Straube, J. (2009, 04 22). *BSD-014 Air Flow Control in Buildings.* Retrieved from buildingscience.com.

6 Lstiburek, J. (2008, 10 17). *BSD-106 Understanding Vapor Barriers.* Retrieved from buildingscience.com.

Double Stud Wall Construction

Double Stud Wall Construction Details (*Wall 4*)[1]

- 2x4 structural exterior wall with cellulose cavity insulation
- 2x3 non-structural interior wall with cellulose cavity insulation
- 6 mil polyethylene vapor barrier
- Cellulose insulation in gap
- OSB exterior sheathing
- Housewrap



Scoring: How It Rates

The scoring of each wall system is based on the following five categories. A score of 1 is the lowest score in each category and represents the worst possible technology for each category or highest possible relative cost. A score of 5 is the highest score available in each category, and is representative of the best available technology available on the market or lowest relative cost.

Thermal Control	4
Durability	3
Buildability	3
Cost	3
Material Use	2
Total	**15**

This is a highly insulated wall system that will work in extreme climates, but still has significant risks to moisture related durability issues and premature enclosure failure. This wall system decreases the interior floor area of a fixed floorplan and may experience thermal and moisture issues at the rim joist unless it's detailed correctly.

Introduction

This two page summary briefly summarizes double stud wall construction including the advantages and disadvantages of this construction strategy. A more detailed analysis and direct comparison to several other walls can be found online.[1] The scoring system is somewhat subjective based on the relative performance and specifications between different wall systems. Complex two dimensional heat flow analysis and one dimensional hygrothermal modeling were used to determine moisture related durability risks for analysis.

For a more complete analysis of this and other wall constructions, go to www.buildingscience.com.

Thermal Control

Installed Insulation R-value: The thickness of double stud walls varies, however, walls with overall insulation thickness of 9.5" appear to be most common. The insulation can be of either fiberglass batt (R-3.5/inch) or blown cellulose insulation (R-3.7/inch) resulting in overall installed insulation R-values of R-33 and 35 respectively.

Whole-wall R-value: Using two dimensional heat flow analysis with thermal bridging effects and average framing factors demonstrates that adding an interior framed wall with a insulation filled gap greatly reduces the thermal breaks through the stud wall and can increases the Clear wall R-value to R-34 depending on the thickness of insulation. However, because of the significant thermal losses at the rim joist, the whole-wall R-value is closer to R-30.[1]

Air Leakage Control: Fiberglass batt, and both blown and sprayed cellulose are air permeable materials allowing possible air paths between the interior and exterior as well as convective looping in the insulation. Although densepack cellulose has less air permeance it does not control air leakage.

Typical Insulation Products: Fiberglass batt, or blown cellulose; blown fiberglass is another option, but not too common.

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Durability

Rain Control: Rain leakage into the enclosure is the leading cause of premature building enclosure failure. Rain control is typically addressed using a shingle lapped and/or taped drainage plane such as building paper or a synthetic WRB (i.e. homewrap). Intersections, windows, doors and other penetrations must be drained and/or detailed to prevent the penetration of rain water beyond the drainage plane.[2]

Air Leakage Control: Air leakage condensation is the second largest cause of premature building enclosure failure with this type of wall construction. It is very important to control air leakage to minimize air leakage condensation durability issues. An air barrier is required in this wall system to ensure that through-wall air leakage is eliminated (ideally) or at least minimized. An air barrier should be stiff and strong enough to resist wind forces, continuous, durable, and air impermeable.[3]

Air need not leak straight through an assembly to cause moisture problems; it can also leak from the inside, through the wall, and back to the inside; or it can leak from the outside, through the wall, and back to the outside. Condensation within the stud space is possible if this type of airflow occurs, depending on the weather conditions. Hence, wall designs should control airflow into the studspace.[4]

Vapor Control: Fiberglass and cellulose are highly vapor permeable materials, so a separate vapor control strategy must be employed to ensure that vapor diffusion does not result in condensation on, or damaging moisture accumulation in, moisture sensitive materials. The permeance and location of vapor control is dependent on the climate zone. Installing the vapor control layer in the incorrect location can lead to building enclosure failure.[5] The IRC building code should be consulted.

Drying: Cellulose and fiberglass insulation allow drying to occur relatively easily, so drying is controlled by other more vapor impermeable enclosure components such as the vapor barrier and OSB sheathing. Installing vapor control on both sides will seal any moisture into the stud space, resulting in low drying potential, and possibly resulting in moisture-related durability risks. Ventilation behind vapor impermeable claddings and interior components (e.g. kitchen cabinets) can encourage drying.

Built- in Moisture: Care should always be taken to build with dry materials where possible, and allow drying of wet materials before close in. Cellulose is often sprayed in damp, and manufacturers recommend drying before close in and moisture content limits. Because of the polyethylene vapor barrier required in many climates, and relatively vapor impermeable OSB sheathing, drying could be slow if built-in moisture is present.

Durability Summary: The primary durability risks associated with these wall assemblies involve moisture damage related to rain water penetration or condensation (most likely the result of air leakage, but also potentially the result of vapor diffusion).

Cellulose insulated walls are slightly more durable because cellulose insulation is capable of storing and redistributing small amounts of moisture. Cellulose insulation is typically treated with borates that have been shown to protect itself and neighboring wood material from mold growth and decay. Cellulose insulation also has decreased flame spread potential relative to other insulation materials.

Buildability

This type of wall construction is more typically found in party walls of multi unit residential because of its superior sound suppression and fire resistance. This wall construction is not very complicated, but does require custom frames around penetrations such as windows and doors. If polyethylene is used as the air barrier, it is critical to seal it perfectly to avoid wintertime air leakage condensation against the sheathing. This construction generally does not address the thermal losses or air leakage at the rim joist. Because the second framed wall is constructed on the interior of the structural wall, the interior floor space is decreased. This wall is quite susceptible to construction deficiencies in the air and vapor barrier.

Cost

The cost of this wall is higher than standard construction, but with a significant increase in thermal performance. This wall construction requires more time and materials for construction.

Material Use

The wall framing material is increased significantly by building a secondary interior wall. This wall is often not structural, which means the stud spacing can be wider, and smaller framing lumber can be used provided an even surface is constructed to install the gypsum board. There is also an increase in insulation, but the embodied energy of cellulose is relatively small, and results in large increases in R-value.

Total Score

This is a highly insulated wall system that will work in extreme climates as part of a high-R enclosure, if the air barrier details are perfect, and the thermal losses at the rim joist are minimized. This construction technique does cost the occupant interior floor space with the thick insulated wall. There is significant risk to moisture related durability issues from wintertime condensation, however, the large amount of cellulose in this wall system will be able to buffer some moisture in the enclosure as long as the safe moisture capacity of the cellulose is not exceeded.

References

1 Straube, J., & Smegal, J. (2009). *Building America Special Research Project - High-R Walls Case Study Analysis*. Retrieved from buildingscience.com.

2 Lstiburek, J. W. (2006). *Water Management Guide.* Westford: Building Science Press Inc.

3 Lstiburek, J. (2008, 08 20). *BSD-104: Understanding Air Barriers*. Retrieved from buildingscience.com.

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5 Lstiburek, J. (2008, 10 17). *BSD-106 Understanding Vapor Barriers*. Retrieved from buildingscience.com.

Truss Wall Construction

Truss Wall Construction Details (*Wall 5*)[1]

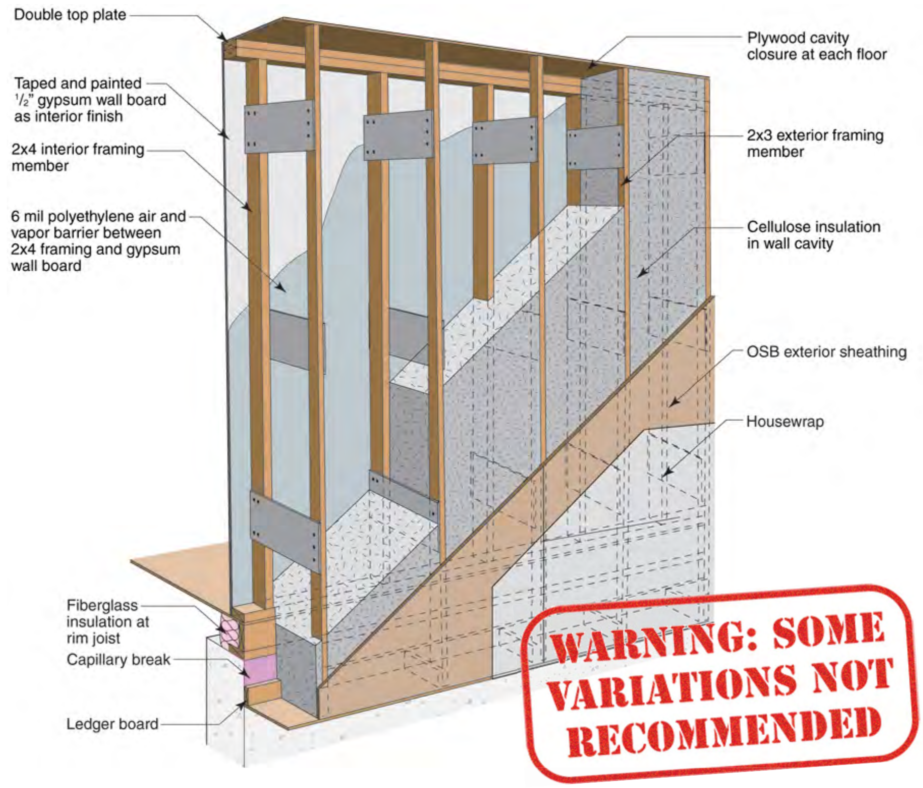
- 2x4 interior framing member
- 2x3 exterior framing member
- 6 mil polyethylene vapor barrier to interior
- Cellulose cavity insulation
- OSB exterior sheathing
- Housewrap

Scoring: How It Rates

The scoring of each wall system is based on the following five categories. A score of 1 is the lowest score in each category and represents the worst possible technology for each category or highest possible relative cost. A score of 5 is the highest score available in each category, and is representative of the best available technology available on the market or lowest relative cost.

Thermal Control	4
Durability	3
Buildability	2
Cost	3
Material Use	2
Total	**14**

The truss wall system can achieve a very high whole wall R-value with minimal thermal bridging and would be perform well in extreme climates provided the air barrier was detailed perfectly minimizing the high risk of air leakage condensation durability issues. It is time consuming to construct and susceptible to premature enclosure failures resulting from poor construction and detailing.



Introduction

This two page summary briefly summarizes the truss wall construction including the advantages and disadvantages of this construction strategy. A more detailed analysis and direct comparison to several other walls can be found online.[1] The scoring system is somewhat subjective based on the relative performance and specifications between different wall systems. Complex two dimensional heat flow analysis and one dimensional hygrothermal modeling were used to determine moisture related durability risks for analysis.

For a more complete analysis of this and other wall constructions, go to www.buildingscience.com.

Thermal Control

Installed Insulation R-value: The thickness of truss walls varies greatly and because it is not a common wall construction, there does not appear to be a established standard construction insulation thickness. These walls are typically insulated with blown cellulose insulation (R-3.7/inch) or fiberglass batt insulation (R-3.5/inch), and overall installed insulation R-values in excess of 50 are possible.

Whole-wall R-value: Using two dimensional heat flow analysis with thermal bridging effects and average framing factors shows that adding the insulation to the exterior of the framing addresses the thermal bridge at the rim joist, studs and top plate. There is a large range of R-values possible with this type of construction, but 12" of cellulose provides a whole-wall R-value of approximately R-36.[1]

Air Leakage Control: Cellulose insulation is an air permeable material allowing possible air paths between the interior and exterior as well as convective looping in the insulation. Although densepack cellulose has less air permeance than some other air permeable insulations, it does not control air leakage.

Typical Insulation Products: Blown cellulose.

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Durability

Rain Control: Rain leakage into the enclosure is the leading cause of premature building enclosure failure. Rain control is typically addressed using a shingle lapped and/or taped drainage plane such as building paper or a synthetic WRB (i.e. homewrap). Intersections, windows, doors and other penetrations must be drained and/or detailed to prevent the penetration of rainwater beyond the drainage plane.[2]

Air Leakage Control: Air leakage condensation is the second largest cause of premature building enclosure failure with this type of wall construction. It is very important to control air leakage to minimize air leakage condensation durability issues. An air barrier is required in this wall system to ensure that through-wall air leakage is eliminated (ideally) or at least minimized. An air barrier should be stiff and strong enough to resist wind forces, continuous, durable, and air impermeable.[3]

Air need not leak straight through an assembly to cause moisture problems; it can also leak from the inside, through the wall, and back to the inside; or it can leak from the outside, through the wall, and back to the outside. Condensation within the stud space is possible if this type of airflow occurs, depending on the weather conditions. Hence, wall designs should control airflow into the stud space.[4]

The truss wall has a much higher R-value that standard construction, and the exterior sheathing is well insulated from the interior conditions. This wall system has greater risk for severe air leakage condensation since the sheathing is considerably colder than standard construction.

Vapor Control: Fiberglass and cellulose are highly vapor permeable materials, so a separate vapor control strategy must be employed to ensure that vapor diffusion does not result in condensation on, or damaging moisture accumulation in, moisture sensitive materials. The permeance and location of vapor control is dependent on the climate zone. Installing the vapor control layer in the incorrect location can lead to building enclosure failure.[5] The IRC building code should be consulted.

There is a higher risk of vapor diffusion condensation if the vapor barrier is not detailed correctly due to the lower wintertime temperature of the sheathing in the truss wall relative to standard construction.

Drying: Cellulose and fiberglass insulation allow drying to occur relatively easily, so drying is controlled by other more vapor impermeable enclosure components such as the vapor barrier and OSB sheathing. Installing vapor control on both sides will seal any moisture into the stud space, resulting in low drying potential, and possibly resulting in moisture-related durability risks. Ventilation behind vapor impermeable claddings and interior components (e.g. kitchen cabinets) can encourage drying.

Built- in Moisture: Care should always be taken to build with dry materials where possible, and allow drying of wet materials before close in. Because of the polyethylene vapor barrier required in many climates, and relatively vapor impermeable OSB sheathing, drying could be slow if built-in moisture is present.

Durability Summary: The primary durability risks associated with these wall assemblies involve moisture damage related to rain water penetration or condensation (most likely the result of air leakage, but also potentially the result of vapor diffusion).

Cellulose insulated walls are slightly more durable than fiberglass insulated walls because cellulose insulation is capable of storing and redistributing small amounts of moisture. Cellulose insulation is typically treated with borates that have been shown to protect itself and neighboring wood material from mold growth and decay. Cellulose insulation also has decreased flame spread potential relative to other insulation materials.

Buildability

This wall construction is not a standard construction practice. The gussets used to space the exterior framed wall off the structure are time consuming to construct, and require tight tolerances to ensure smooth sheathing and cladding. This wall is highly susceptible to construction workmanship and requires a perfect air barrier in cold climates since the potential for wintertime condensation is high. Penetrations such as windows and doors require plywood boxes be installed through the wall.

Cost

This construction requires increases in both time and materials for the enclosure. The wall framing material is essentially doubled, and constructing the exterior wall with gussets is time consuming. The increased thermal performance and decreased thermal bridges may be worth the extra time and money in specific cases.

Material Use

There is a significant increase to framing since every framing member in the structural wall has a corresponding exterior framing member attached with wood gussets.

Total Score

The truss wall system can achieve a very high whole wall R-value with minimal thermal bridging and would be perform well in extreme climates provided the air barrier was detailed perfectly minimizing air leakage condensation durability risks. It is possible to reduce the risk of condensation by using a combination of the truss wall in combination with an air impermeable insulation. One advantage of the truss wall is that it is used in both new construction and retrofit situations to decrease energy consumption, and improve occupant comfort. The truss wall allows the extra insulation to be placed on the exterior of the structural wall that does not affect the interior space, unlike the double stud wall.

References

1 Straube, J., & Smegal, J. (2009). *Building America Special Research Project - High-R Walls Case Study Analysis.* Retrieved from buildingscience.com.

2 Lstiburek, J. W. (2006). *Water Management Guide.* Westford: Building Science Press Inc.

3 Lstiburek, J. (2008, 08 20). *BSD-104: Understanding Air Barriers.* Retrieved from buildingscience.com.

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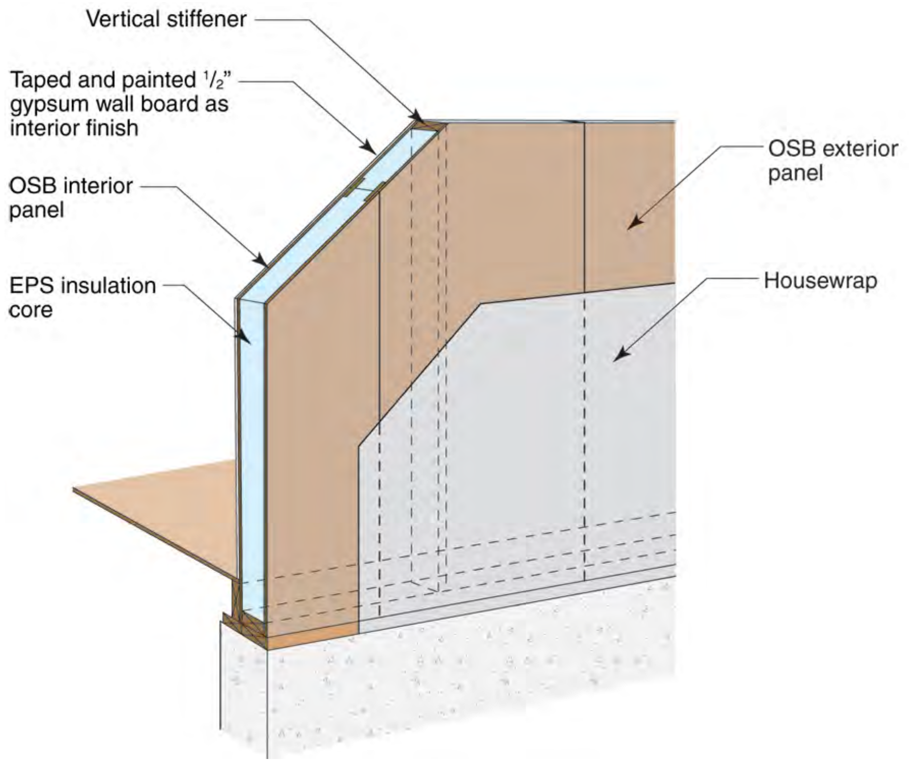
SIPs Wall Construction

SIPs Wall Construction Details (*Wall 6*)[1]

- OSB interior and exterior panels
- EPS insulation core typical
- Housewrap



Scoring: How It Rates

The scoring of each wall system is based on the following five categories. A score of 1 is the lowest score in each category and represents the worst possible technology for each category or highest possible relative cost. A score of 5 is the highest score available in each category, and is representative of the best available technology available on the market or lowest relative cost.

Thermal Control	4
Durability	4
Buildability	3
Cost	3
Material Use	3
Total	**17**

The typical SIPs panels are not constructed with enough insulation to be considered high-R assemblies in heating climates. SIPs installation requires specialized training but is quicker and easier than wood framed construction following training. Historical moisture related durability issues with SIPs have been solved with a better understanding of building science, and airtightness details.

Introduction

This two page summary briefly summarizes SIPs wall construction including the advantages and disadvantages of this construction strategy. A more detailed analysis and direct comparison to several other walls can be found online.[1] The scoring system is somewhat subjective based on the relative performance and specifications between different wall systems. Complex two dimensional heat flow analysis and one dimensional hygrothermal modeling were used to determine moisture related durability risks for analysis.

For a more complete analysis of this and other wall constructions, go to www.buildingscience.com.

Thermal Control

Installed Insulation R-value: Structural Insulated Panels (SIPs) are typically constructed using OSB panels adhered to both sides of an expanded polystyrene (EPS) foam insulation core. The most common SIP insulation thicknesses are 3.5" and 5.5" and are equivalent to R-14 and R-22. It is possible, although not as common, to use different insulation types, and thicker panels to achieve high R wall values.

Whole-wall R-value: Using two dimensional heat flow analysis with thermal bridging effects and average framing factors, the clear wall R-value with the OSB layers, drywall, cladding, and surface films often has an R-value higher than the installed insulation R-value because of fewer thermal bridges in the wall system. The whole-wall R-value depends on thermal bridging through vertical stiffeners, top and bottom plate, as well as the wood bucks for windows and doors.[1]

Air Leakage Control: Both OSB and EPS foam are air impermeable so there is no air leakage through the centre of the SIPS panels; however it is important to address the air tightness of joints between the panels as well as interfaces with other structural elements (i.e. foundation

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walls or roofs) and penetrations such as windows, doors and services.[2] It is relatively easy to achieve a high level of airtightness on a SIPs enclosure.

Typical Insulation Products: EPS foam is the most common, but SIPs have also been constructed with XPS and polyisocyanurate foam cores.

Durability

Rain Control: Rain leakage into the enclosure is the leading cause of premature building enclosure failure. Rain control is typically addressed using a shingle lapped and/or taped drainage plane such as building paper or a synthetic WRB (i.e. homewrap). Intersections, windows, doors and other penetrations must be drained and/or detailed to prevent the penetration of rainwater beyond the drainage plane.[3]

Air Leakage Control: There is no air leakage through the centre of the panel but there is risk of air leakage at the joints between panels if not detailed correctly. Historically, there were design detail issues with the air tightness of the joints between the panels allowing warm moist interior air to condense on the exterior cold OSB layer.[4] Standards of SIPs construction have improved and following the recommended construction guidelines mitigates nearly all of the risk of moisture related durability issues from air leakage.

Vapor Control: A SIPs panel controls vapor well. There is very minimal risk to vapor related moisture damage in SIPs construction.

Drying: Water on either the interior or exterior of the SIPs will dry easily to the interior or exterior in most climates. In very humid or wet climates with minimal drying potential, the OSB may remain wet for an extended period and could result in moisture related durability issues. If moisture accumulates between the interior and exterior OSB faces, it will be difficult to dry.

Built- in Moisture: Water on the surfaces of the panel during construction should dry easily following completion, any water trapped in the panel joints will dry much more slowly.

Durability Summary: If the SIPs are installed according to best practice, with proper air seals and flashed penetrations, the system is very durable in all climates.

Buildability

Using SIPs is relatively easy and quick once the training has been completed. Panels are ordered and shipped to site and assembled with a crane. More specific info can be found at www.sips.org. Generally, most of the services are run on interior partition walls, but there are methods of installing services on the interior of a SIPs panel. A SIPs house can be assembled and dried in more quickly than a wood framed house once the panels are on site.

Cost

SIPs panels range considerably in price depending on the project details and the required thickness of wall panels. It is more expensive than standard construction and can generally only be used on simple geometries.

Material Use

SIPs panels require minimal framing lumber but an increase in structural sheathing panels.

Total Score

SIPs wall panels are generally not constructed with enough insulation to be considered a high R enclosure system on its own in heating climates. It is possible to use thicker insulation panels or to combine SIPs with another insulation strategy in cold climates. It is relatively quick and easy to build with SIPs following training, and refined standard practice techniques have removed nearly all of the historical risks of air leakage condensation. The cost and simple geometries of SIPs houses are two of the main reasons why this technology is not used more often.

References

1 Straube, J., & Smegal, J. (2009). *Building America Special Research Project - High-R Walls Case Study Analysis.* Retrieved from buildingscience.com.

2 Lstiburek, J. W. (2008). *Builder's Guide to Structural Insulated Panels (SIPs) for all Climates.* Westford: Building Science Press Inc.

3 Lstiburek, J. W. (2006). *Water Management Guide.* Westford: Building Science Press Inc.

4 SIPA (n.d.). *Report on the Juneau, Alaska Roof Issue.* Retrieved May 2009 from Structural Insulated panel Association: http://www.sips.org/content/technical/index.cfm?PageId=161.

ICF Wall Construction

ICF Wall Construction Details (*Wall 7*)[1]

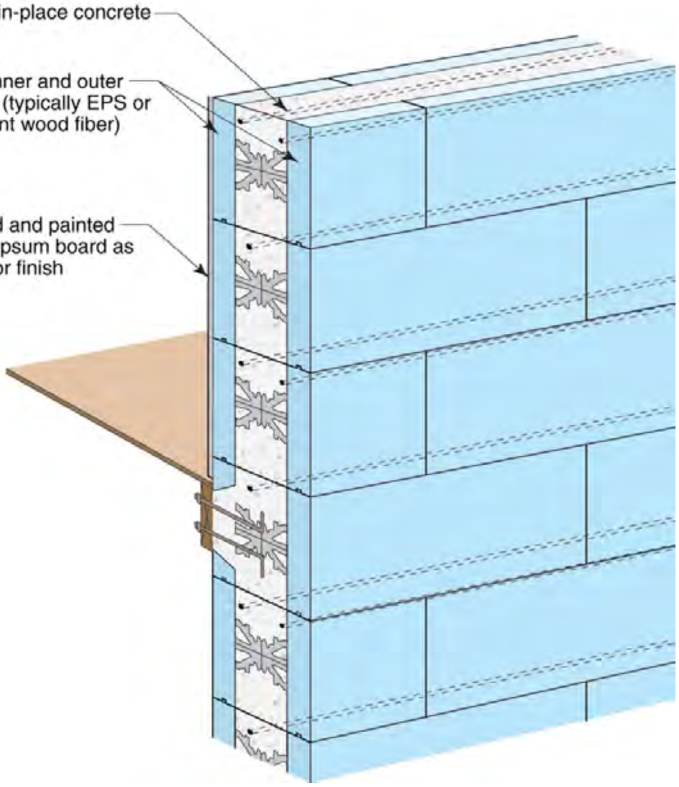
- ICF inner and outer faces; typically EPS or cement wood fiber
- Cast-in-place concrete core

Scoring: How It Rates

The scoring of each wall system is based on the following five categories. A score of 1 is the lowest score in each category and represents the worst possible technology for each category or highest possible relative cost. A score of 5 is the highest score available in each category, and is representative of the best available technology available on the market or lowest relative cost.

Thermal Control	4
Durability	5
Buildability	4
Cost	2
Material Use	3
Total	**18**

ICF construction is a very durable construction strategy provided the rainwater management details are constructed correctly. Generally, ICF construction alone cannot achieve a high R-value and will require other insulation strategies in combination for cold climates, which is commonly done in practice.



Introduction

This two page summary briefly summarizes ICF wall construction including the advantages and disadvantages of this construction strategy. A more detailed analysis and direct comparison to several other walls can be found online.[1] The scoring system is somewhat subjective based on the relative performance and specifications between different wall systems. Complex two dimensional heat flow analysis and one dimensional hygrothermal modeling were used to determine moisture related durability risks for analysis.

For a more complete analysis of this and other wall constructions, go to www.buildingscience.com.

Thermal Control

Installed Insulation R-value: R-values of Insulated Concrete Form construction vary considerably with the type, and thickness of form. The most common ICF form is constructed of EPS insulation in the range of 2" thick on the interior and exterior. Other ICF materials include cementitious wood based forms, some of which are constructed with an extra layer of insulation (e.g. Rockwool) in the form.

Whole-wall R-value: Using two dimensional heat flow analysis with thermal bridging effects and average framing factors shows that there are few thermal breaks from the interior to the exterior on an ICF wall. An 8" foam ICF form with 4" of EPS has a whole-wall R-value of approximately R-16.[1]

Air Leakage Control: Many ICF construction strategies form air barriers in the field of the wall. Air leakage will occur at penetrations through the wall if they are not detailed correctly.[2]

Typical Insulation Products: EPS foam insulation forms, or cementitious wood based forms.

Durability

Rain Control: Rain leakage into the enclosure is the leading cause of premature building enclosure failure. Rain control is typically addressed using a shingle lapped and/or taped drainage plane such as building paper or a synthetic WRB (i.e. homewrap). Intersections, windows, doors and other penetrations must be drained and/or detailed to prevent the penetration of rainwater beyond the drainage plane.[3] There is little to no moisture buffering capacity of and ICF wall so even a minimal amount of water, undetectable in standard construction, will have durability issues in ICF construction.

Air Leakage Control: ICF construction strategies form air barriers in the field of the wall. All through wall penetrations require air sealing details.[4]

Vapor Control: There are no significant risks to moisture durability from vapor drive in ICF construction.

Drying: ICFs will dry both to the interior and exterior depending on climate and time of year.

Built- in Moisture: Since ICFs are poured concrete walls in forms with relatively low vapor permeance surfaces, the concrete will dry very slowly, and should be allowed to dry to both sides following the completion of the wall system.

Durability Summary: There are very few risks associated with air leakage and vapor condensation of ICF construction. The most common durability issue is from rainwater leakage into the enclosure. ICF forms typically do not have any buffering capacity of leakage, so even a small leak, that may occur undetected with no durability risks in a wood framed wall, may affect the interior of and ICF building. The ICF wall itself is not susceptible to moisture related issues but interior finishes are generally sensitive to moisture.

Buildability

Generally, building with ICFs is quite easy and straightforward following initial training. Care should be taken to line the surfaces of the forms up to ensure even drywall if it is directly attached. Problems in the past have occurred with air pockets in the forms, as well as bulging and breaking of forms due to the hydrostatic pressure of concrete. These problems are well documented and there are strategies to address these issues.

Cost

The cost of ICF construction varies considerably depending on the type of forms chosen, geometry of construction and location. ICF construction is more expensive that standard construction and is usually prohibitively expensive in residential housing.

Material Use

ICF walls use less concrete than an alternative wall built entirely with concrete, and concrete is very high in embodied energy. The wood framing can be minimized by attaching the drywall directly to the ICF block on the interior.

Total Score

ICF construction is a very durable construction strategy provided the rainwater management details are constructed correctly. Generally, ICF construction alone cannot achieve a high R-value and will require other insulation strategies in combination for cold climates, which is commonly done in practice. ICF is generally only used in multifamily and mid rise buildings, and not in residential housing.

References

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Spray Foam Wall Construction

Spray Foam Wall Construction Details (*Wall 8a and 8b*)[1]

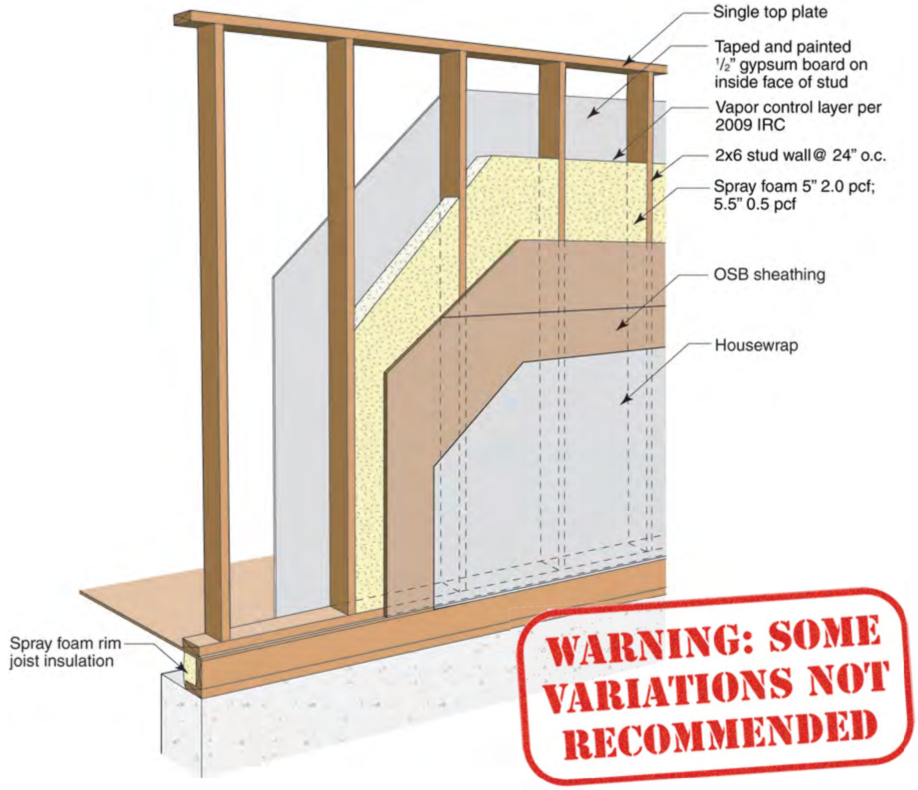
- 2x6 wood frame wall at 24" o.c.
- Spray foam cavity insulation
- OSB sheathing
- Housewrap

Scoring: How It Rates

The scoring of each wall system is based on the following five categories. A score of 1 is the lowest score in each category and represents the worst possible technology for each category or highest possible relative cost. A score of 5 is the highest score available in each category, and is representative of the best available technology available on the market or lowest relative cost.

Thermal Control	5
Durability	5
Buildability	4
Cost	2
Material Use	4
Total	**20**

Both low and high density foam increase the air tightness of the enclosure and reduce the risks to air leakage related durability risks. The R-values of both the low and high density spray foam are significantly reduced by thermal bridging of the wall framing and rim joist, demonstrating the value of insulated sheathing.



Introduction

This two page summary briefly summarizes spray foam wall construction including the advantages and disadvantages of this construction strategy. A more detailed analysis and direct comparison to several other walls can be found online.[1] The scoring system is somewhat subjective based on the relative performance and specifications between different wall systems. Complex two dimensional heat flow analysis and one dimensional hygrothermal modeling were used to determine moisture related durability risks for analysis.

For a more complete analysis of this and other wall constructions, go to www.buildingscience.com.

Thermal Control

Installed Insulation R-value: The installed insulation R-value depends somewhat on the company and but generally speaking, high density foam (2.0 pcf) ranges between R-5.5 and R-6.5 per inch for the aged R-value, and low density foam (0.5pcf) has an R-value of approximately R-3.6/inch. Since high density foam is generally installed short of the cavity to avoid trimming, the installed insulation R-value is approximately R-30 (using R-6/inch). Low density is generally installed deliberately overflowing the cavity and trimmed off resulting in an R-value of approximately R-21.

Whole-wall R-value: Using two dimensional heat flow analysis with thermal bridging effects and average framing factors, it is clear that the thermal bridging through the framing, bottom plate, and top plate reduces the effectiveness of the spray foam insulation.[1] The R-value of the high density spray foam wall decreases from an installed R-value of R-30 to approximately R-20, a decrease of R-10 because of thermal bridging. The low density spray foam wall decreases from an installed insulation R-value of 21 to a whole wall R-value of approximately R-16.

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Air Leakage Control: Both low density and high density foam form an air barrier decreasing thermal losses through air leakage. Air leakage is still common under the bottom plate and at the rim joist if these areas are not detailed correctly.[2]

Typical Insulation Products: Low density 0.5 pcf foam, or high density 2.0 pcf foam.

Durability

Rain Control: Rain control is typically addressed using a shingle lapped and/or taped drainage plane such as building paper or a synthetic WRB (i.e. homewrap). Intersections, windows, doors and other penetrations must be detailed to prevent the penetration of rain water.[3]

Air Leakage Control: Air leakage is significantly minimized by installing spray foam insulation in the stud space since both low density and high density spray foam act as an air barrier. This increases the durability of the wall system considerably over standard construction.[4]

Vapor Control: High density (2.0 pcf) foam forms a vapor control layer reducing vapor movement through the enclosure, minimizing the potential for wintertime vapor condensation and summertime inward vapor drive. Low density foam allows moisture vapor movement through the foam so other methods of vapor control such as poly, kraft paper, or vapor barrier paint may be required based on the geographic location.[5] The IRC building code should be consulted.

Drying: Both of the spray foam walls dry relatively slowly if water enters the enclosure, since they do not experience convective looping and air movement similar to air permeable insulations. Spray foam does not provide any buffering capacity or redistribution. Foam is relatively moisture tolerant and will be able to dry given enough time. Ventilation behind vapor impermeable claddings and interior components (e.g. kitchen cabinets) can encourage drying.

Built- in Moisture: Care should always be taken to build with dry materials where possible, and allow drying of wet materials before close in. High density foam will inhibit the drying of wet building materials more than low density vapor permeable foam.

Durability Summary: The primary durability risks associated with these wall assemblies involve moisture damage related to rain water penetration. Both air leakage and vapor diffusion durability is significantly increased with spray foam but some vapor control may be necessary with low density spray foam in cold climates.

Buildability

Using spray foam as the stud space insulation is a very simple modification to the construction technique. Generally, the wall construction is the same as standard or advanced framing construction, and spray foam is sprayed into the cavity. Spray foam significantly reduces risks of poor air tightness detailing of the exterior sheathing or interior drywall.

Cost

Using spray foam will increase construction costs considerably but these increased costs may be outweighed by the benefits to energy efficiency, and occupancy comfort from reduced drafts.

Material Use

Wood framing required for spray foam insulation is the same required for the standard construction, or advanced framed wall depending on the framing strategy used.

Total Score

Both low and high density foam increase the air tightness of the enclosure and reduce the risks to air leakage related durability risks. A vapor control (ie. polyethylene, kraft paper, SVR) with high density foam is generally not required and vapor control with low density spray foam will be climate specific. The R-values of both the low and high density spray foam are significantly reduced by thermal bridging of the wall framing and rim joist, demonstrating the value of insulated sheathing. It may be possible to use spray foam insulation in combination with another insulation strategy to maximize the R-value gained with the spray foam insulation.

References

1 Straube, J., & Smegal, J. (2009). *Building America Special Research Project - High-R Walls Case Study Analysis*. Retrieved from buildingscience.com.

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Flash-and-Fill Hybrid Wall Construction

Flash-and-Fill Hybrid Wall Construction Details *(Wall 9)*[1]

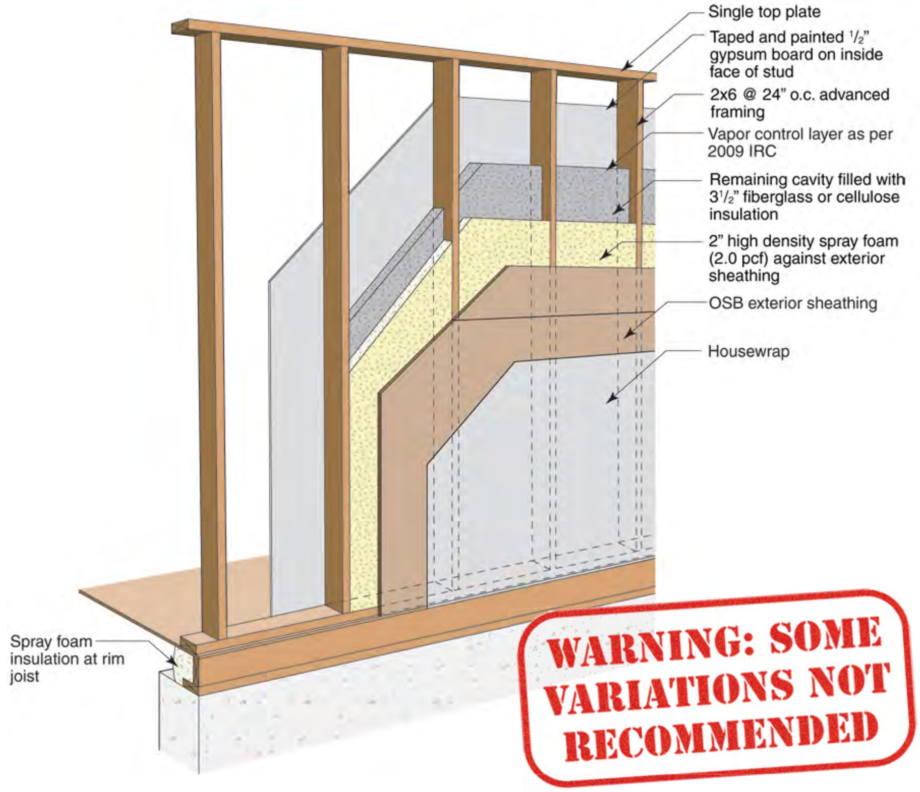
- 2x6 wood frame wall at 24" o.c.
- 2" high density spray foam
- Fiberglass or cellulose cavity insulation
- OSB sheathing
- Housewrap

Scoring: How It Rates

The scoring of each wall system is based on the following five categories. A score of 1 is the lowest score in each category and represents the worst possible technology for each category or highest possible relative cost. A score of 5 is the highest score available in each category, and is representative of the best available technology available on the market or lowest relative cost.

Thermal Control	4
Durability	4
Buildability	4
Cost	3
Material Use	4
Total	**19**

The hybrid wall system significantly reduces air leakage over standard construction or advanced framing, which conserves energy, and reduces the potential for both air leakage and vapor condensation durability issues. Unfortunately, the added cost of the spray foam insulation only adds a minimal amount to the R-value since the thermal bridging of the wall is not addressed. Addressing the thermal bridges would improve this wall construction.



Introduction

This two page summary briefly summarizes flash-and-fill hybrid wall construction including the advantages and disadvantages of this construction strategy. A more detailed analysis and direct comparison to several other walls can be found online.[1] The scoring system is somewhat subjective based on the relative performance and specifications between different wall systems. Complex two dimensional heat flow analysis and one dimensional hygrothermal modeling were used to determine moisture related durability risks for analysis.

For a more complete analysis of this and other wall constructions, go to www.buildingscience.com.

Thermal Control

Installed Insulation R-value: The installed R-value is approximately R-12 for two inches of high density spray foam (2.0 pcf) and R-13 for three and a half inches of fiberglass batt, totaling R-25.

Whole-wall R-value: Using two dimensional heat flow analysis with thermal bridging effects and average framing factors, the R-value decreases from an installed insulation R-value of R-25 to whole wall R-value of approximately R-17 for a the hybrid wall construction in this case.[1] The decrease in R-value is due to the thermal bridging of the wall framing, top and bottom plates.

Air Leakage Control: Fiberglass batt, and both blown and sprayed cellulose are air permeable materials allowing possible air paths between the interior and exterior as well as convective looping in the insulation. Although densepack cellulose has less air permeance it does not control air leakage. In the case of the hybrid wall system, the spray foam is used as an air barrier in the stud space to limit the air movement between the interior and exterior so there are fewer energy losses due to air leakage. It is still possible and common to get air leakage

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below the bottom plate if is not sealed.[2] When spray foam is used in the wall system, it is beneficial to also use it in the rim joist which has a high potential for air leakage.

Typical Insulation Products: Spray foam insulation and fiberglass batt, blown fiberglass, blown cellulose, or sprayed cellulose.

Durability

Rain Control: Rain leakage into the enclosure is the leading cause of premature building enclosure failure. Rain control is typically addressed using a shingle lapped and/or taped drainage plane such as building paper or a synthetic WRB (i.e. homewrap). Intersections, windows, doors and other penetrations must be drained and/or detailed to prevent the penetration of rainwater beyond the drainage plane.[3]

Air Leakage Control: Air leakage condensation is the second largest cause of premature building enclosure failure with wood framed wall construction. It is very important to control air leakage to minimize air leakage condensation durability issues. An air barrier is required in this wall system to ensure that through-wall air leakage is eliminated (ideally) or at least minimized. An air barrier should be stiff and strong enough to resist wind forces, continuous, durable, and air impermeable.[4]

In the hybrid wall system, two inches of spray foam is used as an air barrier to reduce the air leakage. This also reduces the air leakage condensation against the sheathing in the winter as it significantly warms the condensation plane. Since air leakage from the interior, into the studspace and back into the interior can also cause condensation in some climates, it is still important to detail the interior surface as an air barrier as well.

Vapor Control: Fiberglass and cellulose are vapor permeable materials, but including two inches of high density spray foam acts as a vapor barrier limiting vapor movement to the cold exterior sheathing, and significantly reduces the risk of vapor condensation durability issues. High density spray foam also decreases the summer inward vapor drives. If low density spray foam is used, it is not a vapor barrier, and other vapor control may be required depending on the climate. Calculations should be done to ensure a minimum risk to vapor condensation durability issues.[5] The IRC building code should be consulted.

Drying: Using high density spray foam will slow the movement of moisture across the enclosure. and there is no moisture buffering capacity or redistribution within the spray foam. Some vapor control may still be required at the interior surface in cold climates which slows drying. Proper flashing of all penetrations should help minimize moisture in the enclosure. Ventilation behind vapor impermeable claddings and interior components (e.g. kitchen cabinets) can encourage drying.

Built- in Moisture: Care should always be taken to build with dry materials where possible, and allow drying of wet materials before close in. High density spray foam may slow drying across the enclosure since it is a vapor barrier. In geographic regions with reduced drying potential, the moisture content of the sheathing may stay elevated for an extended period due to the inability to dry or redistribute moisture into the wall.

Durability Summary: Hybrid wall construction has a greater resistance to both air leakage condensation and vapor diffusion condensation because of the high density spray foam increasing the dew point of the condensation surface. The primary durability risks associated with these wall assemblies involve moisture damage related to rain water penetration.

Buildability

Hybrid wall construction is not very different from standard wall construction or advanced framing. By filling the stud space with two inches of spray foam, an R-13 batt can still easily be installed against the foam, or cellulose could be sprayed in the remaining stud space. All other aspects of the construction are the same as standard construction or advanced framing. Using high density spray foam reduces the risks from poor workmanship during construction.

Cost

Using spray foam insulation can be costly, and while it reduces the risks of moisture related durability issues, the minimal increase in R-value due to the thermal bridging may not be worth the increased cost of the spray foam insulation.

Material Use

There is no increase in framing materials from standard construction, but the embodied energy of the system increases with the addition of high density spray foam insulation.

Total Score

The hybrid wall system significantly reduces air leakage over standard construction, which conserves energy, and reduces the potential for both air leakage and vapor condensation durability issues. Reducing the air leakage may also increase occupancy comfort by reducing drafts. Unfortunately, the added cost of the spray foam insulation only adds a minimal amount to the R-value since the thermal bridging of the wall is not addressed. This wall is very similar to build as standard construction and less susceptible to poor workmanship during construction. Addressing the thermal bridges would improve this wall construction.

References

1 Straube, J., & Smegal, J. (2009). *Building America Special Research Project - High-R Walls Case Study Analysis*. Retrieved from buildingscience.com.

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DOUBLE STUD WITH SPRAY FOAM WALL CONSTRUCTION

HIGH R-VALUE ENCLOSURE REPORT CASE STUDY

DOUBLE STUD WITH SPRAY FOAM WALL CONSTRUCTION DETAILS *(Wall 10)*[1]

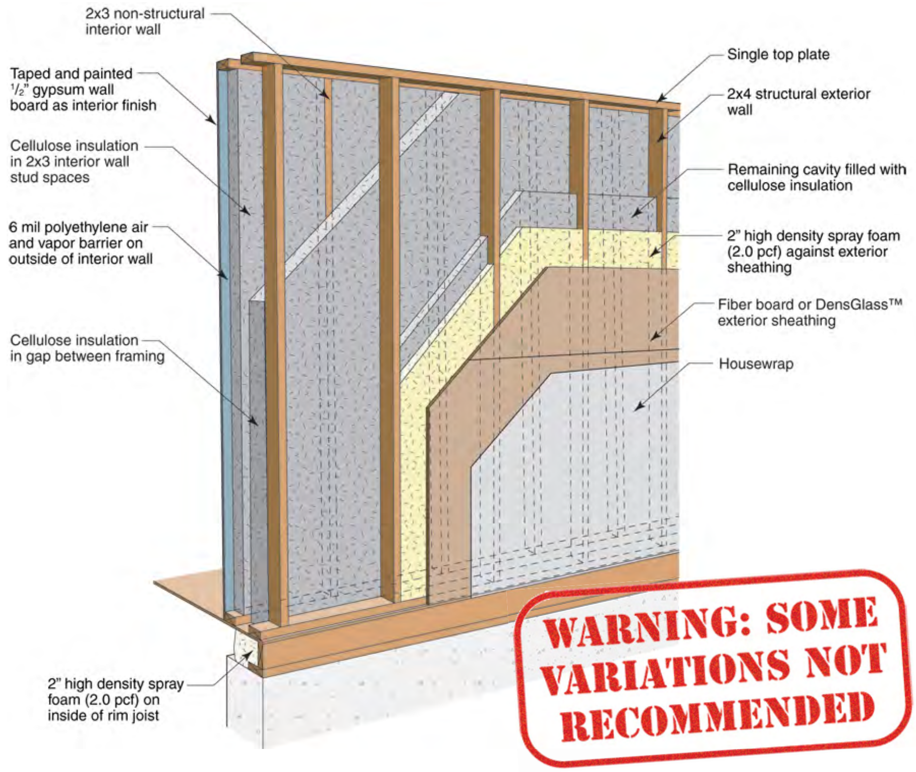
- 2x4 exterior wall framing
- 2" high density spray foam
- Fiberglass or cellulose cavity insulation
- 2x3 interior wall framing
- Fiber board or DensGlass™ sheathing
- Housewrap

SCORING: HOW IT RATES

The scoring of each wall system is based on the following five categories. A score of 1 is the lowest score in each category and represents the worst possible technology for each category or highest possible relative cost. A score of 5 is the highest score available in each category, and is representative of the best available technology available on the market or lowest relative cost.

Thermal Control	5
Durability	4
Buildability	3
Cost	3
Material Use	3
Total	**18**

This is truly a high-R wall assembly, and with the addition of spray foam, there is a reduction in moisture related durability issues. In some extreme climates, two inches of spray foam may not be enough to sufficiently reduce the risk, which means that more spray foam is required, or an interior air barrier and some form of vapor control, likely a Class II or Class II would be sufficient.



INTRODUCTION

This two page summary briefly summarizes double stud with spray foam wall construction including the advantages and disadvantages of this construction strategy. A more detailed analysis and direct comparison to several other walls can be found online.[1] The scoring system is somewhat subjective based on the relative performance and specifications between different wall systems. Complex two dimensional heat flow analysis and one dimensional hygrothermal modeling were used to determine moisture related durability risks for analysis.

For a more complete analysis of this and other wall constructions, go to www.buildingscience.com.

THERMAL CONTROL

Installed Insulation R-value: The thickness of double stud walls varies, however walls with overall insulation thickness of 9.5" appear to be most common. The insulation is most commonly cellulose insulation but could also be sprayed fiberglass. In this system with two inches of high density spray foam (R-6/inch) the installed insulation R-value is approximately R-40. This is an increase of R-5 over the same double stud construction insulated only with cellulose.

Whole-wall R-value: Using two dimensional heat flow analysis with thermal bridging effects and average framing factors shows that adding an interior framed wall with a insulation filled gap greatly reduces the thermal breaks through the stud wall and can increases the Clear wall R-value to R-36 depending on the thickness of insulation. However, because of the thermal losses at the rim joist, the Whole-wall R-value is closer to R-33.[1]

Air Leakage Control: Fiberglass batt, blown and sprayed cellulose are all air permeable materials allowing possible air paths between the interior and exterior as well as convective looping through the material. In this case, the spray foam is used as an air barrier in the stud space to limit the air movement between the interior and exterior so there are fewer energy losses due to air leakage. It is still possible and common to get air leakage below the bottom plate if is

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not sealed.[2] When spray foam is used in the wall system, it is beneficial to also use it in the rim joist that has a high potential for air leakage. Reducing the air leakage with spray foam may also increase occupancy comfort by reducing drafts.

Typical Insulation Products: High density spray foam, blown cellulose, sprayed fiberglass.

Durability

Rain Control: Rain Control – Rain leakage into the enclosure is the leading cause of premature building enclosure failure. Rain control is typically addressed using a shingle lapped and/or taped drainage plane such as building paper or a synthetic WRB (i.e. homewrap). Intersections, windows, doors and other penetrations must be drained and/or detailed to prevent the penetration of rainwater beyond the drainage plane.[3]

Air Leakage Control: Since fibrous insulations are air permeable, air leakage condensation may occur if air moves into the stud space from the interior, or the exterior, depending on the climate. An air barrier is required in this wall system to ensure that air leakage is ideally eliminated, but at least minimized. Air leakage condensation is one of the greatest causes of premature building enclosure failure. An air barrier should be stiff, continuous, durable, strong, and impermeable.[4]

Air need not leak straight through an assembly to cause moisture problems; it can also leak from the inside, through the wall, and back to the inside. Condensation within the stud space is possible if this type of airflow occurs, depending on the weather conditions. Hence, wall designs should control airflow into the stud space.

Vapor Control: Fiberglass and cellulose are vapor permeable materials, so a separate vapor control strategy must be employed to ensure that vapor diffusion from does not result in condensation on or damaging moisture accumulation in moisture sensitive materials. In this case, the high density foam acts as a vapor control layer in the assembly. The permeance and location of vapor control is dependent on the climate zone and in cold climates, further vapor control may be required due to the ratio of insulation interior of the vapor control layer. Some level of vapor control may be needed on the interior surface or the amount of spray foam insulation could be increased. Installing the vapor control layer in the incorrect location can lead to building enclosure failure.[5] The IRC building code should be consulted.

Drying: Cellulose and fiberglass insulation allow drying easily, so drying is controlled by other enclosure components such as the high density spray foam and OSB sheathing. Installing vapor control on both sides will seal any moisture into the stud space, resulting in low drying potential, and possibly resulting in moisture-related durability risks. Ventilation behind vapor impermeable claddings and interior components (e.g. kitchen cabinets) can encourage drying.

Built- in Moisture: Care should always be taken to build with dry materials where possible, and allow drying of wet materials before close in. Cellulose is often sprayed in damp, and manufacturers recommend drying before close in and moisture content limits. Interior vapor control may be required depending on the climate zone, and with the combination of vapor semi-impermeable foam and OSB, will increase the time required for adequate drying.

Durability Summary: The primary durability risks associated with these wall assemblies involve moisture damage related to rain water penetration or condensation (most likely the result of air leakage, but also potentially the result of vapor diffusion). In some extreme cold climates, two inches of spray foam may not be enough insulation to minimize the risk of air leakage and vapor condensation durability issues because of the ratio of insulation to the interior and exterior of the surface of the spray foam. Increasing the amount of spray foam (the amount of insulation exterior of the condensation plane) will further decrease the risk.

An airtight drywall construction approach will also reduce risks associated with air leakage condensation, and some form of vapor control may be needed (poly, kraft paper or vapor barrier paint depending on climate).

Cellulose insulated walls are slightly more durable because cellulose insulation is capable of storing and redistributing small amounts of moisture. Cellulose insulation is typically treated with borates that have been shown to protect itself and neighboring wood material from mold growth and decay. Cellulose insulation also has decreased flame spread potential relative to other insulation materials.

Buildability

A double stud wall requires more effort and time to construct properly compared to standard construction practices. The thickness of the wall requires plywood boxes to install all windows and doors in the enclosure. Installing spray foam reduces the risks from poor workmanship but in some climates more than two inches of high density spray foam may be required to completely avoid the risk of air leakage and vapor condensation. Double stud wall construction reduces the interior living space of the building by adding insulation to the interior of the structural framed wall.

Cost

There are increased costs in the addition of a secondary interior wall, and spray foam insulation. The benefits of reduced condensation potential may not be worth the cost of adding spray foam since there are only minimal benefits to the R-value of the wall assembly.

Material Use

A secondary interior framed wall increases the amount of framing material required for wall construction. Spray foam insulation significantly increases the embodied energy over using cellulose insulation with minimal returns in R-value.

Total Score

This is truly a high-R wall assembly, and with the addition of spray foam, there is a reduction in moisture related durability issues. In some extreme climates, two inches of spray foam may not be enough to sufficiently reduce the risk, which means that more spray foam is required, or an interior air barrier and some form of vapor control, likely a Class II or Class II would be sufficient. The other disadvantage to this wall system is that it reduces the living space of the building.

References

1 Straube, J., & Smegal, J. (2009). *Building America Special Research Project - High-R Walls Case Study Analysis*. Retrieved from buildingscience.com.

2 Straube, J. (2009, 04 22). *BSD-014 Air Flow Control in Buildings.* Retrieved from buildingscience.com.

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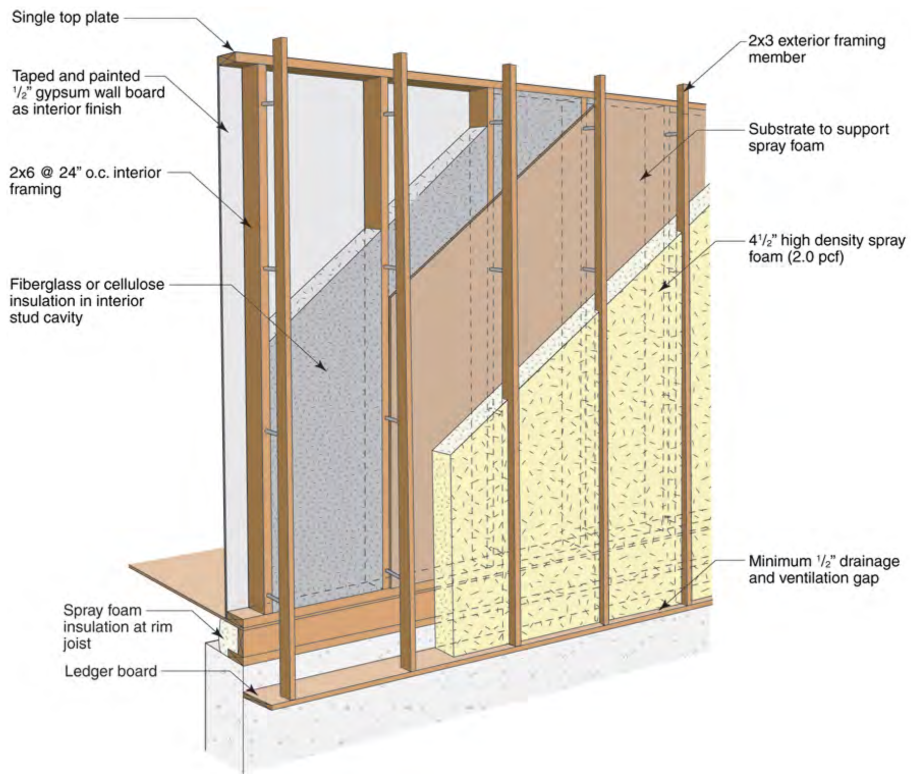
Offset Frame Wall Construction

Offset Frame Wall Construction Details *(Wall 11)*[1]

- 2x6 structural framing wall
- 2x3 cantilevered wall
- 4.5" high density spray foam
- Fiberglass or cellulose cavity insulation
- OSB sheathing



Scoring: How It Rates

The scoring of each wall system is based on the following five categories. A score of 1 is the lowest score in each category and represents the worst possible technology for each category or highest possible relative cost. A score of 5 is the highest score available in each category, and is representative of the best available technology available on the market or lowest relative cost.

Thermal Control	5
Durability	5
Buildability	4
Cost	3
Material Use	2
Total	**19**

The offset frame wall system is ideal in many situations where the cost of high density spray foam is justified. There is very minimal risk to moisture related durability issues from rain penetration or condensation because off the continuous exterior spray foam insulation if the penetrations are detailed correctly. This is a very durable wall system for all climates, and can be built as new construction or a deep retrofit.

Introduction

This two page summary briefly summarizes the offset frame wall construction including the advantages and disadvantages of this construction strategy. A more detailed analysis and direct comparison to several other walls can be found online.[1] The scoring system is somewhat subjective based on the relative performance and specifications between different wall systems. Complex two dimensional heat flow analysis and one dimensional hygrothermal modeling were used to determine moisture related durability risks for analysis.

For a more complete analysis of this and other wall constructions, go to www.buildingscience.com.

Thermal Control

Installed Insulation R-value: The amount of insulation installed in this wall system can be modified quite easily but in this case, 4.5" of high density spray foam (R-6/inch) was used on the exterior, and 5.5" of cellulose (R-3.7/inch) was installed in the stud space for a total installed insulation R-value of R-47. It is possible to install as much or as little spray foam insulation on the exterior as practical in specific cases.

Whole-wall R-value: Using two dimensional heat flow analysis with thermal bridging effects and average framing factors, the thermal bridging in this wall system is significantly reduced by the uniform layer of spray foam over the exterior covering the rim joist and wall framing. The whole wall R-value for this assembly is approximately R-37.[1]

Air Leakage Control: The exterior spray foam insulation is a perfect air barrier for this enclosure eliminating heat losses by air leakage through the wall. Air still could leak around penetrations such as windows, doors, and services if not detailed correctly.[2]

Typical Insulation Products: High density spray foam and fiberglass batt, blown cellulose, sprayed cellulose, or sprayed fiberglass.

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Durability

Rain Control: For this wall system, the continuous drainage plane will be the exterior surface of the high density foam. Rain screen cladding will be installed directly on the exterior framing, and any moisture that passes through the cladding will drain against the high density spray foam. Intersections, windows, doors and other penetrations must be detailed to prevent the penetration of rainwater.[3]

Air Leakage Control: The continuous layer of high density spray foam prevents all air leakage through the enclosure system. Care should be taken to make sure that penetrations through the enclosure (windows, doors, services) are airtight. There should be no risk of air leakage condensation against the sheathing in most climates with 4.5" of exterior spray foam. In climate zone 8, more spray foam may be required, or the stud space insulation can be removed to ensure that there is no condensation.[4]

Vapor Control: The continuous layer of high density spray foam prevents vapor movement through the enclosure system. There should be no risk of vapor condensation against the sheathing in most climates with 4.5" of exterior spray foam. In climate zone 8, more spray foam may be required, or the stud space insulation can be removed to ensure that there is no condensation.[5]

Drying: This enclosure system will dry both to the interior, if the moisture is in the stud space, and to the exterior, if the moisture is in the cladding. Proper flashing of all penetrations should help minimize moisture in the enclosure. Ventilation behind vapor impermeable claddings and interior components (e.g. kitchen cabinets) can encourage drying.

Built- in Moisture: Care should always be taken to build with dry materials where possible, and allow drying of wet materials before closing in. Cellulose is often sprayed in wet, and manufacturer's recommendation is to allow drying before closing in. Because no polyethylene vapor barrier is required, moisture in the stud space will be able to dry quite easily to the interior.

Durability Summary: Provided the minimum amount of spray foam insulation is exceeded for a given climate to keep the condensation plane above the dew point, there is virtually no risk to moisture condensation in the enclosure, and any small amounts of moisture in the enclosure will dry easily.

Cellulose insulation is typically treated with borates that have been shown to protect itself and neighboring wood material from mould and decay. Cellulose insulation also has decreased flame-spread potential.

Buildability

This wall system does require some attention to detailing, and likely some initial training to install the exterior framing material1, but the risks from poor construction are very minimal. Spray foam insulation is shipped as a liquid in two components and only mixed as it is installed, so shipping is much more efficient and reliable than board foam, which has been reported to arrive on the job site damaged, especially in remote areas. It is very quick and easy to dry in a structure with spray foam insulation to weatherproof it, which is critical in environments with short construction seasons. Interior finishing can be done even in inclement weather. This enclosure system has been used both in new construction and in retrofit situations in cold climates.

Cost

In most regions high density spray foam is a relatively expensive method of insulating the enclosure, however the benefits, of a complete air and vapor barrier, occupancy comfort, reduced energy consumption, and reduced risks to contractor errors may be worth the increased cost in some locations and situations.

Material Use

More framing materials are required for this enclosure assembly, as well as the higher embodied energy high density spray foam. Cellulose in the stud space has very low embodied energy.

Total Score

This wall system is ideal in many situations where the cost of high density spray foam is justified. One of the locations where the cost is justified is the extremely cold climates and short construction seasons of the north. Most of the durability related issues are caused by air leakage and vapor condensation on the sheathing causing rot and mold in the enclosure. The common complaints in the remote locations is that the board foam arrives on trucks badly damaged, but with spray foam, the foam is shipped in two liquid components, and more board feet of foam could be shipped on the same truck. The construction season is very short but houses can be dried in during the best weather, and the interior finished later if necessary.

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1 Straube, J., & Smegal, J. (2009). *Building America Special Research Project - High-R Walls Case Study Analysis*. Retrieved from buildingscience.com.

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EXTERIOR INSULATION FINISH SYSTEMS (EIFS) WALL CONSTRUCTION

EXTERIOR INSULATION FINISH SYSTEMS (EIFS) WALL CONSTRUCTION DETAILS

(Wall 12)[1]

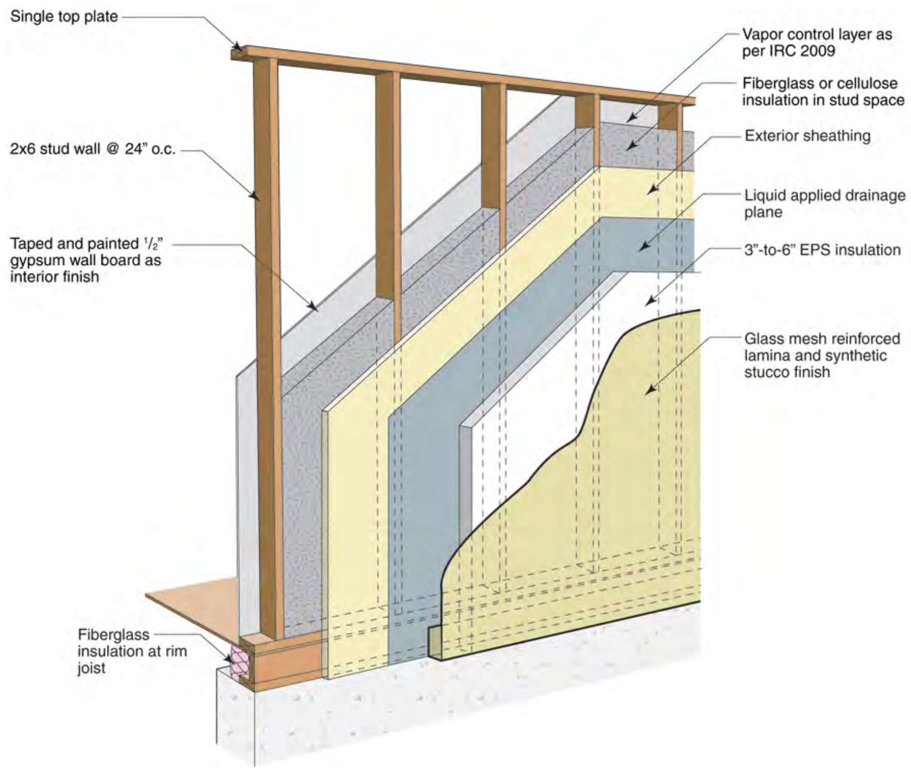
- 2x6 structural framing wall
- Fiberglass or cellulose cavity insulation
- Glass-faced gypsum sheathing
- Exterior EPS insulation
- Stucco finish

SCORING: HOW IT RATES

The scoring of each wall system is based on the following five categories. A score of 1 is the lowest score in each category and represents the worst possible technology for each category or highest possible relative cost. A score of 5 is the highest score available in each category, and is representative of the best available technology available on the market or lowest relative cost.

Thermal Control	5
Durability	5
Buildability	4
Cost	3
Material Use	3
Total	**20**

This wall system is a durable and reliable choice regardless of the historical failures of this construction strategy. A better understanding of enclosure design and building science with drained and ventilated claddings and better design details have nearly eliminated the historical moisture related issues. This wall system has the appearance of a stucco finish, but with significant energy improvements, which is often the reason for using this construction strategy.



INTRODUCTION

This two page summary briefly summarizes EIFS wall construction including the advantages and disadvantages of this construction strategy. A more detailed analysis and direct comparison to several other walls can be found online.[1] The scoring system is somewhat subjective based on the relative performance and specifications between different wall systems. Complex two dimensional heat flow analysis and one dimensional hygrothermal modeling were used to determine moisture related durability risks for analysis.

For a more complete analysis of this and other wall constructions, go to www.buildingscience.com.

THERMAL CONTROL

Installed Insulation R-value: The framed portion of this wall assembly typically has an R-value of R-19-20 when insulated with fiberglass batt or cellulose. Exterior insulation for EIFS is typically EPS at R-4/inch.

Whole-wall R-value: Using two dimensional heat flow analysis with thermal bridging effects and average framing factors demonstrates improvements in the efficiency of the fiberglass batt or cellulose in the stud space by decreasing the thermal bridging effects of the framing and the rim joist. Adding 4" of EPS insulation for a total an increase of R-16 increases the Clear-wall R-value of standard construction by slightly more than R-16 because of thermal bridging of the framing and rim joist. The whole-wall R-value for this system is approximately R-30.[1]

Air Leakage Control: Fiberglass batt, blown and sprayed cellulose are all air permeable materials allowing possible air paths between the interior and exterior as well as convective looping through the material. The air tightness of an EIFS system is typically at the surface of the exterior sheathing (usually glass-faced exterior gypsum) because it is the drainage plane.

Typical Insulation Products: EPS exterior insulation, fiberglass batt, blown cellulose, sprayed cellulose.

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Durability

Rain Control: In the EIFS system, it is critical to correctly detail the drainage plane to adequately handle rain. Historically EIFS were constructed using a face-sealed approach, but this lead to many moisture related durability issues. EIFS can be used as part of a very durable and reliable enclosure system, provided it is drained and ventilated. Intersections, windows, doors and other penetrations must be detailed to prevent the penetration of rain water.[2]

Air Leakage Control: By adding exterior insulation as part of the EIFS construction, the temperature of the sheathing (condensation plane) increases, and the risk of air leakage condensation is reduced. It is always good practice to build airtight enclosure systems, often with both an interior and exterior air barrier to avoid air leakage condensation and windwashing. Air leakage condensation is one of the greatest causes of premature building enclosure failure. An air barrier should be stiff, continuous, durable, strong, and impermeable.[3]

Air need not leak straight through an assembly to cause moisture problems; it can also leak from the inside, through the wall, and back to the inside. Condensation within the stud space is possible if this type of airflow occurs, depending on the weather conditions. Hence, wall designs should control airflow into the studspace.[4]

Vapor Control: By adding exterior insulation as part of the EIFS construction, the temperature of the sheathing (condensation plane) increases, and the risk of moisture vapor condensation is reduced. It may be possible to avoid the use of an interior vapor control layer, or use a higher permeance vapor control layer (Class II or III) depending on the amount of insulation on the exterior and regional building codes. Installing the incorrect vapor control layer or installation in the incorrect location can lead to building enclosure failure.[5] The IRC building code should be consulted.

Drying: Insulating sheathing limits the drying to the exterior, and the wall must be able to dry to the interior. Poly vapor barriers are typically avoided so that this drying can occur. The minimum level of vapor control on the interior surface is determined by the IRC. Installing vapor control on both sides of the enclosure will seal any moisture into the stud space, resulting in low drying potential, and possibly resulting in moisture-related durability risks. Ventilation behind vapor impermeable claddings and interior components (e.g. kitchen cabinets) can encourage drying.

Built- in Moisture: Care should always be taken to build with dry materials where possible, and allow drying of wet materials before close in. Cellulose is often sprayed in damp, and manufacturers recommend drying before close in and moisture content limits.

Durability Summary: The primary durability risks associated with these wall assemblies involve moisture damage related to rain water penetration. Insulating sheathings keep the condensation plane temperature elevated so there is less risk of condensation due to air leakage or vapor diffusion. Framing members are also kept warmer so they are exposed to lower relative humidity levels and generally have lower equilibrium moisture contents. Board foam products are typically less moisture sensitive than wood-based structural sheathing products.

Cellulose insulated walls are somewhat more durable because cellulose insulation is capable of storing and redistributing small amounts of moisture. Cellulose insulation is typically treated with borates that have been argued to protect adjacent wood members from mold and decay.

Buildability

Exterior insulation up to 1.5" requires minimal changes to standard construction practices. Exterior insulation in excess of 1.5" requires minor changes to window and wall construction and detailing which requires training and monitoring during the initial implementation. The EIFS finish system is directly applied to the exterior foam, and requires skilled trades to install. Some EIFS companies produce detail drawings for their products to reduce the risk of construction issues resulting in premature enclosure failure. www.stocorp.com and www.dryvit .ca are two examples that provide detailed drawings on their websites.

Cost

There is an increased cost to EIFS wall construction because of the specialized stucco like finish. It is possible to add exterior insulation with a rain screen cladding as an alternative to the stucco appearance finish that may be more cost effective.

Material Use

Typically, in EIFS construction, structural wood sheathing is exchanged for a more moisture tolerant sheathing such as glass mesh reinforced exterior gypsum board. The addition of EPS foam can usually be sourced locally, and has relatively low embodied energy relative to other board foam insulations.

Total Score

This wall system is a durable and reliable choice regardless of the historical failures of this construction strategy. A better understanding of enclosure design and building science with drained and ventilated claddings and better design details have nearly eliminated the historical moisture related issues. This wall system has the appearance of a stucco finish, but with significant energy improvements, which is often the reason for using this construction strategy. It is possible to use exterior insulation with many different cladding options if a stucco appearance is not the desired architectural result.

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3 Lstiburek, J. (2008, 08 20). *BSD-104: Understanding Air Barriers*. Retrieved from buildingscience.com.

4 Straube, J. (2009, 04 22). *BSD-014 Air Flow Control in Buildings.* Retrieved from buildingscience.com.

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1.5.4. High-R Foundations Case Study Analysis

by Jonathan Smegal, October 2009 – DRAFT

Building America Special Research Project
High-R Foundations Case Study Analysis

2009 10 30

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Table of Contents

A. Introduction

Many concerns, including the rising cost of energy, climate change concerns, and demands for increased comfort, have lead to the desire for increased insulation levels in many new and existing buildings. Building codes are improving to require higher levels of thermal control than ever before for new construction. This report considers a number of promising foundation and basement insulation strategies that can meet the requirement for better thermal and moisture control in colder climates. By code, basements in DOE climate zones require a continuous layer of R10 insulation or R13 in a framed wall. High R basements, for cold climates, in this report are walls that exceed R20. In a warmer climate, that does not require basement insulation, high-R may be considered less.

Basements are stereotypically cool, damp, musty smelling areas of the building that were historically unfinished, unoccupied and used mostly as storage. More and more often, people are finishing their basements to increase the living environment and frequently the basement is transformed into a media room, bedroom, or extra living room. These new environments require greater control of both heat and moisture to provide a healthy living environment with minimal risk to equipment and finishes.

A successful foundation will perform the following tasks

- Hold the building up
- Keep the groundwater out
- Keep the soil gas out
- Keep the water vapor out
- Let the water vapor out that gets in the wall
- Keeps the heat in during the winter
- Keeps the heat out during the summer

Basement failures occur often due to flooding, or vapor diffusion condensation, both of which may result in mould or dust mite problems. By designing the basement or foundation enclosure system properly, the majority of all basement moisture and comfort issues can be avoided.

This study compares over a dozen basement and foundation enclosure designs including historical construction strategies, code minimum construction and highly insulated construction. This demonstrates through computer based simulations and field experience, differences in energy consumption, thermal control, and moisture related issues.

This study is an extension of the previous Building America study of High R wall assemblies (Straube and Smegal 2009), to continue to improve the overall building enclosure and achieve greater energy savings.

1. OBJECTIVE

The goal of this research is to find a optimally designed, cost effective basement insulation system that can be included with other enclosure details to help reduce whole house energy use by 70%.This report will compare a variety of basement and foundation insulating strategies and present their advantages and disadvantages according to several comparison criteria.

2. SCOPE

This study is limited to basement and foundation systems for cold climates. A previous study was conducted for wall systems and further studies should be conducted to address roofs and attics. In general, only cold climates are considered in this report since enclosures in cold climates benefit the greatest from a highly insulated building enclosure, but important conclusions can also be drawn for other climate zones.

3. APPROACH

The quantitative analysis for each wall system is based on a three-dimensional energy modeling program and a one-dimensional dynamic heat and moisture (hygrothermal) model. Minneapolis, MN in IECC climate Zone 6 was used as the representative cold climate for most of the modeling, because of the cold winter weather and fairly warm and humid summer months.

B.Analysis

1. WALL ASSEMBLIES REVIEWED

Because there are a number of variables for each possible wall system depending on the local practices, climate, and architect or general contractor preferences, an attempt was made to choose the most common wall systems and make notes about other alternatives during analysis. This list of chosen systems is explained in more detail in the analysis section for each wall system.

- Case 1 : Un-insulated Basement
- Case 2 : Code minimum R10 continuous insulation
- Case 3 : 3.5 inches fibreglass batt in 2”x4” SPF wood framed wall
- Case 4 : 1 inch XPS + 3.5 inches fibreglass batt in 2”x4” SPF wood framed wall
- Case 5 : 2 inches XPS + 2 inches polyisocyanurate with R10 under slab
- Case 6 : 3.5 inches 2.0 pcf spray foam with R10 under slab
- Case 7 : 6 inches 0.5 pcf spray foam with R10 under slab
- Case 8 : 2 inches XPS + 3.5 inches fibreglass batt in 2”x4” SPF wood framed wall with R10 under slab
- Case 9 : 2 inches polyisocyanurate +3.5 inches cellulose in 2”x4” SPF wood framed wall with R10 under slab
- Case 10 : 6 inches 0.5 pcf spray foam in offset 2”x4” SPF wood framed cavity with R10 under slab
- Case 11 : 4 inches XPS on exterior of basement with R10 under slab
- Case 12 : 4 inches XPS in centre of foundation wall with R10 under slab
- Case 13 : ICF wall with 4” XPS and R10 under slab
- Case 14 : 2 inches XPS + 5.5 inches fibreglass batt in 2”x6” SPF wood framed wall with R10 under slab

2. ANALYSIS CRITERIA

A comparison matrix will be used to quantitatively compare all of the different basement insulation strategies. A value between 1 (poor performance) and 5 (excellent performance) will be assigned, upon review of the analysis, to each of the comparison criteria for each wall. An empty comparison matrix is shown below in Table 1 as an example.

Table 1: Criteria comparison matrix

	Thermal Control	Durability (wetting/dry	Buildability	Cost	Material Use	Total
Criteria Weighting	1	1	1	1	1	
Case 1: uninsulated						
Case 2: R10 continuous with poly (roll batt)						
Case 3: R13 batt, 2x4 wall with poly						
Case 4: 1" XPS, 2x4 framed wall with fgb						
Case 5: 2" XPS, 2" PIC						
Case 6: 3.5" 2.0pcf cc spuf						
Case 7: 6" 0.5pcf oc spuf						
Case 8: 2" XPS, 2x4 framing with fgb						
Case 9: 2" PIC, 2x4 framing with cellulose						
Case10: 2.5" 0.5 oc spuf, 2x4 framing with same foam						
Case 11: 4" XPS on the exterior						
Case 12: 4" XPS in the centre of foundation wall						
Case 13: ICF – 2" XPS interior and exterior						
Case 14: 2" XPS, 2x6 framing with fgb						

The criteria scores will be summed for each insulation strategy, and the walls with the highest scores are the preferred options assuming all of the comparison criteria are weighted equally. It is also possible to weight the different comparison criteria asymmetrically depending on the circumstances surrounding a particular wall design. The weightings for each wall will fall between 1 (least important) and 5 (most important). The weighting is multiplied by the comparison criteria score and added to other weighted values. An example of the weighted conclusion matrix will be shown in the conclusions section of this report.

One of the benefits of using a comparison matrix is that it allows a quantitative comparison when some of the criteria, such as cost may be poorly defined or highly variable. For example, even though the exact costs of different insulations may be uncertain, fibreglass batt insulation is always less expensive than low density (0.5 pcf) spray foam which is less expensive than high density (2.0 pcf) spray foam, so these systems can be ranked accordingly regardless of the actual costs.

Each of the criteria are described in detail below.

2.1 Thermal Control and Heat Flow Analysis

The Heat flow and energy analysis of each basement system was conducted with Basecalc, developed by Canmet ENERGY and is based on the National Research Council of Canada's Mitalas method. Mitalas used mainframe computers to perform finite-element analyses of a large number of basements and analyzed the results to produce a series of basement heat-loss factors, which were then published as a reference (Mitalas 1983).

A user can apply the Mitalas method by using the correct heat-loss factors from the published tables and perform a series of calculations to predict heat and energy losses. Basecalc incorporates the finite-element approach Mitalas used to generate the heat-loss factors. During this study an analysis spreadsheet model was constructed using the Mitalas method and comparisons of the results between the analysis spreadsheet and Basecalc have been conducted.

The Basecalc software is a relatively simple menu driven program that has many options for construction strategies, insulation placement and site conditions (Figure 1).

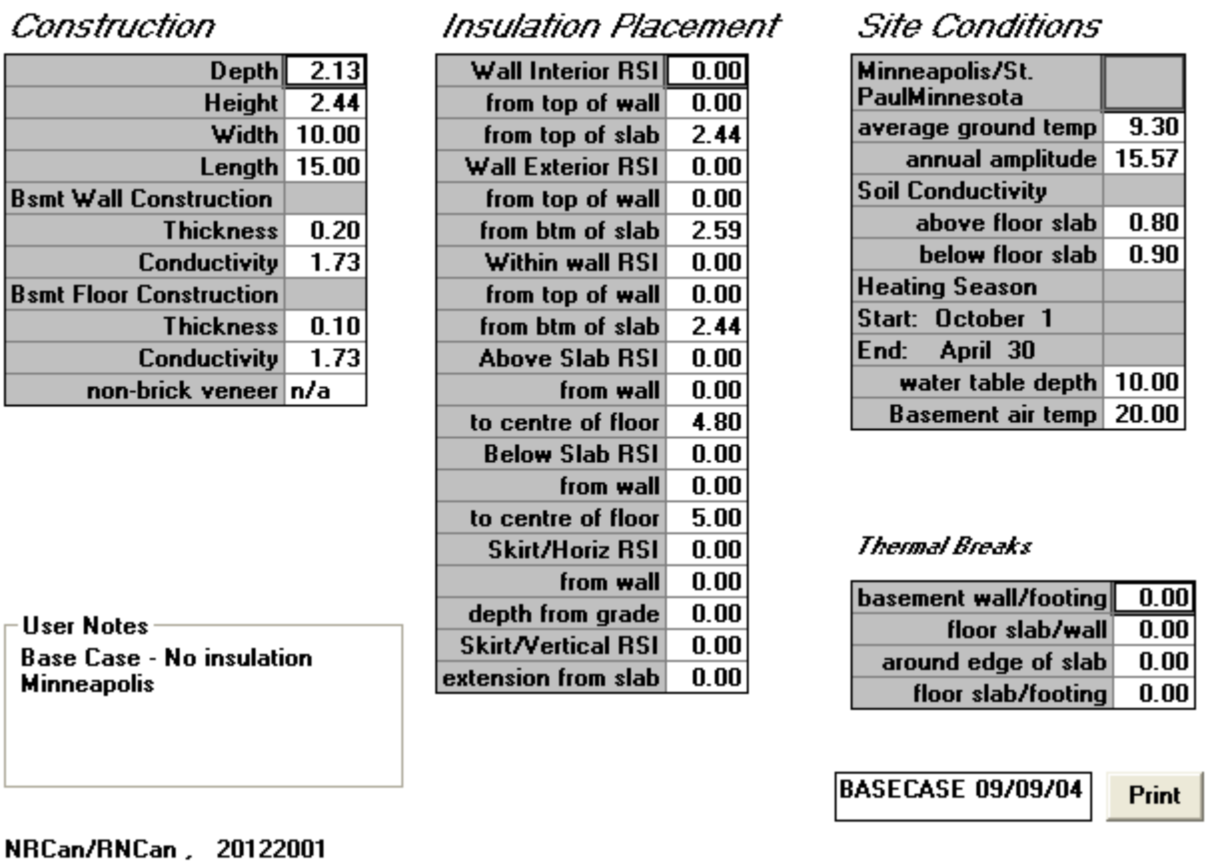


Figure 1 : Screen Capture showing inputs for Basecalc

Some assumptions were made for all of the Basecalc analysis to ensure comparison was possible between resulting simulations. The energy calculated is only for these specific cases, and modifying any of the variables may change the resulting energy requirements. These assumptions are listed below:

- All simulations were run for Minneapolis/St. Paul MN, data included in Basecalc
- Basement interior height - distance from top of slab to top of foundation wall 2.44 m (8 ft)
- Depth (below grade foundation) – distance from top of slab to surface of ground, 2.13 m (7 ft)
- Width - exterior of structural wall to exterior of structural wall, 10 m (32.8 ft)

- Length – exterior of structural wall to exterior of structural wall, 15 m (49.2 ft)

In Basecalc, the rim joist is not considered, but this was analyzed in past research(Straube and Smegal 2009), but thermal bridging across the top of the foundation wall is considered depending on above grade wall construction. For example, one of the most common thermal bridges in construction is the exterior above grade brick cladding sitting on the outside edge of the foundation wall. **(Find image maybe?)** This thermal bridging can be taken into account in Basecalc. For all simulations in this study, the above grade cladding was assumed to be non-brick veneer, to alleviate the issue of a significant thermal break at the top edge of the foundation wall.

All of the Basecalc results are presented in units of MBtus. For clarification 1 MBtu and it's equivalent energy in other common units of measure are show in Table 2.

Table 2 : Conversion of 1 MBtu to Other Common Energy Units

Million Btu's (MBtu's)	**1**
Btu's	**1,000,000**
Therms	**10**
Kilojoules	**1,057,000**
Kilowatt hours	**293.6**

The best way to explain energy savings to homeowners is often in dollars saved since the value of a dollar is commonly known and can be compared to other design decisions. Unfortunately, prices vary considerably across the continent for heating energy, and also vary depending on the technology used for heating, whether it be electricity, natural gas, oil, etc. For analysis purposes, if cost comparisons are used it will always be for electric heating at 15 cents per kilowatt hour ($44/MBtu). This value should be kept in perspective since heating methods and costs will vary. The cost of energy is sure to rise, and even though the rate of increase is unknown, but dollar savings today will be higher in the future.

2.1.1. Building Code Requirements

According to the IECC in climate zones 4 or higher, the building code requires a minimum of R10 continuous insulation (fiberglass roll batt) or R13 discontinuous (framed wall with R13 fiberglass batt). Adding this required amount of insulation makes a significant difference from an energy perspective as shown in Figure 2, but does not adequately address the comfort, moisture and health concerns that can occur in basements. Case 1 in this study is an un-insulated basement as many such cases can be found in new and existing buildings, and Cases 2 and 3 are typical of code minimum basements built in many cold climates.

An initial analysis was conducted to determine the effects of different amounts of insulation and strategies on the total heat loss prior to analyzing the various wall systems. Figure 2 shows the improvements in annual energy loss by insulating the full height of the basement wall with different insulation values over an un-insulated basement. The most significant improvement is achieved by adding R5, which shows that adding any insulation could help with energy losses. Increasing the insulation to R10 which is the code minimum as a continuous insulation results in a predicted energy savings of 31.2 MBtus (savings of $1372/year based on $0.15/kWhr or $44/MBtu). The energy savings should be considered when determining the cost of adding insulation, and whether or not it is cost effective.

Figure 2 also shows the predicted energy savings if the slab is insulated with R10 below the slab. In the un-insulated case there is an improvement of Heating Season Energy Loss of 1.3 MBTUs, and in the R20 insulated wall comparison the improvement is slightly improved with underslab insulation at 1.5 MBtus. However, the most important aspects of the underslab insulation are not shown on this graph. Comfort levels and moisture related issues including dampness and musty smells will decrease if underslab insulation is used. In some cases when radiant floor heating is used, R20 or greater underslab insulation is necessary to reduce the heat loss to the ground.

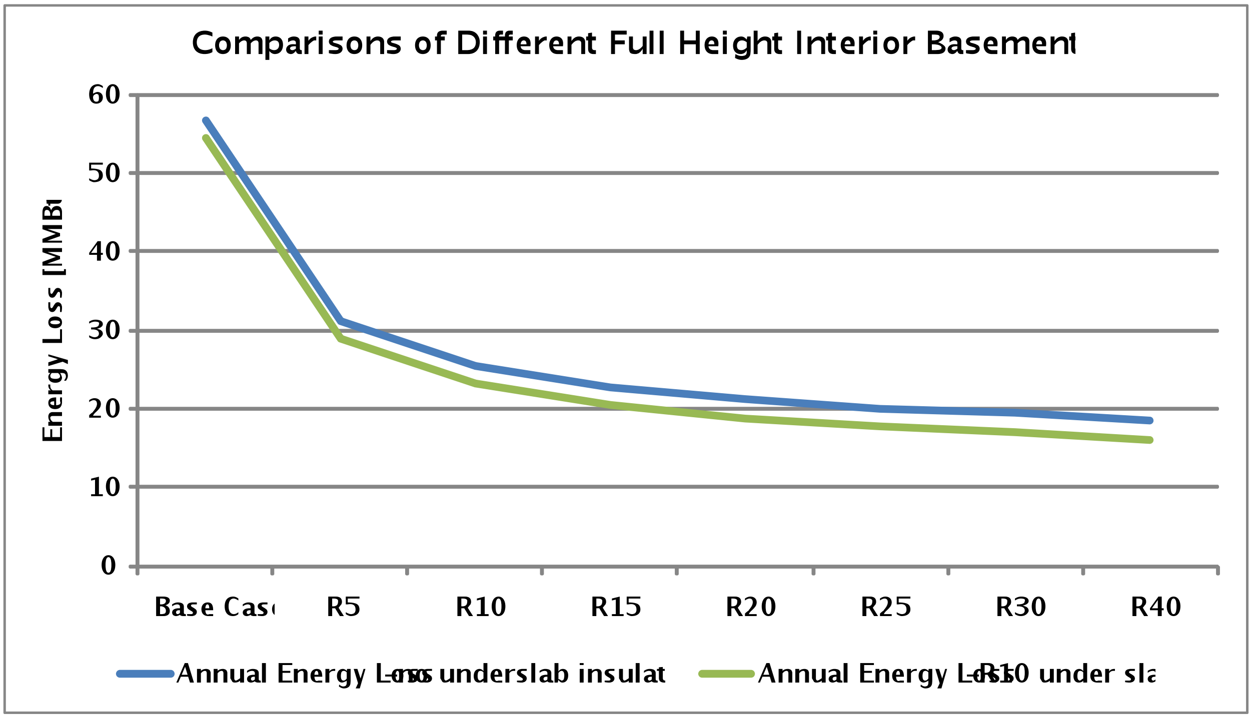


Figure 2 : Reduction in Energy Loss with the Addition of Full Height Foundation Wall Insulation

Two different underslab insulation strategies are compared in Figure 3, while keeping the foundation wall insulation constant at the code minimum continuous R10. Insulating only the perimeter 1.0 m (3.28 ft) saves approximately 1 MBtu when the underslab insulation is increased from 0 to R20, and insulating the entire slab saves approximately 4 MBtus of annual energy loss.

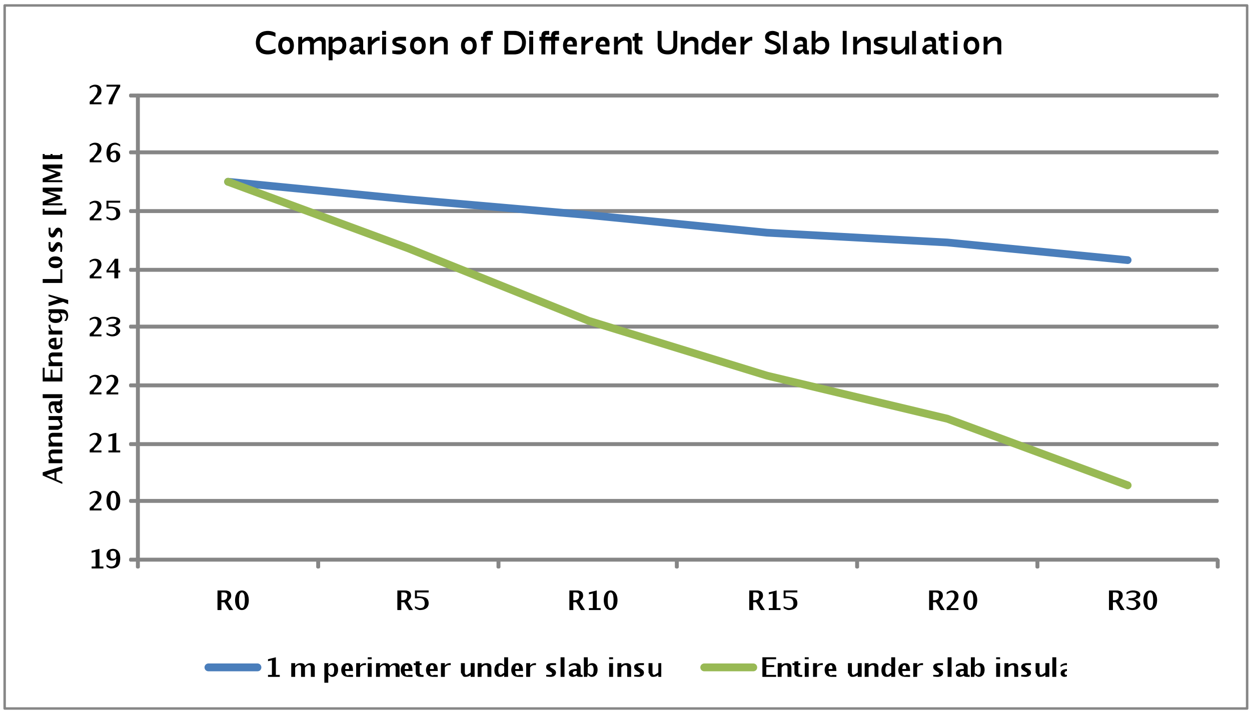


Figure 3 : Comparison of Different Underslab Insulation Techniques

In typical construction, there is a significant thermal break at the connection of the basement slab to the foundation footing and it allows capillary movement of water as discussed previously. If the wall is insulated correctly, and there is underslab insulation, there can still be heat lost and moisture gained through the concrete connection where the edge of the concrete slab meets the foundation wall. There are several methods to limit the capillary wicking of the foundation wall, but to improve both the heat loss and capillary at one time, a non hygroscopic thermal break is recommended between the slab and foundation wall as shown in the analysis wall drawings later in the report. Basecalc is able to predict the energy savings by adding a thermal break. Some common software packages such as Energy Gauge are incapable of assessing the impact of underslab insulation and thermal break. Since the thermal break around the perimeter is installed at the same time as the underslab insulation, this study assumes that the same foam board insulation is used for both applications (typically R10 is recommended as a minimum).

Figure 4 shows the energy improvements realized by installing a thermal break between the edge of the slab and the foundation wall, assuming that there is code minimum R10 continuous insulation on the wall and R10 installed under the slab. The largest improvement occurs when increasing from no insulation to R5 or 1" of XPS, but typically R10 is used since that is also used under the slab. A savings of 1.8 MBtus are predicted with the mentioned assumptions, but there are also improvements to moisture control that cannot be easily quantified in dollars.

[but how do you quantify these improvements? Should more insulation be used? Would be work saying what our recommendation is based on what you have already said about moisture. In the moisture section, this makes me think that you need a strong statement of what the consequences of too much moisture damage in the basement are. Maybe get something out of Joe's BSD on basements?]

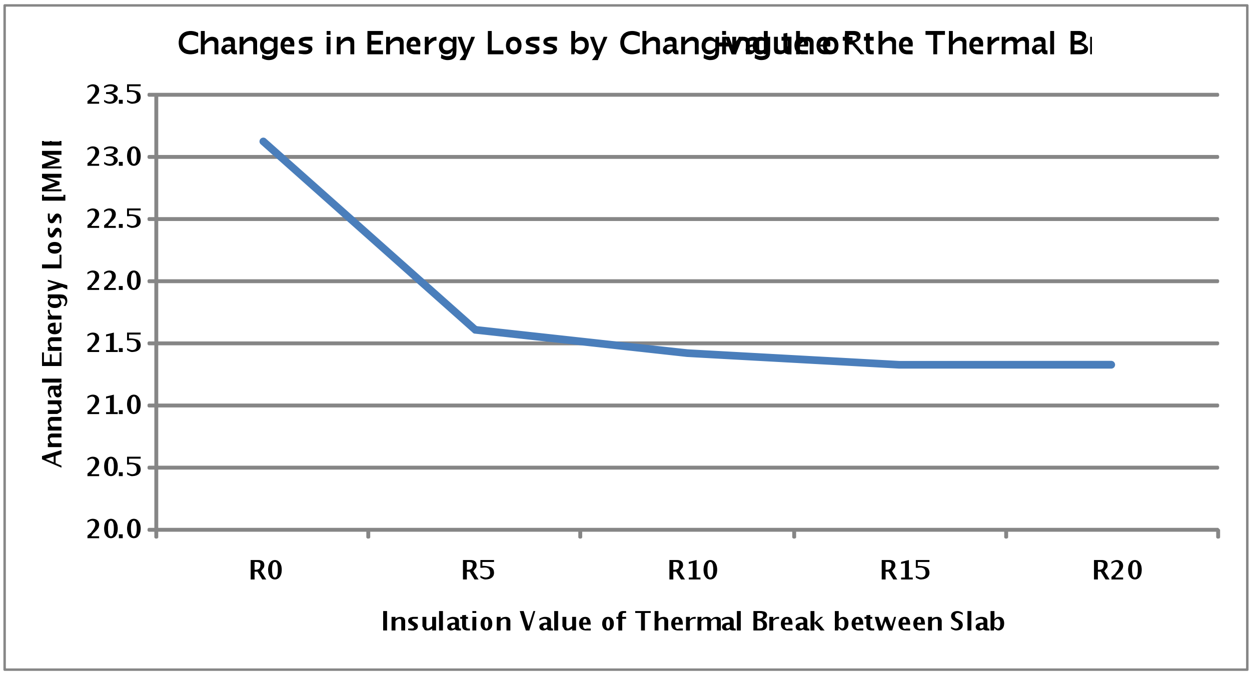


Figure 4 : Energy Savings From Thermal Break Insulation Between Concrete Footing and Slab

2.1.2. Practical Applications – Westford Prototype House

Recently, Building Science Corporation designed and monitored construction of a Building America prototype home in Westford Mass.[1] Simulations were conducted with both Energy Gauge and HOT2000 (H2K) to predict the heating energy losses of the enclosure. The Westford prototype house was constructed with R26 insulation (2 layers of 2" (50 mm) foil faced polyisocyanurate) on the interior of the foundation, R10 under the slab and an R10 thermal break around the perimeter of the slab.

Energy Gauge predicted a whole house heating loss of 277 Therms or 27.7 MBtus. Energy Gauge is not capable of dividing up the energy losses for specific areas of the house nor is it capable of simulating underslab insulation and thermal breaks around the perimeter of the slab.

H2K was also used to simulate the heating energy losses of the Westford prototype house and it was predicted that 6.96 MBtus are lost below grade, and 2.36 MBtus are lost above grade in the basement for a total basement heat loss of 9.32 MBtus in a year. H2K also predicted the total house heating energy losses of 27.16 MBtus, very similar to the Energy Gauge value.

Basecalc was used to determine the total annual energy loss through the basement is 7.1 MBtus which is similar to the H2K value. By modifying some of the insulation values in the basement, the effect on the total house energy can be seen to determine if increases in insulation values are cost effective.

Table 3 shows the effect on the predicted whole house heating energy losses by changing the amount of insulation under the slab.

Table 3 : Effects of Whole House energy by changing Underslab Insulation

[1] Information on this project can be found at http://www.buildingscience.com/documents/case-studies/cs-ba13_MA_Westford_HFH/

	Change in Basement Energy Losses [MBtu]	Change in Whole House Energy Losses [%]
Removing Underslab insulation	-1.3	4.8%
R20 under slab	0.9	3.4%
R30 under slab	1.4	5.0%

Table 3 shows that 1.3 MBtus were saved by adding underslab insulation, a savings of almost 5% of the entire house's heating energy losses. As the underslab insulation is increased, the changes to the entire house's heating energy loses is less significant.

Table 4 shows the effect on the predicted whole house heating energy losses by changing the amount of insulation on the foundation walls.

Table 4 : Effects of Whole House Energy by Changing Foundation Wall Insulation

	Change in Basement Energy Losses [MBtu]	Change in Whole House Energy Losses [%]
R10 code minimum foundation wall insulation	-3.3	11.9%
R40 foundation wall insulation	0.9	3.4%

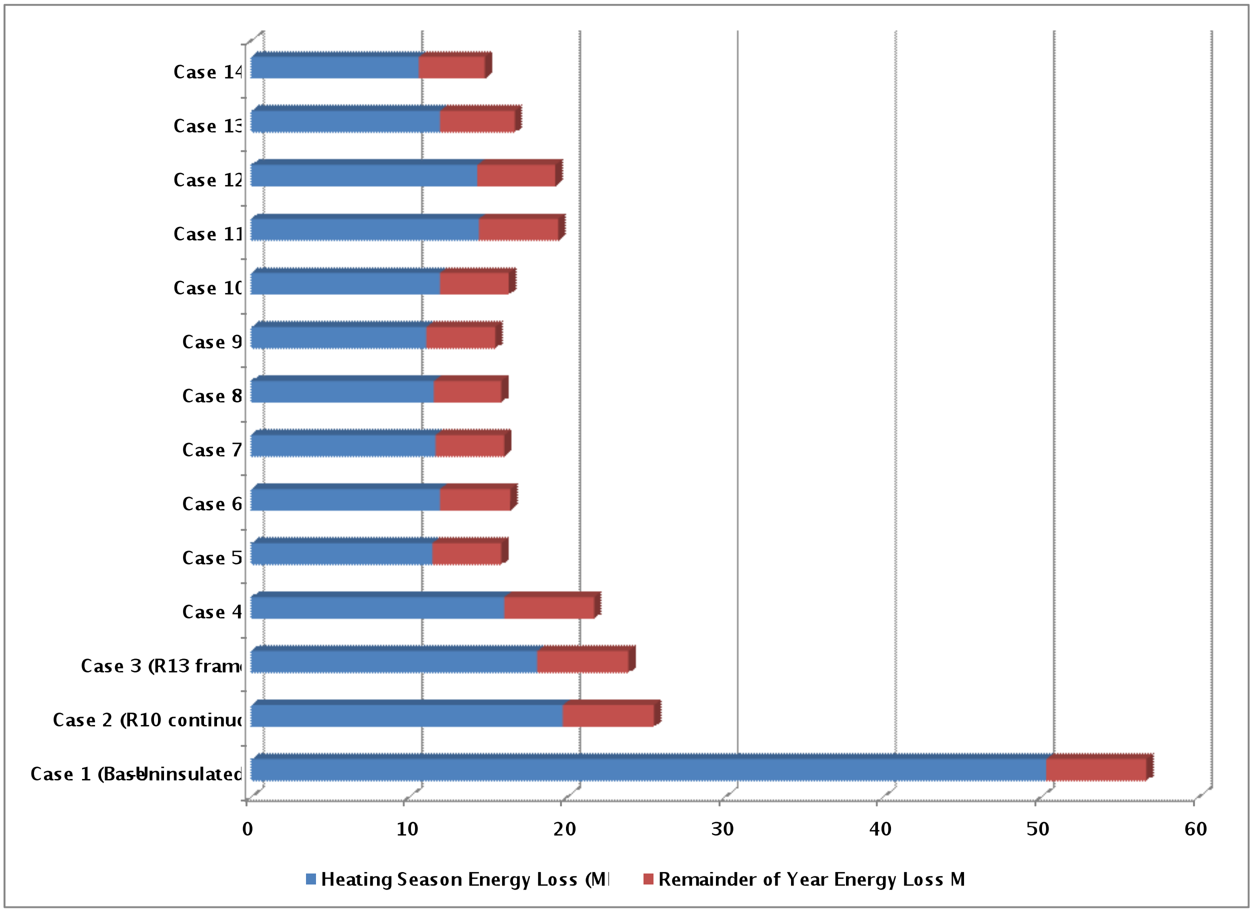
Table 4 shows that 12% of the heating losses of the house are saved from increasing the foundation wall insulation from the code minimum R10 to R26, which is a significant portion of the heating energy losses. This shows that it can be cost effective to insulate the basement in cold climates based on heating energy alone, without considering all of the moisture related benefits.

By increasing the insulation another R13 to R40, results in only a 3.4% decrease in the heating energy losses for the entire house, which is relatively insignificant.

2.1.3. Basement Wall Analysis

Fourteen cases listed previously were simulated in Basecalc, and the heating energy losses were simulated. Some of the proposed wall systems had continuous insulation and the R-values were assumed to be constant. Other proposed wall systems were framed or furred out to the interior and insulated with cavity insulation. The framing materials in these assemblies act as a thermal bridge bypassing the insulation. For the framed walls, the parallel path method was used to calculate the R-value, which is a ratio of the R value through the framing to the R-value through the center of the stud space, assuming a framing spacing of 24" on center. Also taking into account the gypsum wall board and surface film, the thermal bridging of the framing did not significantly affect the R-value, in fact, in some cases the calculated parallel path R-value was slightly higher than the installed insulation R-value.

Underslab insulation and a slab-edge thermal break were only included in simulations for Cases 5 to 14, since it is unlikely in the field to install underslab insulation with minimal foundation wall insulation.



As stated previously, even R10 foundation wall insulation showed a significant amount of energy savings compared to un-insulated basements. However, in some cases, increasing the insulation increases the risk for moisture related problems that will be analyzed in the Hygrothermal Analysis section.

The range of energy loss for the recommended foundation insulation strategies (Cases 5 – 14) is 14.8 to 19.43 MBtus per year. The value of this savings depends on the characteristics of the house, the climate zone, the type of energy used and its associated cost .

The best performing foundation insulation strategies from a heat loss perspective are Case 14 (2" XPS, 5.5" fibreglass batt) and Case 9 (2" PIC, 3.5" cellulose), but there are several others that perform very well. The advantages and disadvantages of the various insulation strategies will be compared further in the Analysis section.

2.2 Hygrothermal Analysis

Moisture Balance

Assessing moisture related durability risks involves three different moisture processes; wetting, drying and moisture redistribution. These three processes in combination with the safe storage capacity of each component will determine the risk of moisture damage to a basement assembly. This report only includes a brief overview of the wetting mechanisms, and was covered in more detail by Joseph Lstiburek 2006.

There are four main wetting mechanisms generally occurring in the foundation and basement. They are:

- Bulk water penetration from the exterior
- Capillary wicking or "rising damp"
- Vapor diffusion (from exterior or interior)
- Plumbing issues on the interior (not considered in this analysis)

The first source of wetting is bulk water from the exterior or from plumbing related issue on the interior. These will cause the greatest amount of damage in the quickest time. The best strategy to avoid water ingress into the basement from the exterior is to drain all of the components away from the building including the site and the exterior of the foundation (**Error! Reference source not found.**). Sometimes it is unavoidable to have liquid water in contact with the foundation and other strategies must be used including exterior drainage mats and sump pumps. In older buildings, foundation walls may have been constructed of rubble or stone and often allow water directly through the foundation wall in the rainy season. Ensuring basement drains are properly located and that they are clear of obstructions will minimize flooding caused by interior plumbing issues. This study does not deal specifically with retrofit strategies, but the possibility of use in retrofit applications will be mentioned for any relevant insulation strategies. Some information regarding the retrofit of basements was written by Betsy Pettit 2005.

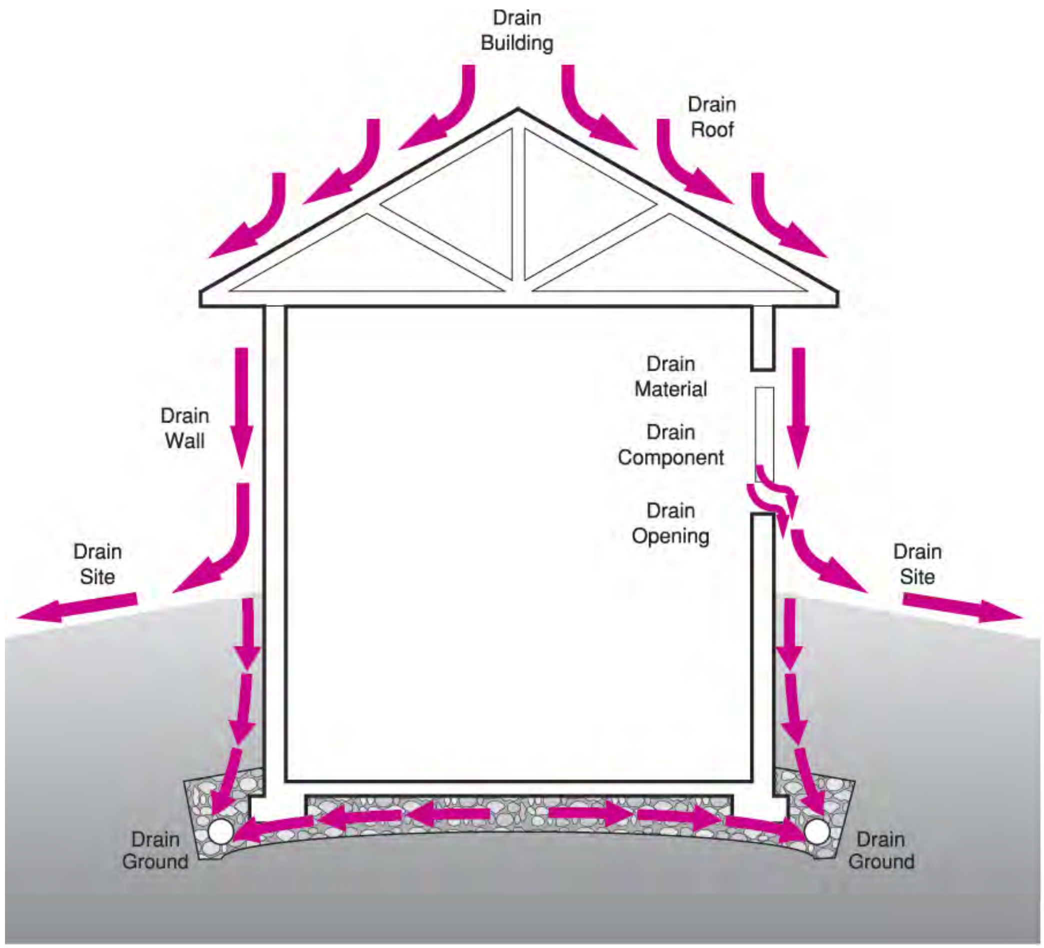


Figure 5 : Drainage details to minimize foundation moisture issues

The second source of moisture in the basement enclosure is caused by capillarity wicking. The physical characteristics and pore size of concrete (10 – 1000 nm) allow it to wick moisture quite effectively against the force of gravity, often with suction pressures of 100 kPa to 10MPa (Straube and Burnett 2005). The most common source of water for capillarity wicking is the footing. In many cases a moisture barrier such as damp-proofing, or a drainage membrane, or both are applied to the exterior of the wall minimizing the risk of absorption through the foundation wall. The floor slab is often poured over gravel which generally acts as a capillary break and should be drained to the exterior drainage tile. In many house foundations, there is no capillary break installed on the footing, and therefore water drawn into the footing is also wicked further up the foundation wall. In a typical basement, the liquid water is drawn to the surfaces of the concrete foundation wall, it will evaporate and dry to the interior or to the exterior as environmental conditions permit. If drying is hindered by a polyethylene vapor barrier, elevated relative humidities may occur near the wall surface or within the wall cavity eventually resulting in mould and other moisture related issues.

As homeowners finish and insulate their basement spaces, a polyethylene vapor barrier is often installed to meet the building code. Some builders who have learned from past experience will remove the bottom couple feet of the polyethylene vapor barrier to avoid mold problems that have been discovered in many basements. Removing the bottom section of the vapor barrier allows liquid water wicked up the footing and into the foundation wall to dry to the interior space. The preferred solution, of course, would be to install a capillary break between the footing and foundation wall during the original construction process to stop moisture from being wicked into the foundation wall.

(Figure if can find one)

The third source of moisture in the basement enclosure is caused by vapor diffusion. As discussed with capillarity above, vapor diffusion occurs from the interior surface of the concrete after water is wicked up the foundation wall. Vapor diffusion can also occur through floor slab if no vapor barrier is installed below the slab. The rate of vapor diffusion is slow, but still may cause durability issues with vapor impermeable floorings installed with water based adhesives, as well as increasing the moisture load in the basement, which can contribute to the common damp, musty odour. Vapor diffusion through the slab can be virtually eliminated by installing a vapor control layer (6 mil polyethylene, board foam insulation or spray foam) under the slab. Interior moisture vapor could also be an issue, especially in late spring and early summer as the environmental relative humidity increases but the concrete foundation temperatures are still cooler because of the seasonal temperature lag of the earth and thermal mass.

Vapor diffusion drying of the concrete can last for several years until the concrete fully hydrates, even if other sources of moisture are eliminated. If there is no moisture barrier on the exterior of the concrete, then the concrete will never dry completely and water vapor will always be passing into and through the concrete.

Drying is important since nearly all building enclosures will experience wetting at some point. In above-grade foundation walls, there is drying potential to both the interior and exterior if the enclosure design allows. Below grade, however, drying can only occur to the interior since the exterior surface of a below grade wall is at essentially at 100% humidity all year round.

The safe storage capacity (balance of wetting and drying) of an individual material or enclosure system is fundamental to good building design (**Error! Reference source not found.**). It is rarely economical to build an enclosure with no risk of wetting but managing the risk is important. In any building enclosure, building materials should be chosen based on moisture tolerance that correlate to the risk of moisture in the enclosure. In all cases drying should be maximized, and attention to good design details should be used.

[So, was there any analysis done for moisture? Or maybe you should say that all walls are assessed based on their ability to handle the three moisture sources that you mention by a combination of “safely” draining, deflecting or drying.]

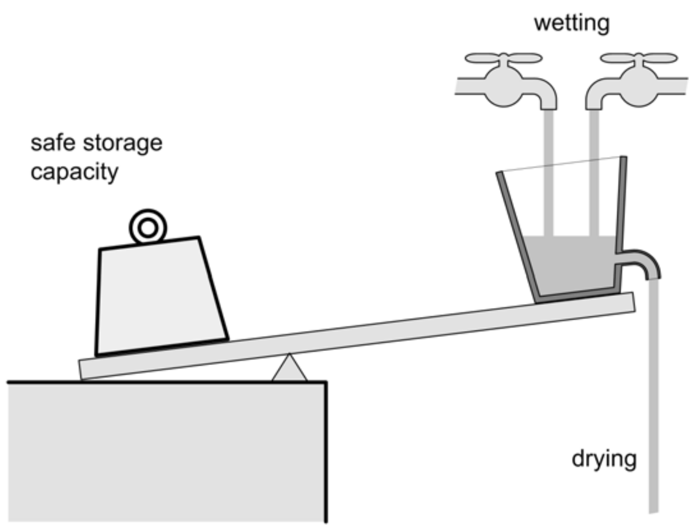


Figure 6 : Moisture balance

Many houses have damp, musty smelling basements that are uncomfortable, and can be unhealthy. Historically, people did not finish their basements into living spaces so it was not as much of a concern, but now basements are being converted to living areas, entertainment centres and bedrooms, so health and comfort are as much a concern as for above-grade space.

A foundation should control the amount of liquid water and water vapor entering the interior space from the exterior environment. This study assumes drainage details have been constructed correctly to limit the exposure of the exterior of the foundation to liquid water. There are many different strategies to ensure water is drained away from the foundation, but all systems require properly detailed drainage along the foundation footing to remove standing water. The foundation wall needs to have a drainage plane that directs bulk water to this footing drain. Often, a drainage membrane is installed against the exterior of the foundation wall to perform as both liquid water and water vapor barrier. The drainage membrane is rippled or corrugated and forms a space between the membrane and dampproofed concrete foundation wall, allowing any water against the foundation to drain to the drainage tile. This ensures that the foundation does not experience any liquid pressure head.

Even in arid climates, the ground is very close to 100% relative humidity. This means that moisture experienced by the foundation wall varies both over the height and over the year. At the bottom of the basement wall, the vapor drive is to the interior for the entire year, and the temperature is relatively stable. The above grade portion of the foundation wall is very different from below grade: the vapor drive is cycled daily through environmental variations of precipitation, wind and sun.

The hygrothermal simulations in this study do not consider liquid water uptake by capillarity into the footing and foundation wall, only vapor diffusion. It is important to recognize that water is often wicked up through the footing into the concrete wall. Once the liquid water reaches the interior or exterior of the basement wall, it must be evaporated to water vapor and travels by vapor diffusion. Since the exterior of the foundation is already close to 100% relative humidity, the moisture cannot dry to the exterior and it can only evaporate to the inside, which adds to the moisture load at the insulation layer. Water that is wicked through the footing can be stopped by applying a capillary break between the footing and the foundation wall. There are both liquid and sheet applied capillary breaks that will decrease the moisture load into the foundation wall and into the interior environment.

Since the foundation wall below grade is unable to dry to the exterior and there can be a significant amount of moisture present in the concrete, intuitively, the vapor drives should be allowed to dry to the interior and a polyethylene vapor barrier should not be built into the interior of the wood framed wall. Unfortunately, building codes have often specified polyethylene vapor barriers on the interior of framed walls in finished basements and these walls will be analyzed to understand why they often have serious moisture related problems.

The hygrothermal simulations conducted for this study are a one dimensional approximation of the hygrothermal behaviour of each wall system. In reality there are two and three dimensional interactions such as heat transfer up and down the concrete foundation wall as well as convective looping and moisture transport through air and vapor permeable insulations.

Boundary Conditions

The WUFI simulations were conducted in three parts because of the different hygrothermal regimes at the top above grade portion, middle and bottom below grade portions of the wall. The exterior below grade temperatures used for hygrothermal simulations were based on monitoring of ground temperatures in St. Paul MN as shown in Figure 7. The above grade temperatures for Minneapolis are included in the weather data for WUFI.

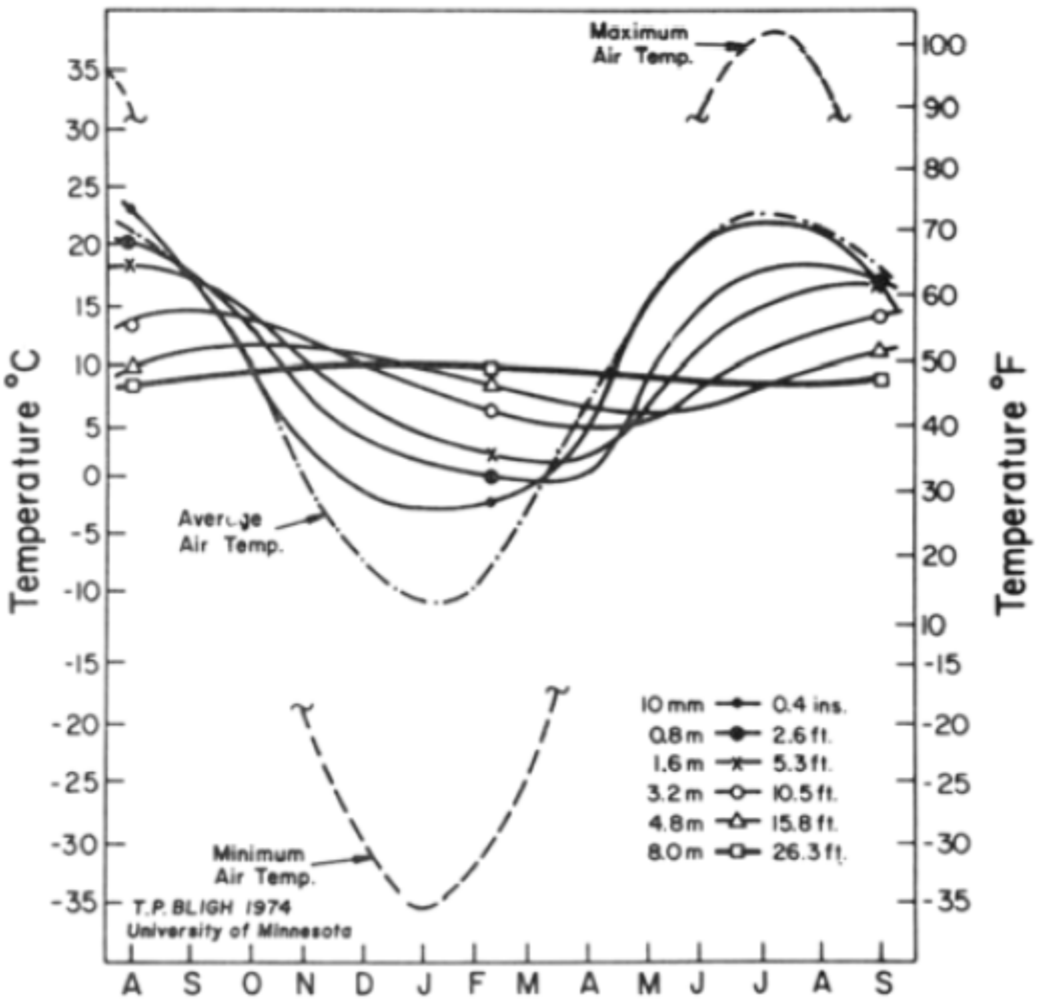


Figure 7 : Monthly temperature variation with soil depth, St.Paul, MN (Bligh 1975)

The relative humidity of the exterior for both the mid height and bottom of the foundation wall were set at 99.9%. In these simulations, only vapor diffusion from both the interior and exterior were simulated. If the concrete is in contact with liquid water, which is not uncommon, especially at the footing, capillary wicking will occur and significantly increase the moisture load to the surface of the concrete not only at the base of the wall but further up as well.

Interior temperature and relative humidities were chosen to represent a slightly higher than average moisture load for a cold climate house (Figure 8). These boundary conditions were simulated for 10 years to ensure that the foundation system was at equilibrium with both the exterior and interior environments.

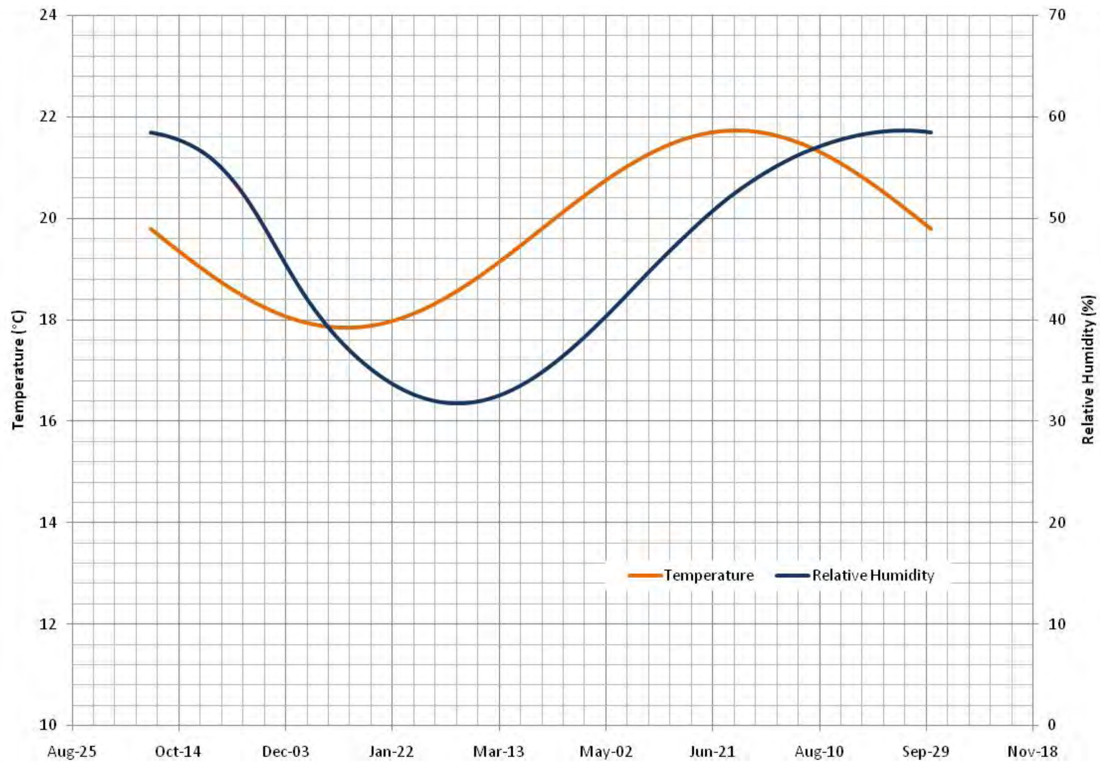


Figure 8 : Interior Temperature and Relative Humidity for Hygrothermal Simulations

2.2.1. *Wintertime Condensation*

In above grade walls, winter time air leakage and vapor condensation are concerns in cold climates. In the basement, the below grade foundation wall is often warmer than the exterior environment in the winter due to the heat sink of the ground, and the thermally massive storage. This means that winter time condensation is less of a concern on the foundation wall itself. In the above grade portion of the basement wall, there can be condensation as shown in the following hygrothermal analysis.

Of greater concern is the early summer when the foundation wall is cooler than the exterior environment and often the relative humidity in the environment can be quite high. If the relative humidity increases in the basement, this could result in condensation and elevated humidities at enclosure surfaces such as on the walls and floor. In basements with a carpet, the concrete slab is slightly insulated from the interior warmth and higher relative humidities are possible since the carpet is vapor permeable.

2.2.2. *Summer Inward Vapor Drives*

At the top of the foundation above grade wall there is potential for inward vapor drives because it is subjected to the warm summertime temperatures and solar drives. This will only occur where the wall is heated sufficiently to drive the vapor into the enclosure, and is evident in some wall assemblies in the hygrothermal analysis.

Polyethylene sheet bonded to batt insulation has typically been the construction strategy used for insulating basements in the past, but now, with increased understanding about the moisture physics of basements and below grade walls, the IRC states that Class I and II vapor retarders should not be used on any below grade wall or basements.

Some insulations installed directly against the foundation are effective vapor control layers and insulation layers as shown in the hygrothermal analysis.

2.2.3. *Wall Drying*

Below grade walls experience elevated relative humidites on the exterior and thus must dry to the interior at all times. The above grade portion of the foundation wall can dry to either the interior or exterior depending on wall construction, but it is recommended that the entire basement wall be able to dry to the interior. In some cases, lower permeance coatings may be required but a Class I or II vapor control layer should be avoided.

2.2.4. Case 1 Un-insulated

Figure 9 shows the moisture behaviour of an un-insulated basement wall. Predicted relative humidities at the surface of the concrete wall show there is very little potential for condensation, only at the coldest time of year on the north orientation with no solar energy does the interior of the concrete get cold enough to condense water vapor from the interior environment with the simulated interior relative humidity levels.

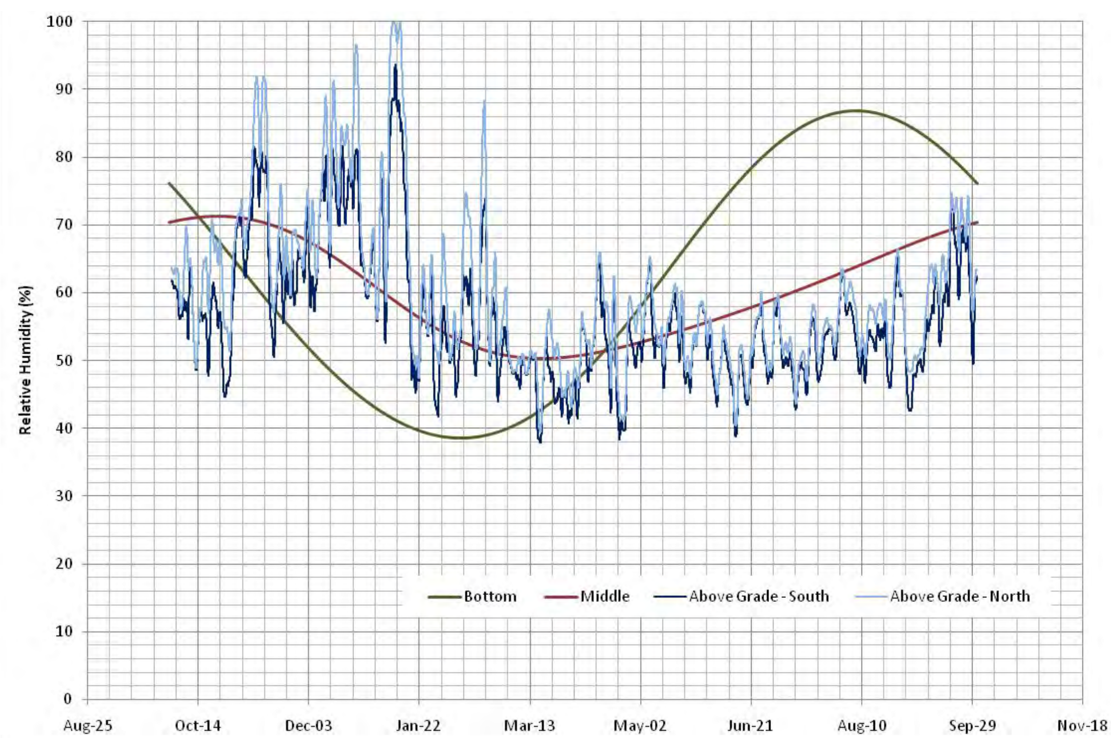


Figure 9 : Predicted Relative Humidity at the Surface of the Concrete Foundation Wall for Case 1

The predicted surface temperatures of the foundation wall and the dewpoint of the interior air are shown in Figure 10. This shows only a couple short instances of predicted condensation in early January, and only on the above grade portion of the north wall.

This analysis for the un-insulated basement assumes that the interior relative humidity is controlled to XX. This would likely require a dehumidifier since there are no vapor control layers on the foundation wall or basement slab and the moisture load from these surfaces would keep the RH in the basement space high. If the relative humidity is controlled to the these relative humidities as a minimum control, then this basement will perform reasonably from a moisture perspective, with little risk of mould. From a thermal control perspective, however, this wall is a very poor performer.

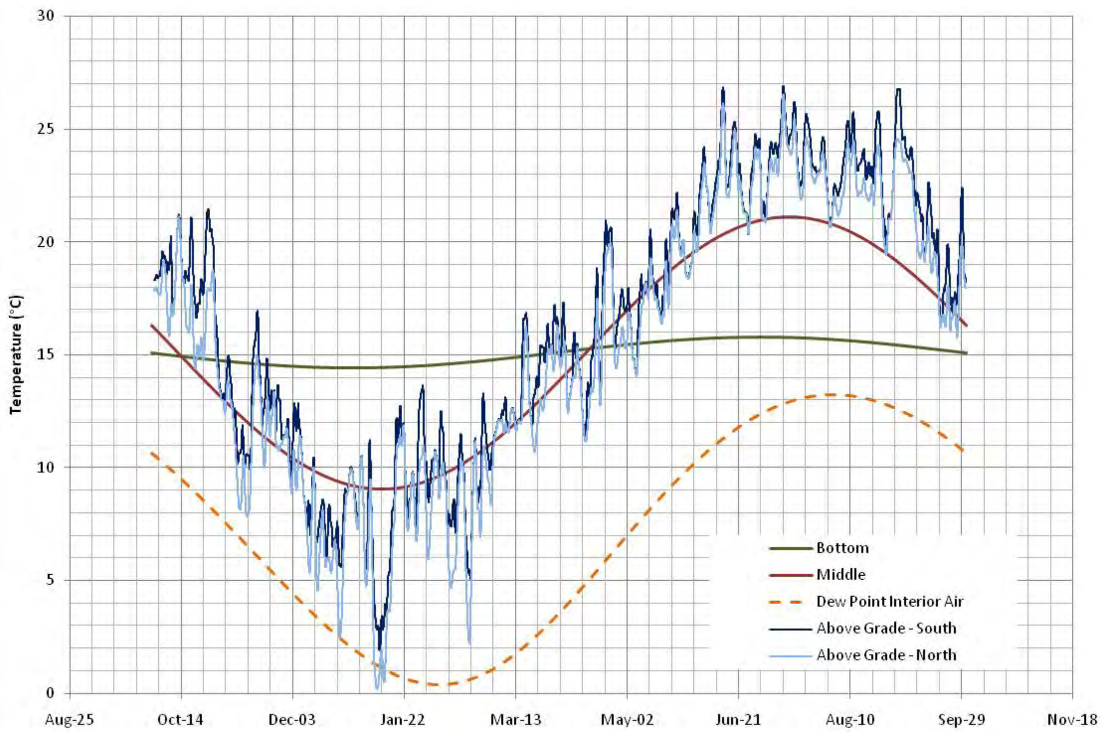


Figure 10 : Condensation Potential for Interior air on the Surface of the Concrete Foundation Wall

2.2.5. Case 3 code basement

Cases 2 and 3 were similar enough that separate simulations for both conditions were not required. These simulations were conducted with a polyethylene vapor barrier because there are many basements in existence built with a polyethylene vapor barrier on the interior surface of the wall. The IRC says in R601.3 that a Class I or II vapor retarder is not required on basement walls or the below grade portion of any wall. In other geographic areas such as parts of Canada, the building code with respect to basements has not been modified to reflect the large number of building failures, and the moisture physics of basements.

Many companies have an insulation product similar to a traditional roll batt with poly, but with a perforated facer that allows vapor to pass both ways through the interior surface, depending on the time of year and interior conditions. Simulations were not conducted yet to address a perforated facer, but intuitively, vapor diffusion will be higher both ways, and air leakage condensation will be significantly greater across a perforated facer than a non perforated facer. This is not a recommended insulation strategy.

Figure 11 shows the relative humidity at the surface of the foundation wall for wall Case 3. Not surprisingly it is quite high. The concrete is generally wet, both from capillary wicking and by vapor diffusion from the exterior. The relative humidity does decrease at the top of the foundation wall in the summer months, when the concrete is warmed by exterior temperatures. A perforated facer may decrease the relative humidity slightly, depending on the vapor permeance.

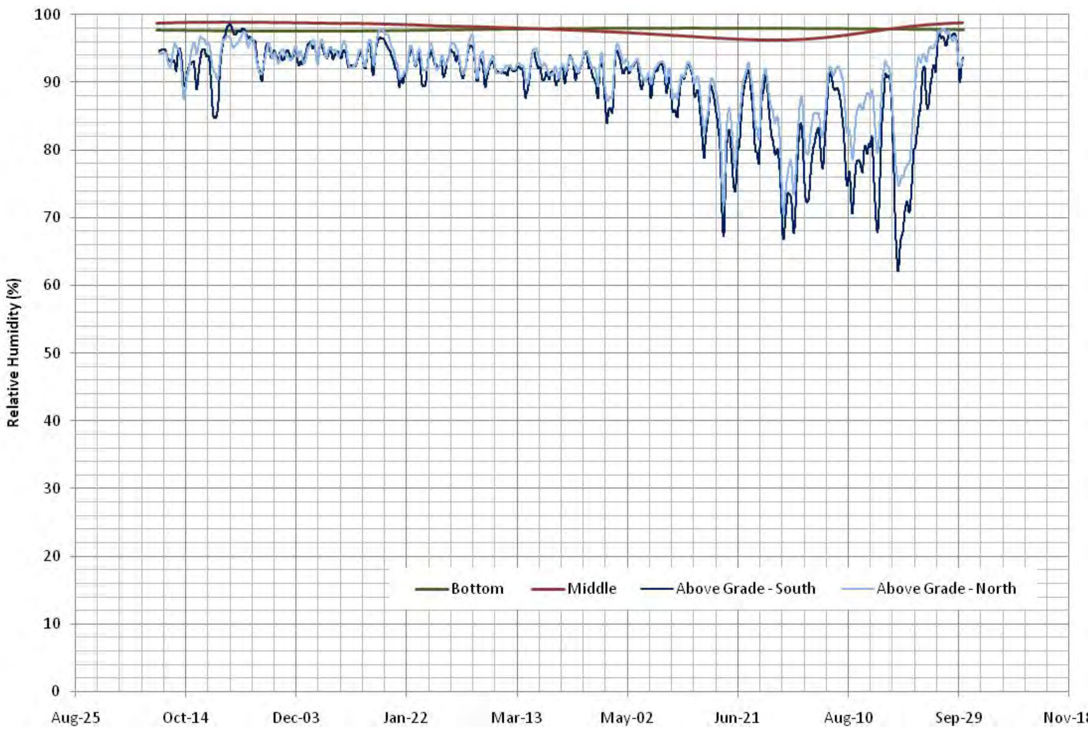


Figure 11 : Predicted Relative Humidity at the Surface of the Concrete Foundation Wall for Case 3

In the case of a well detailed polyethylene vapor barrier, it traps significant moisture in the wall as the wet concrete dries to the interior, but does not allow air leakage condensation. Figure 12 shows the potential air leakage condensation when the temperature of the foundation wall falls below the dewpoint of the interior air. There is significant condensation potential between October and January for the top half of the foundation wall, and from June to October at the bottom of the foundation wall. There is condensation potential for most of the year on the concrete foundation wall with the assumed conditions. A perforated facer would allow air leakage condensation to occur resulting in significant condensation.

This means that the wood framing near the concrete is sustained at or above 90% relative humidity all year, which will eventually cause mould since it is likely that there will be liquid water condensation in the wall system under these sustained conditions.

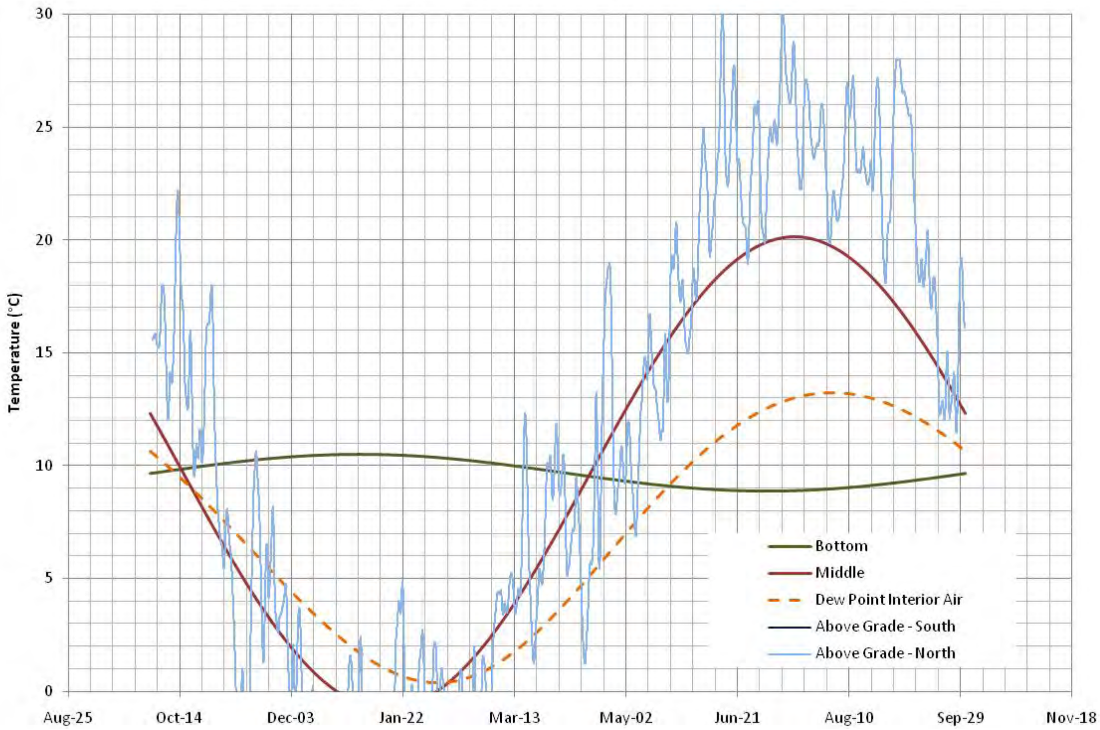


Figure 12 : Interior Air Leakage Condensation Potential for Case 3 Code Minimum Wall

Predictions were also made for the relative humidity at the exterior surface of the polyethylene vapor barrier since it is common in a basement to see condensation on the exterior surface of the poly. Figure 13 shows that between June and August, the relative humidity near the top of the wall is approximately 100% (higher on the south than north) resulting from inward vapor drives. A perforated facer could decrease this potential for increased relative humidity at the poly.

As mentioned previously, these simulations do not include capillary wicking for this analysis. In the future, this may be included, since the capillary wicking is a significant source of moisture in the concrete and basement wall system.

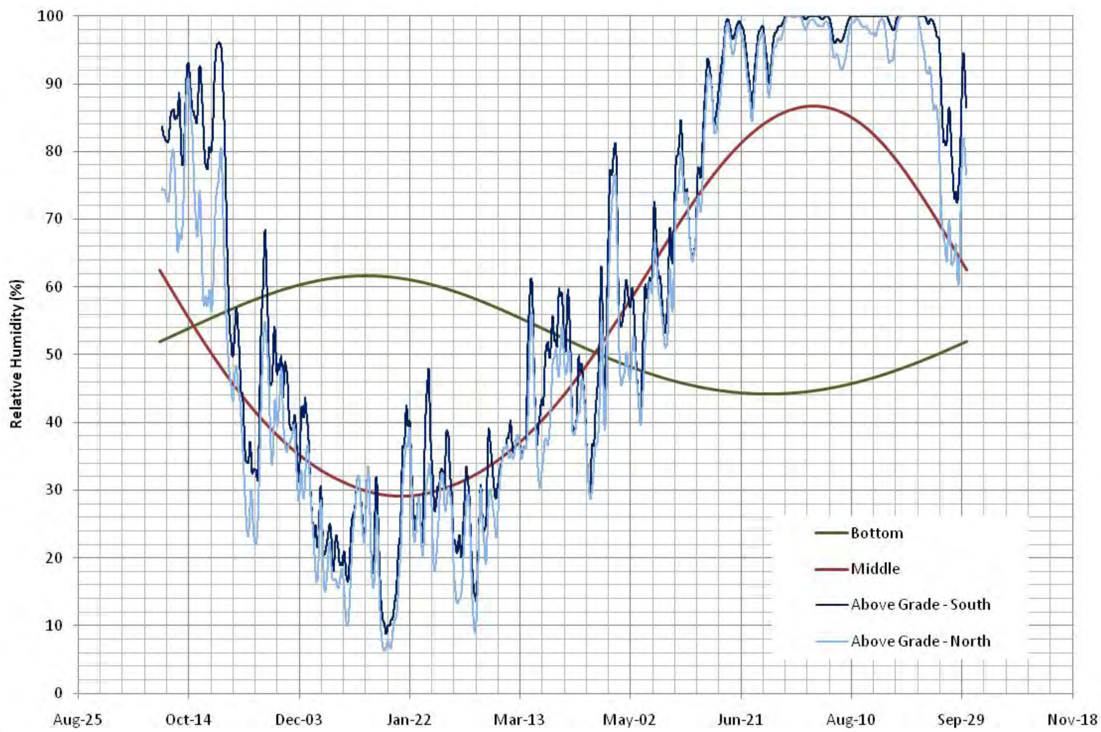


Figure 13 : Predicted Relative Humidity at the Surface of the Polyethylene Vapor Barrier for Case 3

2.2.6. Case 4 - 1" XPS and 3.5" Fibreglass Batt

Case 3 has serious moisture related risks caused by both vapor diffusion and air leakage condensation. One method of minimizing the potential risks is to install a vapor retarding layer that also provides insulation against the concrete foundation. 1" of XPS is only slightly vapor permeable, and has an R-value of R5. Assuming the XPS is well sealed to the concrete foundation, the condensation plane is now the interior XPS surface and will be warmer than the concrete, which should result in less potential condensation, and less vapor diffusion from the concrete. Expanded polystyrene (EPS) would also work as an air barrier but has a higher vapor permeance, so there would be more vapor diffusion from the exterior. Simulations would need to be conducted to assess the durability of substituting EPS for XPS.

Figure 14 shows the predicted relative humidity at the surface of the concrete foundation wall at the bottom and at the top of the foundation wall on the north orientation with three different vapor control strategies. Using only latex paint, the relative humidity reaches approximately 100% at the top in the winter and at the bottom in the summer. By using a vapor barrier paint (approximately 1 perm) on the drywall, the relative humidity in both the winter and summer improved.

Intuitively, by adding a polyethylene vapor barrier, the relative humidities were expected to increase. At the top of the wall, the relative humidity increased and was sustained for approximately three months, but the bottom of the wall showed no increase in relative humidity.

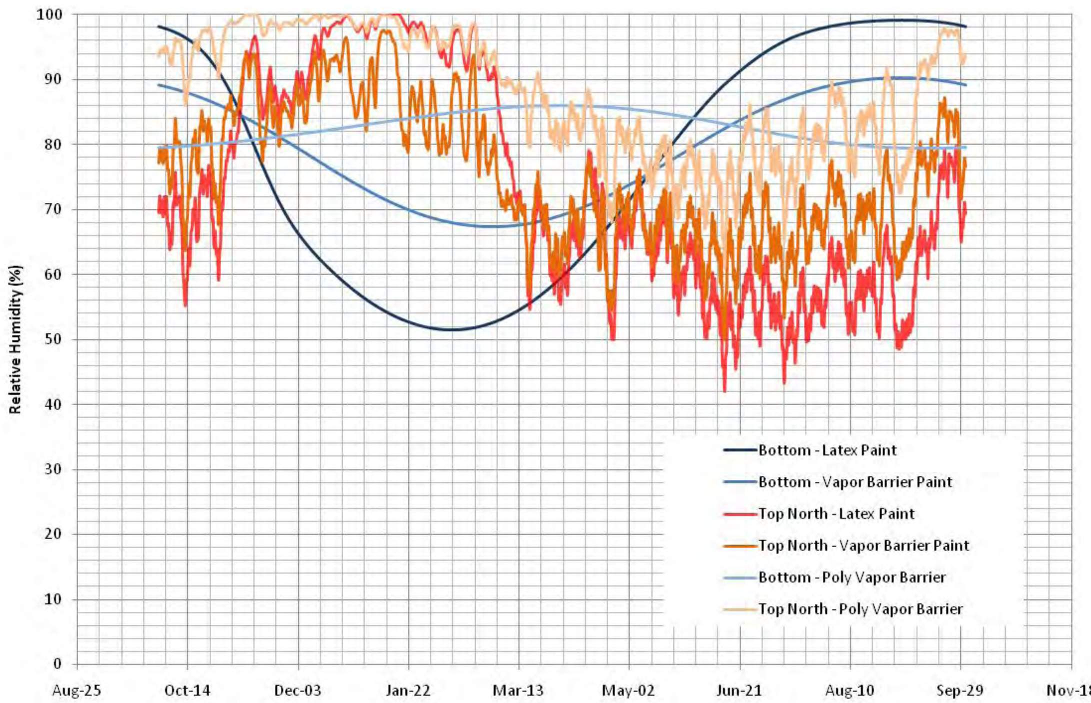


Figure 14 : Predicted Relative Humidity at the Interior Surface of XPS for Case 4

The air leakage condensation potential of Case 4 was much improved over Cases 2 and 3 as shown in Figure 15. There is still air leakage potential so the drywall must be made as air tight as possible.

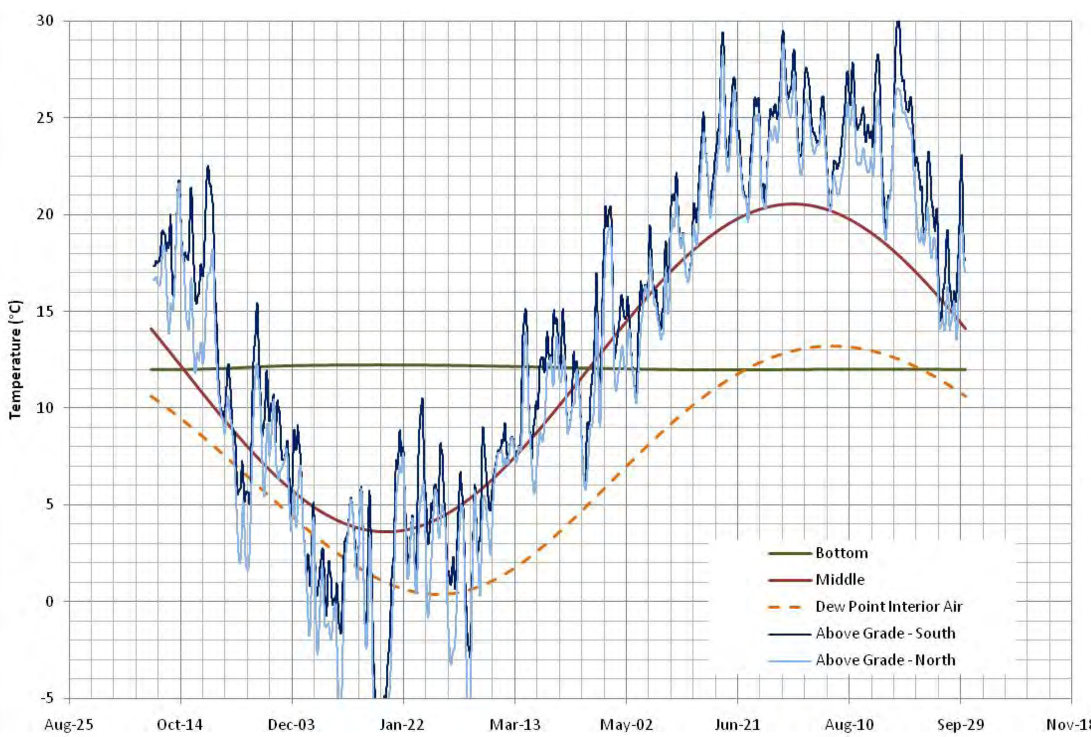


Figure 15 : Interior Air Leakage Condensation Potential for Case 4 Wall

Figure 16 shows the predicted surface relative humidites at the exterior of the drywall/poly vapor barrier depending on construction for Case 4. The top of the wall experiences inward vapor drives, so the wall with poly has the highest relative humidity. The vapor barrier paint allows more drying, and the latex painted wall has the lowest relative humidity.

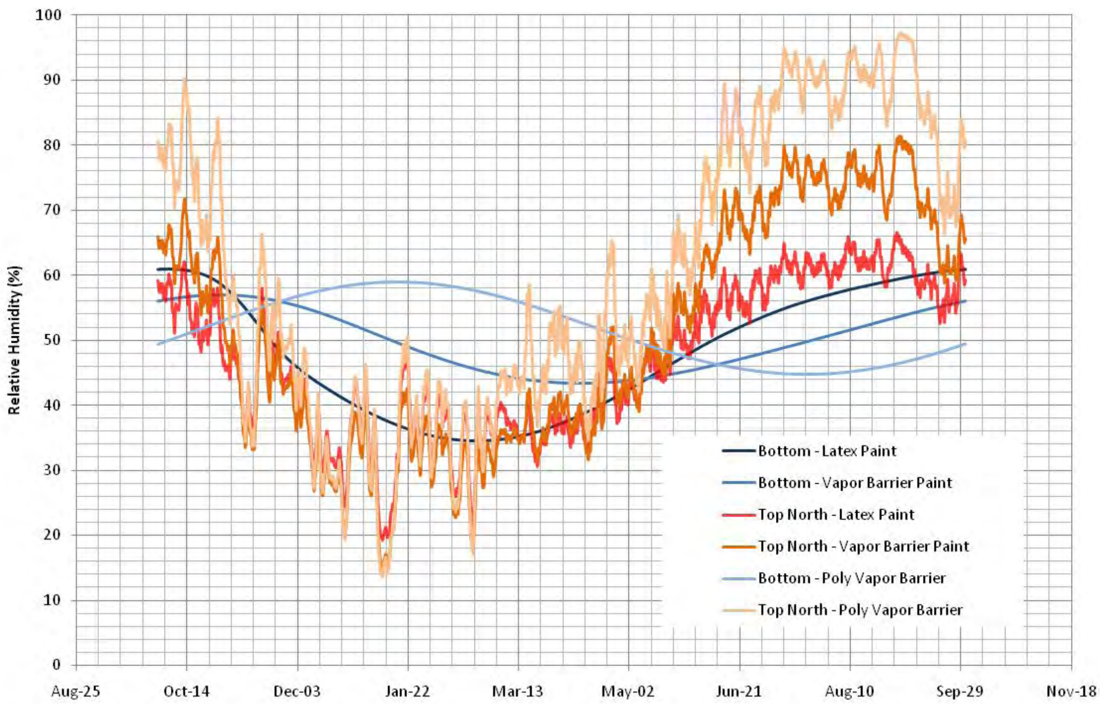


Figure 16 : Predicted Relative Humidity at the Exterior Surface of the Gypsum Board for Case 4

Case 5 - 2" XPS, 2" foil faced polyisocyanurate (PIC)

There was no reason to conduct hygrothermal simulations on Case 5. Provided there is no way for air to bypass the board foam insulation installed against the concrete foundation, there are no moisture related risks. The Insulation is an air barrier and vapor retarding, and is not moisture sensitive.

2.2.7. Case 6 - 3.5" 2.0 pcf spray foam

There were no expected moisture related issues with 3.5" of closed cell spray foam since the insulation is completely air impermeable and highly vapor retarding. The relative humidity between the concrete and spray foam is maintained at approximately 100% but neither material is moisture sensitive. One simulation was conducted to show the relative humidity at the midpoint of the spray foam once the system reaches equilibrium (Figure 17). There are no moisture related concerns with this wall construction strategy.

Closed cell spray foam is a useful method for retrofitting basements that have moisture and/or energy related issues, since it can act as a vapor barrier, air barrier, and capillary break.

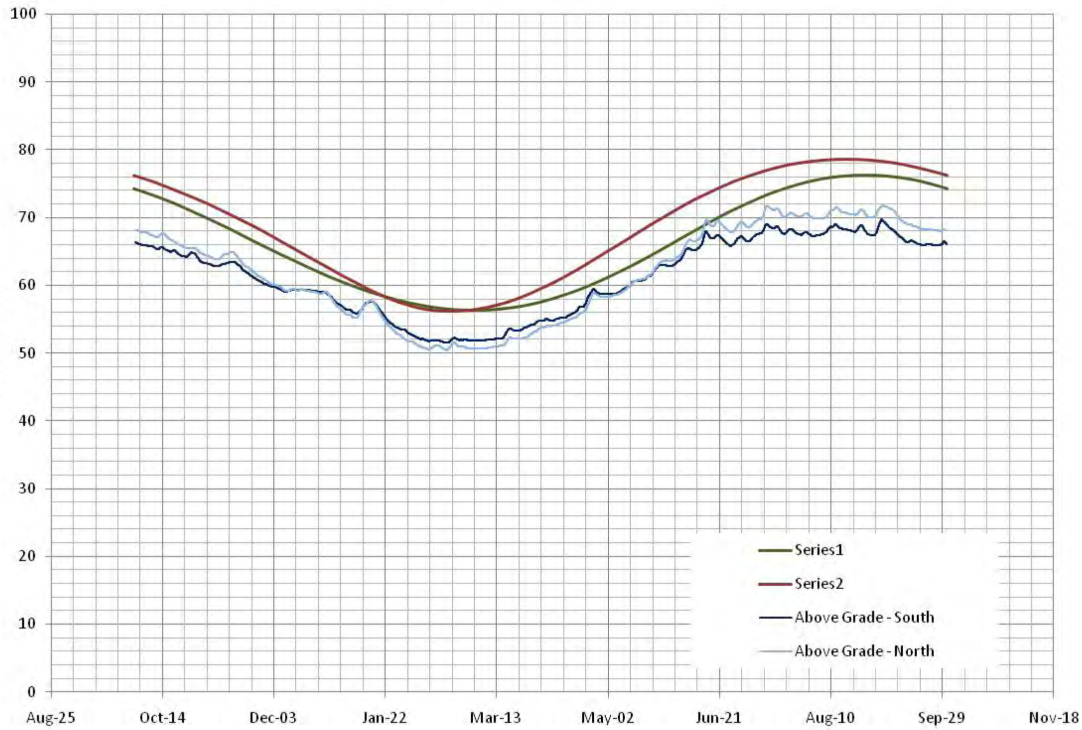


Figure 17 : Predicted Relative Humidity in the Center of Closed Cell Spray Foam Case 6

2.2.8. Case 7 - 6" 0.5 pcf spray foam

Similar to Case 6, open cell spray foam can be sprayed directly against the concrete foundation wall as an insulation strategy to form an excellent air barrier system. However, 0.5 pcf open cell foam is vapor permeable, so moisture related issues could occur under specific conditions. Using six inches of foam will help retard the vapor, and a simulation were conducted in the midpoint of the foam after the system reaches equilibrium to ensure that the relative humidities have decreased significantly from the foundation wall interface, which will be at approximately 100% relative humidity. Figure 18 shows that the relative humidities in the foam have dropped significantly and there are no moisture related risks for this system, provided no polyethylene vapor barrier is used on the interior surface to trap moisture into the system.

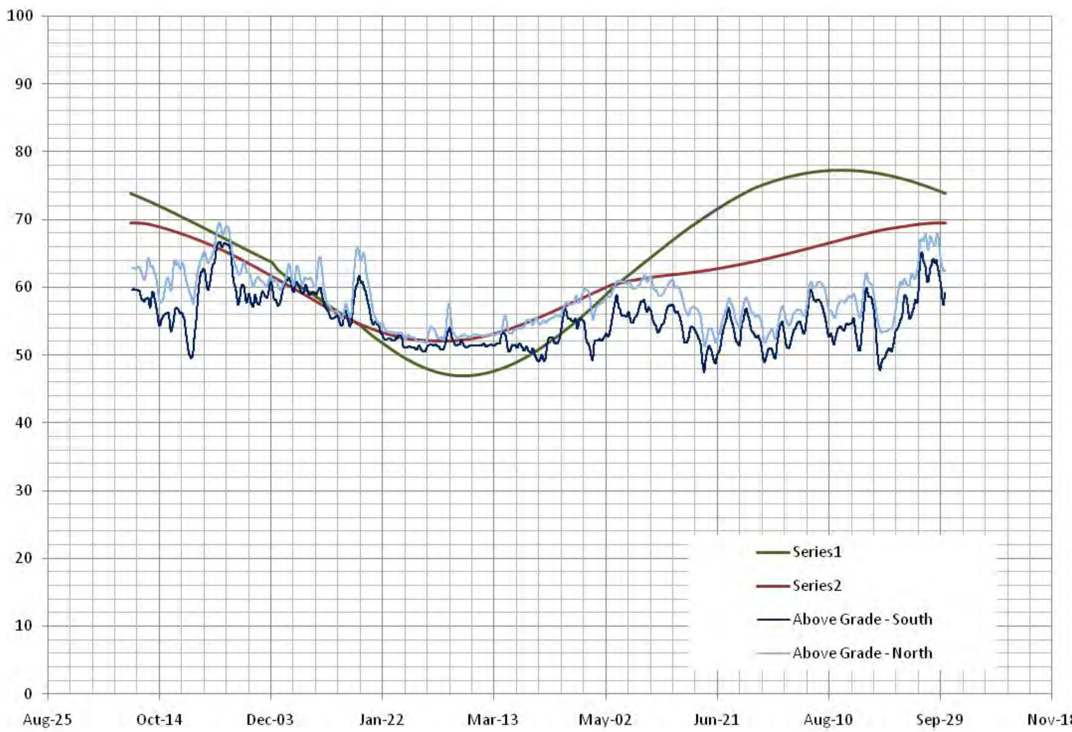


Figure 18 : Predicted Relative Humidity in the Center of Open Cell Spray Foam Case 7

2.2.9. Case 8 - 2" XPS and 3.5" fibreglass batt

Case 8 was not simulated because it will perform even better than Case 14, due to decreased insulation on the exterior of the condensation plane.

2.2.10. Case 9 - 2" PIC and 3.5" cellulose

Simulations were not conducted on Case 9 because of the similarity to Case 8 and Case 14. The PIC in Case 9 has a greater insulation value and decreased vapor transmission, so less moisture will enter the framed wall from the concrete foundation than in both Case 8 and Case 14.

2.2.11. Case 10 – 6" 0.5 pcf open cell foam with 2x4 framing offset 2" from foundation

No simulations were conducted on Case 10 because it will perform the same from a moisture perspective as case 7 as it also has 6" of 0.5 pcf open cell foam.

2.2.12. Case 11 - 4" XPS on the exterior

There are no moisture related issues with Case 11 if a capillary break is used at the bottom of the foundation wall. The XPS on the exterior acts as a vapor control layer, and capillary break, so the foundation sill stay warm, and drier (following drying of construction moisture). The largest source of moisture will be capillary wicking through the footing and bottom of foundation wall if it is not addressed.

2.2.13. Case 12 - 4" XPS in the center of foundation wall

Adding 4" of XPS to the center of the foundation wall acts as both a capillary break and vapor control layer resulting in less moisture on the interior and warmer surface temperatures. There is no need to simulate this assembly and little chance of moisture related issues. The largest source of moisture will be capillary wicking through the footing and bottom of foundation wall if that is not addressed.

2.2.14. Case 13 – ICF, 2" XPS on interior and exterior

Insulated Concrete Form foundations are a very durable and reliable construction strategy. The total of 4" of XPS will perform as both a capillary break and vapor control layer resulting in less moisture on the interior and warmer surface temperatures. The concrete in this wall system will take a very long time to dry completely since it is poured between two vapor control layers. This will not affect moisture related durability issues provided there is no Class I or II vapor retarder on the interior.

2.2.15. Case 14 - 2" XPS 5.5" Fibreglass Batt

Case 14 is the highest R-value assembly in this study at an installed insulation R-value of R29 with 2" of XPS at R10 and an R19 fibreglass batt. This wall was simulated with both latex paint and vapor barrier paint, since simulations with Case 4 a similar wall construction showed that a polyethylene vapor barrier increased moisture related durability risks.

Figure 19 shows that there are elevated relative humidities at the surface of the XPS caused by vapor diffusion for a short period during the winter months at the above grade portion of the wall. This risk is decreased slightly with a vapor barrier paint on the gypsum board.

In the summer months, the relative humidity is elevated at the bottom of the wall if latex paint is used as vapor control but decreased if a vapor barrier paint is used.

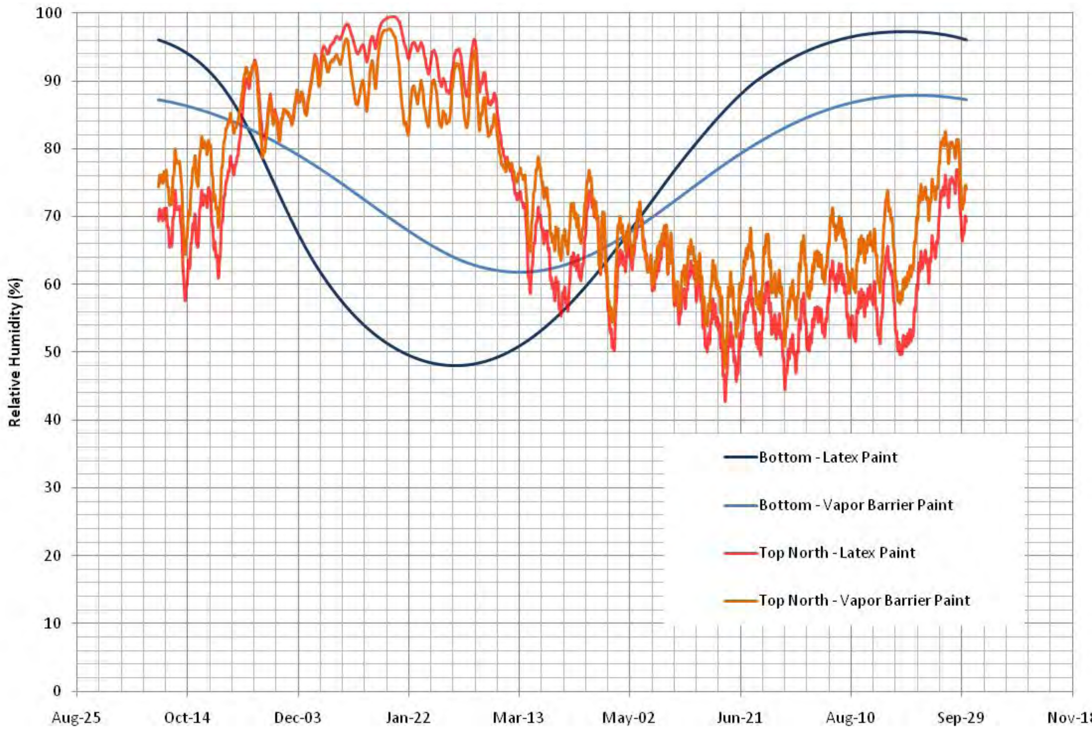


Figure 19 : Predicted Relative Humidity at the interior Surface of the XPS for Case 14

There is potential for some air leakage condensation in the above grade portion of this wall system although significantly less than Case 4. Cases 8 and 9 with less air permeable insulation to the interior of the XPS will have even less potential since the condensation plane will be warmer. Airtight drywall details can be used to minimize the potential for air leakage condensation.

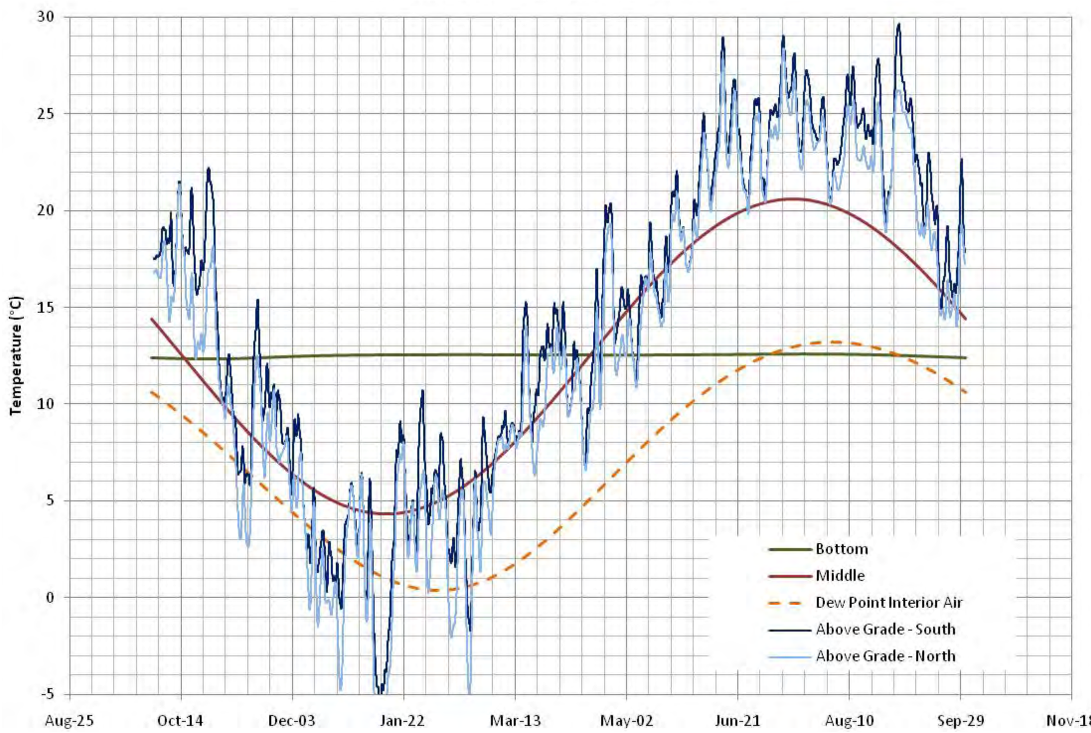


Figure 20 : Interior Air Leakage Condensation Potential for Case 14 Wall

The relative humidity was predicted at the exterior surface of the gypsum wall board in Figure 21, which shows there is no moisture related issues at the interior of the wall system. As shown previously, a polyethylene vapor barrier would increase the relative humidity in the system, and significantly decrease drying of the wall system.

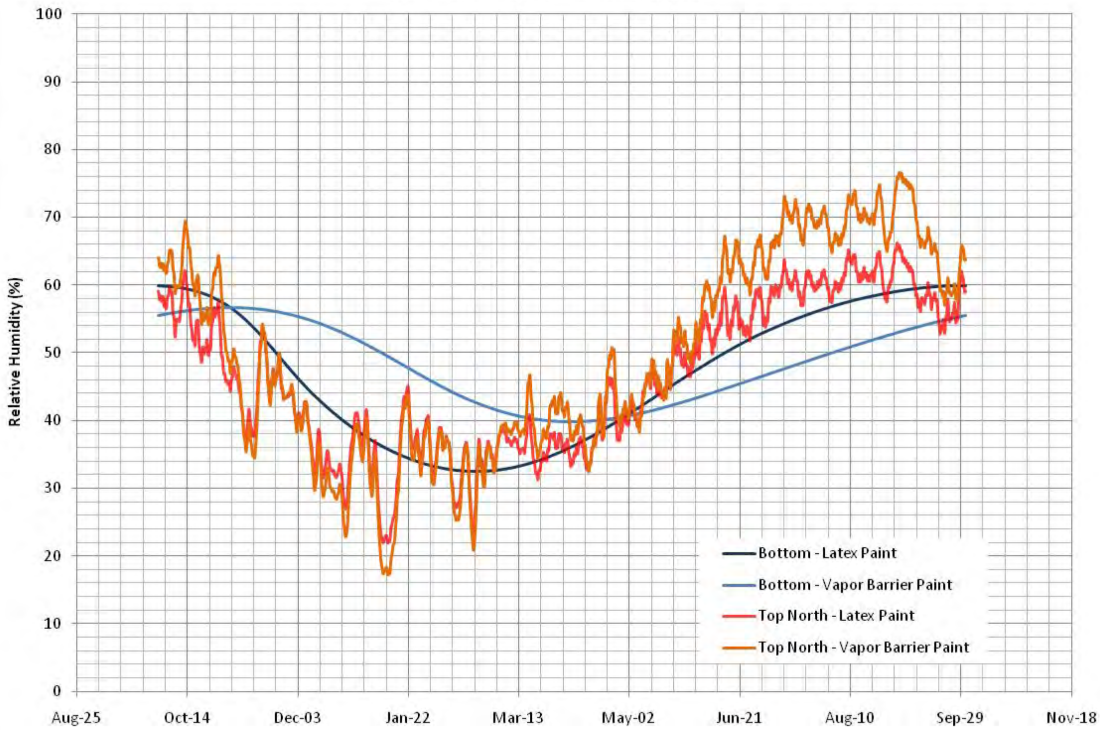


Figure 21 : Predicted Relative Humidity at the Exterior Surface of Gypsum Board for Case 14

2.3 Enclosure Durability

Durability of the building enclosure system was also used to classify the different wall construction scenarios. Durability is used in this report to group together multiple durability related criteria such as drying of water leakage events, air leakage condensation, built in moisture, and susceptibility of different building materials to moisture related issues. The durability assessment will be determined from hygrothermal modeling, as well as qualitatively based on the knowledge and experience of building material characteristics such as vapor permeability, hygric buffering capacity, and susceptibility to moisture related damage.

2.4 Buildability

Buildability is a key comparison criterion for practical purposes. Often, the general contractor and trades will influence design decisions based on the perceived complexity of different construction techniques or deviation from their standard practice. Any enclosure system and detailing should be buildable on a production level to achieve the greatest benefit even though the trades are often resistant to changes in construction practices.

The susceptibility of the enclosure system to poorly constructed water management details and poor workmanship is also considered in buildability. The simpler a system is to install correctly, the more preferable it is to use.

2.5 Material Use

Material use is becoming a critical design issue with the increasing concerns of depleting resources, and increasing costs of materials and energy. Some construction strategies use more construction materials, and the advantages of increased thermal control should be balanced against the disadvantages of increasing the building materials and embodied energy.

In the case of some insulations such as XPS and high density spray foams, the global warming potential is quite high, meaning the effect on global warming can be two orders of magnitude greater than other insulation strategies. These significant global warming potentials are caused by the use of chemicals used in the production of the insulation such as HFC-142b, HFC-134a, and HFC-245fa. These chemical have between 1000 and 2000 times more global warming potential than Carbon dioxide meaning that one kg of HCFC-142b is 2000 times worse for blobal warming than 1 kg of CO_2.

Embodied energy is the total energy required to get a specific product to the construction site including all energy to obtain the raw materials, processing energy and transportation energy. In some cases, materials that have less embodied energy, or recycled material, such as cellulose insulation could be used instead of the more energy intensive insulations. Materials that are produced locally require less shipping and decrease the embodied energy required.

2.6 Cost

The factor which generally has the greatest influence on implementation of a building enclosure strategy, particularly for production builders, is cost. Because the cost of some materials varies significantly depending on location and case-specific relationships between builders and suppliers, the cost of a building enclosure system will be perceived relative to other systems. When deciding which recommended system to use, some cost estimates should be determined for your locale.

2.7 Other Considerations

There are often factors, such as occupancy comfort and health that do not quite fit in the other categories, but are rather a combination of the other comparison criteria. One health related criteria, generally associated with basements is radon gas. Radon protection is not dealt with in this report, but during construction, it is very easy to install components that will make radon protection simple in the future should radon be an issue. In fact, some recommended measures taken to increase the thermal resistance of a basement assembly can be detailed to be part of a passive radon system. For example, the subslab gravel bed, which has been identified as a capillary break in this report, also serves the purpose of collecting soil gas if a vent stack is also installed during construction. Also, detailing air barrier system in a continuous manner through the foundation assemblies increases the thermal performance and blocks soil gas infiltration.

In some geographic areas, some levels of radon protection will be required in new construction under the building code in the near future. More information about radon and soil gas resistant construction can be found on the US EPA's website (http://www.epa.gov/radon/).

C.Results

1. CASE 1 : UNINSULATED FOUNDATION WALLS AND SLAB

The uninsulated basement case was included in this analysis because there are uninsulated basements in existence even though the code requirements in DOE climate zones 4 and higher do not allow an uninsulated basement in new construction. The uninsulated basement was included as a baseline for comparison purposes.

1.1 Thermal Control

There is no thermal control in the foundation walls or slab. This results in high energy losses for most of the year. Significant whole house energy savings can be experienced if the basement is insulated but care should be taken to design the thermal control appropriately to the construction type to decrease the risk of moisture related issues following an energy retrofit. Predicted annual heating energy loss based on the selected simulation criteria is 57 MBtus.

1.2 Moisture Control

Since there is no insulation, there is likely no moisture control in the basement. Water vapor from the exterior is a constant moisture source, and capillary wicking through the footing and/or foundation wall may also be a significant moisture source increasing the risk of moisture related issues.

WUFI analysis of the uninsulated basement in the Hygrothermal analysis section showed no significant moisture related issues (Figure 9 and Figure 10), if the relative humidity is controlled with a dehumidifier, although the basement will likely still smell damp and musty.

1.3 Constructability and Cost

There is no construction cost to leaving the basement uninsulated, but there are significantly higher energy costs.

1.4 Other Considerations

It is not recommended to leave the basement uninsulated from an energy, comfort, and health perspective. There are many different retrofit strategies that could be used, some of which are included in this analysis.

2. CASE 2 : CODE MINIMUM R10 CONTINUOUS INSULATION

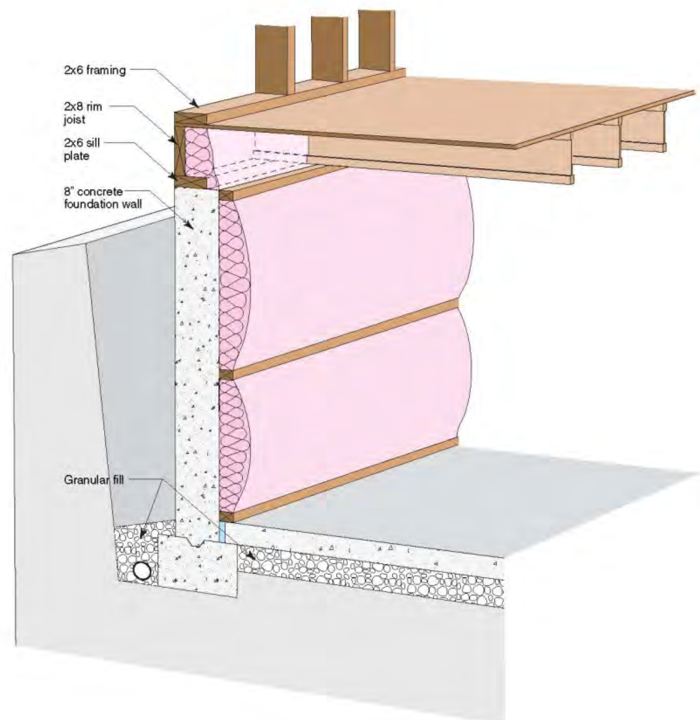


Figure 22 : Typical Code Compliant Basement Insulation Strategy

According to the IECC, new residential construction in DOE climate zones 4 and greater must be constructed with continuous R10 insulation or R13 in a framed wall. Continuous R-10 is typically installed by applying a roll batt directly to the foundation wall which consist of fiberglass batt. In some areas, the roll batt is covered with a polyethylene vapor barrier, as was simulated in the hygrothermal analysis. In the IRC, there have been improvements to the building code which do not allow Class I or II vapor control layers in the basement or on the below grade portion of any wall. Commonly a perforated facer is used which is vapor and air permeable.

2.1 Thermal Control

The installation of R10 continuous insulation, even as a roll batt, has significant energy improvements over uninuslated foundations, with savings of approximately 31 MBtus (more than half of an uninsulated basement) according to simulations. Roll batt is used because it is very inexpensive and meets code, although there are other alternatives that peform better, as shown in some of the following cases. These alternatives are more expensive for the contractor, and homeowners are unaware of the benefits.

2.2 Moisture Control

There are moisture issues with this insulation strategy that are evident both in field investigations and simulations. Fiberglass batt is air and vapor permeable, so moisture and air can move through the insulation. As can be seen in Figure 11, the relative humidity against the concrete foundation wall is elevated through the entire year. If there is air leakage (or the facer is air permeable) there is condensation potential on the concrete foundation through most of the year as shown in Figure 12. Because these simulations are one dimensional, they are good approximations, but heat flow in the foundation wall is three dimensional. Also, in the air permeable insulation, convective looping is likely, which may increase the condensation above predicted results. Field investigations show that it is quite common to get high quantities of mould in this wall system

2.3 Constructability and Cost

This is the most inexpensive alternative in terms of initial capital cost, which is the reason it is chosen. Continuous roll batt makes finishing the basement with gypsum board difficult, unless the roll batt is removed.

2.4 Other Considerations

This wall is not recommended based on this analysis, other reports, and field investigations of mouldy basements.

3. CASE 3 : R13 FIBERGLASS BATT IN A 2X4 FRAMED WALL

Case 3 is a second alternative to the minimum code required basement insulation in DOE climate zones 4 and higher. This construction uses a 2x4 framed wall against the concrete foundation with R13 batts in the stud space. The hygrothermal simulation and a polyethylene vapor barrier on the interior.

3.1 Thermal Control

This construction technique performs very similarly to Case 2. The parallel path method, taking into account the higher conductivity of the framing members at 24" on center results in a R-value inside the concrete wall of R12.6**.** This results in a total annual predicted heating energy loss 23.9 MBtus.

3.2 Moisture Control

This insulation strategy has a very similar poor moisture control level to Case 2. Moisture is constantly moving from the below grade exterior portion of the foundation wall to the interior, and becoming trapped in the framed wall cavity. The relative humidity is elevated and condensation is almost guaranteed both on the concrete wall and on the polyethylene vapor barrier throughout the year (Figure 11**)**. If there is air leakage (or the facer is air permeable) there is condensation potential on the concrete foundation through most of the year as shown in Figure 12. Because these simulations are one dimensional, they are good approximations, but heat flow in the foundation wall is three dimensional. Also, in the air permeable insulation, convective looping is likely, which may increase the condensation above predicted results. Field investigations show that it is quite common to get high quantities of mould in this wall system

3.3 Constructability and Cost

This wall is slightly more expensive than Case 2 because of the framing lumber required but does have the added benefit of being able to finish it easier by adding services and ddrywall easier.

3.4 Other Considerations

This wall construction technique is not recommended, because of the obvious moisture related durability issues observed continuously in the field, and shown by simulations. The wood framing in this wall is at risk for mould and rot after prolonged exposure to the conditions predicted in the wall system.

4. CASE 4 : 1" XPS, 2X4 WOOD FRAMED WALL WITH FIBREGLASS BATT

This insulation strategy is similar to case 3 but with the added insulation value, and moisture control, of 1" of XPS between the framed wall and concrete foundation wall.

4.1 Thermal Control

This wall has a parallel path calculation method of R18 because the thermal bridging of the framed wall is minimized, the overall improvement in Rvalue is R5.4 for one inch of R5 insulation. Adding 1” of XPS results in an energy savings of 2.2 MBtu over Case 3 without an inch of XPS, but will also reduce convective looping because the temperature gradient in the framed wall is less.

4.2 Moisture Control

The greatest benefit to adding 1” of XPS is arguably for moisture control and not thermal control. XPS controls the flow of water vapor from the concrete to the framed wall, from both vapor diffusion through the concrete and capillary wicking up the wall, reducing the relative humidity in the wall cavity. Small amounts of moisture (too small to drain) between the XPS and concrete is irrelevant because neither concrete or XPS is susceptible to moisture issues. The XPS must be well attached to the concrete foundation, and sealed, so air is not able to bypass the XPS insulation.

Ths XPS insulation also increases the temperature of the condensation plane, minimizing condensation of elevated interior relative humidity. Figure 15 shows that there is still potential for moisture condensation but it is significantly less than Case 3.

Figure 14 shows the relative humidity levels at the interior surface of the XPS which are significantly lower than the surface of the concrete in Case 3. The relative humidity is shown to be a function of the vapor control on the interior surface, with vapor barrier paint (approx 1 perm) performing better than latex paint or a poly vapor barrier. Even with just latex paint, the risk of moisture issues is minimal, if the relative humidity in the basement is controlled.

4.3 Constructability and Cost

The constructability of this wall system is not difficult, but care should be taken that air is unable to get behind the XPS. This could be accomplished with tape, caulking, cans of spray foam or a combination of the three. It is not likely that tape will maintain a good air seal for the desired lifetime of the wall system. This wall performs significantly better than Case 3, at only a small increased cost.

4.4 Other Considerations

This wall construction is recommended over Cases 2 and 3, but there are better options for thermal and moisture control that are more recommended and discussed in the following Cases. This is an affordable option that many people could do themselves, with significantly less moisture related risks than Cases 2 and 3, resulting in a more comfortable and healthy space.

5. CASE 5 : 2” XPS, 2” FOIL FACED POLYISOCYANURATE

When constructing with plastic board foams, the building codes require that the foam not be left exposed as a fire hazard. Thermal barriers are required over both board foams and spray foams in many cases. Thermax™ from Dow is a thermally rated foam board insulation that can be left exposed and could be used in this system. Gypsum board could also be used to cover the insulation, but in some geographic areas, gypsum board can only be installed if the basement is wired to code.

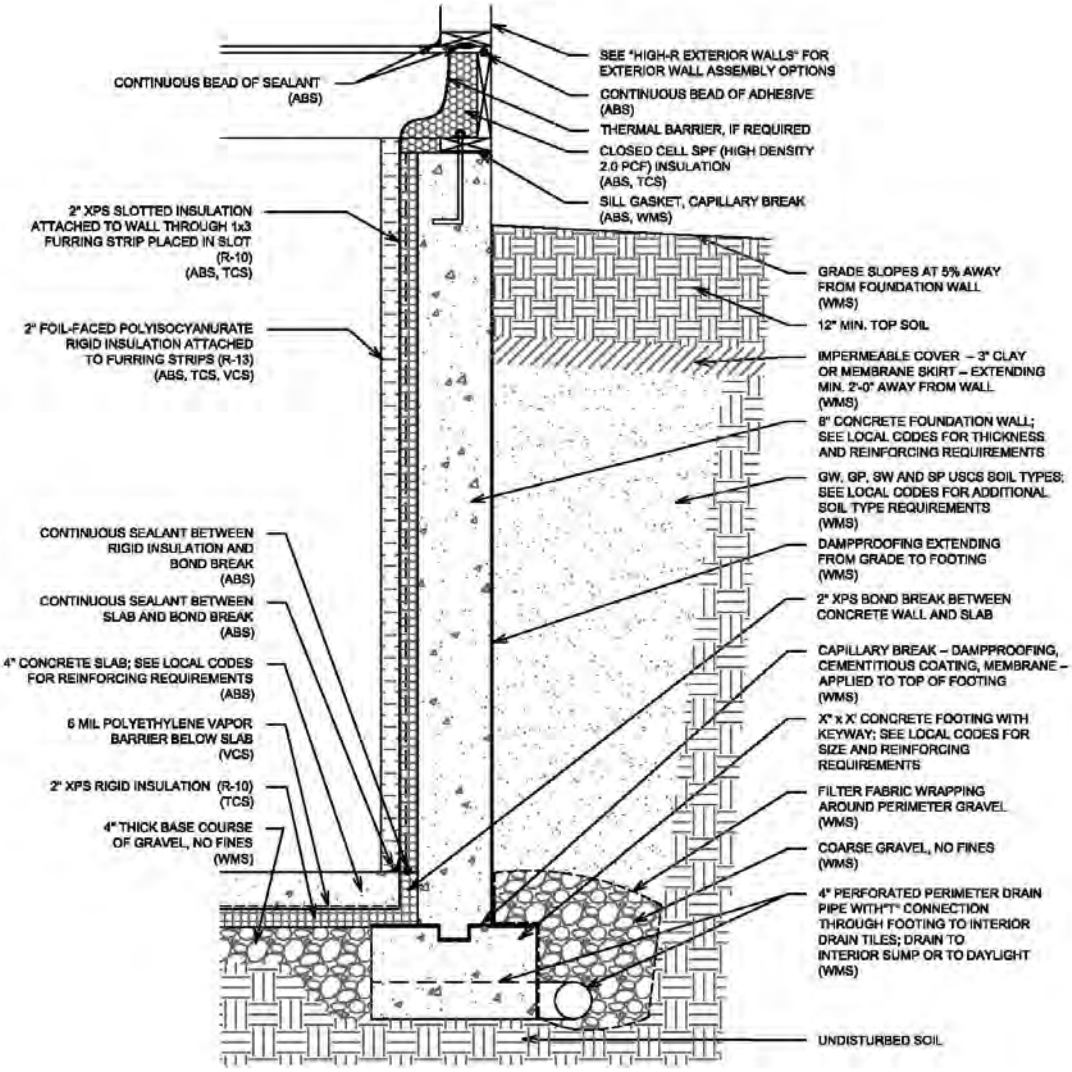


Figure 23 : Case 5 Detailed Drawing – Recommended Foundation Wall System

5.1 Thermal Control

This proposed wall system performs very well thermally at approximately R23, and in combination with underslab insulation and thermal break at the slab edge as shown in Figure 23, the predicted annual heating energy loss is 15.8 MBtus. This is an improvement of 40.8 MBtus over an uninsulated wall.

5.2 Moisture Control

Provided that air can not bypass the insulation layers, this strategy will not experience any moisture related issues from vapor diffusion, or capillary wicking. Capillary wicking is limited by the thermal/capillary break at the edge of the slab, and specified on top of the footing.

5.3 Constructability and Cost

The seams in the two layers of foam insulation should be offset and well sealed. A thermal barrier is required by code in most jurisdictions. Thermax ™ by Dow is a foil faced polyisocyanurate insulation that is code compliant.

5.4 Other Considerations

A stud wall will still need to be constructed to finish this basement with services and drywall, so if the long term plan is to finish basement, this proposed wall system may not be the most economical choice.

This basement insulation strategy is recommended as a durable, comfortable, and healthy basement system.

6. CASE 6 : 3.5" 2PCF CLOSED CELL SPRAY POLYURETHANE FOAM

As shown in Figure 24, the spray foam can be applied directly to the concrete, but as previously mentioned (and specified in the design details), if the foam is left exposed it will require a thermal barrier, typically a spray-on thermal barrier. The other option is to build a stud wall in front of the spray foam and use gypsum wall board is the thermal barrier.

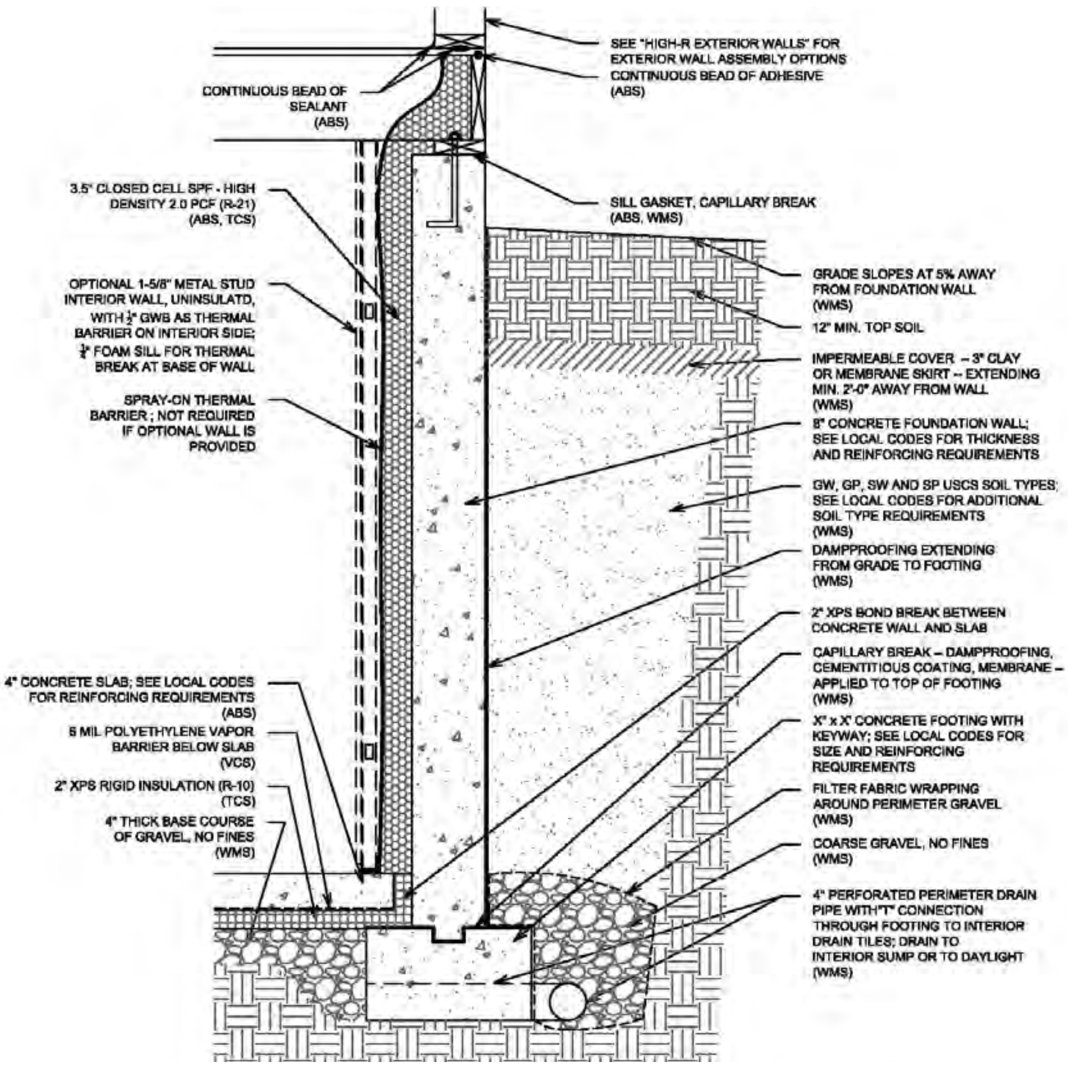


Figure 24 : Case 6 Detailed Drawing – Recommended Foundation Wall System

6.1 Thermal Control

Closed cell spray foam provides very good continuous thermal control. Spray foam is an air barrier, so convective looping and air leakage thermal losses do not occur. This wall system has an R-value of R21 and a predicted annual heating energy loss of 16.4 MBtus. More thermal control could easily be added by spraying more foam against the wall.

6.2 Moisture Control

Because closed cell spray foam is an air and vapor barrier, there are no risks to air leakage or vapor diffusion condensation. The concrete is unable to dry to the interior through closed cell spray foam, but concrete is generally not affected by a high moisture content. Figure 17 shows the relative humidity in the middle of the foam does not exceed 80%, which means there are no moisture related risks from vapor diffusion.

6.3 Constructability and Cost

In this proposed wall system, it is possible to embed the framing members in the foam (similar to Case 10, to increase the interior space. The framing should not be in contact with the foundation wall to limit thermal bridghing, and potential moisture related issues with the framing members. Closed cell spray foam can be more expensive than other options, but reduces labour time over some of the other walls, and is applied by a skilled labourer so the system is very durable as a long term solution.

Spray on thermal barriers can add significant cost to the spray foam installation, but are region specific.

Closed cell spray foam installed on the interior of the concrete foundation wall is the easiest and safest way to retrofit an existing basement. Spray foam can be installed in combination with a drainage matt and interior drainage tile in basements that are very leaky.

6.4 Other Considerations

Spray foams have been improved considerably for human health and the environment. Ozone depleting substances in the process have been removed, but some spray foams use greenhouse gases that are much worse than carbon dioxide. There are options available of more environmentally friendly spray foams that do not release green house gases, such as water blown foams, on the market and should be considered.

7. CASE 7 : 6” 0.5PCF OPEN CELL SPRAY FOAM

As shown in Figure 25, open cell spray foam can be applied directly to the concrete, but as previously mentioned (and specified in the design details), if the foam is left exposed it will require a thermal barrier, typically a spray-on thermal barrier.

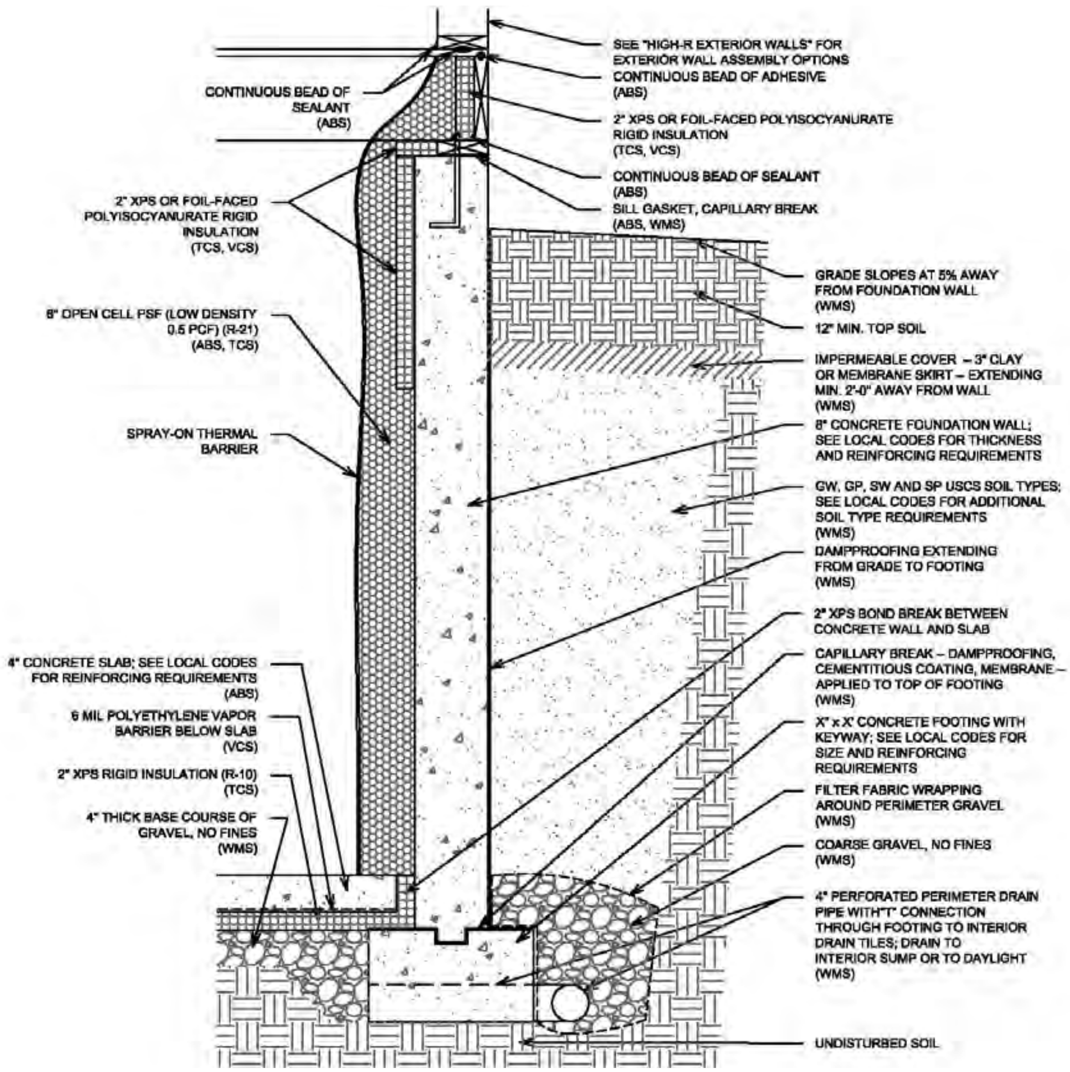


Figure 25 : Case 7 Detailed Drawing – Recommended Foundation Wall System

7.1 Thermal Control

Open cell spray foam provides very good continuous thermal control. Spray foam is an air barrier, so convective looping and air leakage thermal losses do not occur. This wall system has an R-value of R21 and a predicted annual heating energy loss of 15.8 MBtus.

7.2 Moisture Control

Open cell spray foam is an air barrier, but is vapor permeable. Figure 25 shows the XPS insulation detail required at the above grade portion of the foundation wall for cold climate construction to minimize moisture condensation at the cold concrete in the winter months, and minimize inward driven vapor in the summer months.

The relative humidity was predicted in the center of the open cell spray foam insulation and was found to be at safe levels (Figure 18).

Low permeance interior wall finishes should be avoided with this construction strategy.

7.3 Constructability and Cost

Open cell spray foam is less expensive than closed cell spray foam but vapor control should be considered, and does decrease the interior useful space.

This proposed wall system does not allow for finishing of the basement without installing an interior framed wall. If the longterm goal is to finish the interior of the basement, Case 10 should be considered instead.

Spray on thermal barriers can add significant cost to the spray foam installation, but are region specific.

7.4 Other Considerations

This is a recommended wall construction provided that the details for cold climates are followed, including an extra layer of vapor condensation protection for the above ground portion of the wall.

Spray foams have been improved considerably for human health and the environment. Ozone depleting substances in the process have been removed, but some spray foams use greenhouse gases that are much worse than carbon dioxide. There are options available of more environmentally friendly spray foams that release green house gases, such as water blown foams, on the market and should be considered.

8. CASE 8 : 2" XPS, 2X4 FRAMING WITH FIBREGLASS BATT

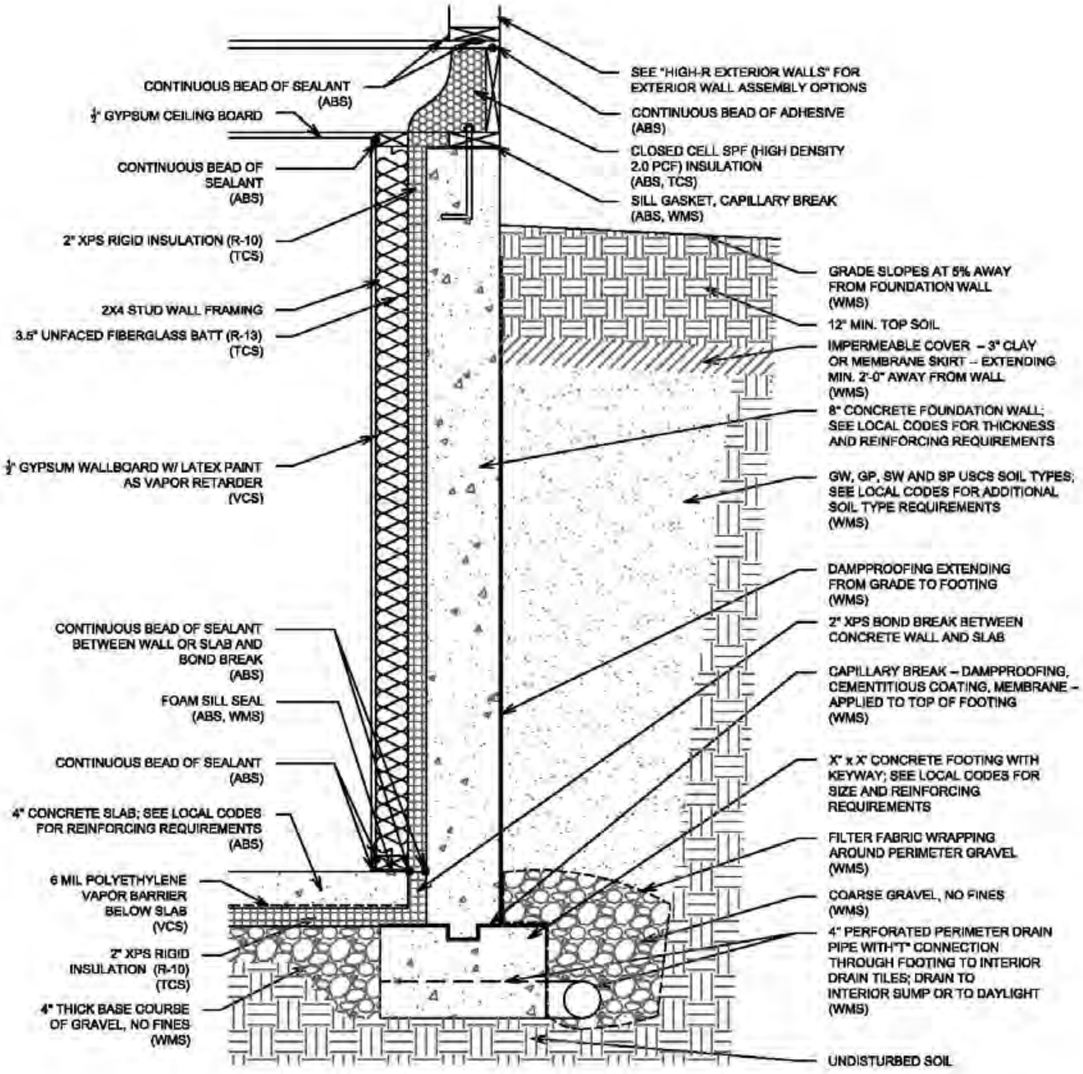


Figure 26 : Case 8 Detailed Drawing – Recommended Foundation Wall System

8.1 Thermal Control

This wall system has an installed insulation R-value of R23 which is only slightly lower based on the parallel path calculation method which accounts for the wall framing assuming 24" on center. This basement combined with R10 under the slab and R10 thermal break results in an annual predicted heating energy loss of 15.83 MBtus.

8.2 Moisture Control

The water vapor diffusion and capillary wicking are controlled by 2" of XPS insulation assuming that the XPS is well sealed to the concrete. This wall system was not hygrothermally simulated since it will perform better than Case 14 from a moisture point of view, and Case 14 performed well. Case 14 has 5.5" of fibreglass batt insulation which will result in colder condensation plane. Case 14 had some condensation potential but improved performance with a vapor retarding paint. There was some potential for air leakage condensation at the above grade section of the wall in the winter alternating with drying periods.

8.3 Constructability and Cost

It may be difficult to get 2” boards of XPS attached well to the nonuniform surface of the concrete foundation because the insulation is so stiff. It is easier in some cases to use 2 1” thick boards, that will flex over imperfections. The joints in the insulation should be offset if two layers of 1” XPS are used.

8.4 Other Considerations

Case 8 is one of the simplest and least expensive methods of minimizing the moisture risk and saving energy. It is possible to use other air permeable insulations instead of fibreglass batt including damp spray cellulose, or spray fibreglass.

9. CASE 9 : 2" POLYISOCYANURATE INSULATION, 2X4 FRAMING WITH CELLULOSE

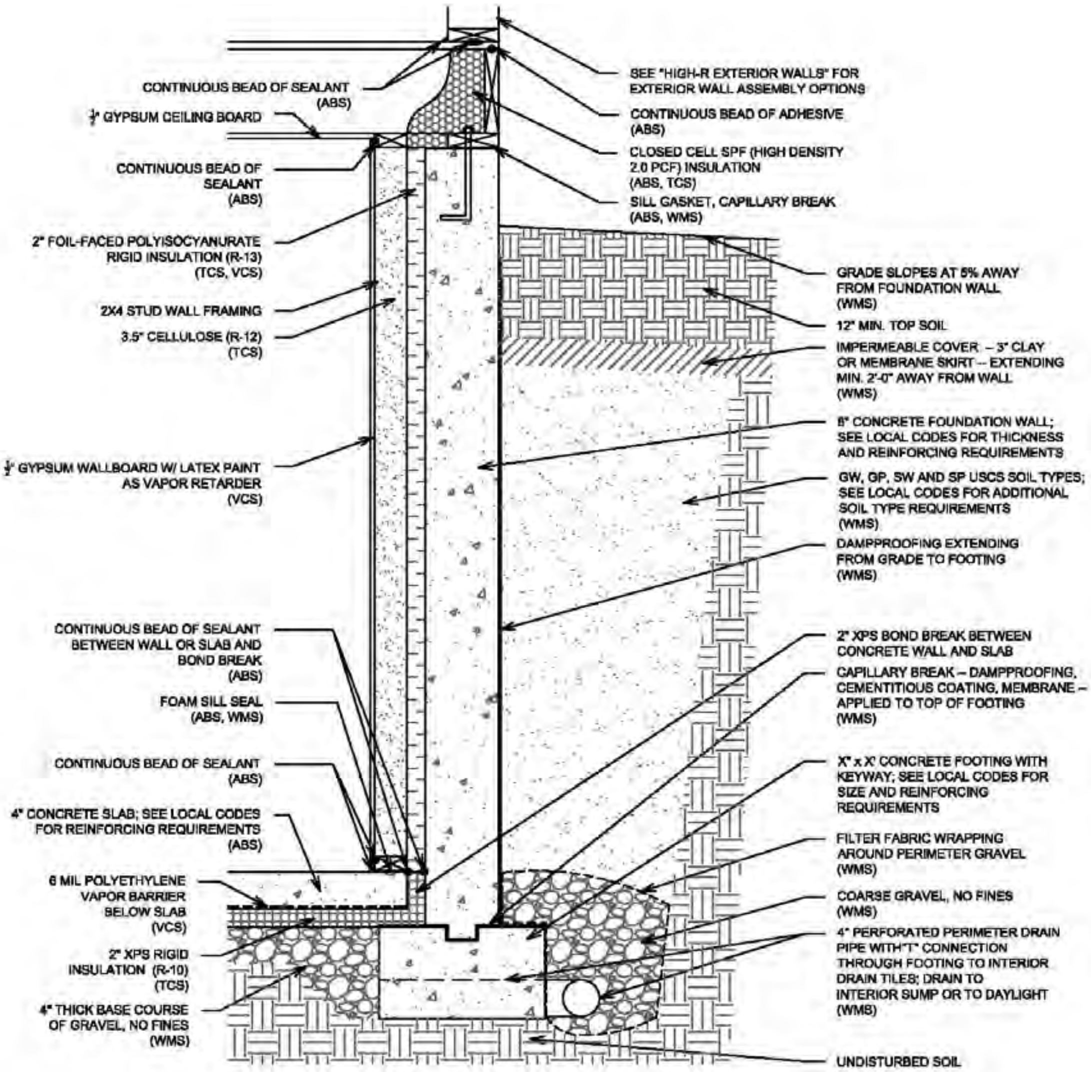


Figure 27 : Case 9 Detailed Drawing – Recommended Foundation Wall System

9.1 Thermal Control

This wall system has an installed insulation R-value of R25 which is only slightly lower based on the parallel path calculation method which accounts for the wall framing assuming 24" on center. This basement combined with R10 under the slab and R10 thermal break results in an annual predicted heating energy loss of 15.45 MBtus.

9.2 Moisture Control

The water vapor diffusion and capillary wicking are controlled by 2" of PIC insulation assuming that the PIC is well sealed to the concrete. This wall system was not hygrothermally simulated since it will not experience any moisture related issues. The foil face on the polyisocyanurate will not allow vapor diffusion from the concrete foundation, and the increased R-value of PIC compared to XPS will increase the condensation surface temperature compared to Case 8 and Case 14, resulting in decreased condensation potential.

9.3 Constructability and Cost

Fiberglass batt insulation could be used in the place of cellulose to decrease the cost of the assembly.

9.4 Other Considerations

Case 8 is one of the simplest methods of minimizing the moisture risk and saving energy which also allows the basement to be finished. It is possible to use other air permeable insulations instead of cellulose including fibreglass batt or spray fibreglass.

10. CASE 10 : 6" 0.5 PCF SPRAY FOAM WITH 2X4 FRAMING OFFSET 2.5" FROM CONCRETE

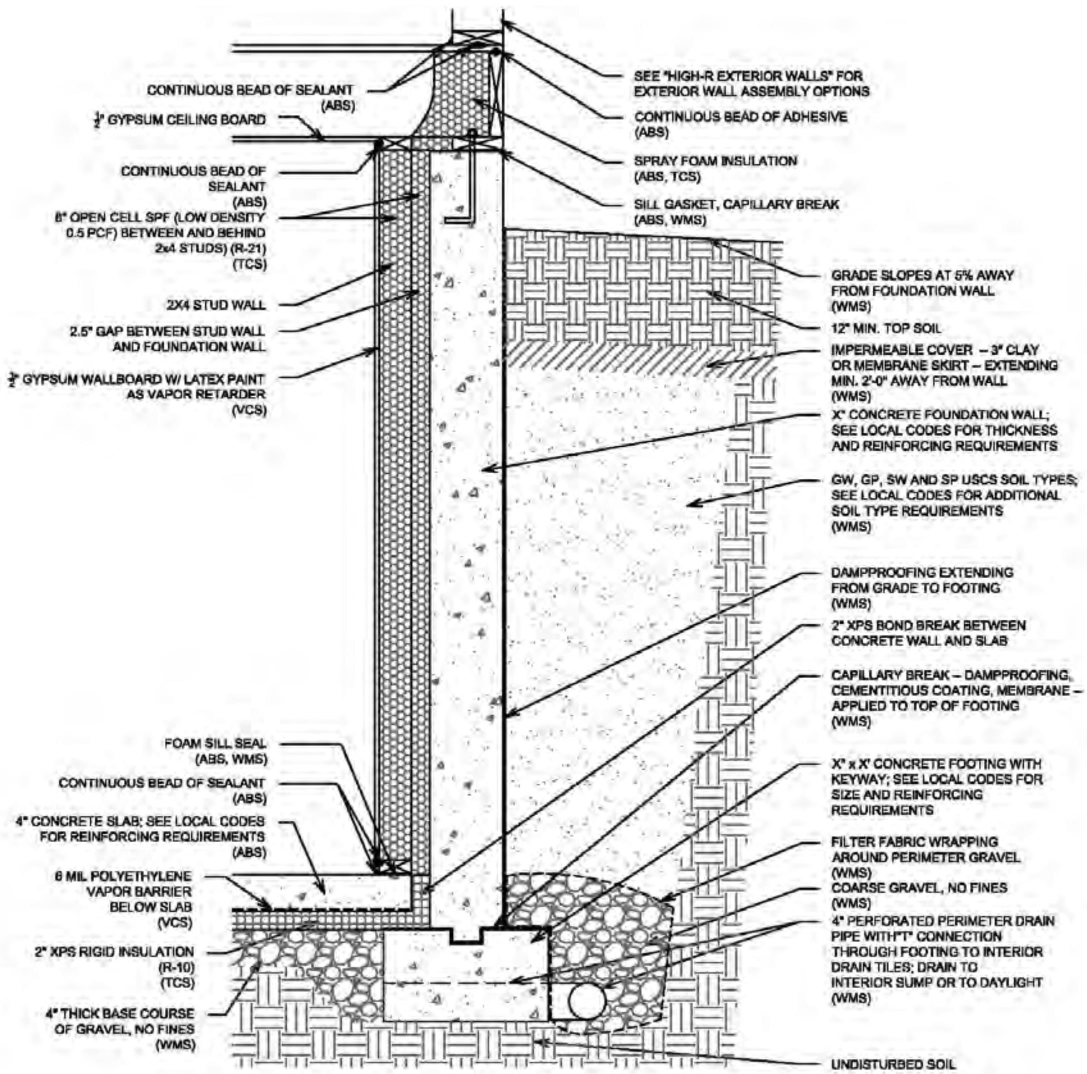


Figure 28 : Case 10 Detailed Drawing – Recommended Foundation Wall System

10.1 Thermal Control

Open cell spray foam provides very good continuous thermal control. Spray foam is an air barrier, so convective looping and air leakage thermal losses do not occur. This wall system has an R-value of R21 and a predicted annual heating energy loss of 16.3 MBtus.

10.2 Moisture Control

Open cell spray foam is an air barrier, but is vapor permeable. The relative humidity was predicted in the center of the open cell spray foam insulation and was found to be at safe levels (Figure 18).

Low permeance interior wall finishes should be avoided with this construction strategy.

10.3 Constructability and Cost

This solution is more practically than Case 7 if the plan is to finish the interior of the basement.

10.4 Other Considerations

Spray foams have been improved considerably for human health and the environment. Ozone depleting substances in the process have been removed, but some spray foams use greenhouse gases that are much worse than carbon dioxide. There are options available of more environmentally friendly spray foams that release green house gases, such as water blown foams, on the market and should be considered.

11. CASE 11 : 4" XPS INSULATION ON THE EXTERIOR OF FOUNDATION WALL

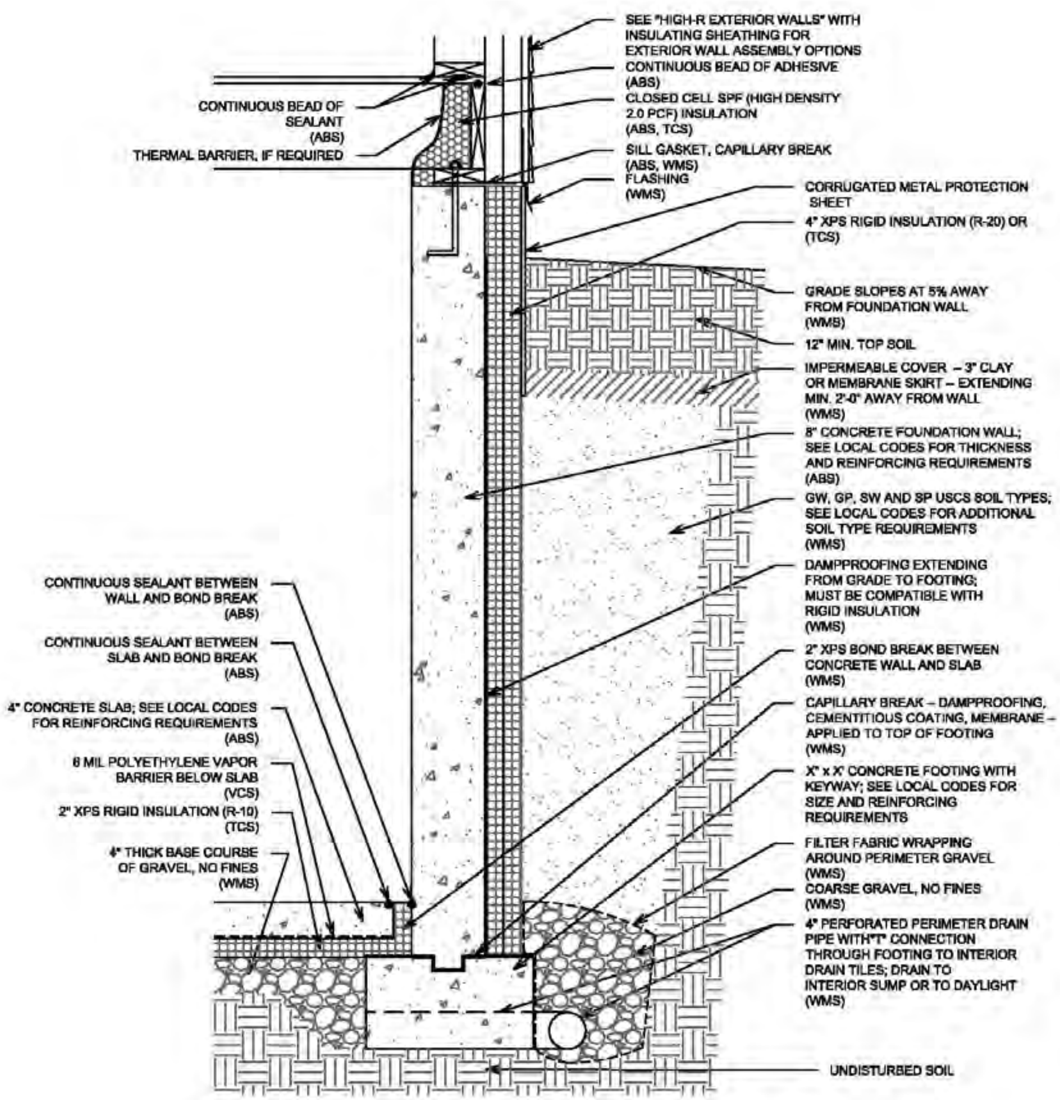


Figure 29 : Case 11 Detailed Drawing – Recommended Foundation Wall System

11.1 Thermal Control

This proposed wall system has an installed insulation R-value of R20 and results in heating energy use of 19.43 MBtus for the specific chosen parameters. The advantage of insulating on the exterior is that the insulation on the exterior of the foundation can be joined with the exterior insulation on the first floor, which forms a continuous layer of insulation and vapor control. The disadvantages of this system are that there is a thermal bridge through the concrete wall, and footing into the ground, and the above grade portion of the foundation insulation is perceived to be difficult to detail.

11.2 Moisture Control

Four inches of XPS is a great vapor diffusion resister and capillary break for inward moisture movement. There is still capillary wicking potential through the footing into the interior surface of concrete resulting in moisture at the interior surface evaporating into the interior space if it is not detailed correctly. This potential moisture issue can be solved by using a capillary break (either liquid applied or plastic based) on the top of the footing as noted in the design details. Unlike some of the other proposed foundation wall systems, the exposed concrete in this system will provide moisture buffering capacity, once it has dried.

11.3 Constructability and Cost

This proposed wall system with exterior insulation is perceived as difficult to the construction trades, and the finishing of the above grad portion may not be architecturally desirable. In some cases the timing of the insulation installation trades can be tricky since the entire house is not insulated at once in this case.

11.4 Other Considerations

In some cases, exterior foundation is not allowed by the building code due to complications with termites and other insects. Where insects may be an issue, Case 12 proposed wall system could be used.

12. CASE 12 : 4" XPS INSULATION IN THE CENTER OF FOUNDATION WALL

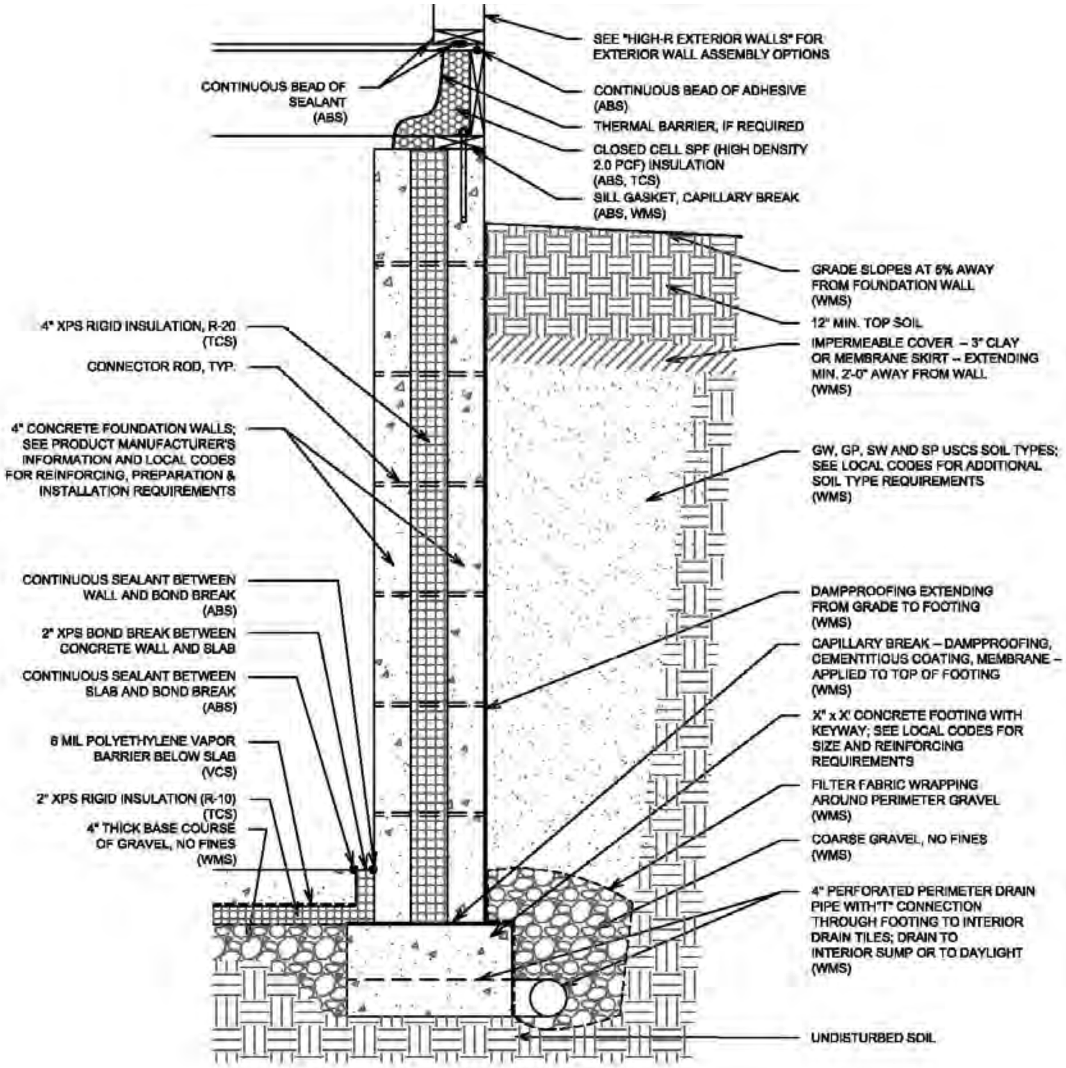


Figure 30 : Case 12 Detailed Drawing – Recommended Foundation Wall System

12.1 Thermal Control

This construction strategy has an installed insulation R-value of R20, and has a predicted annual heating energy loss of 19.24 MBtus. Unlike some of the other wall systems there are thermal mass benefits of the interior exposed surface of concrete. There is a small thermal bridge through the footing and interior surface of concrete that does increase the energy required over a wall that is insulated completely on the interior

12.2 Moisture Control

Four inches of XPS is a great vapor diffusion resister and capillary break for inward moisture movement. There is still capillary wicking potential through the footing into the interior surface of concrete resulting in moisture at the interior surface evaporating into the interior space if it is not detailed correctly. This potential moisture issue can be solved by using a capillary break (either liquid applied or plastic based) on the top of the footing as noted in the design details (Figure 30). Unlike some of the other proposed foundation wall systems, the exposed concrete in this system will provide moisture buffering capacity, once it has dried.

12.3 Constructability and Cost

This construction strategy is not very common, but is very durable because the XPS is sealed into the concrete and protected from interior and exterior damage. This wall design is more expensive than installing 4” on the interior or the exterior.

12.4 Other Considerations

This proposed wall type may not be locally available.

13. CASE 13 : INSULATED CONCRETE FORMS, 2” XPS ON INTERIOR AND EXTERIOR

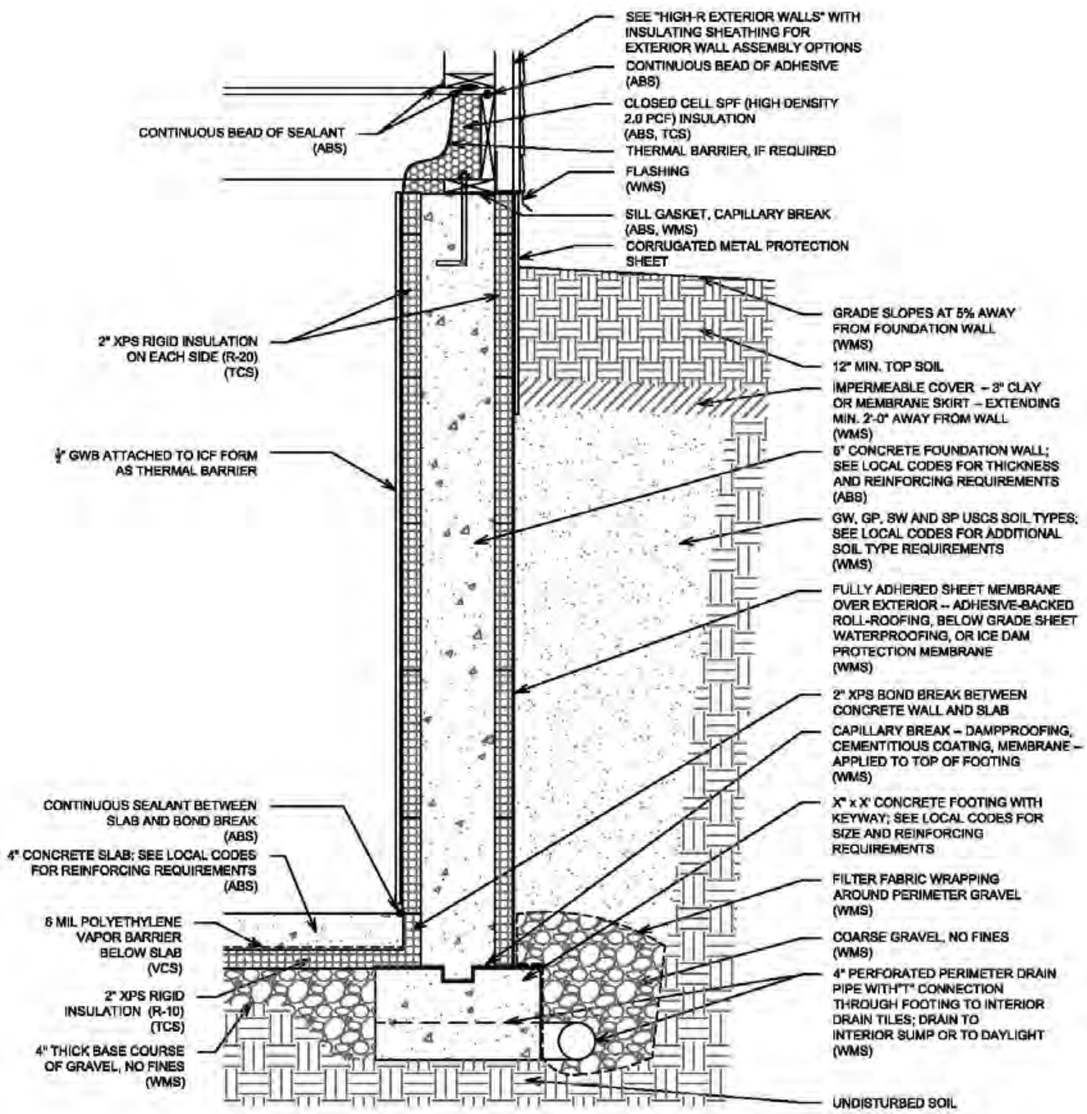


Figure 31 : Case 13 Detailed Drawing – Recommended Foundation Wall System

13.1 Thermal Control

This construction strategy has an installed insulation R-value of R20, and has a predicted annual heating energy loss of 16.7 MBtus.

13.2 Moisture Control

Two inches of XPS on the interior, connected to the thermal break at the slab edge, controls the interior vapor drive and capillary wicking to the interior so there are no moisture related issues from inward vapor diffusion or capillary wicking.

13.3 Constructability and Cost

The interior of the insulated concrete form will require drywall or other thermal barrier to achieve the fire rating required by code. The gypsum board is very easy to attach to the plastic clips designed into the ICF. The drywall should not be painted, if it is not necessary, to allow maximum drying of the concrete. It may be easier and more practical to install a thin framed wall (eg. 2x3 wood or steel framing) on the interior of the ICF to allow any necessary services to be run in the wall, and potentially more insulation.

13.4 Other Considerations

Because the concrete is installed between two vapor retarding layers, it will take several years for the concrete to dry to equilibrium. The interior vapor control should be no more than latex paint on the interior surface of the drywall.

14. CASE 14 : 2" XPS, 2X6 FRAMING WITH FIBREGLASS BATT

14.1 Thermal Control

This foundation wall system has a calculated parallel path R-value of R28.7, and a yearly heating energy consumption of 14.79 MBTus assuming R10 under the slab and in the thermal break.. This is the highest Rvalue foundation system in this study, and likely the maximum insulation that could cost effectively be used in the basement based on Figure 2 in the Heat Flow Analysis section. Only if the rest of the enclosure is super insulated, and airtight, in a very cold climate will it make sense to increase the R-value of the foundation wall. It may make sense with an R30 foundation wall to increase the underslab insulation to R15 or R20. This should be examined in more detail.

14.2 Moisture Control

This wall was analyzed in WUFI to predict the moisture related risk in the wall system, and it was shown that the RH at the surface of the XPS in the above grade portion of the wall is elevated in the winter months (Figure 19), and that there is some condensation potential alternating with periods of drying potential at the top of the foundation wall. (**Error! Reference source not found.**). There is little risk of moisture related issues in this all system if the interior RH is controlled with a dehumidifier, and the interior drywall is well air sealed.

14.3 Constructability and Cost

This wall system is slightly more expensive than Cases 8 and 9 by increasing the depth of the framed cavity with 2x6 framing instead of 2x4 framing. It is possible to use 2x4 framing stood out from the XPS by 2 inches, and use R19 fiberglass batts, or blown cellulose or fibreglass. R19 fiberglass batts should be less expensive than R13 fiberglass batts because the manufacturing process for both R19 and R13 batts uses the same amount of fibreglass, but the R13 batts require more time and effort to compact to 3.5" making them more expensive to produce.

14.4 Other Considerations

D.Conclusions

Heating energy loss calculations for all of the assemblies were calculated using Basecalc and the summary is shown in Table 5 below. The heating energy losses were conducted for a basement in Minneapolis (DOE climate zone 6), with an area of 1614 ft^2.

Table 5 : Summary of Basecalc Results

Case	Descrption	location	Installed Insualation R-value	Parallel Path Method	underslab and thermal break R10	MMBtus Annual Enery Los
1	no insulation	NA	0	na	N	56.7
2	R10 continuous, code min. (roll batt)	interior	10	na	N	25.5
3	2x4 wood framed, R13 fiberglass batt (code min.)	interior	13	12.6	N	23.9
4	1" XPS, 2x4 wood framed, R13 fiberglass batt	interior	18	18	N	21.7
5	2" Polyisocyanurate, 2" XPS	interior	23	23.4	Y	15.8
6	3.5" 2.0 pcf closed cell spray foam	interior	21	na	Y	16.4
7	6" 0.5 pcf open cell spray foam	interior	21	22.3	Y	16.0
8	2" XPS, 2x4 wood framed, R13 fiberglass batt	interior	23	23.2	Y	15.8
9	2" Polyisocyanurate, 2x4 wood framed, R	interior	25	25.4	Y	15.4
10	6" 0.5 pcf spuf, 2x4 wood framed offset 2" from concrete	interior	21	21.3	Y	16.3
11	4" XPS on the exterior of foundation wall	exterior	20	na	Y	19.4
12	4" XPS in the middle of foundation wall	interstital	20	na	Y	19.2
13	Insulated Concrete Form - 2" XPS int. and ext.	int/ext (ICF)	20	na	Y	16.7
14	2" XPS, 2x6 wood framed, R19 fiberglass batt	interior	29	28.7	Y	14.8

Analysis showed that even a small amount of insulation on the foundation wall decreased the heating energy losses significantly compared to an uninsulated basement, and the benefits of increasing insulation decrease as more insulation is added. In Cases 5 through 13, none of the walls perform significantly better than the others from a heating energy losses perspective, so any decisions will be made on cost, durability and desired finish.

Insulating below the basement slab and at the interface of the foundation wall and basement slab will result in energy savings, but the greatest benefit is moisture related since they form a vapor diffusion and capillary break between the moisture and the interior environment, resulting in a drier, healthier interior environment.

Besides bulk water movement, which is not specifically addressed in this report, there are two modes of wetting in the foundation; vapor diffusion and capillary wetting. The exterior surface of the below grade portion of any foundation wall is maintained at approximately 100% relative humidity so moisture movement below grade is always to the interior and drying is not possible to the exterior. The IRC has been modified to reflect this, not recommending a Class I or II vapor control layer on the interior of any below grade wall.

Capillary wicking through the footing into the foundation wall is generally not addressed by production builders, and can result in significant amounts of moisture evaporating from the interior surface of the basement wall.

Cases 2 and 3 represent code minimum basement insulation amounts, although these were hygrothermally simulated with an interior poly layer instead of a perforated layer, which should be simulated in future work. With a polyethylene vapor barrier, these walls perform very poorly, with high relative humidities in the insulation, and air leakage condensation potential for nearly the entire year. Intrusive investigations of buildings in the field have shown that moisture related issues (including mould, rot, and odours) can be expected with this type of wall construction.

Cases 4, 8, 9, and 14 with a rigid foam against the concrete foundation and air permeable insulation in a wood framed wall (fiberglass batt or cellulose) showed significant improvements in moisture performance over Case 2 and

3. There is still some predicted air leakage condensation potential, but generally isolated to the above grade portion of the wall, due to the very cold exterior temperatures.

Case 5 with 2” of XPS and 2” of polyisocyanurate has no moisture related issues and performs very well, but does not easily allow for interior finishes compared to some other proposed foundation insualation systems.

Case 6, 7, and 10 use spray foam applied directly against the foundation wall, which forms an air barrier system resulting in no air leakage condensation. Closed cell spray foam is a vapor barrier limiting diffusion to the interior and open cell foam is more vapor permeable, but simulations predicted no moisture related issues from vapor diffusion due to the thickness of foam, and the ability of small amount of vapor to dry to the interior through the foam and interior finish. At the above grade portion of the wall in cold climates, a lower permeance board foam is recommended to control the inward vapor drive in the summer months, and limit the vapor diffusion condensation in the winter months. There are no moisture related issues predicted for the spray foam walls.

Cases 11, 12, and 13 are all constructed with 4” of XPS in different locations on the foundation wall, and all result in good moisture performance. A capillary break is always recommended between the footing and the foundation wall, and in Case 11, and 12, it is required since the vapor control layer, that decreases the evaporation and vapor diffusion from the interior surface, is discontinuous on the interior surface. Cases 11, and 12 also have slightly higher heating energy losses because of the thermal bridge along the interior surface of the foundation wall through the footing, but they do have the advantage of both thermal and moisture buffering if the interior of the concrete wall is left exposed.

Following the analysis of all proposed foundation wall systems, values were assigned for the five comparison criteria;

- Thermal control
- Durability
- Buildability
- Cost
- Material use

These walls were scored on a scale of 1 to 5 for each criterion, one being the lowest, and five being the best performing, and the results are shown in Table 6. Based on the selected criteria, the two highest scoring walls were the 6” of open cell spray foam with and without framing. Because some of the criteria such as Material Use and Cost could be different in other regions, the final results could be different in different parts of the continent.

All of the criteria are currently weighted evenly, but they could be changed depending on the concerns of the contractor or homeowner. Using multipliers between 1 and 5 before summing the scores could result in different results based on the importance of different criteria.

Table 6 : Comparison Criteria Matrix with Scoring Results

	Thermal Control	Durability (wetting/dry	Buildability	Cost	Material Use	Total
Criteria Weighting	1	1	1	1	1	
Case 1: uninsulated	–	–	–	–	–	
Case 2: R10 continuous with poly (roll batt)	1	1	5	5	5	17
Case 3: R13 batt, 2x4 wall with poly	1	1	4	4	5	15
Case 4: 1" XPS, 2x4 framed wall with fgb	2	3	3	3	4	15
Case 5: 2" XPS, 2" PIC	4	4	3	3	3	17
Case 6: 3.5" 2.0pcf cc spuf	4	5	5	3	3	20
Case 7: 6" 0.5pcf oc spuf	4	4	5	4	4	21
Case 8: 2" XPS, 2x4 framing with fgb	3	3	3	3	4	16
Case 9: 2" PIC, 2x4 framing with cellulose	3	3	3	3	4	16
Case10: 2.0" 0.5 oc spuf, 2x4 framing with sam	4	4	4	3	3	18
Case 11: 4" XPS on the exterior	4	4	2	2	3	15
Case 12: 4" XPS in the centre of foundation	4	4	3	1	3	15
Case 13: ICF 2" XPS interior and exterior	4	5	4	1	3	17
Case 14: 2" XPS, 2x6 framing with fgb	5	4	3	2	3	17

E. Future Work

While conducting this analysis, some questions were encountered that require further research, analysis and simulations to more completely understand the moisture and thermal performance of basement insulation systems. These areas include;

- Determining the effect of perforated facers on code compliant R10 roll batts
- Researching field testing data on basement monitoring data that has been conducted and correlate to the proposed wall systems.
- Further analysis of the Mitalas finite element analysis method of heating energy loss for basements.
- Attempt to quantify the role of capillary wicking through the basement wall relative to the vapor diffusion load.

Following the completion of the High-R basement and foundation report, an analysis report will be completed for roofs and attics regarding historical, code compliant and super insulated roof strategies. Similarly to the previous High R Wall Report and this Basements/Foundations report, the Roof and Attic report will be a combination of both field testing/monitoring, thermal and hygrothermal analysis, years of experience.

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1.5.5. Construction, Commissioning & Calibration of a Novel Hot Box Apparatus for High-R Enclosure Performance Measurement

by Christopher Schumacher, December 2009

Building America High-R Enclosures Research Project: Construction, Commissioning & Calibration of a Novel Hot Box Apparatus for High-R Enclosure Performance Measurement

2009 December
Chris Schumacher

Abstract:

*This report documents the construction, commissioning and calibration of a novel hot box apparatus designed and constructed to measure the heat transfer through high-*R *building enclosures under real temperature conditions, with and without airflow in and through the enclosure.*

Introduction

The R-value has long been the industry standard for assessing the thermal performance of insulation materials. Building designers directly apply R-value to the thermal performance of building enclosures. This practice has recently come into question as energy-cost and security issues have generated demand for building enclosures that exhibit higher levels of thermal performance. The market has responded with new insulation products and novel building enclosure systems such as: various types of spray foam and spray-applied fibrous insulations, exterior insulated sheathing, Structural Insulated Panel Systems (SIPS), Insulated Concrete Forms (ICF), and Radiant Barrier Systems (RBS), etc.

Because contemporary insulation materials and systems control heat flow in different, new and non-traditional ways, they are more or less sensitive to thermal bridging, workmanship (i.e. quality of installation), internal convection and through convection (i.e. infiltration, exfiltration, windwashing & re-entrant looping). The impact of such 'anomalies' and 'defects' is not captured in the R-value metric. Furthermore, the discrepancy between the real heat flow and that predicted by combining R-values increases the absolute temperature, the temperature difference and the net resistance to heat flow increase. These realizations have generated an increasing amount of interest in the development of a new metric for the thermal performance of building enclosures.

The goal of this work is the development of a new metric for the thermal performance of building enclosures that better accounts for the known physical heat flow mechanisms (particularly natural and forced convection) and operating conditions. The metric employs equipment and techniques based on existing ASTM procedures as much as practical.

Previous BSC Work

In FY07 BSC completed a report entitled "Review of the R-value as a Metric for High Thermal Performance Building Enclosures" that summarized the extensive existing research of heat flow through walls and highlighted physical mechanisms that are not usually included in codes and designer specifications. The impact of thermal bridging, and convective loops, although well understood, has not been sufficiently well quantified to allow for prediction. Air infiltration and exfiltration through the wall assembly were identified as a major unquantified heat flow mechanisms in current approach to building enclosure thermal testing. From this review, a need was identified for measuring and rating heat flow across a wall under realistic temperature ranges (both cold & hot exterior conditions) and under the influence of air movement (both in and through the building enclosure).

This was followed by a FY08 report entitled "Development of a Test Procedure and Apparatus for Measuring High Thermal Performance Walls" that outlined a new metric for the thermal performance of building enclosures. New equipment and techniques, based on existing ASTM standards, were proposed to better account for the known physical heat flow mechanisms (particularly natural and forced convection) and operating conditions.

BSC assembled a consortium of 6 building product manufacturers to participate in the privately-funded development of the new thermal performance metric and the associated test method. These partners include:

- NAIMA (North America Insulation Manufacturer's Association) with technical representatives from Certainteed and Johns Manville
- Huntsman Polyurethanes
- Honeywell
- Icynene
- Dow Chemical
- US Greenfiber

The partners designed and built (with private funding) a novel hot box apparatus to permit the highly accurate measurement of heat flow under realistic operating conditions. This report documents the apparatus construction and summarizes the commissioning and calibration activities that were undertaken in 2009.

Test Apparatus

This section of the report provides a summary of the construction and operation of the apparatus as context for later discussion on commissioning and calibration.

In general the test apparatus has been designed & constructed in accordance with ASTM C1363, "Standard Test Method for Thermal Performance of Building Materials and Envelope Assemblies by Means of a Hot Box Apparatus." A number of modifications were made to meet the specific objectives of the research.

The key improvements over other (i.e. conventional) hot box testing is the ability to test higher R-value enclosure assemblies (which have lower heat fluxes), a procedure and apparatus that exposes enclosure wall samples to realistic temperature differences while maintaining the interior temperature at normal room temperatures, and the ability to measure the impact of imposed air flow.

Conventional Hot Boxes

ASTM C1363 recognizes two configurations for hot box test apparatuses: *guarded* and *calibrated*. Figure 1 provides a schematic of a conventional guarded hot box apparatus which comprises three boxes: the climate box, the meter box and the guard box. The wall test specimen is installed between a climate box and a meter box so that the drywall side (i.e. inside) of the wall faces the meter box and the cladding side (i.e. outside) of the wall faces the meter box.

The climate box is typically cooled to maintain a temperature of 50 or 55°F (10 or 12.8°C) and a measured amount of heat is added to the meter box to maintain a temperature of 95 or 100°F (35 or 37.8°C) so that the average temperature across the test wall specimen is 75°F (23.9°C). Air is typically heated and circulated through the space between the guard box and the meter box to minimize the temperature difference (deltaT), and therefore the heat flux across the meter box wall so that any heat added to the meter box must flow through the test wall specimen.

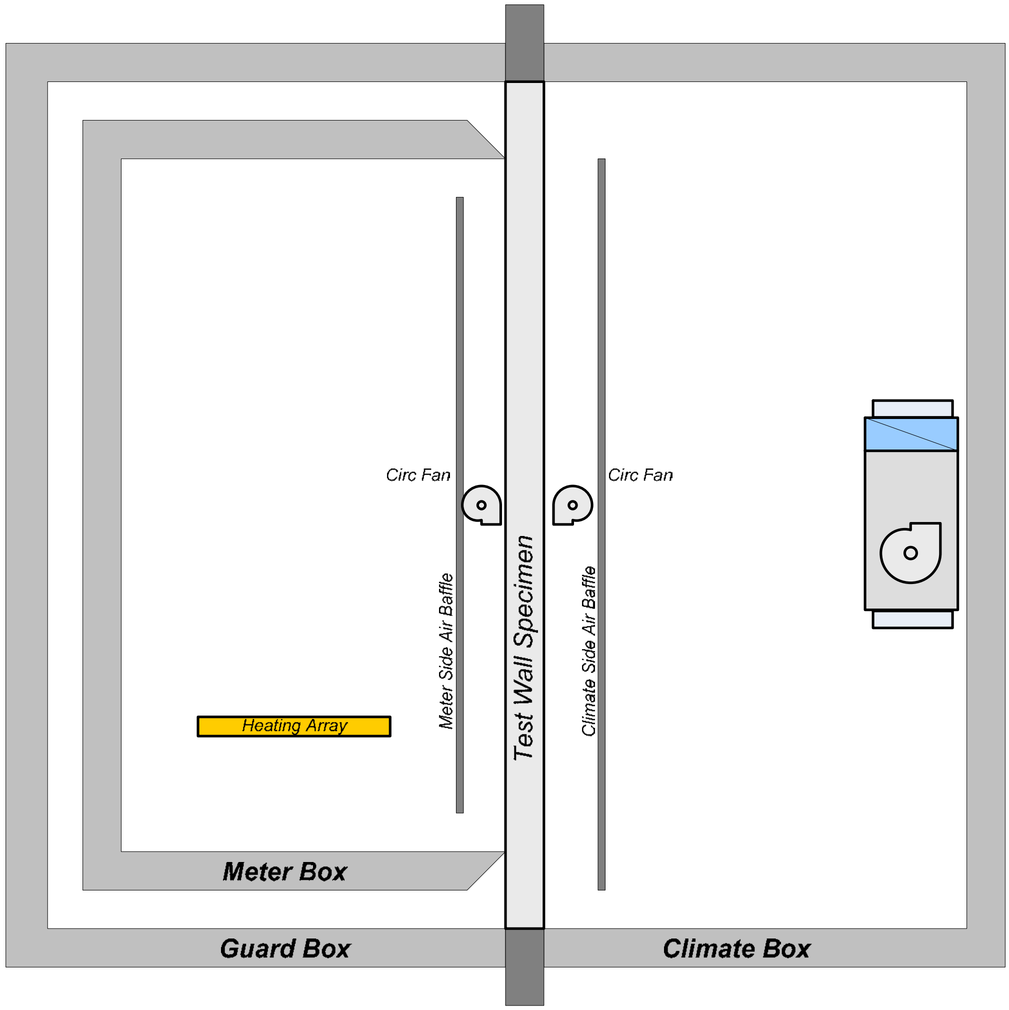

Figure 1 – Schematic of Conventional Guarded Hot Box Apparatus

Guarded Hot Boxes

In a conventional guarded hot box apparatus, the test wall specimen is larger than the opening of the meter box. The meter box walls taper to a thin edge that interfaces (i.e. seals against) the test wall specimen. When the temperatures in the guard box and the meter box are equal, all of the heat flow at this interface is perpendicular to the plane of the wall so there is no "flanking loss."

Calibrated Hot Boxes

In a conventional calibrated hot box apparatus, there is no guard box; the meter box opening is the same size as the climate box opening; and the test wall specimen is typically the same size as the meter box opening. Conditions in the lab space are controlled sufficiently to permit calculation of the heat flux across the calibrated meter box walls so the measured heat input can be corrected.

Limitations of Conventional Hot Boxes

Most conventional hot boxes apparatuses are designed to operate within a limited temperature range. Temperatures in the climate box and the meter box are often not representative of real climate and room temperature conditions.

Few meter boxes are equipped with the ability to provide any measured cooling. This means that hot weather (i.e. cooling climate) tests must be run well above the temperature of the laboratory (calibrated boxes only) or the specimen must be removed from apparatus and turned around so that the cladding side (i.e. outside) of the wall faces into the meter box while the drywall side (i.e. inside) faces the climate box.

Finally, it is common to install axial fans at mid-height between the test wall specimen and the air baffle. These fans drive airflow parallel to the surface of the wall specimen and can easily be setup to switch direction, however the fan location can create non-uniform pressure gradients in the plane of the wall specimen.

Thermal Metric Research Hot Box

With the aid of industrial partners, a novel hot box apparatus was designed and constructed for the purposes of the Thermal Metric (TM) research project. In as much as possible, the apparatus, depicted by the schematic in Figure 2, has been based on ASTM C1363, however a number of improvements have been made to facilitate the research. These include:

- A deeper meter box to permit the testing of wall-wall and wall-floor intersections at close to full scale.
- Metered equipment to both heat & cool the meter box
- Draw-through fans to create more realistic airflow over the inside surface of the wall specimen
- A double guard (insulated guard box + liquid guard loop) to improve control over the temperature differential across the meter box walls and minimize uncertainties.
- A modified specimen frame or ‘cartridge’ to control flow of heat & mass at the perimeter of the metered area of the test wall specimen
- An air transfer system to induce infiltration / exfiltration

General Construction Details

The walls of the TM hot box are custom assembled structural insulated panels comprising 11 mm (7/16 in) good one side plywood adhered to either side of a solid layer of 100 mm (4 in) XPS insulation to create a stiff, strong, airtight wall with an unbridged, continuous thermal resistance of more than RSI 3.7 (R21). These SIPs are attached to the inside of a steel exo-skeleton using fasteners that only penetrate the outer layer of plywood.

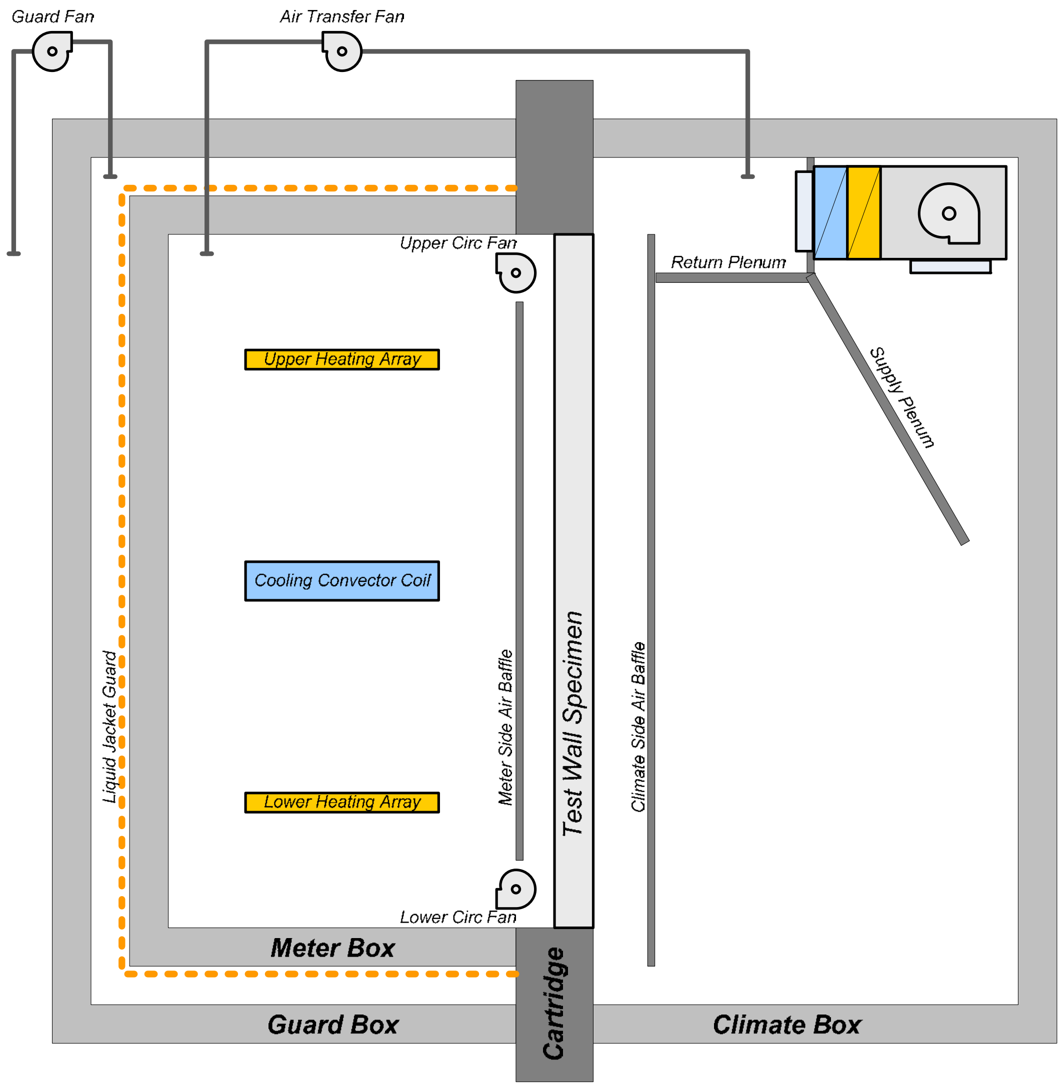

Figure 2 – Schematic of Thermal Metric Research Hot Box Apparatus

Meter Box

The meter box walls are insulated with an additional RSI 1.76 (R10) of foil-faced insulation. The foil acts as an isothermal surface to which to fasten temperature sensors, and as a low emissivity surface that ensures a uniform radiant exposure behind the insulated air baffles.

The insulated baffles are used to form consistent vertical airflow patterns over the interior faces of the test wall specimen. The baffles consist of RSI 0.88 (R5) insulation boards with a low emissivity foil skin facing the inside of the meter box and a painted plastic skin facing the wall specimen. The low emissivity foil skin and the insulation ensure that the baffle is at a constant temperature close to that of the air that is travelling across the face of the test wall specimen. The painted plastic skin ensures that the surface of the test wall specimen radiates to the baffle as a real wall would to its surrounding environment. Calibrated precision thermistors (+/-0.1°C) are used to measure temperatures at 24 points on the baffle surface, 24 corresponding points in the air stream and at 24-36 points on the interior surface of the wall test specimen.

Airflow in the baffle space is induced by a set of DC axial circulation fans at the top or the bottom of the baffle. The fan speed can be adjusted to draw the air through the baffle space at velocities representative of natural convection in real world conditions, typically 0.3 m/s (1 fps). The lower fans are used to draw air in and down the wall during cold climate tests while the upper fans are used to draw air in and up the wall during hot climate tests. The use of draw through fans ensures that velocities over the test wall specimen are uniform and the flow is not turbulent. The voltage and current to the circulation fans are measured across precision (+/-0.01%) resistors so that the power may be calculated.

The temperature in the meter box is controlled by electric heat and hydronic cooling. Two heating arrays, each consisting of 16 heaters and 8 mixing fans, are installed in the upper and lower portions of the mixing part of the meter box as seen in Figure 3. The size, number and distribution of the heaters and fans ensure that the temperature is relatively uniform throughout the meter box. Again, voltage and current supplied to the heaters and mixing fans are measured across precision (+/- 0.01%) resistors so that the power may be calculated.

Figure 3 – Upper & Lower Heating Arrays & Cooling Coil in Meter Box

Cooling is achieved by a large, finned convection coil mounted at mid-height in the mixing part of the meter box. The large heat transfer area permits the removal of significant amounts of heat with only modest (e.g. 1°C or 1.8°F) temperature increases across the coil. Distilled water is pumped from a chilled, constant temperature (+/-0.05°C) buffer tank, into the meter box, through the convection coil, and back out of the meter box. The flow rate is measured using a NIST traceable +/-0.2% of reading flow meter and the supply and return temperatures are measured using a pair of precision thermistors (+/-0.1°C) and a pair of ultra precision RTDs (+/-0.012ohm). These measurements can then be used to calculate the power extracted by the cooling.

The cooling coil and the two heating arrays are mounted on a rack that can be moved forward or deeper into the meter box as necessitated by the geometry of the test specimen.

The meter box has a depth of 1.5 m (5 ft) to permit testing of wall-wall and wall-floor intersections at full scale. This is significantly deeper than conventional hot boxes which are usually designed to minimize depth and, as a result, wall area in an effort to minimize heat loss across the meter box walls. The TM hot box design uses a double guard and significant meter box wall insulation to offset the additional wall area associated with the increased depth of the box.

The Double Guard

The TM hot box employs a double guard: an insulated guard box surrounds the meter box and a hydronic (liquid) guard loop is installed over the outside surface of the meter box as seen in the photograph of Figure 4. The guard box minimizes the influence of temperature changes in the lab and reduces spatial temperature gradients over the surface of the meter box. The liquid guard loop further reduces any spatial temperature gradients and all but eliminates any temperature difference between the inside and the outside of the meter box walls.

The temperature difference is measured by paired precision thermistor arrays that are applied to the inside & outside of each of the five faces of the meter chamber at a density of more than 5 sensors per square meter. In all, the temperature difference is measured at 176 locations. The hot box control system uses the aggregated differential temperature measurements to control the guard loop supply temperature to reduce the average temperature difference across the meter box walls to less than 0.05°C (0.09°F).

Each of the guard loops can be individually controlled with metering valves to allow the flows to be calibrated from time to time to ensure spatial uniformity of the temperature. The water flow of each loop has been designed to absorb or release the expected heat flow through the R20 walls of the guard chamber walls (in the range of 2 to 4 W per loop) with a temperature rise of less than 0.005°C (0.009°F).

Figure 4 – Double Guard: Guard Box (Left) and Liquid Guard Loop on Meter Box (Right)

The Wall Cartridge

Section 6.7.1 of ASTM C1363 requires the provision of a specimen frame to support the wall test specimen in position between the meter box and climate box and to insulate the perimeter of the specimen to reduce flanking losses. In a conventional guarded hot box, the wall test specimen area extends beyond the perimeter of the meter box so that the portion of the wall that is between the meter box and the climate box see the same heat flow as the portion of the wall that is between the guard box and the climate box. This is an extremely effective method of minimizing flanking losses; however, when hollow (e.g. framed) walls are tested, it provides paths for to flow not just between the climate box and the meter box, but also between these two boxes and the guard box.

The interaction between heat and airflow is of particular interest in the Thermal Metric research program, hence the team felt it necessary to design a specimen frame that would not only minimize flanking losses, but also eliminate airflow outside of the area of the wall test specimen. The TM hot box specimen frame or ‘cartridge’ comprises alternating layers of 11 mm (7/16 in) plywood and 100 mm (4 in) XPS foam board glued up to create an exceptionally stiff sandwich panel as seen in Figure 5. Two 38 x 38 mm (nominal 2 x 2 in.) nailers are embedded in the cartridge to provide fastening support. A 100 mm (4 in) thick XPS thermal break lines the entire rough opening of the cartridge so that the finished opening and the size of the wall test specimen match the meter box opening: 3.66 m (12 ft) wide by 2.44 (8 ft) high.

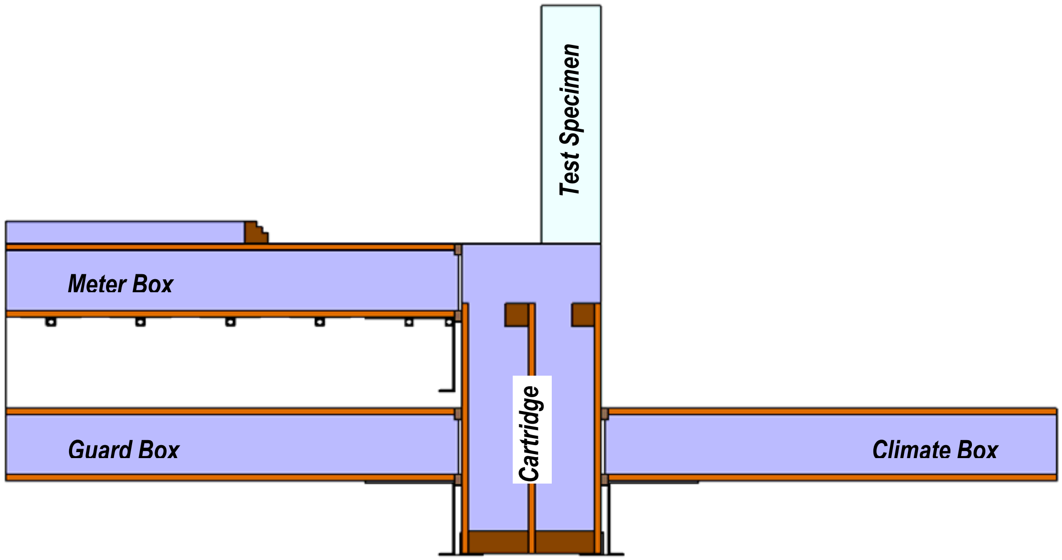

Figure 5 – Section through Wall Cartridge with Meter, Guard and Climate Boxes in Position

The wall test specimen is positioned so that its cladding is in plane with the climate side of the wall cartridge. The geometry allows space for air in the climate box to turn the corner and regain some uniformity before it passes over the surface of the wall test specimen. This is important when considering the interaction between heat flow and airflow. The arrangement does however complicate the flanking loss because there is a portion of the cartridge that is exposed to the meter box yet is not guarded (i.e. that portion of the thermal break that lies between the inside face of the drywall and outside of the meter box gasket. Steady state 2-dimensional heat flow analysis was conducted using HEAT2 to optimize the wall cartridge design and to reduce flanking losses so that they were comparable to those in heat boxes operated by the industry partners that were participating on the Thermal Metric research team. Figure 6 shows the temperature distribution and heat flux vectors acting across the wall cartridge for meter box temperature of 22°C (71.6°F) and a climate box temperature of -18°C (0.4°F).

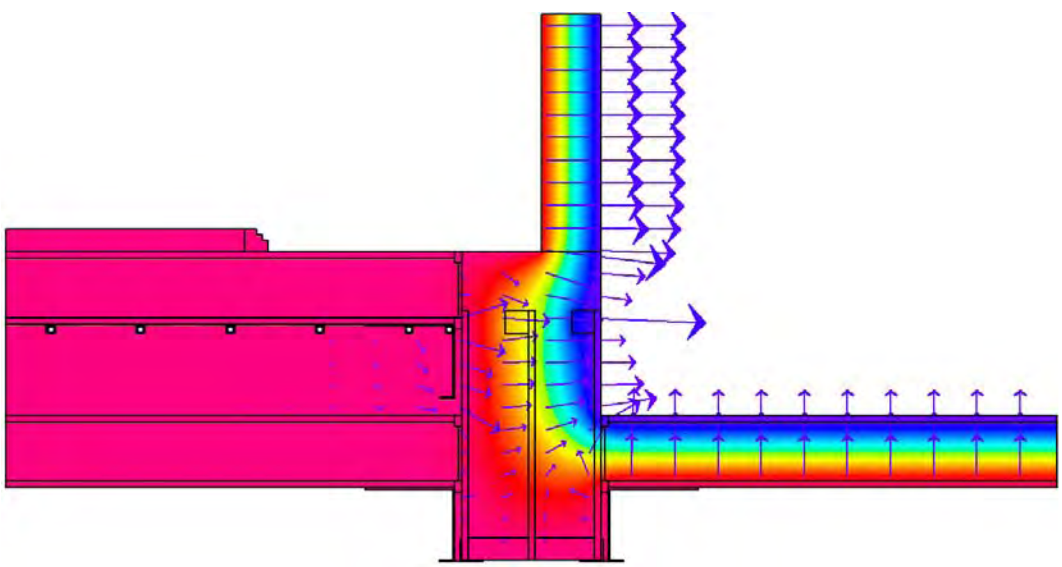

Figure 6 – Temperatures & Heat Flux @ 22°C (71.6°F) Meter Side & -18°C (0.4°F) Climate Side

The wall cartridge is completed by a heat shrink air barrier is applied over the thermal break to prevent air from moving from one box to another through the wall cartridge. The heat shrink cover over the thermal break is evident as the black border in the photo of Figure 7.

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Figure 7 – Wall Cartridge with Test Wall Specimen Installed & Instrumented for Testing

Climate Box

The climate box has the same dimensions and construction as the guard box. The climate side air baffles are constructed using the same materials and methods as the air baffles in the meter box. Foil-faced insulation is also used to form the return plenum at the ceiling and the supply plenum that runs half way down the back wall of the climate box.

The temperature in the climate box is controlled by a series of four fan coils connected to a 8 kW @-20 °C (and 4.5 kW@-30C), capacity air-cooled liquid chiller and a 6 kW hydronic heater. The airflow in the climate side can be adjusted between approximately 150-1000 lps (300-2000 cfm) to control mixing and air velocity over the test wall specimen. The oversized coils allow for a very small temperature drop across the coil during most test conditions. Reheat coils and individually-controlled tight-fitting dampers allow for individual defrost. This feature allows three fan coils to continue conditioning and circulating air while the fourth is defrosted. The reheat coils can be used for humidity control, and the low temperature drop cooling coils allow RH levels of 90 to 95RH to be maintained over most of the temperature range.

Air Transfer System

One of the most novel aspects of the TM hot box is the air transfer system (ATS). The system, pictured in Figure 8, generates a pressure difference between the meter box and the climate box to drive airflow through available paths in the test wall specimen. The system comprises an inline fan, an inline heater, a high accuracy (+/-2% of reading) mass flow sensor and piping and valves to allow negatively pressurize (i.e. induce infiltration) or positively pressurize (i.e. induce exfiltration) the meter box. A guard fan is used to minimize the pressure difference between meter and guard boxes so that airflow only occurs between the meter and the climate boxes.

Typical flow rates are expected to be in the range of 0.1 and 20 liters per minute (2 to 50 cfm) at pressures of 2 to 25 Pa. This will impose leakage rates of 0.01 to 2.25 lps/m2 (0.02 to 0.50 cfm/ft2).

Heat transfer associated with the airflow is calculated using the measured flow rate, the heat capacity of air at the measured pressure, temperature & humidity and the temperature difference between the delivered air temperature (measured using an ultra precision RTD @ +/-0.012 ohm) and the air temperature in the meter box (measured using an array of precision thermistors @ +/-0.1°C).

Figure 8 – Guard Fan (Left) & Air Transfer System (Center)

TM Hot Box Operating Modes & Energy Balances

The TM hot box has been designed to operate in a number of different modes to facilitate testing over a realistic range of temperatures and representative air leakage scenarios. This section of the report describes the typical operating modes and summarizes the equipment, measurements and energy balance for each.

General Energy Balance without Induced Airflow

All measurements of heat flow are made in the meter box, regardless of the operating mode. When no airflow is induced, the TM hot box operates in a manner similar to other hot boxes. Heat is added to the box by the heating arrays and the circulation fans. These are indicated in the diagram of Figure 9 as Q_h and Q_f respectively. Heat is removed from the box by the cooling coil (Q_c). A small amount of heat flows into or out of the meter box walls (Q_{mw}) depending on how well the guard loop eliminates the temperature difference across the walls of the box. When the climate box is maintaining heating climate (i.e. cold) temperatures heat will flow out of the perimeter, flanking the guard. In hot box terminology this is usually referred to as a flanking loss (Q_{fl}). When the climate box is maintaining cooling climate (i.e. hot) temperatures, heat will flow into the perimeter so that the flanking loss appears as a gain.

Q_h, Q_f and Q_c can be measured directly; Q_{mw} and Q_{fl} can be predicted using temperature measurements and calibration factors. The only missing heat flow in the meter box system is then the heat that flows into or out of the test wall specimen. This is typically idealized as conductive heat flow ($U \cdot A \cdot \Delta T$) and can be calculated using the other five heat flow terms and the heat balance equation shown in Figure 9.

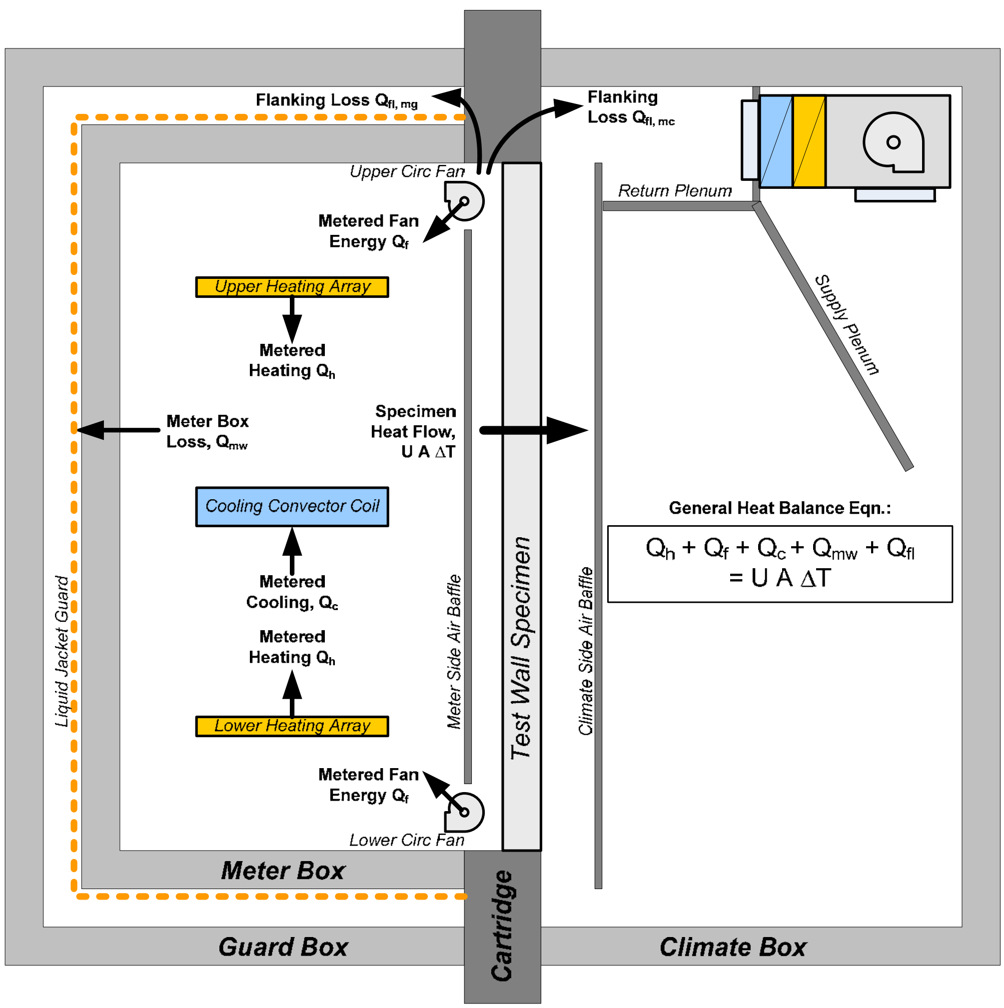

Figure 9 – General Energy Balance Diagram for Modes with No Induced Airflow

General Energy Balance with Induced Airflow

When airflow is induced, two additional heat flows must be considered: heat moved with the air through the transfer fan and heat moved with the air infiltrating or exfiltrating through the test wall specimen. The transfer air heat flow, denoted by Q_t in Figure 10, is measured directly. It is much more difficult to isolate the heat moved by infiltration or exfiltration.

If the meter and climate boxes are connected with airtight seals against the cartridge, then the system is closed and the airflow through the test wall specimen must be equal to the airflow measured by the mass flow sensor in the air transfer system (ATS). In theory, the heat moved by this airflow can be calculated using m·c·ΔT and the general heat balance equation would be as shown in Figure 10, however airflow through the test wall specimen changes the temperature field in the test wall specimen so that the apparent conductance of the test wall specimen is changed. This is referred to as the 'interaction' between airflow and heat flow. The TM research team plans to account for this interaction in the new thermal metric.

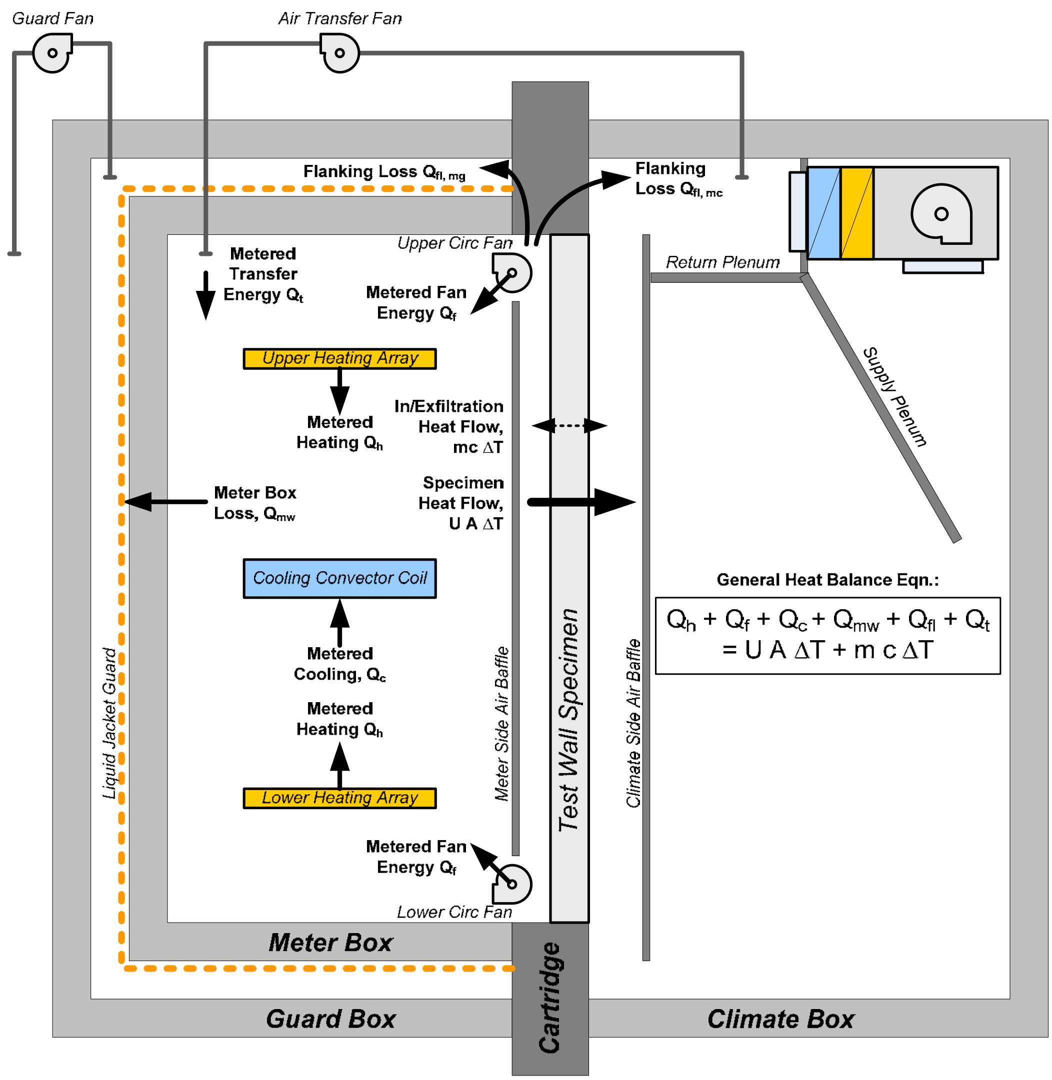

Figure 10 – General Energy Balance Diagram for Modes with Induced Airflow

Cold Climate, No Induced Airflow

Figure 11 shows the equipment state, air circulation patterns and heat flows associated with the cold climate mode when there is no induced airflow. The temperature in the meter box is maintained by adding heat using the upper and lower heating arrays. The lower circulation fans are used to generate a cold climate convection pattern on the inside of the wall test specimen; air enters the top of the baffle space, cools as it passes down the wall and is pushed back into the mixing portion of the meter box at the bottom of the baffle space. Q_h & Q_f are measured directly while Q_{mw} & Q_{fl} calculated from measurements and calibration factors. The test wall specimen heat flow is then calculated using the heat balance equation of Figure 11.

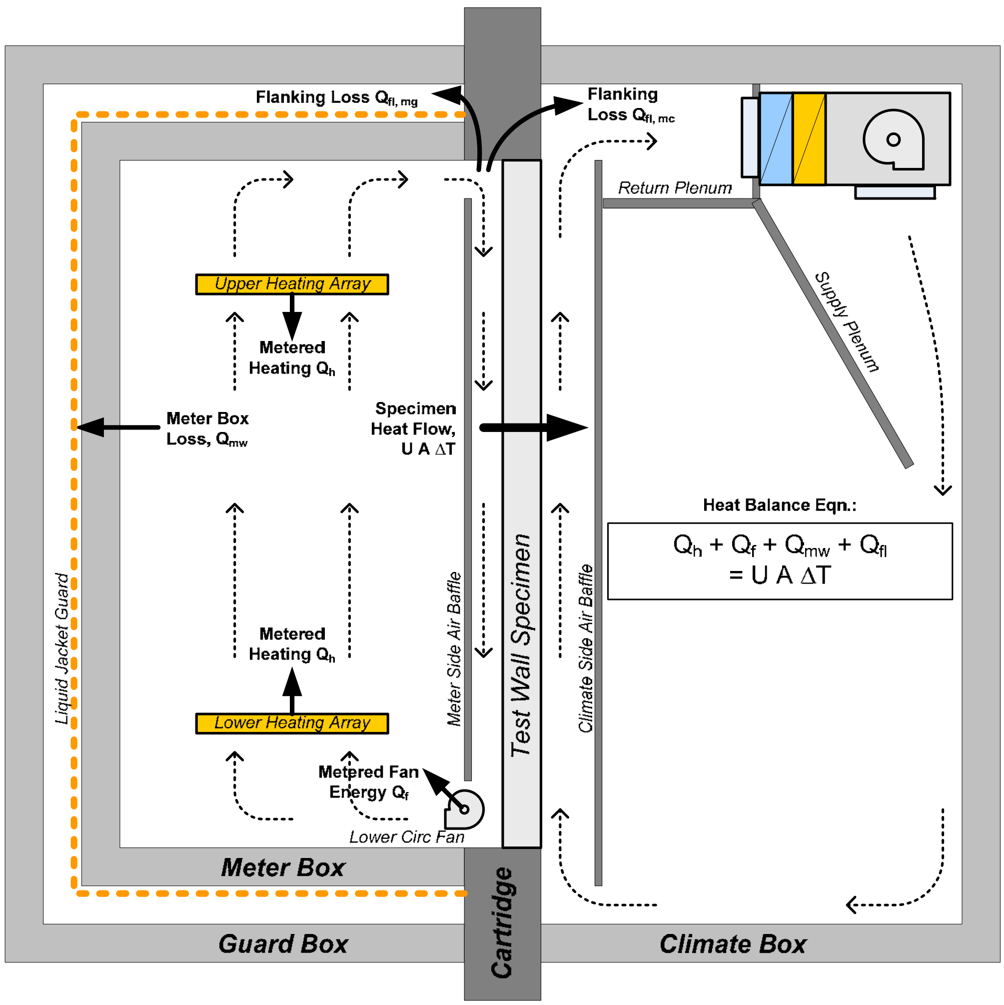

Figure 11 – Cold Climate Mode with No Induced Airflow

Cold Climate, Induced Infiltration

In the cold climate mode with induced air infiltration, the air transfer fan is used to negatively pressurize the meter box relative to the climate box as illustrated in Figure 12. The pressure difference causes air to move through the wall specimen from outside to in, opposite the direction of heat flow. For cold climates, infiltration represents contraflux heat flow.

Under the cold climate infiltration mode the mass flow sensor is used to measure the air transfer flow rate which is assumed to be equal to the infiltration flow rate. If there were no interaction between the air infiltration and heat flow through the wall, then air transfer heat flow, Q_t, would be equal to the infiltration heat flow, $m \cdot c \cdot \Delta T$.

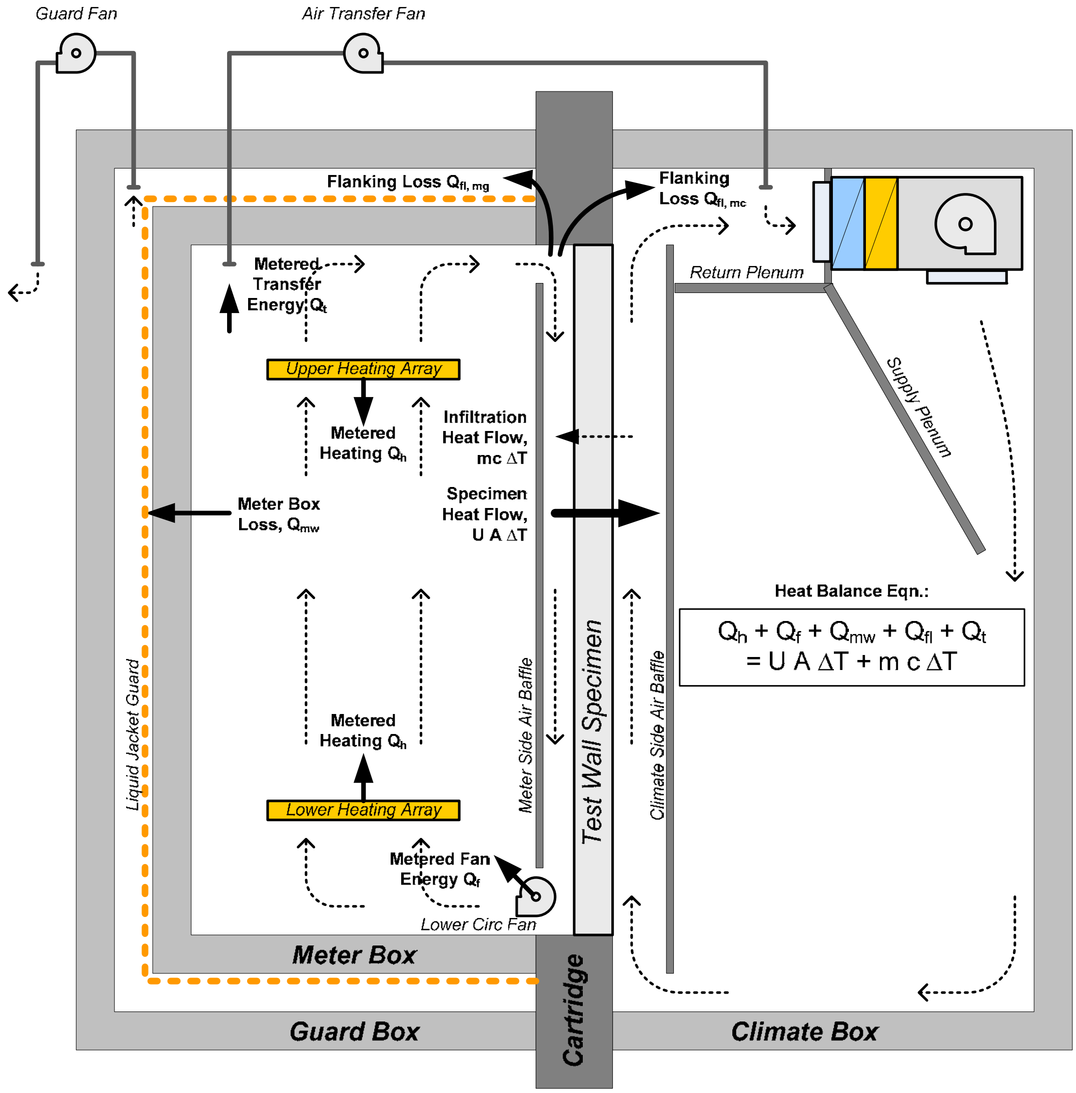

Figure 12 – Cold Climate Mode with Induced Air Infiltration

Cold Climate, Induced Exfiltration

In the cold climate mode with induced air exfiltration, the air transfer fan is used to positively pressurize the meter box relative to the climate box as illustrated in Figure 13. The pressure difference causes air to move through the wall specimen from inside to out, in the same direction as the heat flow. For cold climates, exfiltration represents proflux heat flow.

Under the cold climate exfiltration mode the mass flow sensor is used to measure the air transfer flow rate which is assumed to be equal to the exfiltration flow rate. If there were no interaction between the air exfiltration and heat flow through the wall, then air transfer heat flow, Q_t, would be equal to the exfiltration heat flow, $m \cdot c \cdot \Delta T$.

The design of the ATS permits the transfer air to be heated so it can be delivered at the temperature of the air in the meter box.

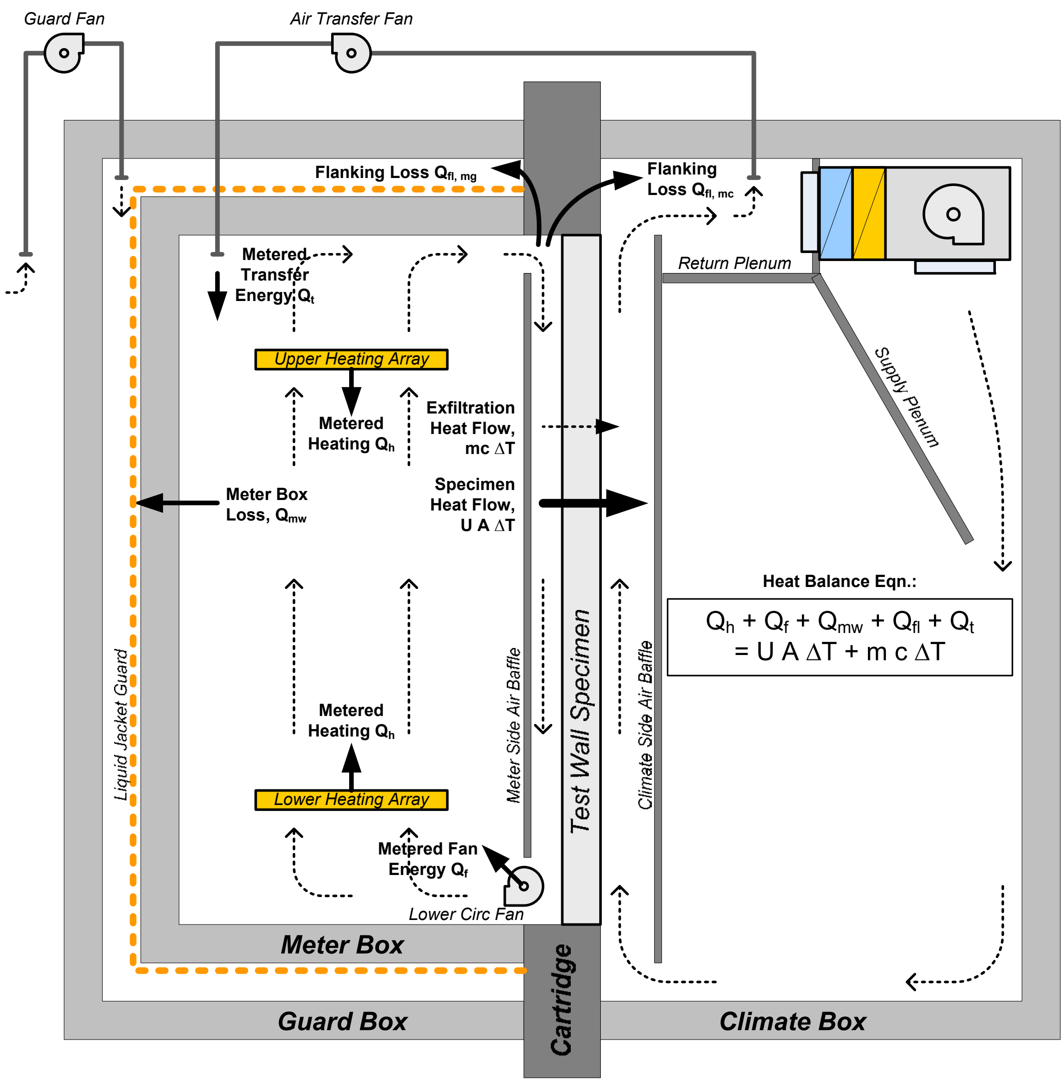

Figure 13 – Cold Climate Mode with Induced Air Exfiltration

Hot Climate, No Induced Airflow

Figure 14 shows the equipment state, air circulation patterns and heat flows associated with the hot climate mode when there is no induced airflow. The temperature in the meter box is maintained by removing heat using the cooling coil. Where extremely fine temperature control is necessary, some heat can be added using the upper and lower heating arrays. The upper circulation fans are used to generate a hot climate convection pattern on the inside of the wall test specimen; air enters the bottom of the baffle space, warms as it passes up the wall and is pushed back into the mixing portion of the meter box at the top of the baffle space. Q_h & Q_f are measured directly while Q_{mw} & Q_{fl} calculated from measurements and calibration factors. The test wall specimen heat flow is then calculated using the heat balance equation of Figure 14Figure 11.

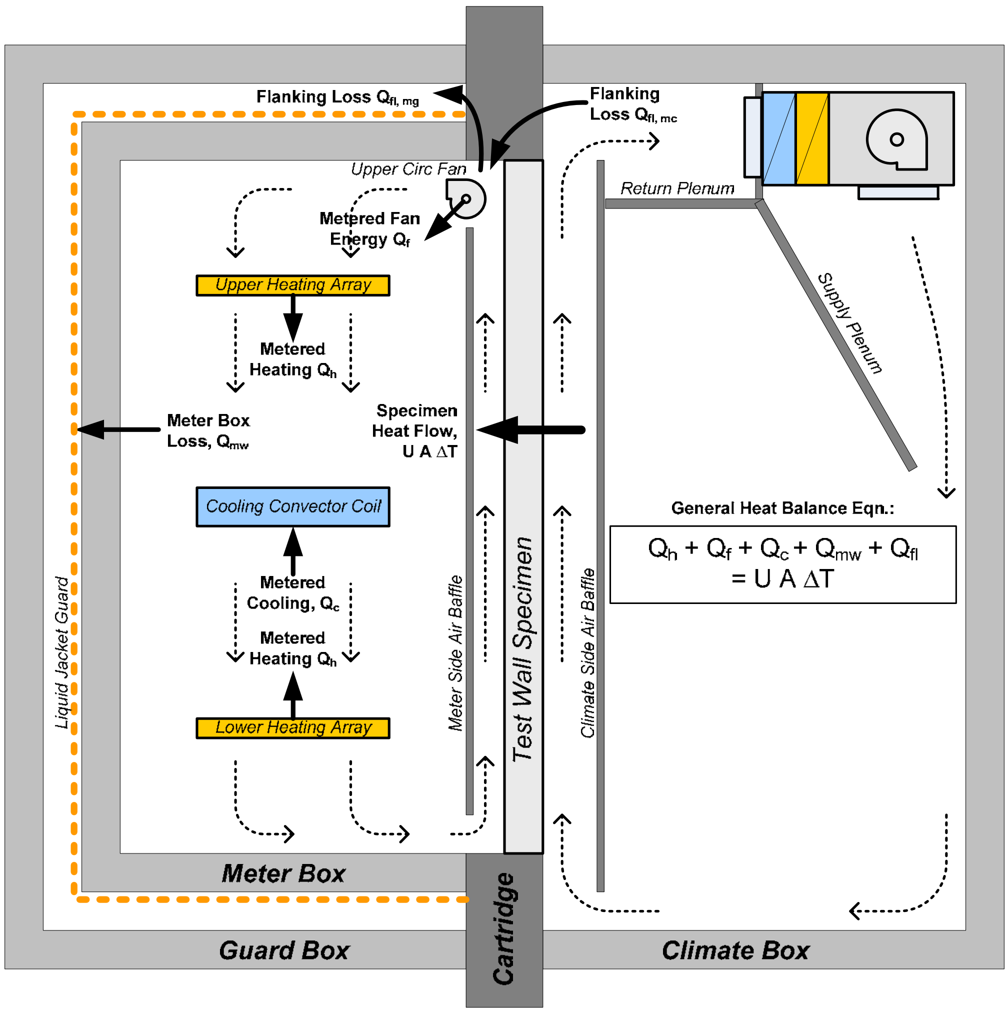

Figure 14 – Cold Climate Mode with No Induced Airflow

Hot Climate, Induced Infiltration

In the hot climate mode with induced air infiltration, the air transfer fan is used to negatively pressurize the meter box relative to the climate box as illustrated in Figure 15. The pressure difference causes air to move through the wall specimen from outside to in, in the same direction as the heat flow. For hot climates, infiltration represents proflux heat flow.

Under the hot climate infiltration mode the mass flow sensor is used to measure the air transfer flow rate which is assumed to be equal to the infiltration flow rate. If there were no interaction between the air infiltration and heat flow through the wall, then air transfer heat flow, Q_t, would be equal to the infiltration heat flow, $m \cdot c \cdot \Delta T$.

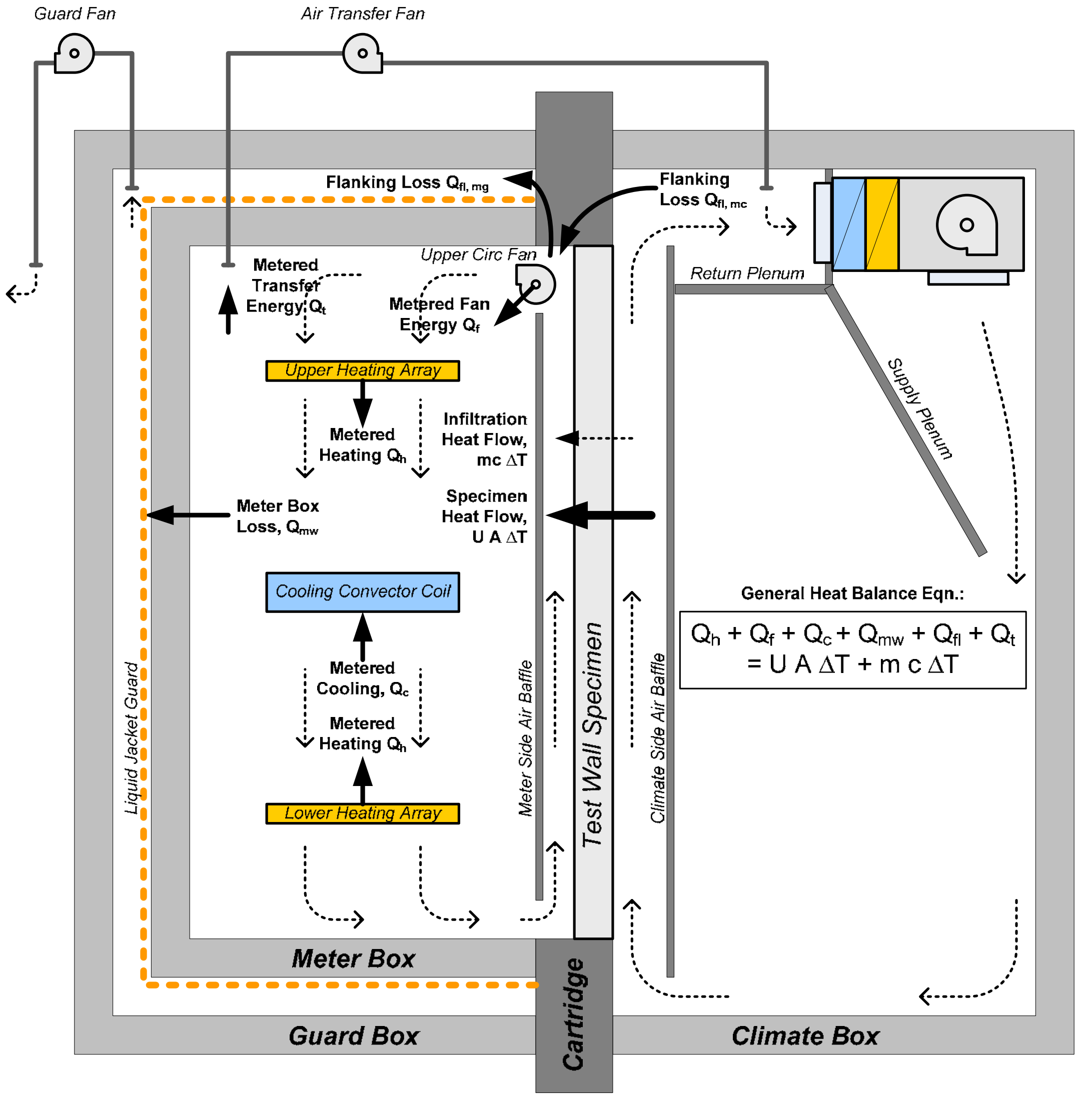

Figure 15 – Hot Climate Mode with Induced Air Infiltration

Hot Climate, Induced Exfiltration

In the hot climate mode with induced air exfiltration, the air transfer fan is used to positively pressurize the meter box relative to the climate box as illustrated in Figure 16. The pressure difference causes air to move through the wall specimen from inside to out, in the opposite the direction of heat flow. For hot climates, exfiltration represents contraflux heat flow.

Under the hot climate exfiltration mode the mass flow sensor is used to measure the air transfer flow rate which is assumed to be equal to the exfiltration flow rate. If there were no interaction between the air exfiltration and heat flow through the wall, then air transfer heat flow, Q_t, would be equal to the exfiltration heat flow, $m \cdot c \cdot \Delta T$.

At this point in time the design of the ATS does not permit cooling of the transfer air so, in hot climate modes it is not possible to deliver transfer air at the temperature of the air in the meter box.

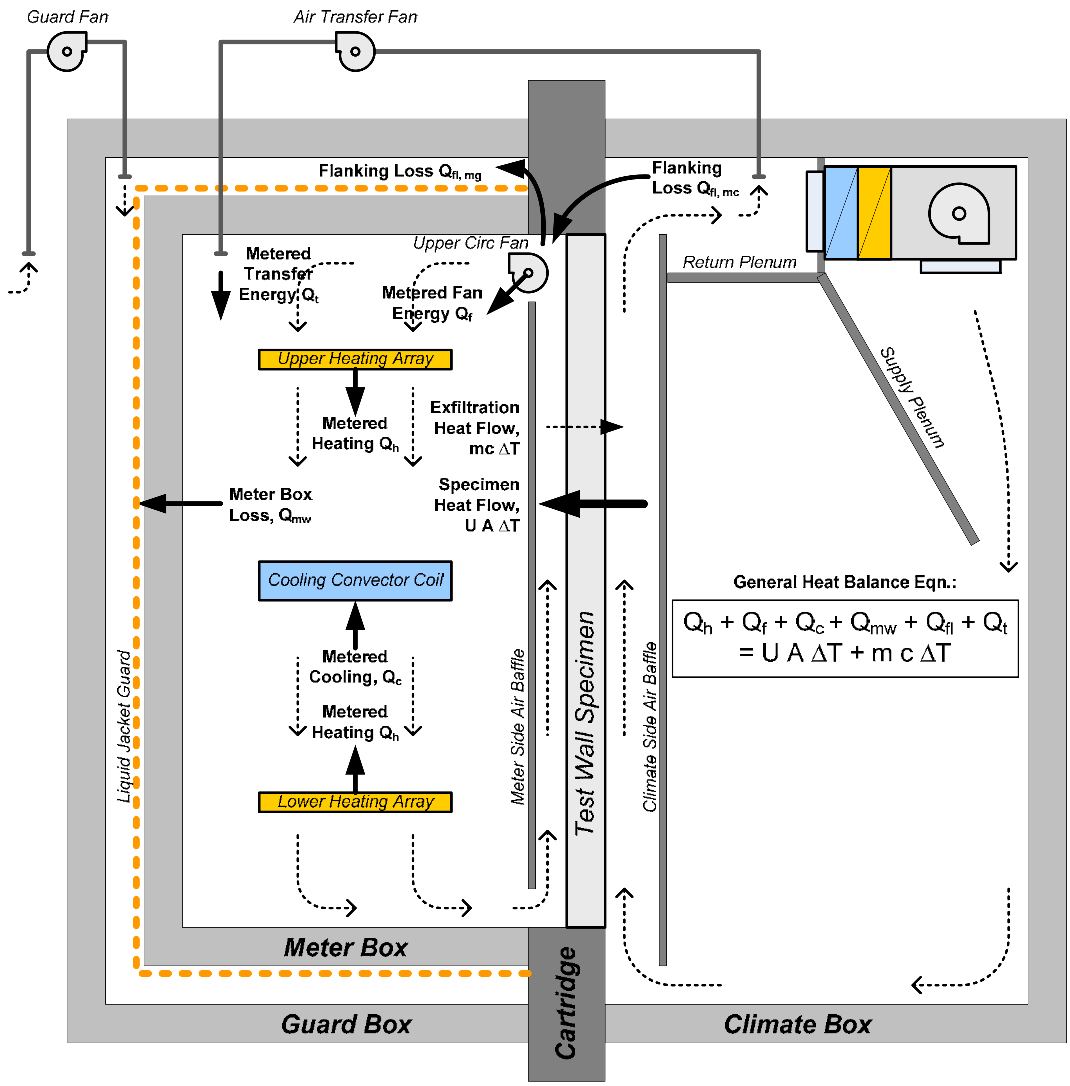

Figure 16 – Hot Climate Mode with Induced Air Exfiltration

Commissioning & Calibration of Subsystems

The TM hot box uses several subsystems to control the different operating modes and make measurements necessary for calculating the energy balances. This section of the report addresses the commissioning & calibration of these subsystems.

Meter Box Temperature Differences

The liquid guard loop controls the temperature on the outside of the meter box to minimize the temperature difference (delta-T) across the meter box walls. Temperature differences are measured using custom fabricated & calibrated temperature sensors.

The sensors were fabricated using 10 kOhm NTC precision thermistor components (Honeywell/Fenwall 192-103LET-A01) soldered to 28 AWG leads. The resulting temperature sensors, pictured in Figure 17, are approximately the same size as the thermocouples that are typically used in hot box research.

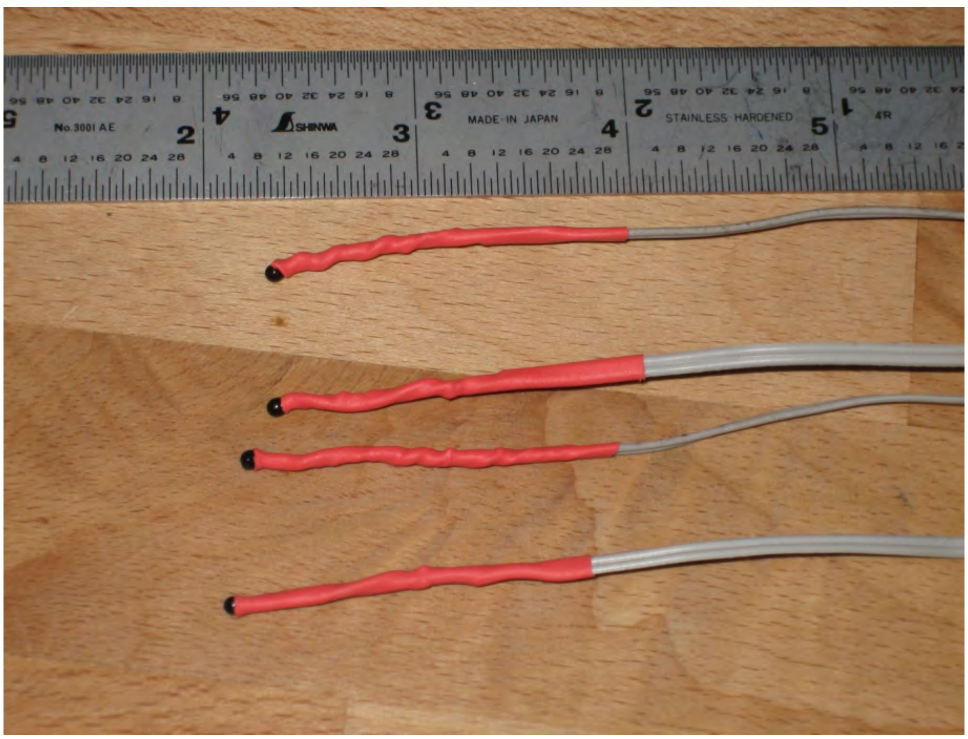

Figure 17 – Small Package Thermistor-based Temperature Sensors

From the manufacturer these sensors have a tolerance of +/- 0.2°C. The research team sought to reduce as many uncertainties as possible; hence sensors were individually calibrated over the range of temperatures in which they were to be used. The meter box guard sensors were calibrated at 16, 18, 20, 22, and 24°C while the baffle surface, air space and wall specimen sensors were calibrated at -30, -20, -10, 0, 10, 20 and 30°C.

Roughly 600 of the temperature sensors were fabricated to instrument the TM hot box and use on the test wall specimens for the first phase of research. Each sensor was assigned a unique serial number and calibrated in an aluminum calibration block set in a controlled temperature bath as pictured in Figure 18.

Figure 18 – Temperature Sensor Calibration Setup

The controlled temperature bath, a VWR 1157P, is capable of maintaining the bath temperature within +/- 0.01°C of the setpoint. The aluminum calibration block further ensures the spatial and temporal stability of the temperature during calibration. A NIST traceable HH41 reference thermometer (+/- 0.023°C or over the range of -20 to 60°C) was inserted in a 100 mm (~4 in.) deep hole in the middle of the block. Sensors were calibrated in sets by inserting them in the 12 holes that circle the reference thermometer.

For each setpoint, the bath was brought to equilibrium and allowed to run for 15-20 minutes after which 5 readings were taken at 1 minute intervals. For each reading, the time, the bath temperature and the reference thermometer temperature were manually recorded. Meanwhile, the resistances of the thermistor-based temperature sensors were automatically measured and recorded using a Campbell Scientific CR1000 measurement & control system and a half-wheatstone bridge circuit with a precision (+/- 0.01%) sense resistor.

The data was then summarized in a spreadsheet, an example of which is presented in Figure 19, and regression was performed to determine sensor specific calibration coefficients for a 3rd order polynomial equation. Figure 20 shows a typical regression graph for one of the TM hot box temperature sensors. As a result of the custom calibration, temperature sensor uncertainty is better than +/- 0.05°C.

BSCI Thermistor Calibration Data Analysis Serial Nos. **09/03-001** through **09/03-012**

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			Data File Name		BSCI_Benchtop_CalibData_001-012aw.dat											
			Sensor ID		**09/03-001**	**09/03-002**	**09/03-003**	**09/03-004**	**09/03-005**	**09/03-006**	**09/03-007**	**09/03-008**	**09/03-009**	**09/03-010**	**09/03-011**	**09/03-012**
			Wiring Position on MUX		1H	1L	2H	3H	3L	4H	5H	5L	6H	7H	7L	8H
			Field Name in Data File		TRes(1)	TRes(2)	TRes(3)	TRes(4)	TRes(5)	TRes(6)	TRes(7)	TRes(8)	TRes(9)	TRes(10)	TRes(11)	TRes(12)
Temperature (°C)			**Field No. in Data File**		19	20	21	22	23	24	25	26	27	28	29	30
Target	**Reference**	**Bath**	**Date & Time**	**Row No.**	**Ln [Measured Electrical Resistance (Ohms)]**											
	-29.88	-29.88	2009-03-13 15:44	201	12.033	12.018	12.011	12.031	12.015	12.018	12.038	12.008	12.011	12.035	12.009	12.017
	-29.83	-29.83	2009-03-13 15:45	202	12.033	12.017	12.011	12.030	12.015	12.018	12.038	12.008	12.011	12.035	12.009	12.016
-30	-29.81	-29.81	2009-03-13 15:46	203	12.033	12.016	12.011	12.030	12.014	12.018	12.036	12.008	12.010	12.034	12.008	12.015
	-29.9	-29.9	2009-03-13 15:47	204	12.033	12.017	12.009	12.029	12.014	12.017	12.036	12.007	12.009	12.034	12.007	12.015
	-29.91	-29.91	2009-03-13 15:48	205	12.034	12.018	12.011	12.030	12.014	12.018	12.036	12.008	12.010	12.034	12.008	12.016
	-19.85	-19.84	2009-03-13 16:25	242	11.465	11.456	11.450	11.463	11.453	11.457	11.468	11.449	11.450	11.466	11.447	11.456
	-19.85	-19.87	2009-03-13 16:26	243	11.465	11.457	11.450	11.462	11.454	11.457	11.468	11.449	11.450	11.466	11.447	11.456
-20	-19.86	-19.85	2009-03-13 16:27	244	11.466	11.457	11.451	11.463	11.454	11.457	11.468	11.450	11.450	11.466	11.448	11.456
	-19.85	-19.84	2009-03-13 16:28	245	11.465	11.457	11.451	11.462	11.454	11.457	11.468	11.449	11.450	11.466	11.447	11.456
	-19.86	-19.88	2009-03-13 16:29	246	11.465	11.457	11.451	11.463	11.454	11.457	11.469	11.450	11.450	11.466	11.448	11.457
	-9.85	-9.97	2009-03-14 11:37	283	10.915	10.911	10.905	10.911	10.908	10.911	10.917	10.905	10.905	10.914	10.903	10.911
	-9.84	-10.02	2009-03-14 11:38	284	10.915	10.911	10.905	10.911	10.908	10.911	10.917	10.904	10.904	10.914	10.903	10.910
-10	-9.85	-10.01	2009-03-14 11:39	285	10.915	10.912	10.906	10.912	10.909	10.912	10.918	10.905	10.904	10.915	10.903	10.911
	-9.85	-9.97	2009-03-14 11:40	286	10.915	10.911	10.905	10.912	10.908	10.911	10.917	10.905	10.904	10.914	10.903	10.910
	-9.84	-10.01	2009-03-14 11:41	287	10.915	10.911	10.905	10.911	10.908	10.911	10.917	10.904	10.904	10.914	10.903	10.910
	0.11	-0.01	2009-03-14 14:18	444	10.392	10.391	10.386	10.389	10.388	10.392	10.393	10.386	10.385	10.391	10.384	10.391
	0.12	-0.01	2009-03-14 14:19	445	10.391	10.391	10.386	10.389	10.388	10.392	10.393	10.386	10.385	10.392	10.384	10.391
0	0.12	-0.02	2009-03-14 14:20	446	10.392	10.392	10.386	10.389	10.388	10.392	10.394	10.386	10.384	10.392	10.384	10.391
	0.12	-0.03	2009-03-14 14:21	447	10.392	10.391	10.386	10.389	10.388	10.392	10.393	10.386	10.384	10.391	10.384	10.391
	0.12	-0.01	2009-03-14 14:22	448	10.391	10.391	10.386	10.389	10.388	10.391	10.393	10.386	10.384	10.391	10.383	10.391
	10.07	10.04	2009-03-14 14:37	463	9.898	9.898	9.893	9.895	9.894	9.898	9.900	9.894	9.892	9.897	9.892	9.898
	10.11	10.03	2009-03-14 14:38	464	9.896	9.897	9.892	9.893	9.893	9.897	9.898	9.892	9.890	9.896	9.890	9.896
10	10.1	10.01	2009-03-14 14:39	465	9.895	9.895	9.892	9.893	9.893	9.897	9.897	9.892	9.890	9.895	9.889	9.896
	10.12	10	2009-03-14 14:40	466	9.895	9.896	9.891	9.893	9.893	9.897	9.897	9.892	9.890	9.895	9.890	9.895
	10.11	9.99	2009-03-14 14:41	467	9.895	9.897	9.892	9.893	9.893	9.897	9.897	9.892	9.890	9.895	9.890	9.896
	20.17	20.05	2009-03-14 14:59	485	9.427	9.428	9.424	9.426	9.425	9.428	9.429	9.425	9.423	9.427	9.423	9.427
	20.15	20.03	2009-03-14 15:00	486	9.428	9.428	9.425	9.427	9.426	9.429	9.430	9.426	9.423	9.428	9.424	9.428
20	20.13	20.01	2009-03-14 15:01	487	9.429	9.429	9.425	9.427	9.426	9.430	9.431	9.427	9.424	9.429	9.424	9.429
	20.12	20	2009-03-14 15:02	488	9.429	9.430	9.426	9.428	9.427	9.431	9.431	9.427	9.425	9.429	9.425	9.430
	20.11	20	2009-03-14 15:03	489	9.430	9.431	9.426	9.428	9.428	9.431	9.432	9.428	9.425	9.430	9.425	9.430
	30.11	30	2009-03-15 15:29	522	8.990	8.990	8.987	8.989	8.988	8.991	8.991	8.989	8.986	8.990	8.986	8.990
	30.11	30	2009-03-15 15:30	523	8.990	8.991	8.987	8.989	8.988	8.991	8.995	8.989	8.986	8.990	8.987	8.990
30	30.11	30	2009-03-15 15:31	524	8.991	8.991	8.987	8.989	8.988	8.991	8.993	8.989	8.986	8.990	8.987	8.990
	30.11	30	2009-03-15 15:32	525	8.990	8.991	8.987	8.989	8.988	8.991	8.992	8.989	8.986	8.990	8.987	8.990
	30.11	30	2009-03-15 15:33	526	8.990	8.991	8.987	8.989	8.988	8.991	8.992	8.989	8.986	8.990	8.987	8.990
	40.08	40	2009-03-15 15:56	549	8.577	8.577	8.574	8.576	8.574	8.577	8.578	8.576	8.573	8.576	8.574	8.576
	40.07	40	2009-03-15 15:57	550	8.577	8.577	8.574	8.576	8.574	8.578	8.578	8.576	8.573	8.577	8.574	8.576
40	40.07	40	2009-03-15 15:58	551	8.577	8.577	8.575	8.576	8.574	8.578	8.579	8.576	8.573	8.577	8.574	8.576
	40.08	40	2009-03-15 15:59	552	8.577	8.577	8.574	8.576	8.574	8.578	8.577	8.576	8.573	8.576	8.574	8.576
	40.07	40	2009-03-15 16:00	553	8.577	8.577	8.575	8.576	8.574	8.578	8.577	8.576	8.573	8.577	8.574	8.577
			Sensor Series	**09/03**	001	002	003	004	005	006	007	008	009	010	011	012
Calibration Coeffs for equation:				**C3**	-1.526E-01	-1.597E-01	-1.599E-01	-1.517E-01	-1.600E-01	-1.575E-01	-1.491E-01	-1.605E-01	-1.614E-01	-1.509E-01	-1.573E-01	-1.603E-01
T(R)=C3*(lnR)^3+C2*(lnR)^2+C1*lnR+C0				**C2**	5.817E+00	5.990E+00	6.001E+00	5.793E+00	5.998E+00	5.924E+00	5.709E+00	6.016E+00	6.050E+00	5.767E+00	5.922E+00	6.005E+00
				C1	-9.105E+01	-9.242E+01	-9.260E+01	-9.088E+01	-9.249E+01	-9.176E+01	-8.996E+01	-9.274E+01	-9.312E+01	-9.057E+01	-9.183E+01	-9.254E+01
				C0	4.893E+02	4.929E+02	4.936E+02	4.890E+02	4.930E+02	4.907E+02	4.858E+02	4.942E+02	4.955E+02	4.879E+02	4.912E+02	4.932E+02
				R²	0.999999	0.999999	0.999999	0.999999	0.999999	0.999999	0.999998	0.999999	0.999999	0.999999	0.999999	0.999999

Figure 19 – Screen Capture of Temperature Sensor Calibration Spreadsheet

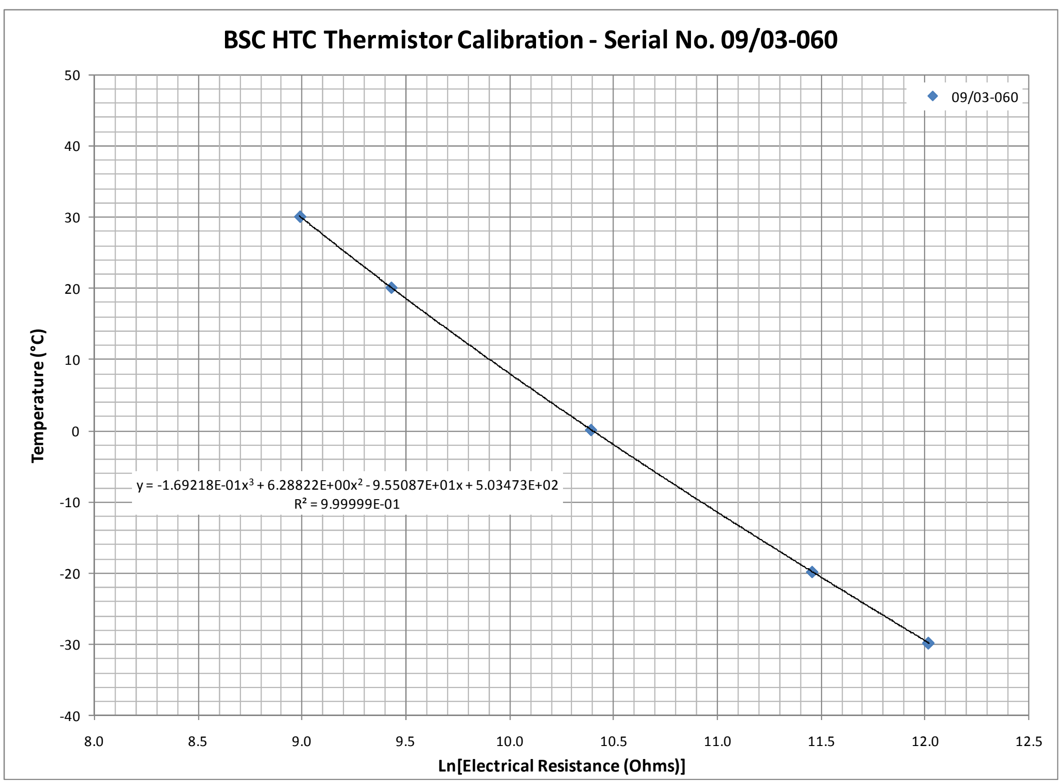


Figure 20 – Typical Data Regression for Temperature Sensor Calibration

In total, 176 pairs of the calibrated temperature sensors were installed on the inside and outside of the meter box as guard sensors. Individual sensors are measured using the hot box measurement and control system (MCS), a CR1000 and the temperature difference of each pair of sensors is determined, then area weighted temperature differences calculated for each surface of the meter box. Finally, the average temperature difference over all five sides of the meter box is calculated and this is relayed to the liquid guard loop controller, an Omega CN3251.

Heat is removed from the distilled water in the guard loop by running it through a heat exchanger that is temperature modulated by a 3-way valve controlled by the hot box MCS. This provides coarsely controlled temperature of the guard loop. Fine tuning of the guard loop temperature is achieved using in-line heaters that are controlled by the Omega CN3251. Once tuned, the liquid guard is capable of limiting meter box temperature differences to less than 0.05°C (0.09°F) and often on the order of +/- 0.02°C (0.036°F). Figure 21 shows the temperature difference recorded over a typical 6 hr period. The potential error associated with this tight control is less than 0.03 W.

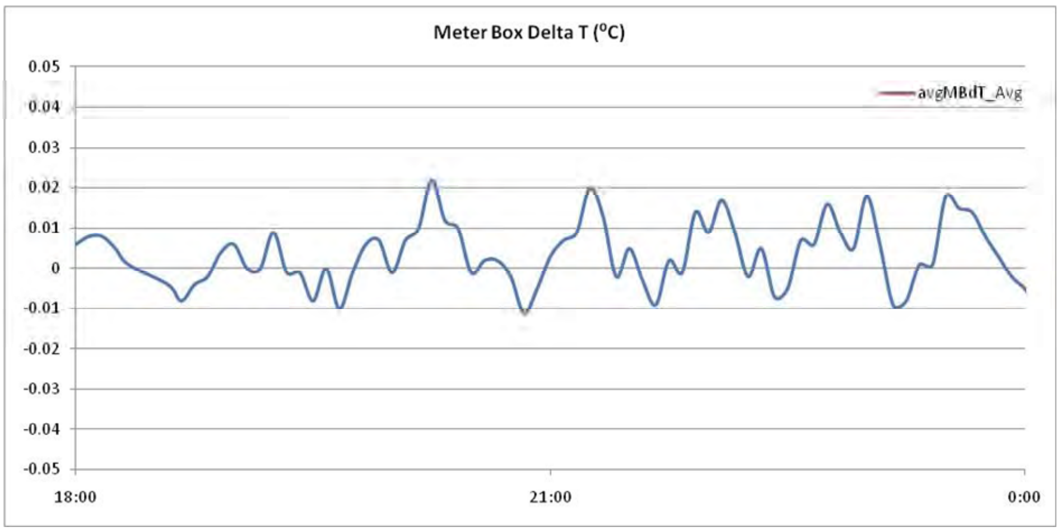


Figure 21 – Typical Meter Box Temperature Difference

Meter Box Resistance Heater & Fan Arrays

Heat is added to the meter box by a system of 96 resistors and 16 DC mixing fans. The resistors, each 4 ohm +/-1% 50 W with built in heat sink, are divided into 4 banks of 4 branches of 6 resistors each (i.e. 4 parallel banks of 4 parallel circuits of 6 resistors in series). The mixing fans are then wired in parallel with the 4 branches in 2 of the resistor banks. Figure 22 shows an arrangement of 6 resistors for one branch in the foreground with another 6 resistors for a second branch in the background. One can also make out the white label on the impeller of one the mixing fans on the right side of the photo.

Each bank of resistors has two branches on the lower heater array, located roughly 600 mm (24 in.) above the finished floor, and two branches on the upper heater array, located the same distance below the finished ceiling.

By distributing a large quantity of oversized resistors with built in heat sinks and forced convection (i.e. by the mixing fans), the team was able to maximize uniformity of temperature in the mixing portion of the meter box.

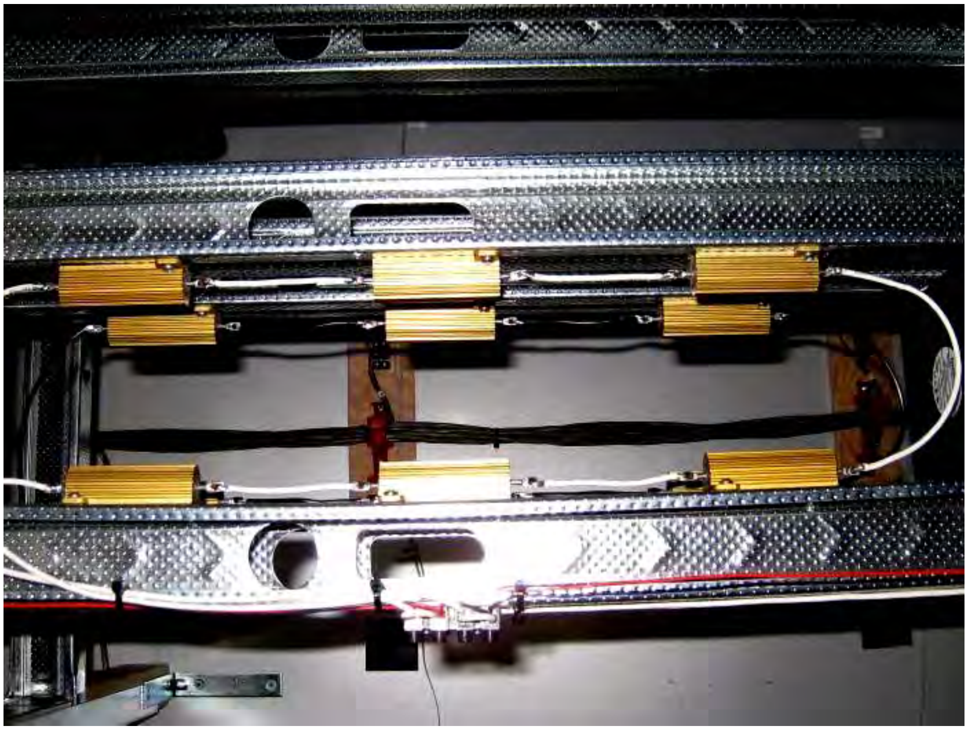


Figure 22 – Meter Box Resistance Heaters

Power for the resistors and fans is provided by a BK Precision VSP4030 remotely programmable power supply controlled by an Omega CN3251 controller that receives its process signal from an ultra precision RTD located in the middle of the mixing portion of the box. At 40 VDC, with all 4 resistor banks engaged, the system is capable of adding over 1 kW of heat to the meter box.

The power added by the heater resistors is calculated as the sum of the products of the measured voltage and the current for each of the 4 resistor banks:

$$Q = \sum V \cdot I$$

The voltage drop across each bank is measured, using the hot box MCS, across a voltage divider comprising eight 1 Mohm +/- 0.1% installed in parallel with the resistors. The MCS also measures the current in each branch of each bank (i.e. 16 measurements) as the voltage drop across 1 ohm +/- 0.01% 7 W resistors with Kelvin connections. The measurement circuits for the ‘blue’ and ‘red’ resistor banks can be seen in Figure 23.

The total uncertainty associated with the heating power measurement depends on the voltage supplied to the circuit and the number of resistor banks that are engaged. The purple line in Figure 24 shows the heating power uncertainty when all 4 banks are engaged and 0-40 VDC power is provided.

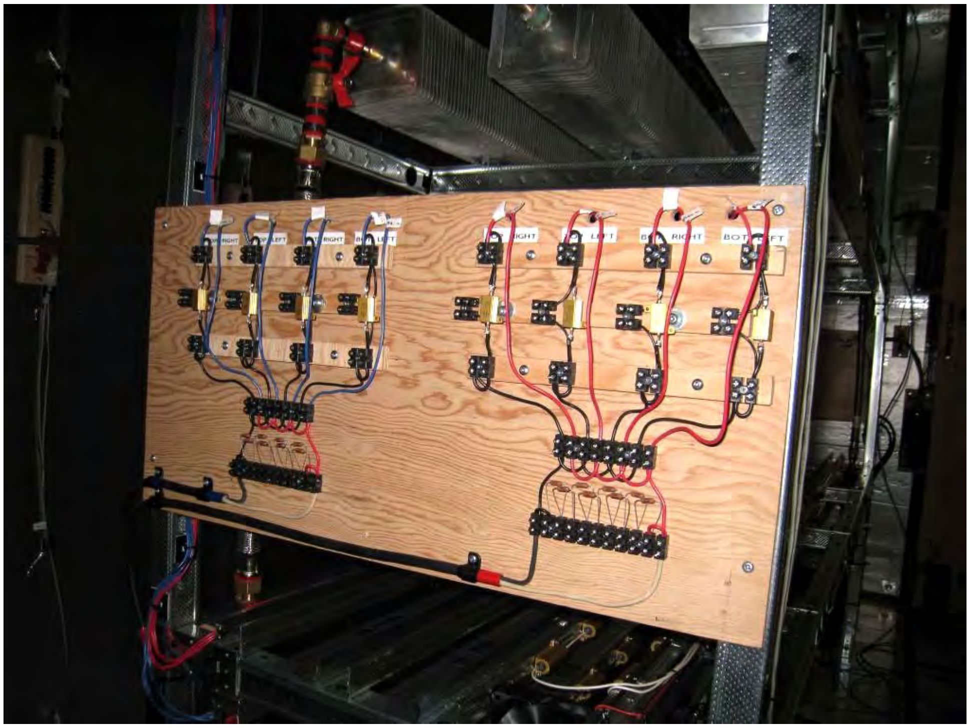


Figure 23 – Resistance Heater Measurement Circuit

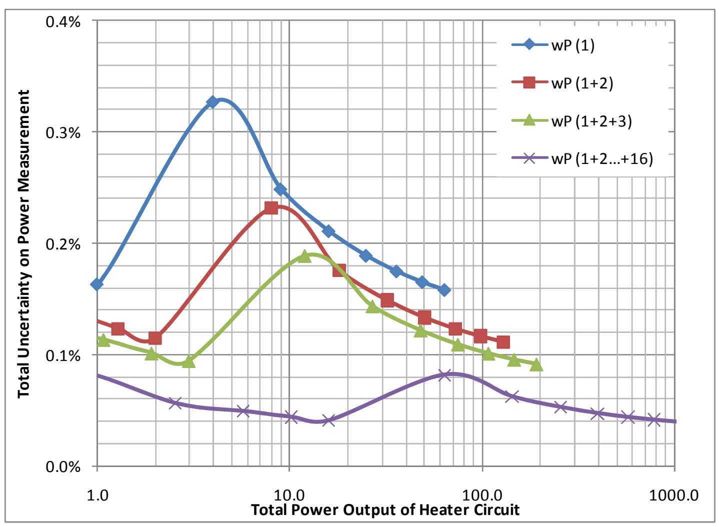


Figure 24 – Heating Power Measurement Uncertainty

Very tight temperature control results from the combination of the distributed resistance heaters, mixing fans, variable voltage power supply and PID controller. Figure 25 shows the baffle inlet temperature (i.e. the temperature of the air coming out of the mixing portion of the meter box) over a 24 hr period of testing.

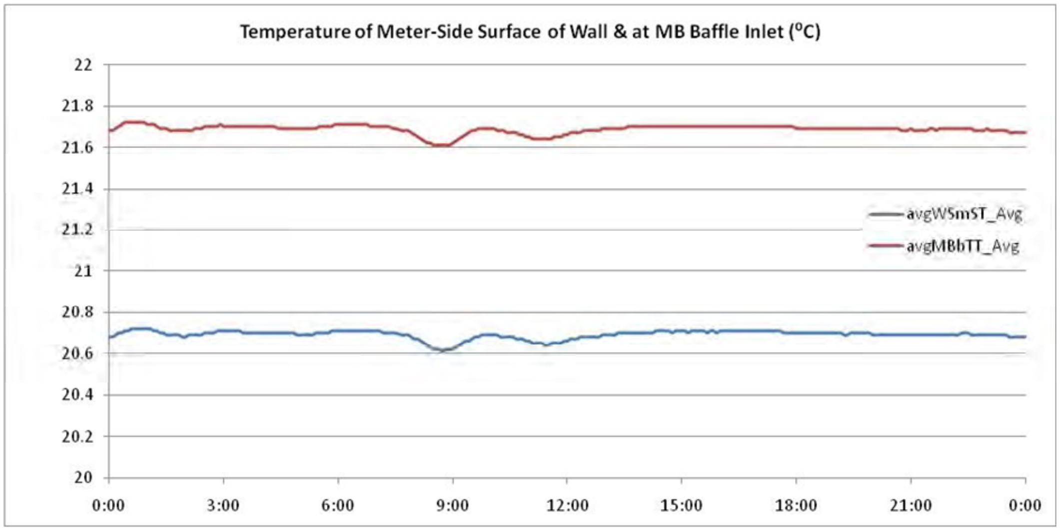


Figure 25 – Typical Meter Box Baffle Inlet (red) and Wall Specimen Surface (blue) Temperatures

Meter Box Convective Cooling Coil

Heat is removed from the meter box by chilled, distilled water circulated through the large finned cooling coil that can be seen in the upper portion of the photo of Figure 23. The coil is located at mid height on the equipment rack, half way between the upper and lower heating arrays.

By using a large format coil, adequate heat can be removed with low temperature differences and low convection velocities, both of which serve to maximize temperature uniformity in the mixing portion of the meter box.

The power removed by the cooling coil can be calculated using the product of the mass flow rate of the liquid, its heat capacity and the temperature difference:

$$Q = \dot{m} \cdot c \cdot \Delta T$$

The cooling water temperature difference (deltaT) is measured by ultra precision RTDs that are positioned within 50 mm (2 in.) of the location where the cooling water supply and return pipes penetrate the meter box. The sensor is installed in a tee fitting so that its tip is held in position in the middle of the flow. To minimize gains from the meter box and ensure measurement accuracy, the entire assembly is well insulated as seen in the photograph of Figure 26.

The accuracy of the heat removal calculation is highly dependent on the uncertainty of the cooling water temperature measurement. Water has a relatively high heat capacity, so large amounts of heat can be moved even when temperature differences are small. At a flow rate of 0.095 lps (1.5 gpm), an error in deltaT of 0.01°C (0.018°F) results in an error of approximately 4 W.

To minimize the uncertainties associated with the temperature measurements, the system was modified during commissioning so that 4-20 mA transmitters are used to read the RTDs and relay a high level signal to the hot box MCS so that the influence of electrical noise is minimized. The 4-20 mA transmitter were scaled over the range of 12-44°C (53.6-111.2°F) using a precision decade box (0.01 ohm resolution, +/-0.1 ohm) and calibrated with the controlled temperature bath.

Figure 26 – Insulation around Meter Box Cooling Water Return Temperature Measurement

Several of the custom calibrated thermistor sensors were installed in parallel with the RTDs as a second, verification measurement of deltaT.

The cooling water flow rate is measured using a NIST traceable Omega FTB-901T flow meter (+/- 0.5% of reading) and a FLSC-61 signal conditioner as seen in the picture of Figure 27.

The cooling water flow measurement system was calibrated by pumping water out of a constant head reservoir and into a tank on a electronic scale to allow for a gravimetric comparison. Results for a flow rate of approximately 0.095 LPS (1.51 GPM) are presented in Figure 28. The 0.0004 LPS discrepancy between the flow meter measurement and the gravimetric measurement represents an error of approximately 0.8 W when the deltaT is accurately measured.

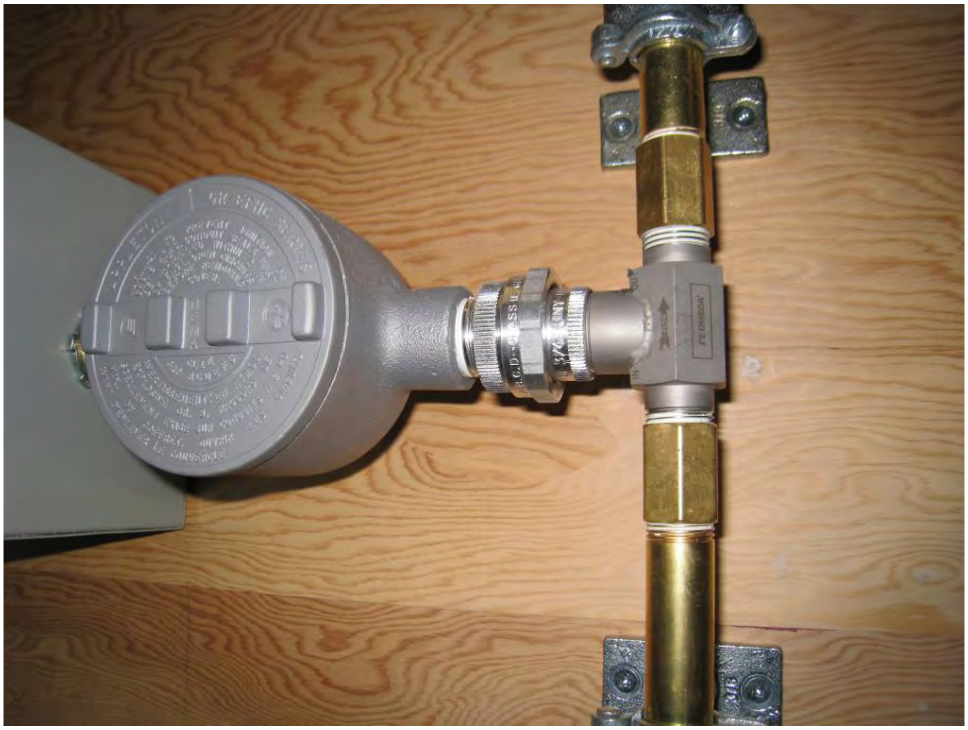


Figure 27 – Cooling Water Flow Meter (right) and Signal Conditioner (left)

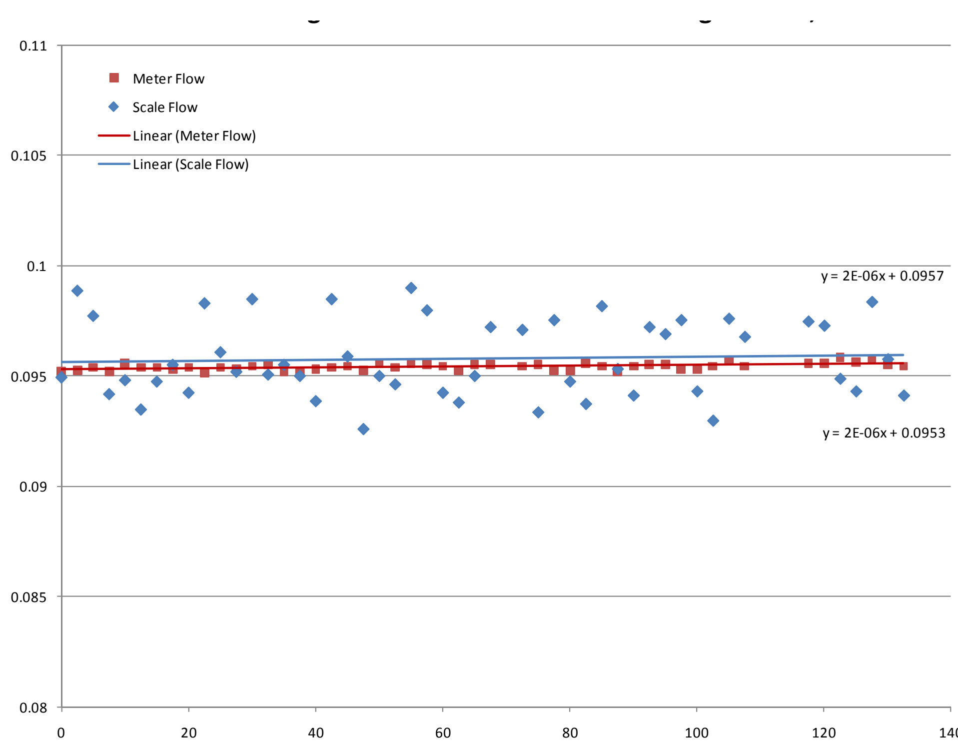


Figure 28 – Cooling Water Flow Meter Commissioning – Approx 380 Hz, 0.095LPS

Air Transfer System

The Air Transfer System (ATS) moves air between the meter box and the climate box to generate a pressure difference between the two and induce either infiltration or exfiltration. Heat is moved through the ATS along with the air and it is therefore necessary to calculate the additional load applied to or heat provided to the meter box.

The additional load or heat provided by the ATS can be calculated using the product of the mass flow rate of the air, its heat capacity and the temperature difference:

$$Q = \dot{m} \cdot c \cdot \Delta T$$

Differential temperature measurement for the ATS is accomplished in a manner similar to the cooling water system. The ATS uses a series of ultra precision RTDs and custom calibrated thermistor sensors to measure the temperature difference between the air supplied to the meter box and the air in the meter box.

A TSI 4021 high performance mass flowmeter (+/- 2% of reading) is used to measure the mass flow rate of air removed from or delivered to the meter box by the ATS. The ATS flow rate measurement was commissioned by passing the airflow through a 0 to 80 SCFH rotometer in series with the TSI 4021 as illustrated in Figure 29. The meter and rotometer readings agreed to within 2% for the full range of the rotometer.

Figure 29 – Air Transfer System Commissioning

Commissioning & Calibration of Complete TM Hot Box Apparatus

Having completing the commissioning and calibration of the measurement and control subsystems, the research team undertook the commissioning and calibration of the complete TM hot box apparatus using a series of calibration panels and ideal wood-framed, fiberglass insulated test wall specimens. These activities are summarized in this portion of the report.

Air Tightness

Air movement is a major component of the TM research project. It is therefore necessary to eliminate any air movement outside of the ATS and the test wall specimen. Figure 30 shows the air leakage between the meter box and guard box for a series of 4 different tests.

Air leakage rates were measured using a CanBest window test kit. A second fan was used to pressurize/depressurize the climate box to the same pressures as the meter box to permit differentiation between the meter box air leakage and air leakage through the test wall specimen. Air pressures were measured using an Energy Conservatory DG700.

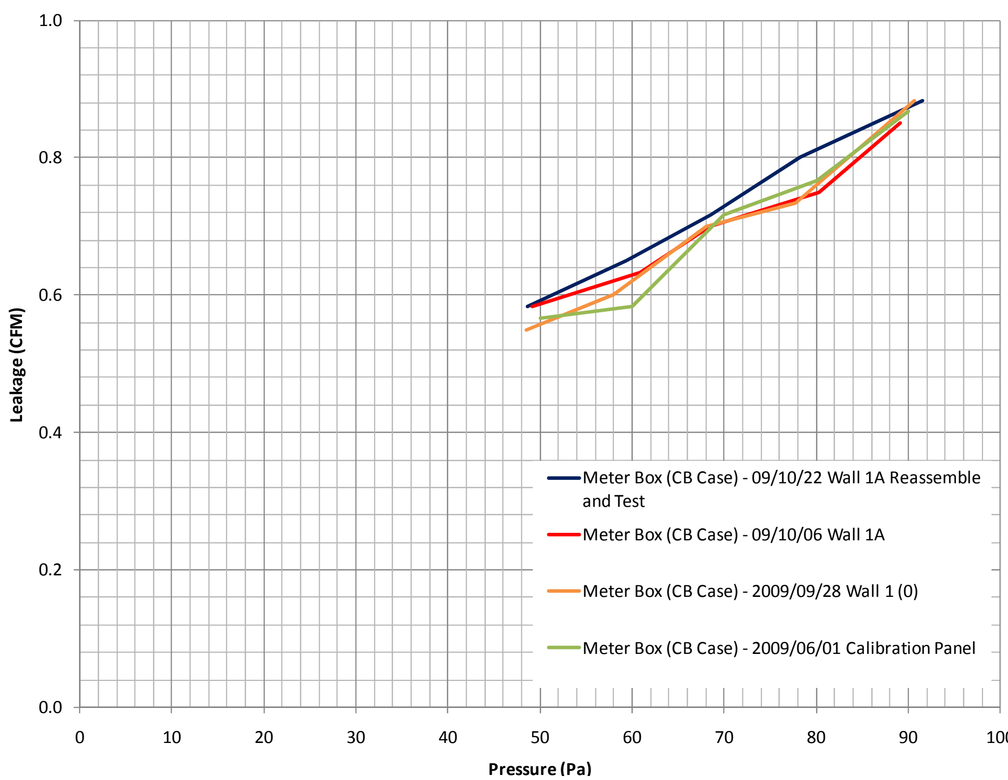


Figure 30 – Air Leakage Characterization for the Meter Box over a Series of 4 Tests

The results of the tests demonstrate the ability to repeatedly achieve a good seal between the meter box and the wall cartridge so that air leakage between the two is minimized.

It is also desirable to characterize the air leakage between the meter box and the climate box, through the test wall specimen. This was done using a similar approach: a second fan was used to balance the pressure between the meter box and the guard box to permit isolation of the air leakage through the wall assembly.

Figure 31 shows this characterization for the same series of 4 tests illustrated in Figure 30. The lowest line (green) represents a calibration panel that comprises a solid 100 mm (4 in.) thick panel of HDEPS insulation. The only leakage paths in this case exist around the perimeter of the panel where it meets the cartridge. It is therefore very tight.

The second lowest line (yellow) represents a 2x4 wood frame test wall specimen with 12 mm (1/2 in.) GWB, R13 fiberglass batt, OSB sheathing with a 3 mm (1/8 in.) horizontal joint, a Tyvek WRB and vinyl siding. The wall was constructed to be as tight as reasonably possible.

The third and fourth lines (red & blue respectively) represent a second construction of the same framed wall, but with two standard (non-airtight) electrical boxes, a 14-2 Romex cable, and without sealing the joint at the top and the bottom of the Tyvek WRB. These were constructed to be representative of standard construction practices. The clearly show more leakage than the wall represented by the yellow line and good repeatability from one test, through the removal of the calibration panel, two the reassembly of the test apparatus.

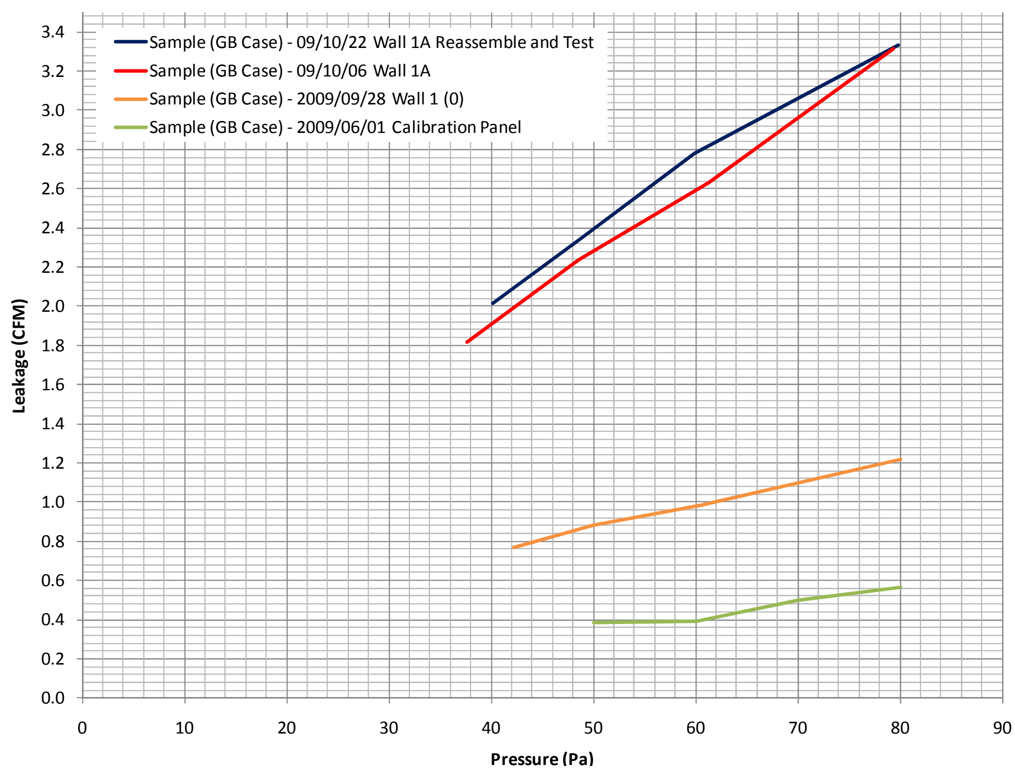


Figure 31 – Test Wall Specimen Air Leakage Characterization for a Series of 4 Tests

Calibration Panels

Three full-size calibration panels were constructed to facilitate the calibration of the complete TM hot box apparatus. The calibration panels each comprise two layers of HDEPS foam insulation, glued as pictured in Figure 32, to form a planar, solid, continuous layer of homogenous insulation. Two of the calibration panels are 100 mm (4 in.) thick while the third is 64 mm (2.5 in.) thick. The panels can be used individually or combined to permit calibration of the apparatus for testing walls with different thicknesses and apparent R-values.

Figure 32 – Fabrication of an HDEPS Calibration Panel

Upon the recommendation of several of the experienced industry partners, the surfaces of the calibration panels were painted with two coats of black latex paint. A number of 300x300 mm (12x12 in.) test samples were cut from the excess panel material to facilitate conductivity testing in BSC's ASTM 514 machine, a ThermoFox 314, pictured in Figure 33.

Figure 34 summarizes the ASTM 514 test results for 12 of the HDEPS calibration panel samples. The standard deviation of the R-value test results was less than 0.35% for all samples over the full temperature range.

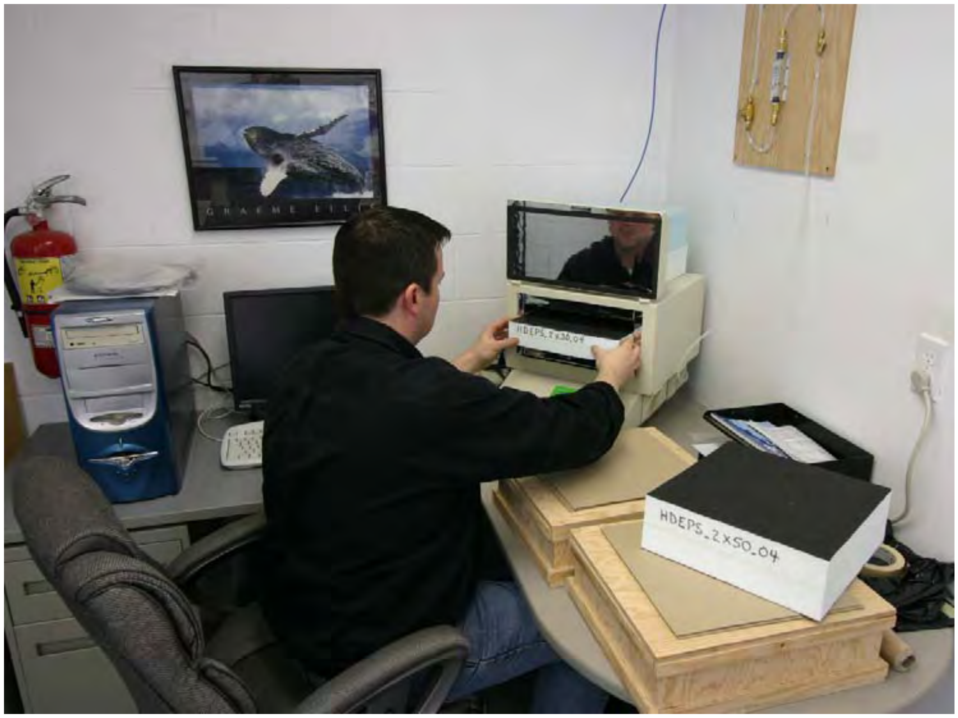


Figure 33 – Testing Calibration Panel Specimens in BSC's 514 Test Machine

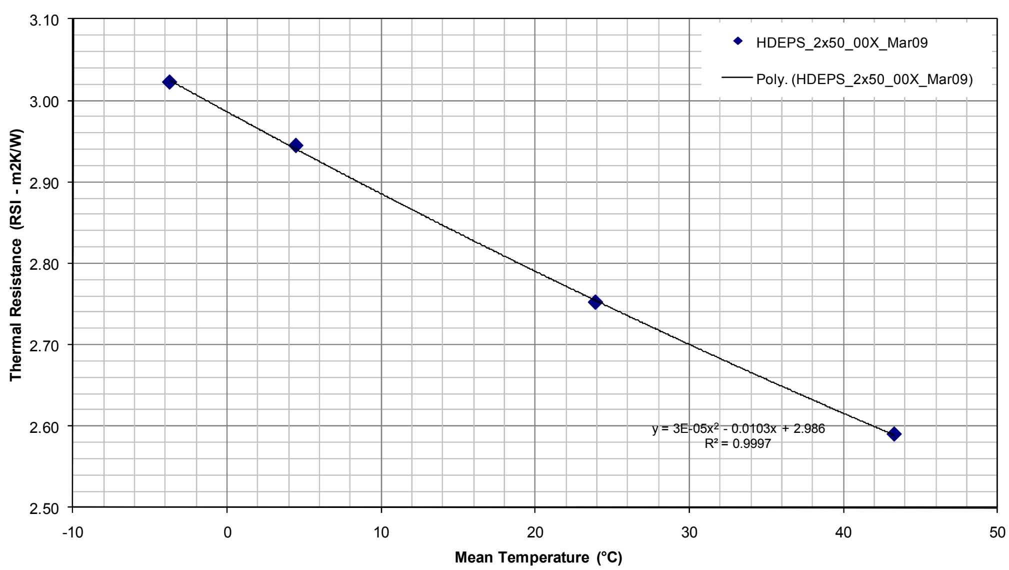


Figure 34 – Average ASTM 514 Test Results for Twelve 100 mm HDEPS Calibration Panel Samples

A similar set of test temperatures were then run in the TM hot box so the ASTM 514 results could be compared to the full-size test results. Figure 35 shows the climate side air and wall surface temperatures for a test in which the climate box was run at 2°C (35.6°F) while the meter box was maintained at 22°C (71.6°F) for an air to air temperature difference of 20°C (36°F) and a mean assembly temperature of 12°C (53.6°F).

From the graph of Figure 35 it can be seen that the climate box temperature is a little lower than the 2°C setpoint; however, it is still well within acceptable limits and shows excellent stability with less than 0.05°C standard deviation over time.

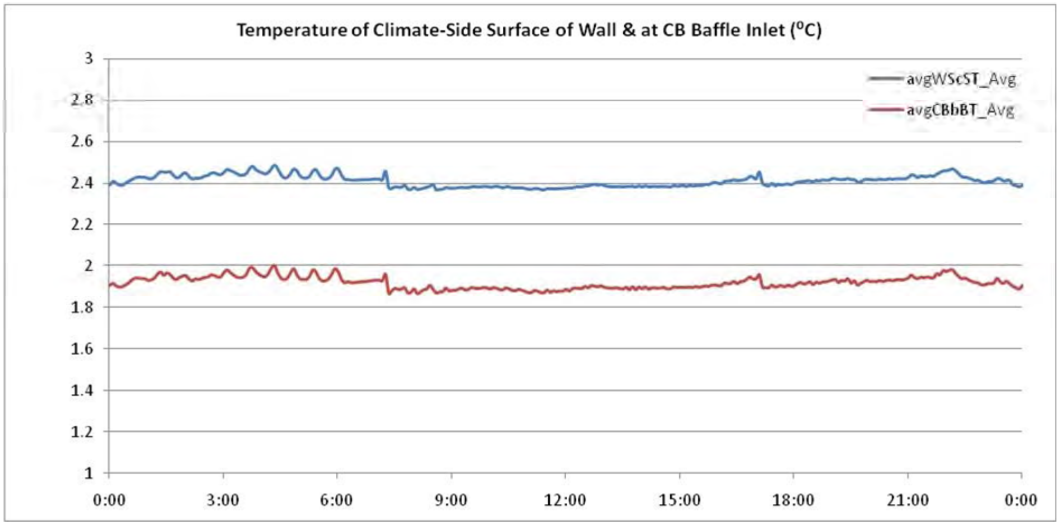


Figure 35 – Climate Box Baffle Inlet (red) and Wall Specimen Surface (blue) Temperatures

The total measured heat flow into the meter box is presented in Figure 36. The system shows excellent stability with standard deviation of less than 0.5 W.

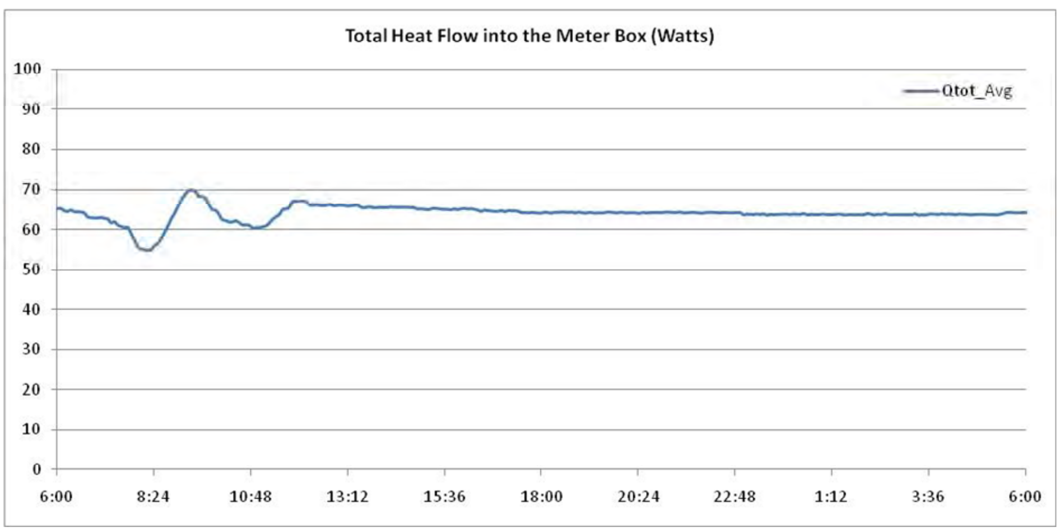


Figure 36 – Measured Total Heat Flow into the Meter Box for 100 mm HDEPS Calibration Panel, 22/2°C

Once adjustments are made for flanking losses, etc. the results of the TM hot box and the ASTM 514 test for the 100 mm (4 in.) calibration panel agree to within 3%.

Conclusions

In previous work, BSC identified the need for a more comprehensive and appropriate metric for the thermal performance of wall assemblies, especially those with higher apparent R-value. BSC followed this with a second document that proposed an apparatus and methodology for examining the problem of combined heat and airflow in wall assemblies.

BSC assembled a consortium of 6 building product manufacturers to participate in the privately-funded development of a new thermal metric through the construction and application of a new 'Thermal Metric hot box'. This report documents the construction, commissioning and calibration of this apparatus.

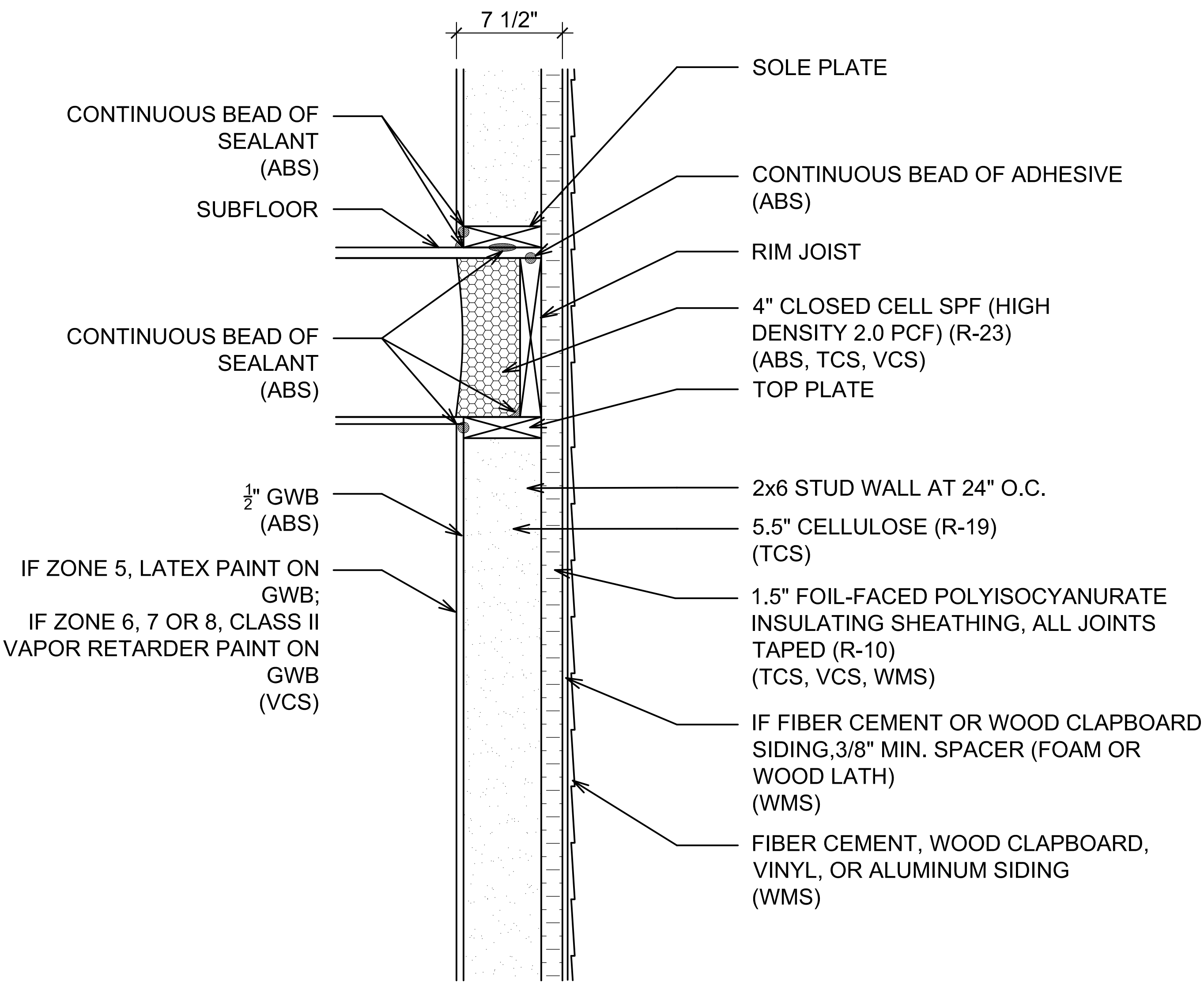
The TM hot box uses some novel systems and features to maximize its operating modes while reducing as many errors and as much noise as possible. Early calibration and testing work demonstrate that the apparatus meets the objectives laid out in BSC's FY08 report entitled "Development of a Test Procedure and Apparatus for Measuring High Thermal Performance Walls".

1.5.6. High R-value Enclosure Details

by Cathy Gates and BSC Staff

Framing:	2x6 STRUCTURAL STUD
Exterior Framing:	VENTED LAP SIDING
Location of Insulation:	CAVITY AND INSULATING SHEATHING
Location of Drainage Plane:	INSULATING SHEATHING
Location of Air Barrier:	AIRTIGHT DRYWALL APPROACH
Insulation Type, R-Value:	5.5" CELLULOSE + 1.5" FOIL-FACED POLYISOCYANURATE, R-29
Climate/Zone:	ALL CLIMATES IN U.S.

ABS: Air Barrier System component
TCS: Thermal Control System component
VCS: Vapor Control System component
WMS: Water Management System component

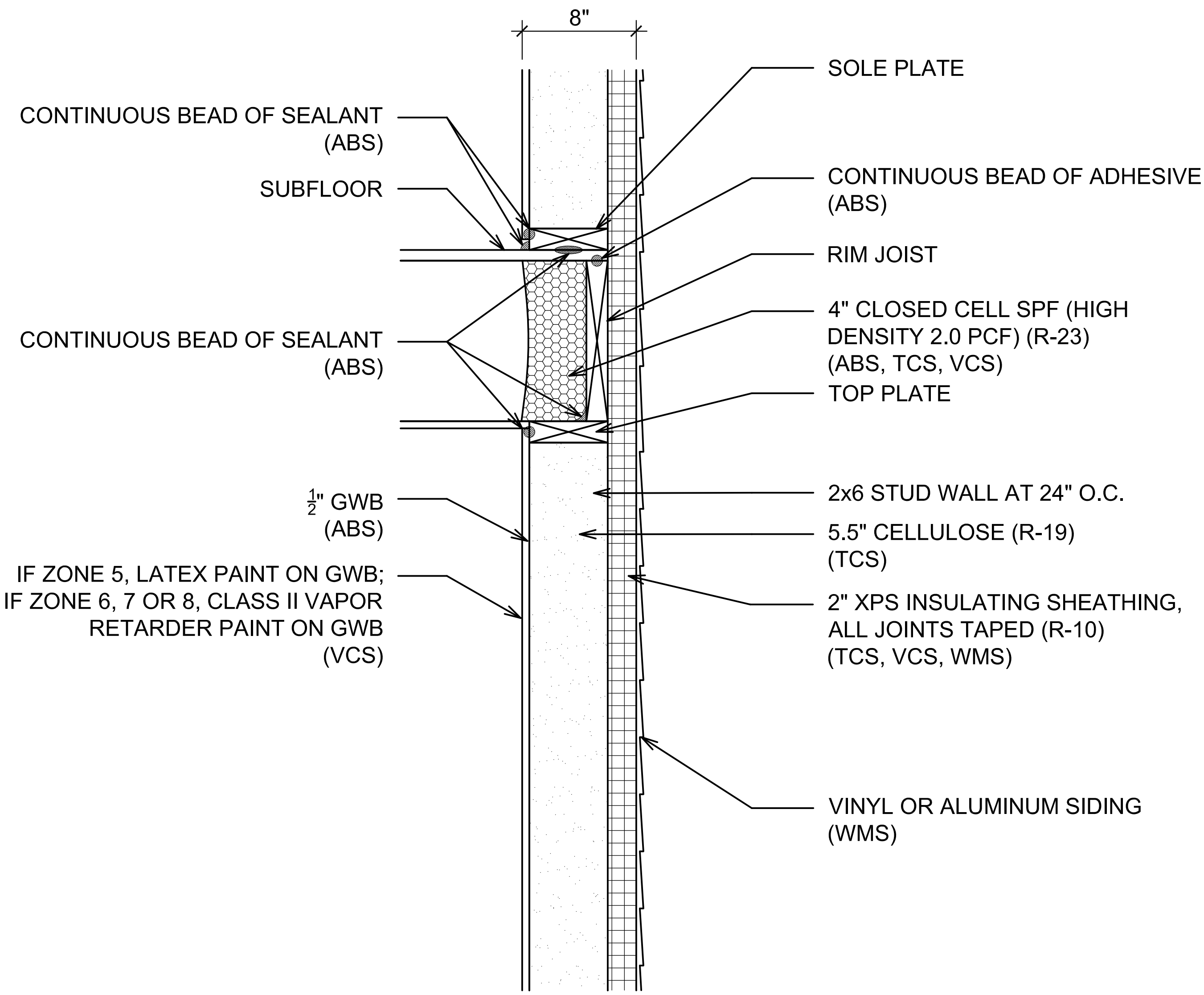


BSC with U.S. Department of Energy Building America

Project:	High-R Enclosures
Date:	2009-09-09
Drawing Title:	High-R Walls
Drawing File:	HighR-Wall-02-1
Drawing Scale:	1" = 1'-0"

High-R Wall: 1 1/2" Insulating Sheathing Wall Construction

Framing:	2x6 STRUCTURAL STUD	ABS: Air Barrier System component
Exterior Framing:	VINYL OR ALUMINUM SIDING	TCS: Thermal Control System component
Location of Insulation:	CAVITY AND INSULATING SHEATHING	VCS: Vapor Control System component
Location of Drainage Plane:	INSULATING SHEATHING	WMS: Water Management System component
Location of Air Barrier:	AIRTIGHT DRYWALL APPROACH	
Insulation Type, R-Value:	5.5" CELLULOSE + 2" XPS SHEATHING, R-29	
Climate/Zone:	ALL CLIMATES IN U.S.	

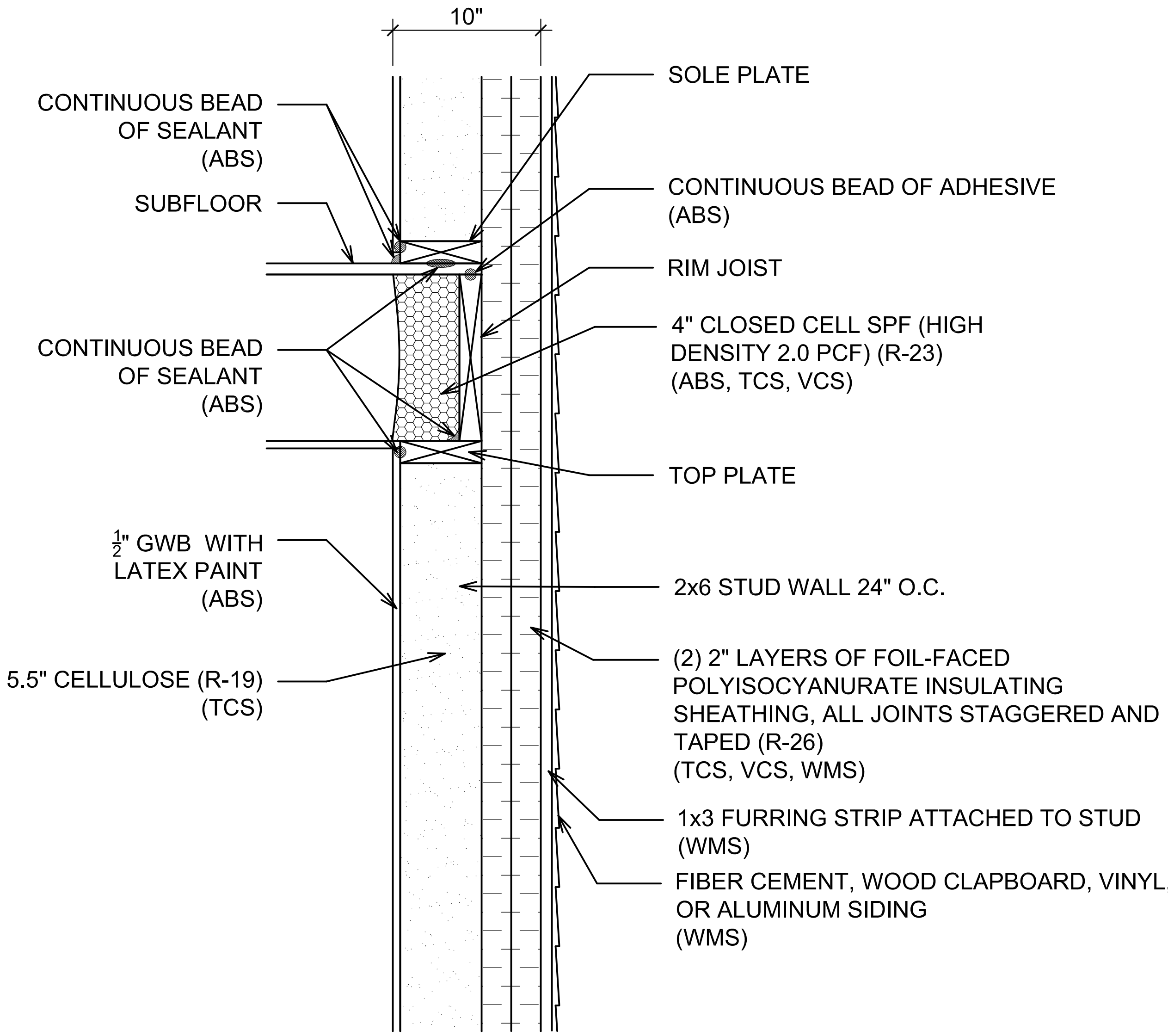


BSC with U.S. Department of Energy Building America

Project:	High-R Enclosures
Date:	2009-09-29
Drawing Title:	High-R Walls
Drawing File:	HR-Wall-02-2
Drawing Scale:	1" = 1'-0"

High-R Wall: 2" Insulating Sheathing Wall Construction

Framing:	2x6 STRUCTURAL STUD	ABS: Air Barrier System component
Exterior Framing:	VENTED LAP SIDING	TCS: Thermal Control System component
Location of Insulation:	CAVITY AND INSULATING SHEATHING	VCS: Vapor Control System component
Location of Drainage Plane:	INSULATING SHEATHING	WMS: Water Management System component
Location of Air Barrier:	AIRTIGHT DRYWALL APPROACH	
Insulation Type, R-Value:	5.5" CELLULOSE + 4" FOIL-FACED POLYISOCYANURATE, R-45	
Climate/Zone:	COLD / ZONES 5, 6, 7 AND 8	



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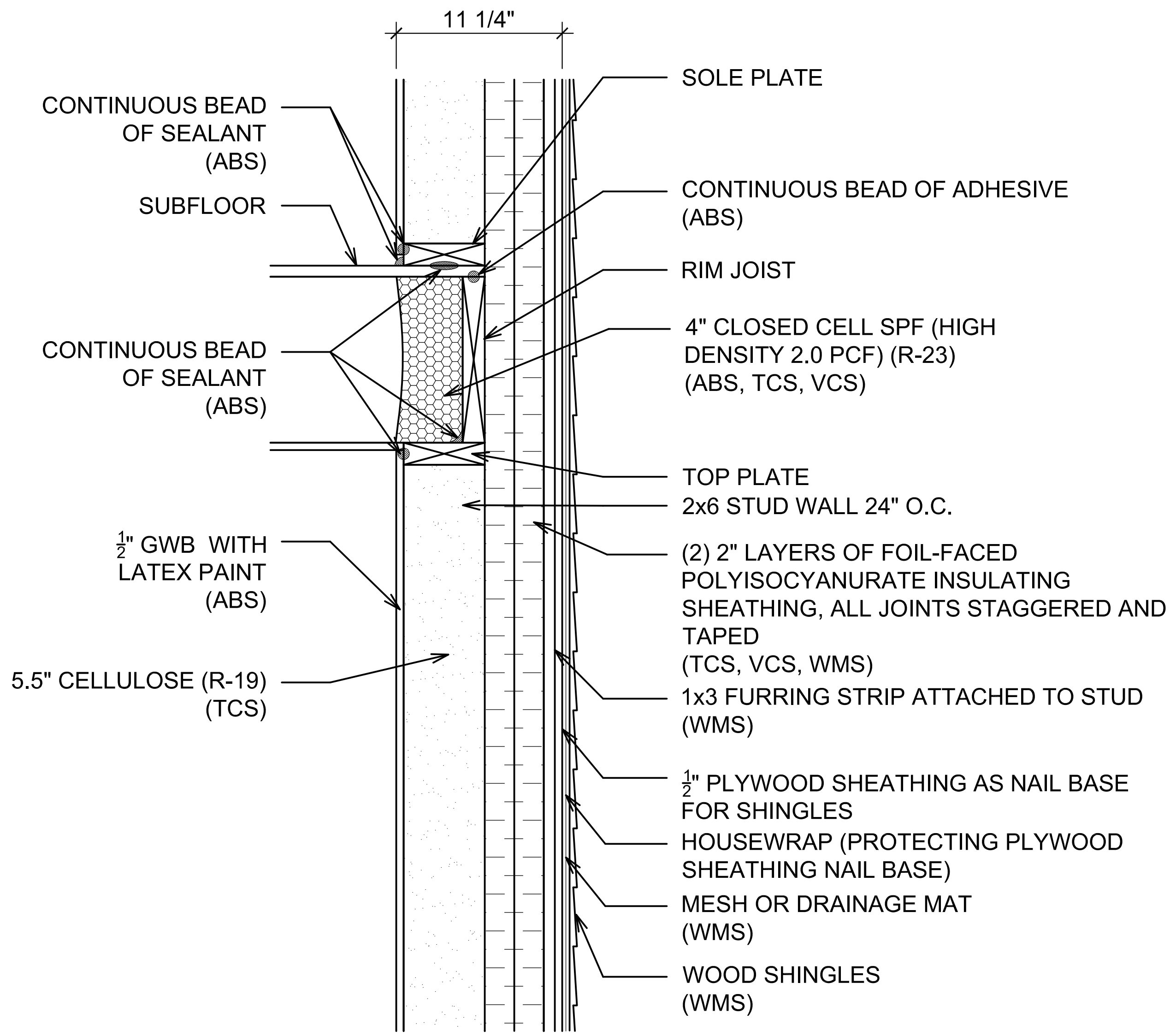
Project:	High-R Enclosures
Date:	2009-09-29
Drawing Title:	High-R Walls
Drawing File:	HighR-Wall-02-3
Drawing Scale:	1" = 1'-0"

High-R Wall: 4" Insulating Sheathing Wall Construction

Framing:	2x6 STRUCTURAL STUD
Exterior Framing:	WOOD SHINGLES
Location of Insulation:	CAVITY AND INSULATING SHEATHING
Location of Drainage Plane:	INSULATING SHEATHING
Location of Air Barrier:	AIRTIGHT DRYWALL APPROACH
Insulation Type, R-Value:	5.5" CELLULOSE + 4" FOIL-FACED POLYISOCYANURATE, R-45
Climate/Zone:	COLD / ZONES 5, 6, 7 AND 8

ABS: Air Barrier System component
TCS: Thermal Control System component
VCS: Vapor Control System component
WMS: Water Management System component



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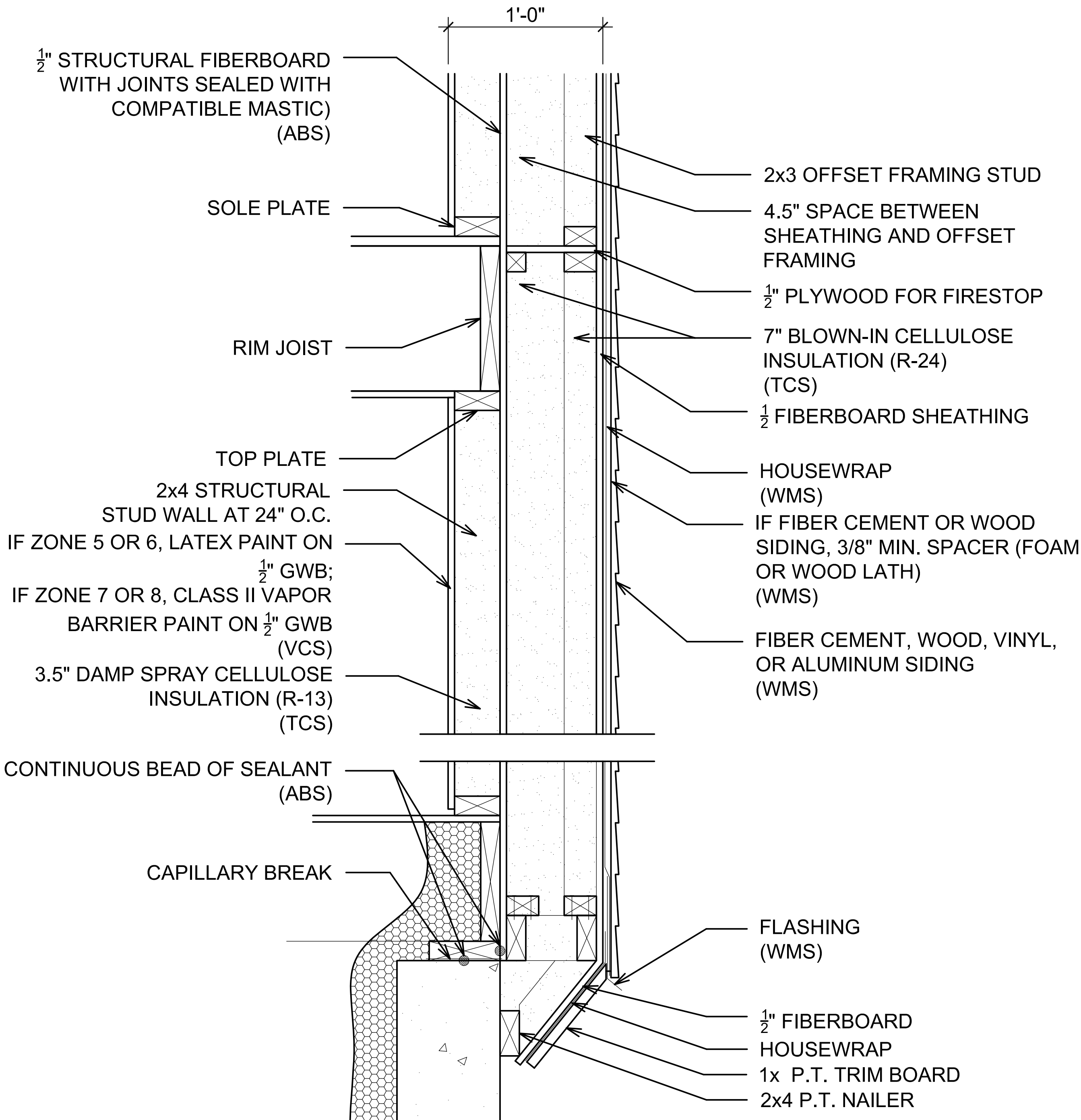
Project:	High-R Enclosures
Date:	2009-09-29
Drawing Title:	High-R Walls
Drawing File:	HighR-Wall-02-4
Drawing Scale:	1" = 1'-0"

High-R Wall: 4" Insulating Sheathing with Shingles Wall Construction

Framing:	DOUBLE STUD WALL: 2x4 INTERIOR STUD + 2x3 EXTERIOR STUD
Exterior Framing:	VENTED LAP SIDING
Location of Insulation:	INTERIOR AND EXTERIOR WALL CAVITIES
Location of Drainage Plane:	HOUSEWRAP ON EXTERIOR SHEATHING
Location of Air Barrier:	FIBERBOARD SHEATHING ATTACHED TO INTERIOR STUD WALL
Insulation Type, R-Value:	10.5" CELLULOSE, R-37
Climate/Zone:	COLD / ZONES 5, 6, 7, AND 8

ABS: Air Barrier System component
TCS: Thermal Control System component
VCS: Vapor Control System component
WMS: Water Management System component



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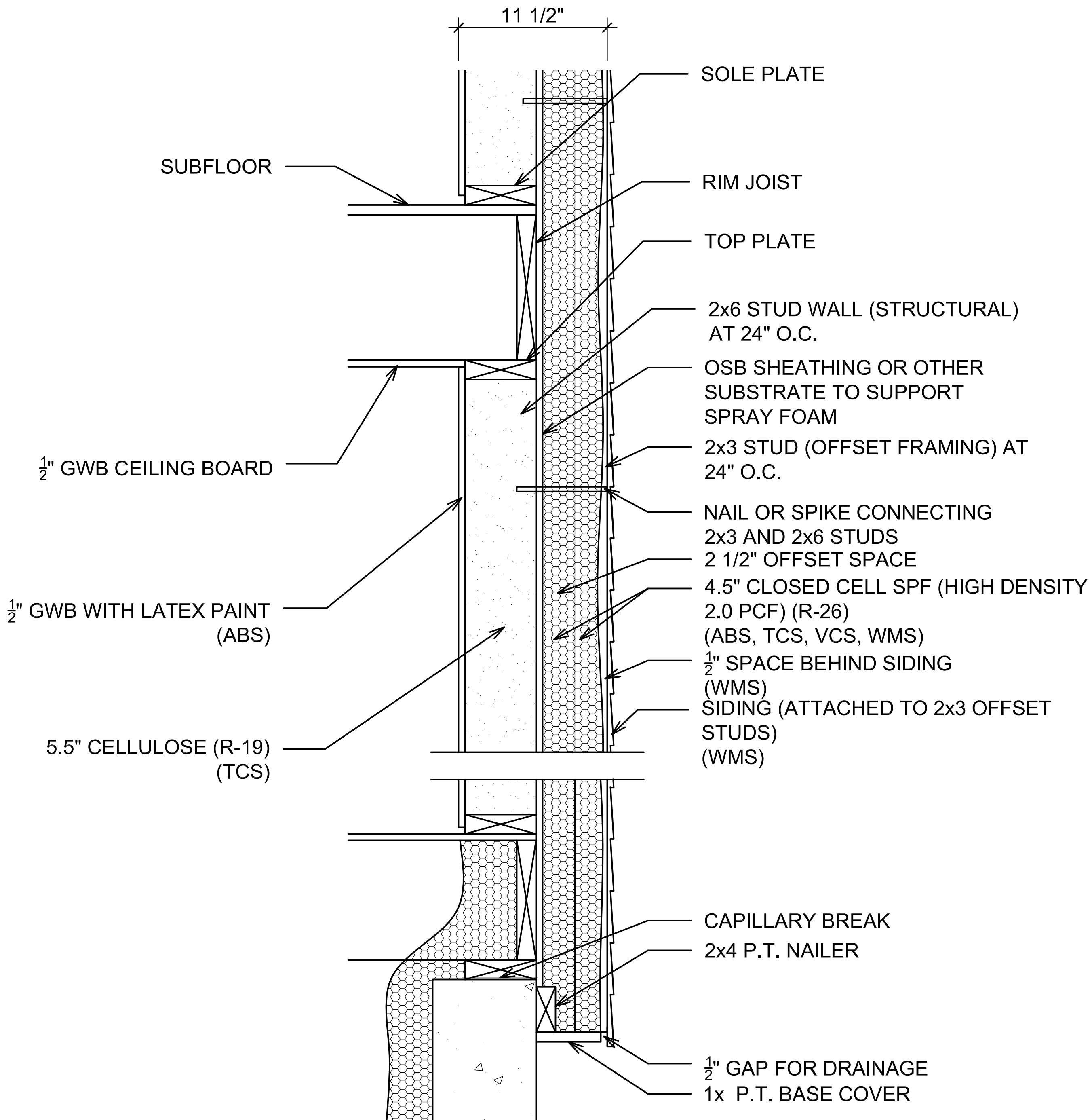
Project:	High-R Enclosures
Date:	2009-09-09
Drawing Title:	High-R Walls
Drawing File:	HighR-Wall-04-1
Drawing Scale:	1" = 1'-0"

High-R Wall: Double Stud w/ Interior Load Bearing Wall Construction

Framing:	2x6 STRUCTURAL STUD W/ 2x3 EXTERIOR OFFSET FRAMING	ABS: Air Barrier System component
Exterior Framing:	VENTED LAP SIDING	TCS: Thermal Control System component
Location of Insulation:	CAVITY AND IN FRAMING OFFSET SPACE	VCS: Vapor Control System component
Location of Drainage Plane:	EXTERIOR FACE OF CLOSED CELL	WMS: Water Management System component
Location of Air Barrier:	CLOSED CELL INSULATION	
Insulation Type, R-Value:	5.5" CELLULOSE + 4.5" CLOSED CELL SPF (HIGH DENSITY 2.0 PCF), R-46	
Climate/Zone:	COLD / ZONES 5, 6,7, AND 8	



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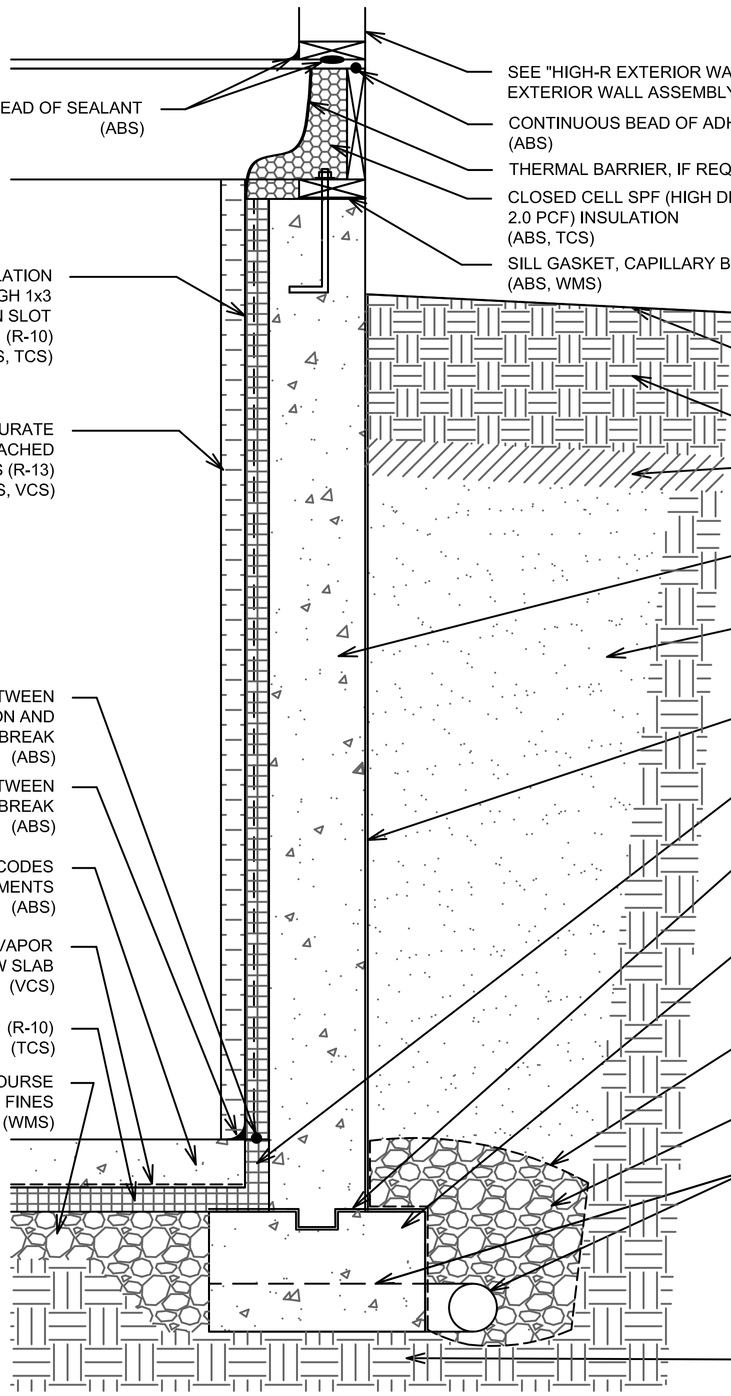
Project: High-R Enclosures
Date: 2009-09-29
Drawing Title: High-R Walls
Drawing File: HighR-Wall-11
Drawing Scale: 1" = 1'-0"

High-R Wall: Offset Framing Wall Construction

Foundation:	CONCRETE
Basement:	UNFINISHED
Location of Insulation:	INTERIOR
Insulation Type, Insulation R-Value:	

Concrete wall dries to the outside (above grade)
2" XPS + 2" FOIL-FACED POLYISOCYANURATE, R-23

ABS: *Air Barrier System component*
TCS: *Thermal Control System component*
VCS: *Vapor Control System component*
WMS: *Water Management System component*



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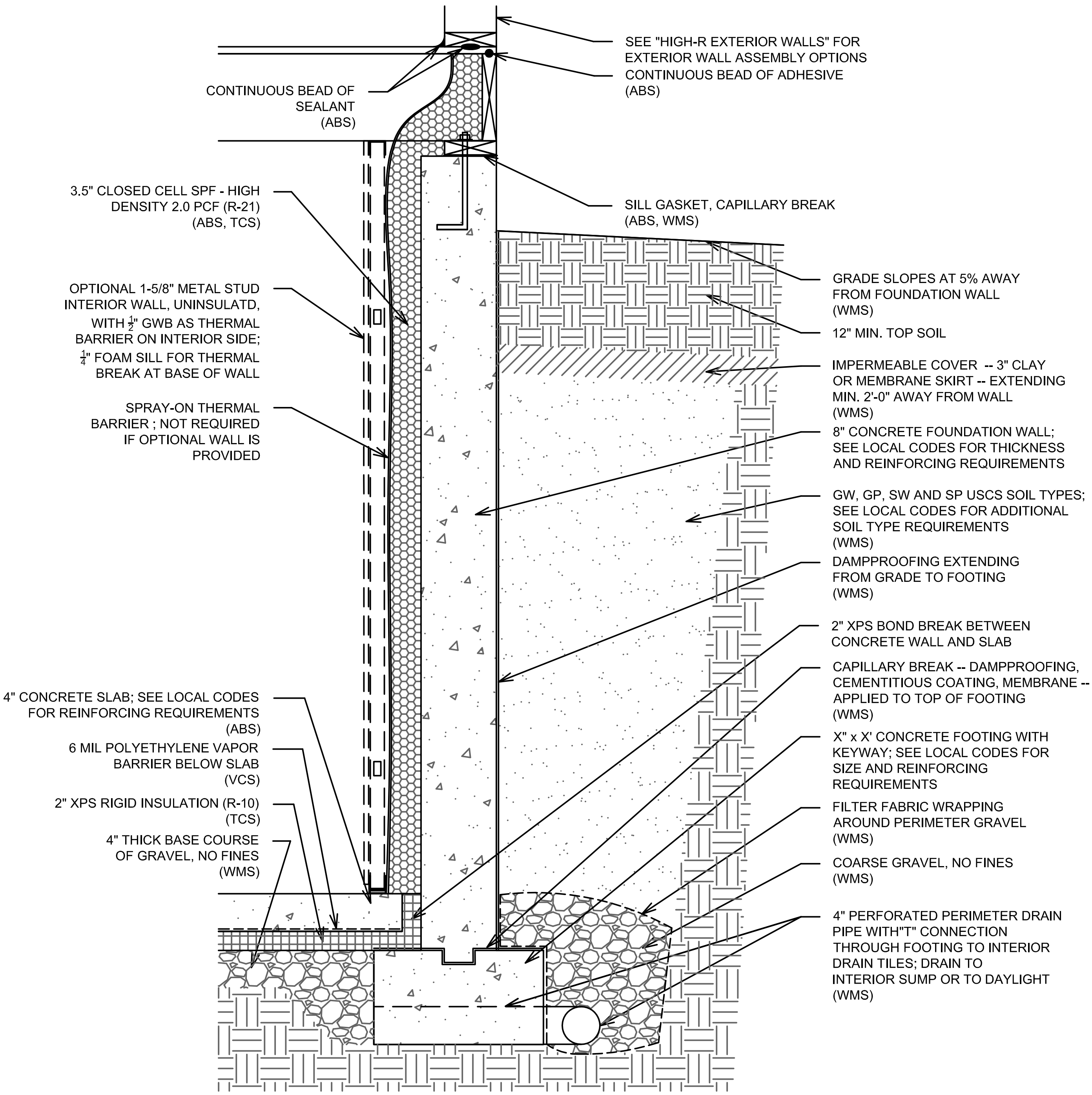
Project:	High-R Foundation Walls	*Sheet Title:*
Date:	2009-06-03 DRAFT	
Drawing Title:	Foundation Walls	Bsmt Type #1
Drawing File:	FoundationDetails.dwg	
Drawing Scale:	3/4" = 1'-0"	

Foundation:	CONCRETE
Basement:	UNFINISHED (OPTIONALLY FINISHED)
Location of Insulation:	INTERIOR
Insulation Type, Insulation R-Value:	

Concrete wall dries to the outside (above grade)
3-1/2" CLOSED CELL SPF (HIGH DENSITY 2.0 PCF),R-21

ABS: *Air Barrier System component*
TCS: *Thermal Control System component*
VCS: *Vapor Control System component*
WMS: *Water Management System component*



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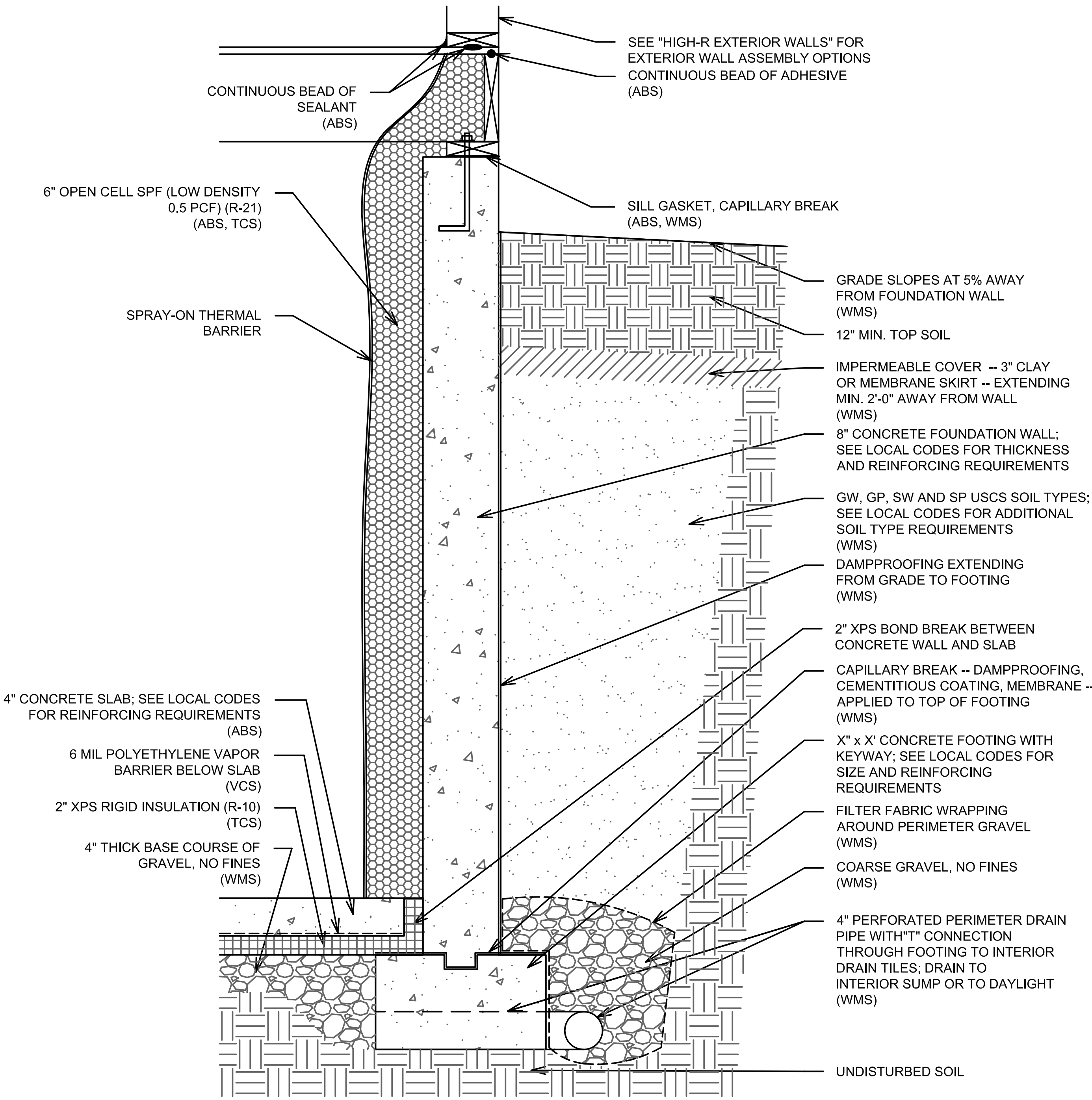
Project:	High-R Foundation Walls
Date:	2009-06-03 DRAFT
Drawing Title:	Foundation Walls
Drawing File:	FoundationDetails.dwg
Drawing Scale:	3/4" = 1'-0"

Sheet Title:

Bsmt Type #2

Foundation: CONCRETE
Basement: UNFINISHED
Location of Insulation: INTERIOR
Insulation Type, Insulation R-Value:
Concrete wall dries to the inside and outside (above grade)
6" OPEN CELL SPF (LOW DENSITY 0.5 PCF), R-21
Appropriate for Zone 5

ABS: *Air Barrier System component*
TCS: *Thermal Control System component*
VCS: *Vapor Control System component*
WMS: *Water Management System component*



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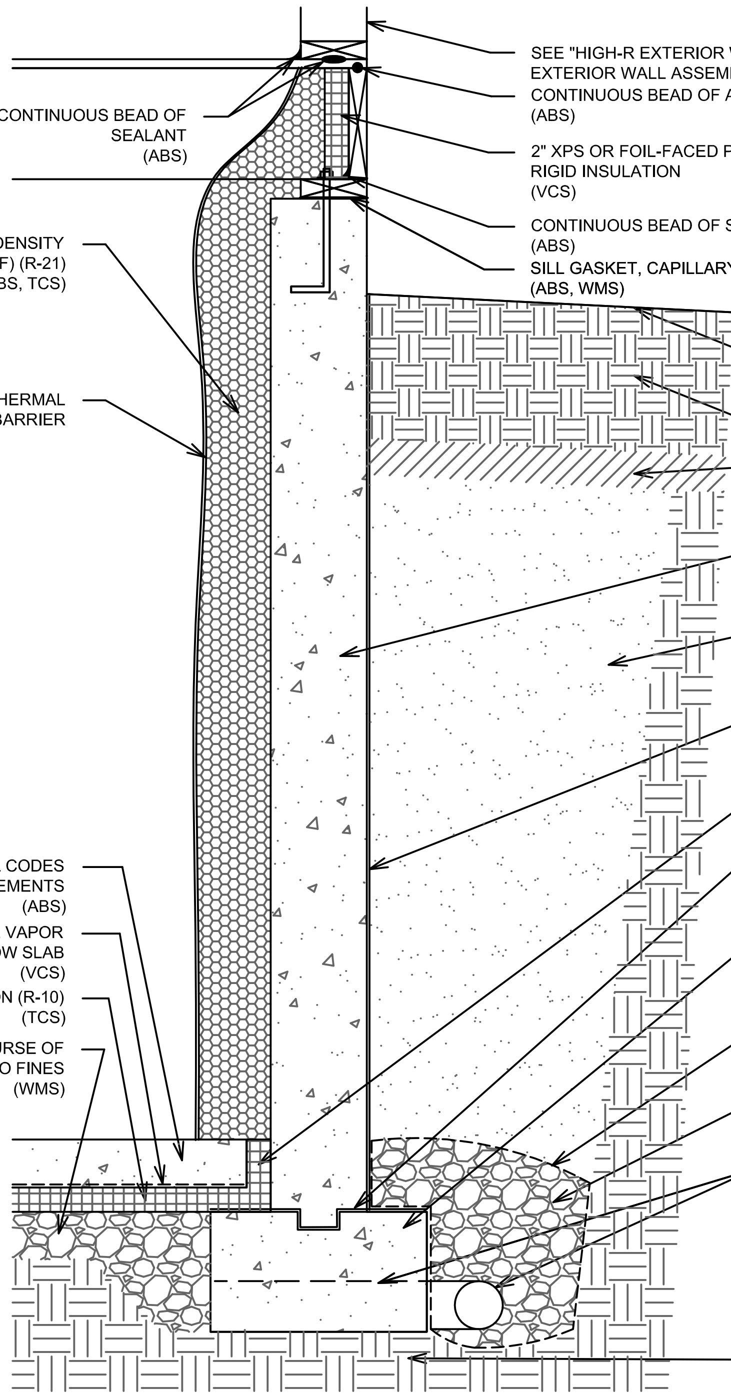
Project:	High-R Foundation Walls
Date:	2009-06-03 DRAFT
Drawing Title:	Foundation Walls
Drawing File:	FoundationDetails.dwg
Drawing Scale:	3/4" = 1'-0"

Sheet Title:

Bsmt Type #3

Foundation: CONCRETE
Basement: UNFINISHED
Location of Insulation: INTERIOR
Insulation Type, Insulation R-Value:
Concrete wall dries to the inside and outside (above grade)
6" OPEN CELL SPF (LOW DENSITY 0.5 PCF), R-21
Appropriate for Zone 6

ABS: *Air Barrier System component*
TCS: *Thermal Control System component*
VCS: *Vapor Control System component*
WMS: *Water Management System component*



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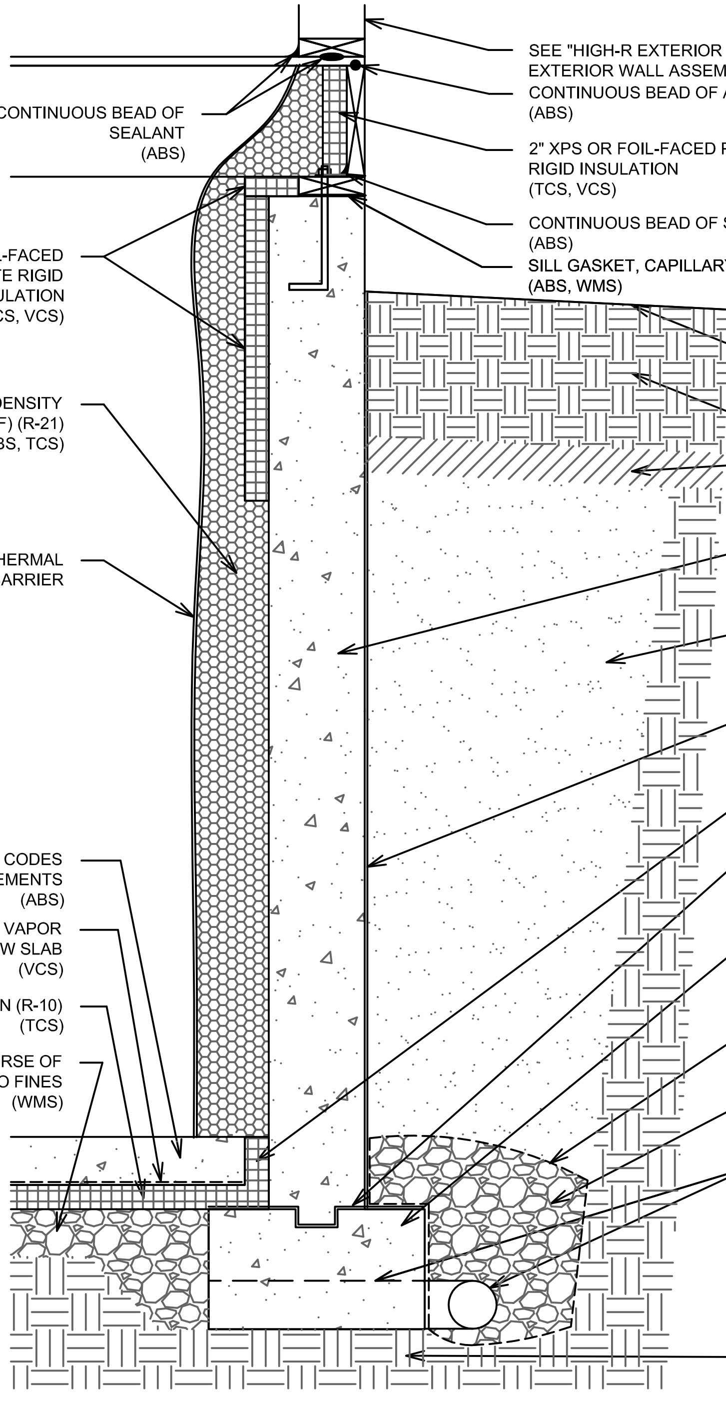
Project:	High-R Foundation Walls
Date:	2009-06-03 DRAFT
Drawing Title:	Foundation Walls
Drawing File:	FoundationDetails.dwg
Drawing Scale:	3/4" = 1'-0"

Sheet Title:

Bsmt Type #3A

Foundation: CONCRETE
Basement: UNFINISHED
Location of Insulation: INTERIOR
Insulation Type, Insulation R-Value:
Concrete wall dries to the inside and outside (above grade)
6" OPEN CELL SPF (LOW DENSITY 0.5 PCF), R-21
Appropriate for Zone 7 and higher

ABS: *Air Barrier System component*
TCS: *Thermal Control System component*
VCS: *Vapor Control System component*
WMS: *Water Management System component*



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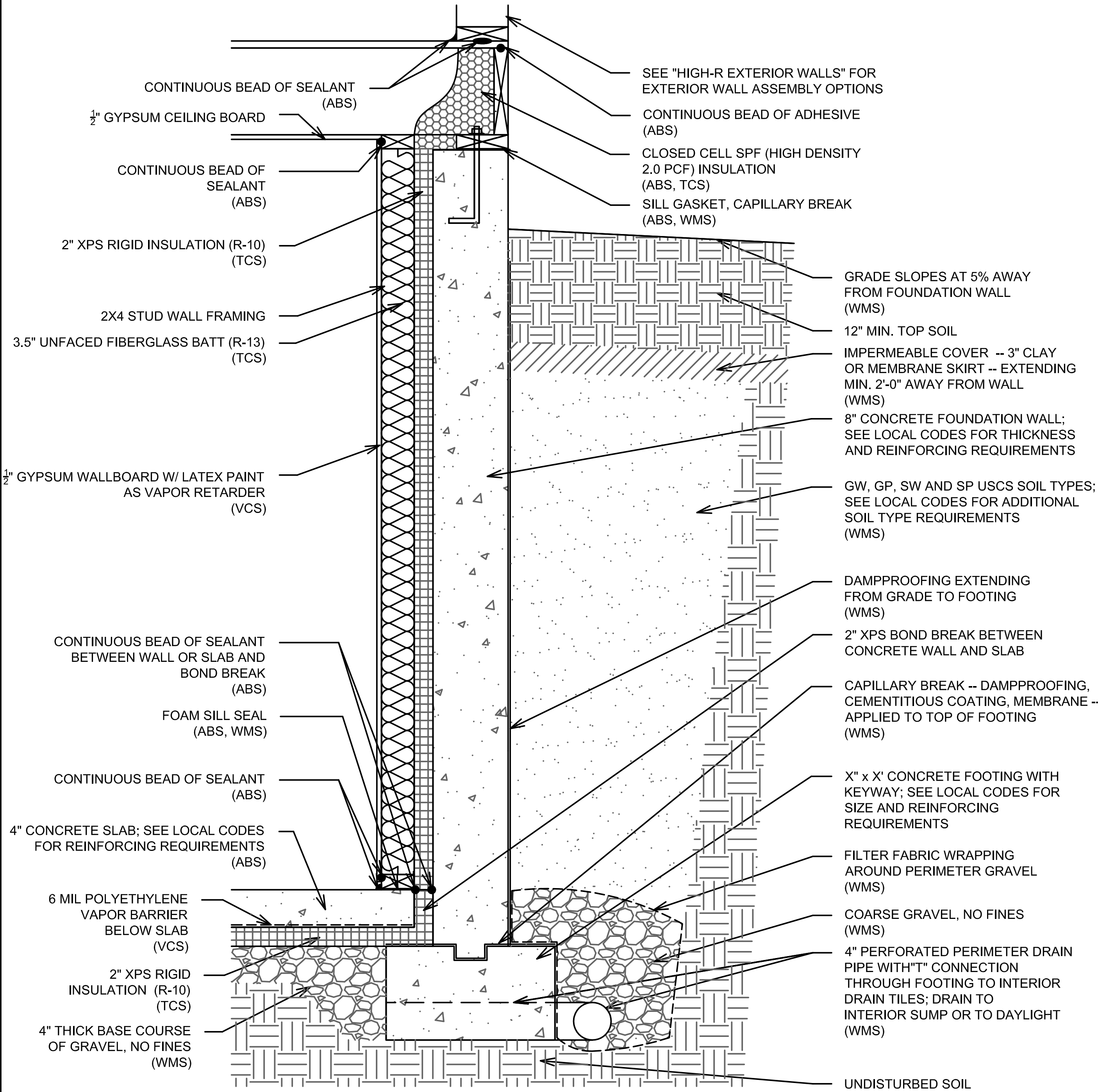
Project:	High-R Foundation Walls
Date:	2009-06-03 DRAFT
Drawing Title:	Foundation Walls
Drawing File:	FoundationDetails.dwg
Drawing Scale:	3/4" = 1'-0"

Sheet Title:
Bsmt Type #3B

Foundation: CONCRETE
Basement: FINISHED
Location of Insulation: INTERIOR
Insulation Type, Insulation R-Value:
Concrete wall dries to inside and to outside (above grade)
2" XPS + 3.5" FIBERGLASS BATT, R-23

ABS: *Air Barrier System component*
TCS: *Thermal Control System component*
VCS: *Vapor Control System component*
WMS: *Water Management System component*



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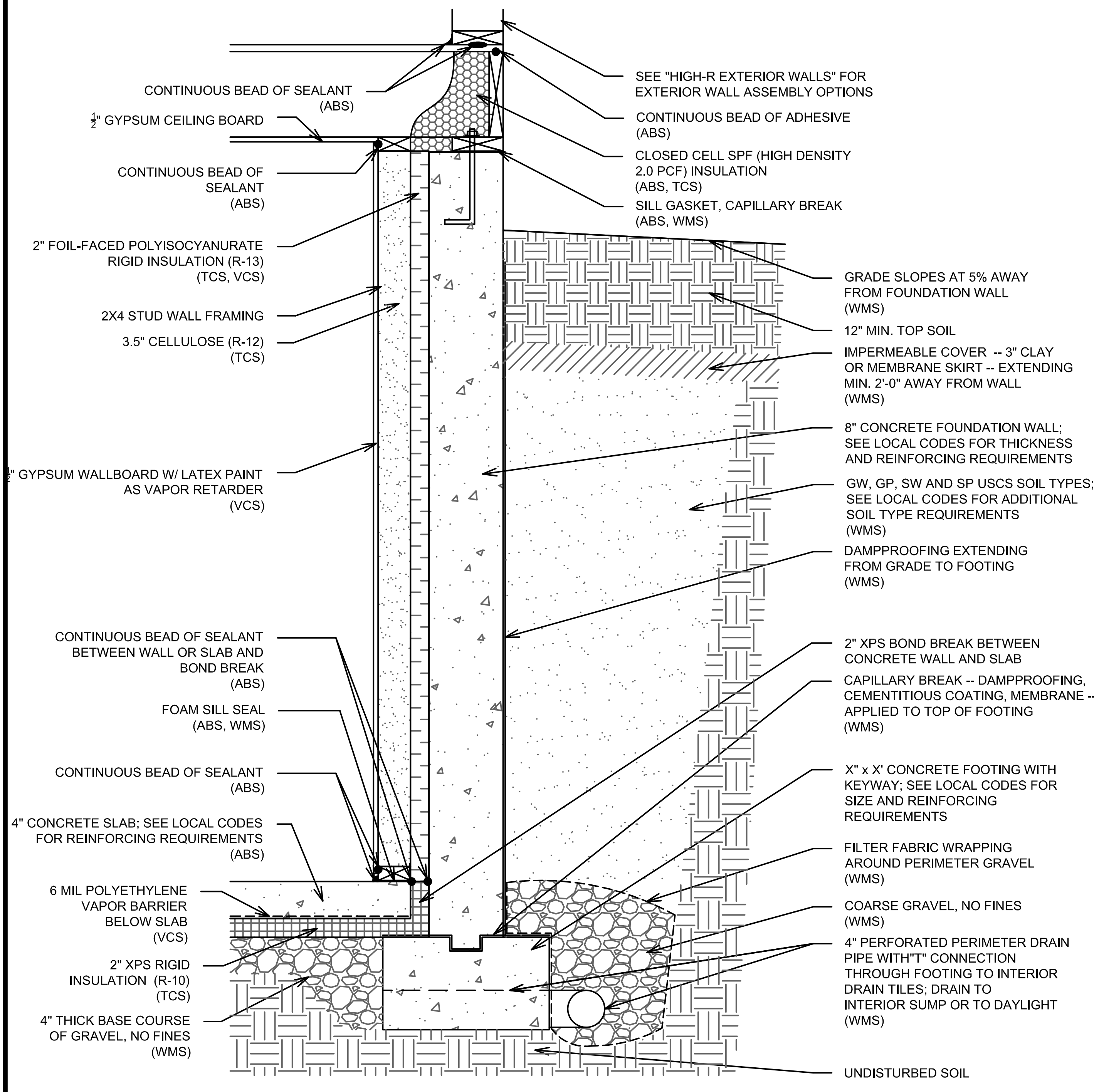
Project:	High-R Foundation Walls
Date:	2009-06-03 DRAFT
Drawing Title:	Foundation Walls
Drawing File:	FoundationDetails.dwg
Drawing Scale:	3/4" = 1'-0"

Sheet Title:

Bsmt Type #4

Foundation: CONCRETE *Basement:* FINISHED *Location of Insulation:* INTERIOR *Insulation Type, Insulation R-Value:* *Concrete wall dries to outside (above grade)* 2" FOIL-FACED POLYISOCYANURATE + 3.5" CELLULOSE, R-25	ABS: *Air Barrier System component* TCS: *Thermal Control System component* VCS: *Vapor Control System component* WMS: *Water Management System component*



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Project:	High-R Foundation Walls
Date:	2009-06-03 DRAFT
Drawing Title:	Foundation Walls
Drawing File:	FoundationDetails.dwg
Drawing Scale:	3/4" = 1'-0"

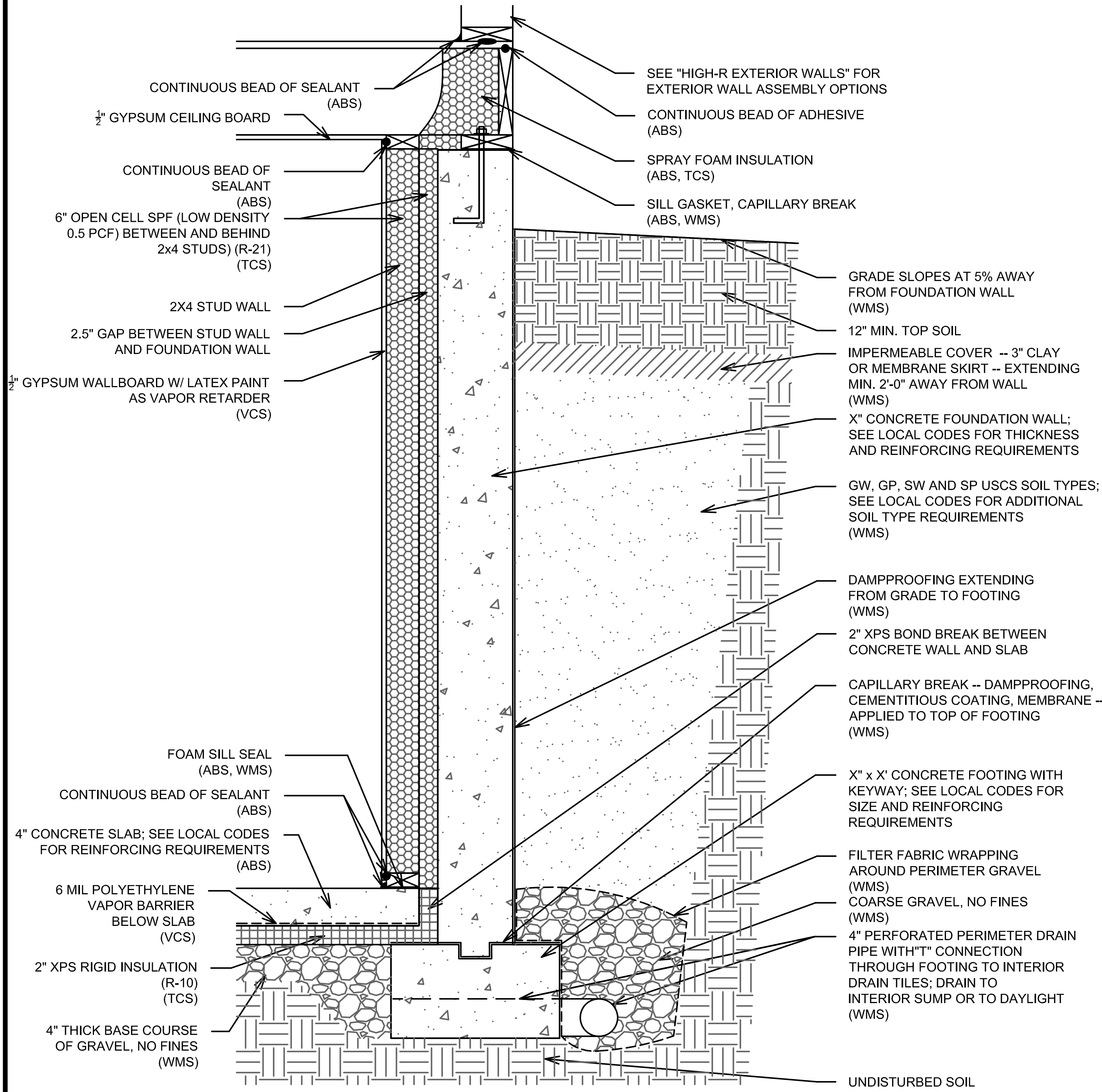
Sheet Title:

Bsmt Type #5

Foundation: CONCRETE
Basement: FINISHED
Location of Insulation: INTERIOR
Insulation Type, Insulation R-Value:
Concrete wall dries to the inside and outside (above grade)
6" OPEN CELL SPF (LOW DENSITY 0.5 PCF), R-21

Appropriate for Zone 5

ABS: *Air Barrier System component*
TCS: *Thermal Control System component*
VCS: *Vapor Control System component*
WMS: *Water Management System component*



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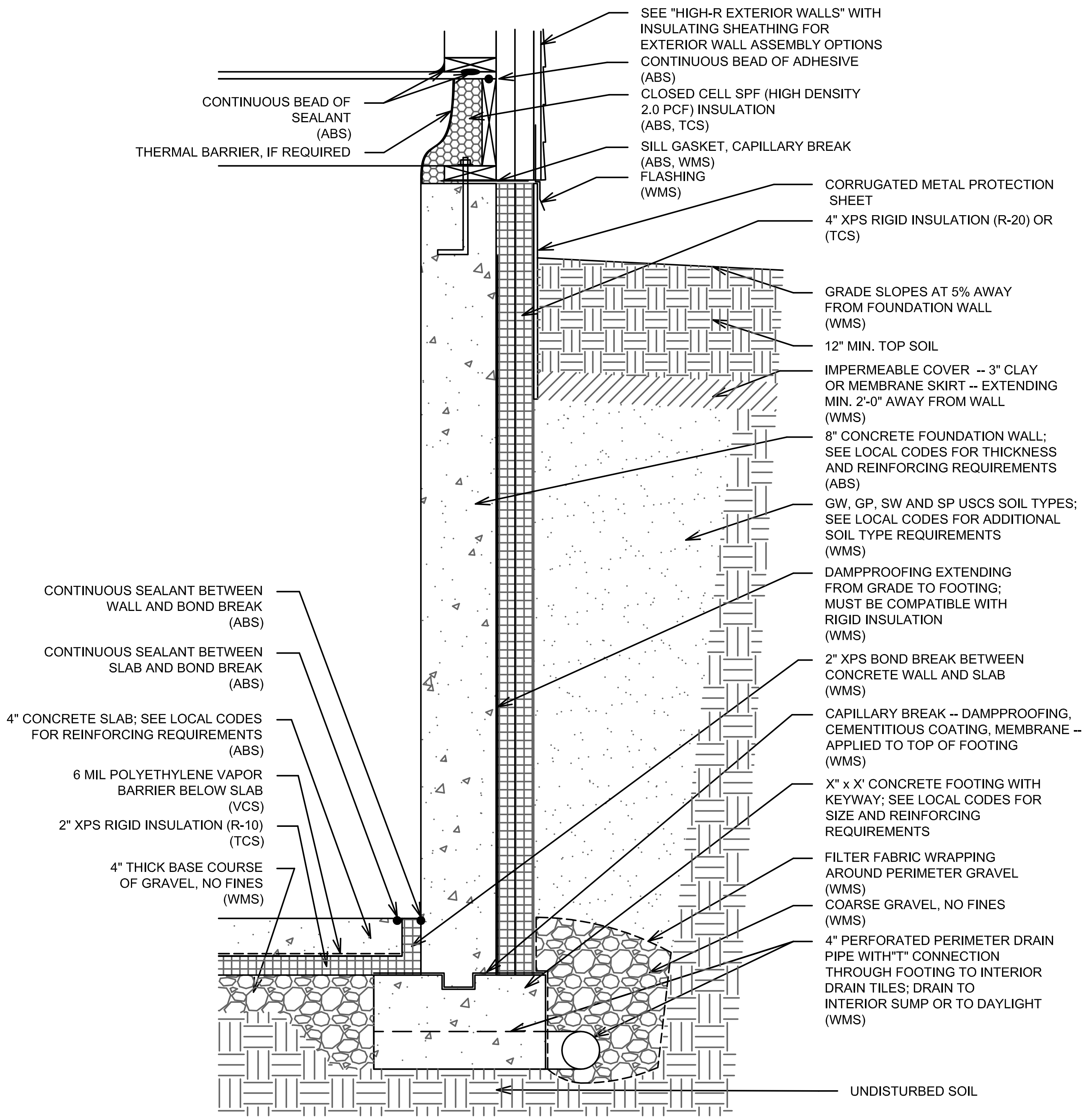
Project: High-R Foundation Walls
Date: 2009-06-03 DRAFT
Drawing Title: Foundation Walls
Drawing File: FoundationDetails.dwg
Drawing Scale: 3/4" = 1'-0"

Sheet Title:
Bsmt Type #6

Foundation:	CONCRETE
Basement:	UNFINISHED
Location of Insulation:	EXTERIOR
Insulation Type, Insultaion R-Value:	
	Concrete wall dries to inside
	4" XPS, R-20

ABS: *Air Barrier System component*
TCS: *Thermal Control System component*
VCS: *Vapor Control System component*
WMS: *Water Management System component*



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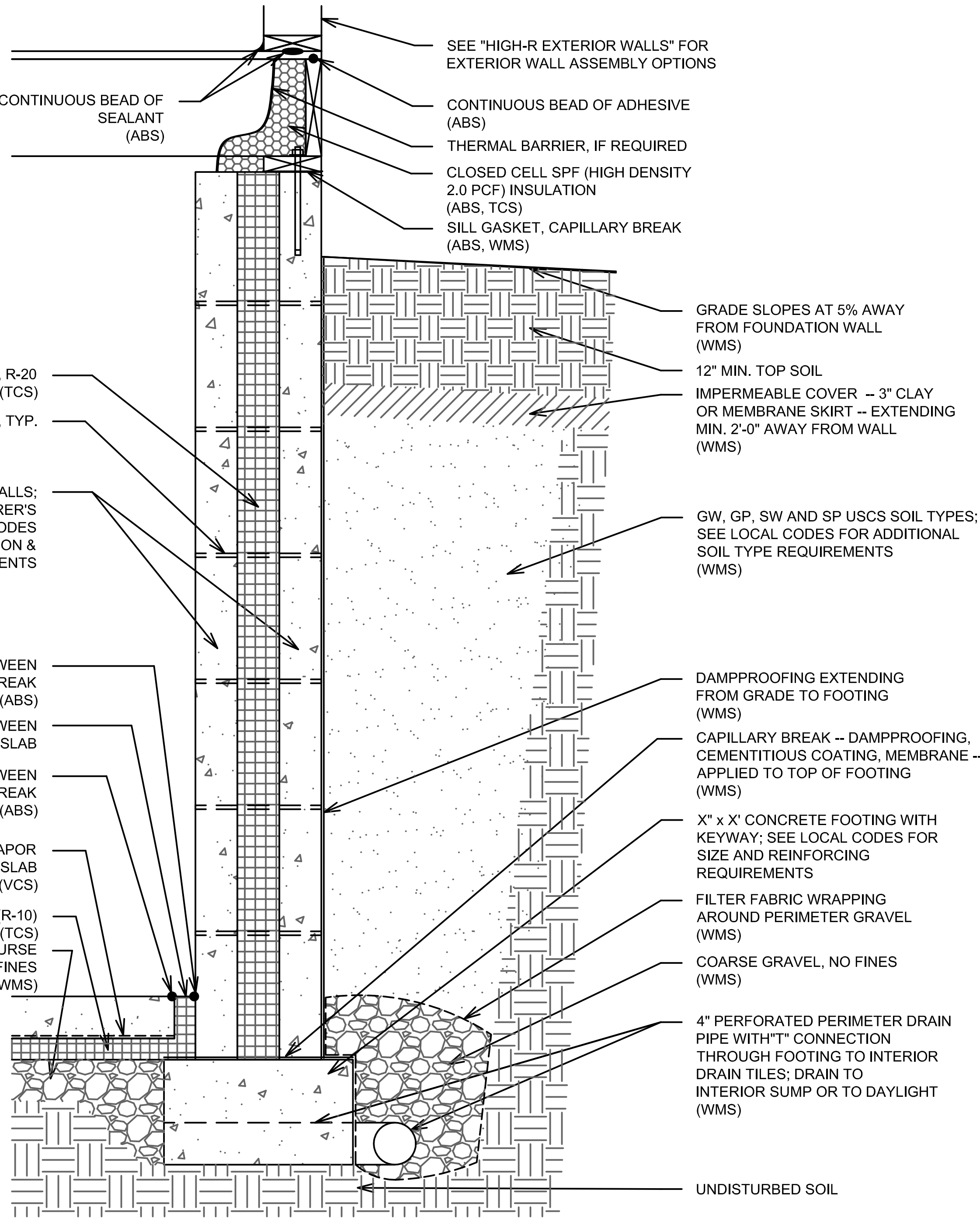
Project:	High-R Foundation Walls
Date:	2009-06-03 DRAFT
Drawing Title:	Foundation Walls
Drawing File:	FoundationDetails.dwg
Drawing Scale:	3/4" = 1'-0"

Sheet Title:

Bsmt Type #7

Foundation: CONCRETE
Basement: UNFINISHED
Location of Insulation: MIDDLE OF WALL
Insulation Type, Insulation R-Value:
Concrete wall dries to the inside and outside (above grade)
4" XPS, R-20

ABS: *Air Barrier System component*
TCS: *Thermal Control System component*
VCS: *Vapor Control System component*
WMS: *Water Management System component*



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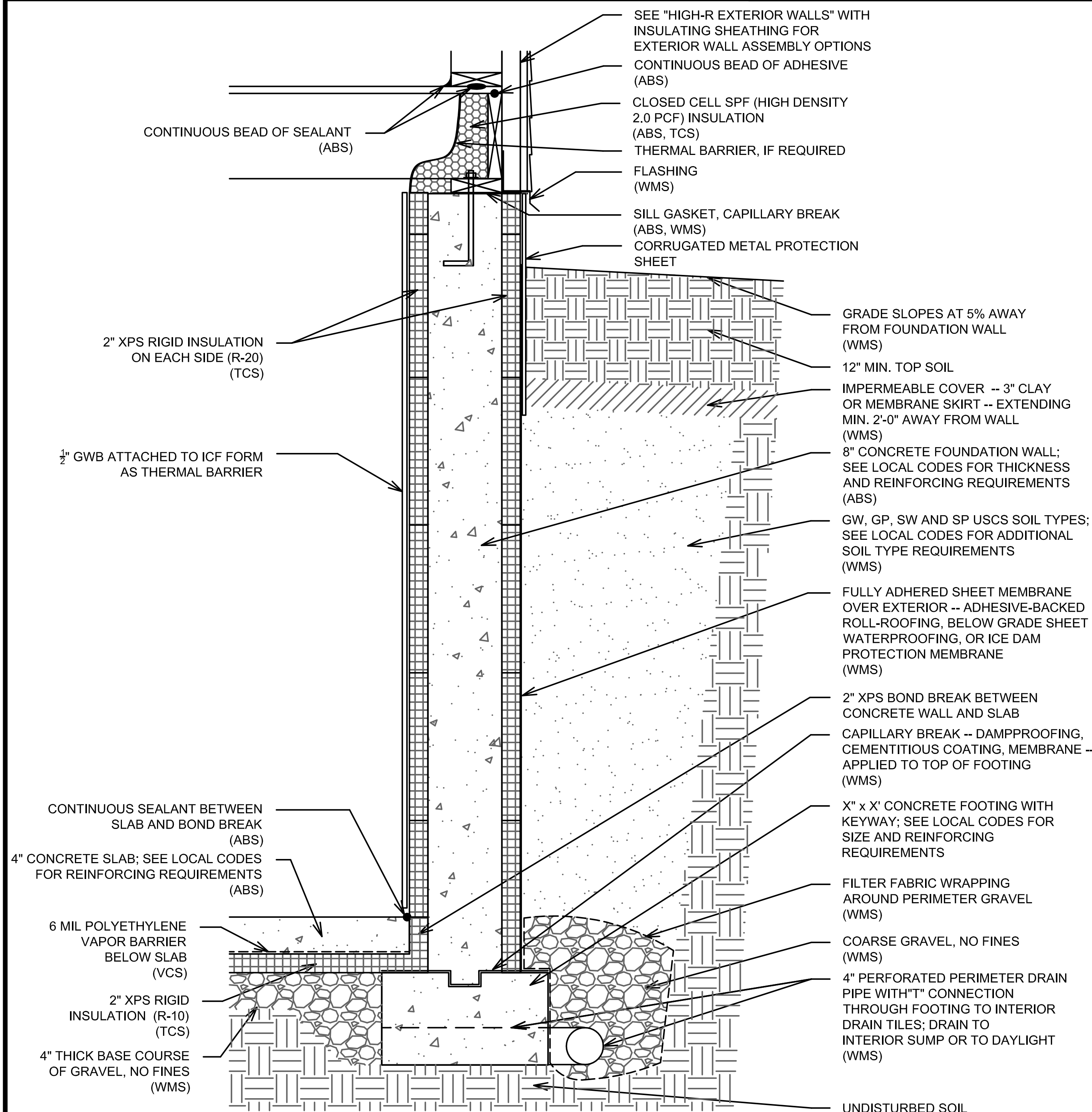
Project:	High-R Foundation Walls
Date:	2009-06-03 DRAFT
Drawing Title:	Foundation Walls
Drawing File:	FoundationDetails.dwg
Drawing Scale:	3/4" = 1'-0"

Sheet Title:

Bsmt Type #8

Foundation: CONCRETE (ICF)
Basement: UNFINISHED
Location of Insulation: INTERIOR AND EXTERIOR
Insulation Type, Insulation R-Value:
Concrete wall dries to the inside and outside (above grade)
4" XPS, R-20

ABS: *Air Barrier System component*
TCS: *Thermal Control System component*
VCS: *Vapor Control System component*
WMS: *Water Management System component*



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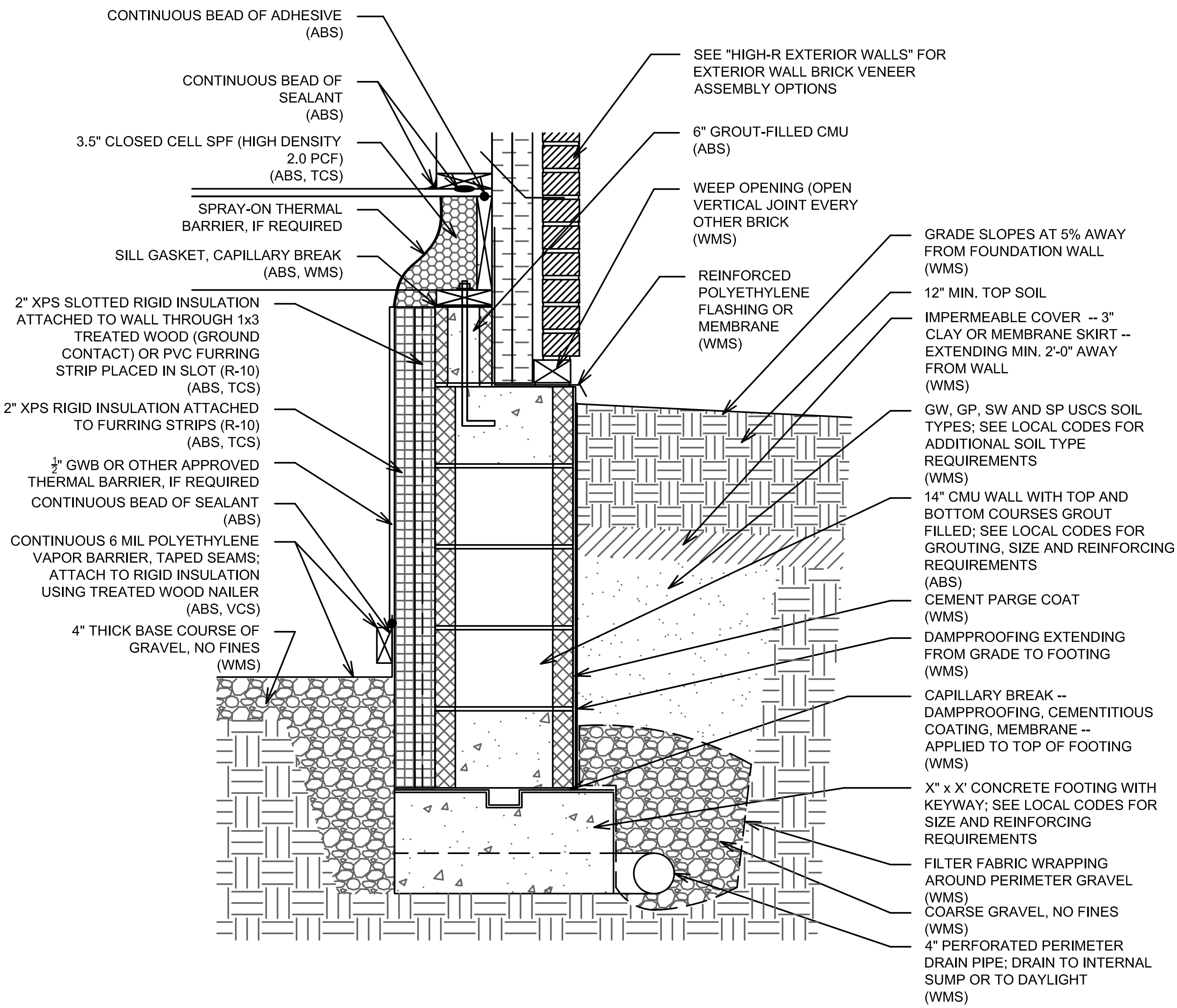
Project:	High-R Foundation Walls
Date:	2009-06-03 DRAFT
Drawing Title:	Foundation Walls
Drawing File:	FoundationDetails.dwg
Drawing Scale:	3/4" = 1'-0"

Sheet Title:

Bsmt Type #9

Foundation:	14" CMU WALL WITH BRICK VENEER	
Crawl Space:	UNVENTED	
Ground Cover:	CONTINUOUS POLYETHYLENE VAPOR BARRIER	
Location of Insulation:	INTERIOR OF FOUNDATION WALL	
Drying:	WALL DRIES TO OUTSIDE (ABOVE GRADE);	
Insulation Type, Insulation R-Value:	4" XPS RIGID INSULATION, R-20	

ABS: *Air Barrier System component*
TCS: *Thermal Control System component*
VCS: *Vapor Control System component*
WMS: *Water Management System component*



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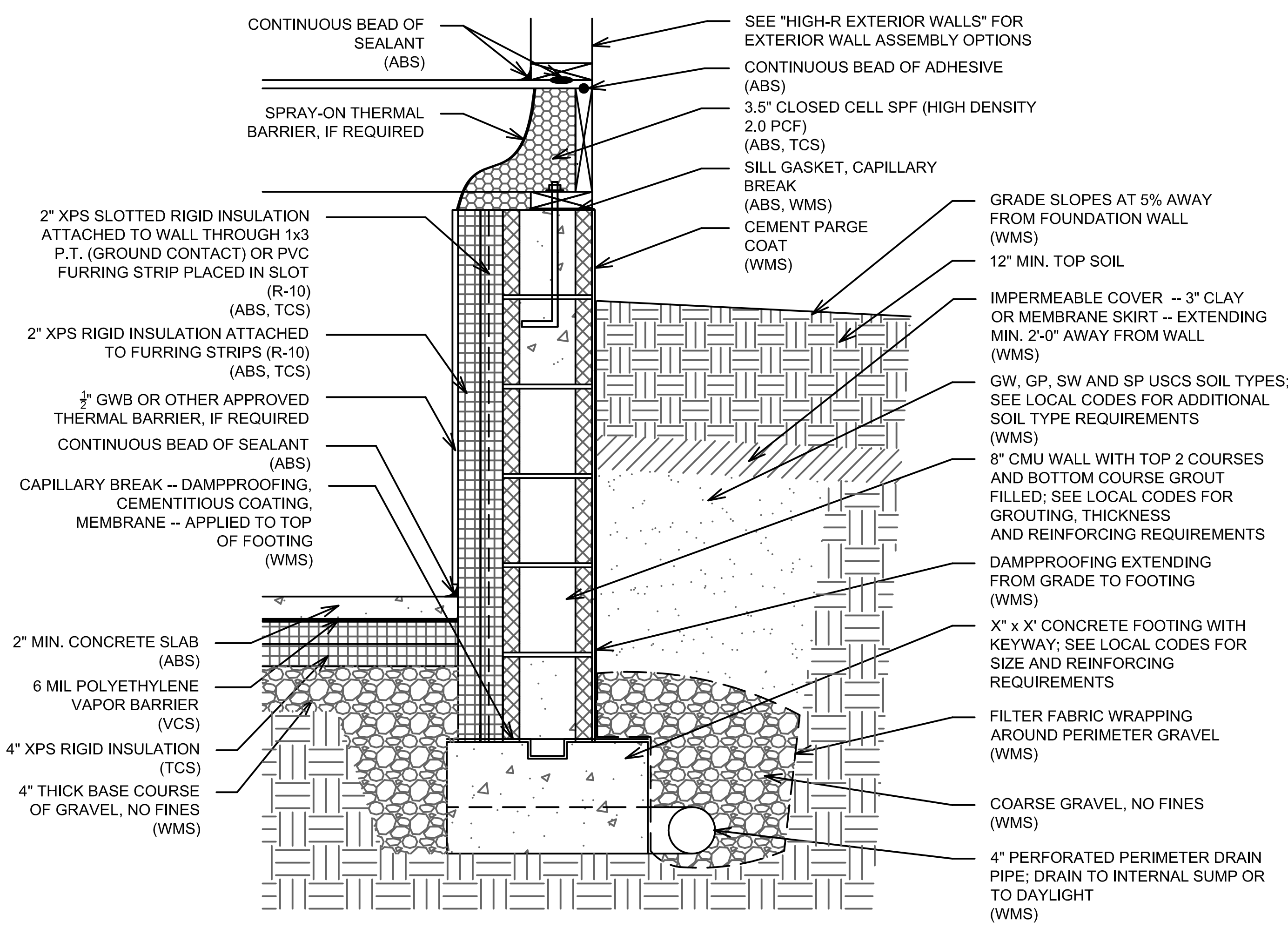
Project:	High-R Foundation Walls
Date:	2009-06-03 DRAFT
Drawing Title:	Foundation Walls
Drawing File:	FoundationDetails.dwg
Drawing Scale:	3/4 = 1'-0"

Sheet Title:

CS Type #1

Foundation:	8" CMU WALL
Crawl Space:	UNVENTED
Ground Cover:	2" CONCRETE SLAB
Location of Insulation:	INTERIOR OF FOUNDATION WALLS AND UNDER SLAB
Drying:	WALL DRIES TO OUTSIDE (ABOVE GRADE); SLAB DRIES TO INTERIOR
Insulation Type, Insulation R-Value:	4" XPS RIGID INSULATION, R-20

ABS: *Air Barrier System component*
TCS: *Thermal Control System component*
VCS: *Vapor Control System component*
WMS: *Water Management System component*



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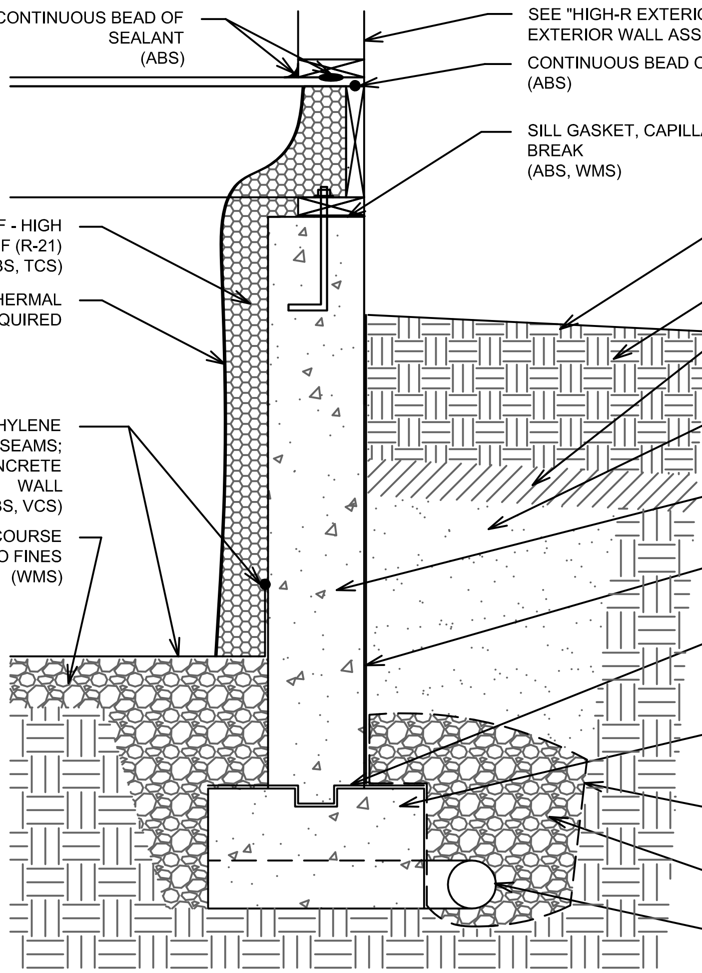
Project:	High-R Foundation Walls
Date:	2009-06-03 DRAFT
Drawing Title:	Foundation Walls
Drawing File:	FoundationDetails.dwg
Drawing Scale:	3/4 = 1'-0"

Sheet Title:

CS Type #2

Foundation:	8" CONCRETE WALL	ABS: *Air Barrier System component*
Crawl Space:	UNVENTED	TCS: *Thermal Control System component*
Ground Cover:	CONTINUOUS POLYETHYLENE VAPOR BARRIER	VCS: *Vapor Control System component*
Location of Insulation:	INTERIOR OF FOUNDATION WALL	WMS: *Water Management System component*
Drying:	WALL DRIES TO OUTSIDE (ABOVE GRADE)	
Insulation Type, Insulation R-Value:	3.5" CLOSED CELL SPF (HIGH DENSITY 2.0 PCF), R-21	

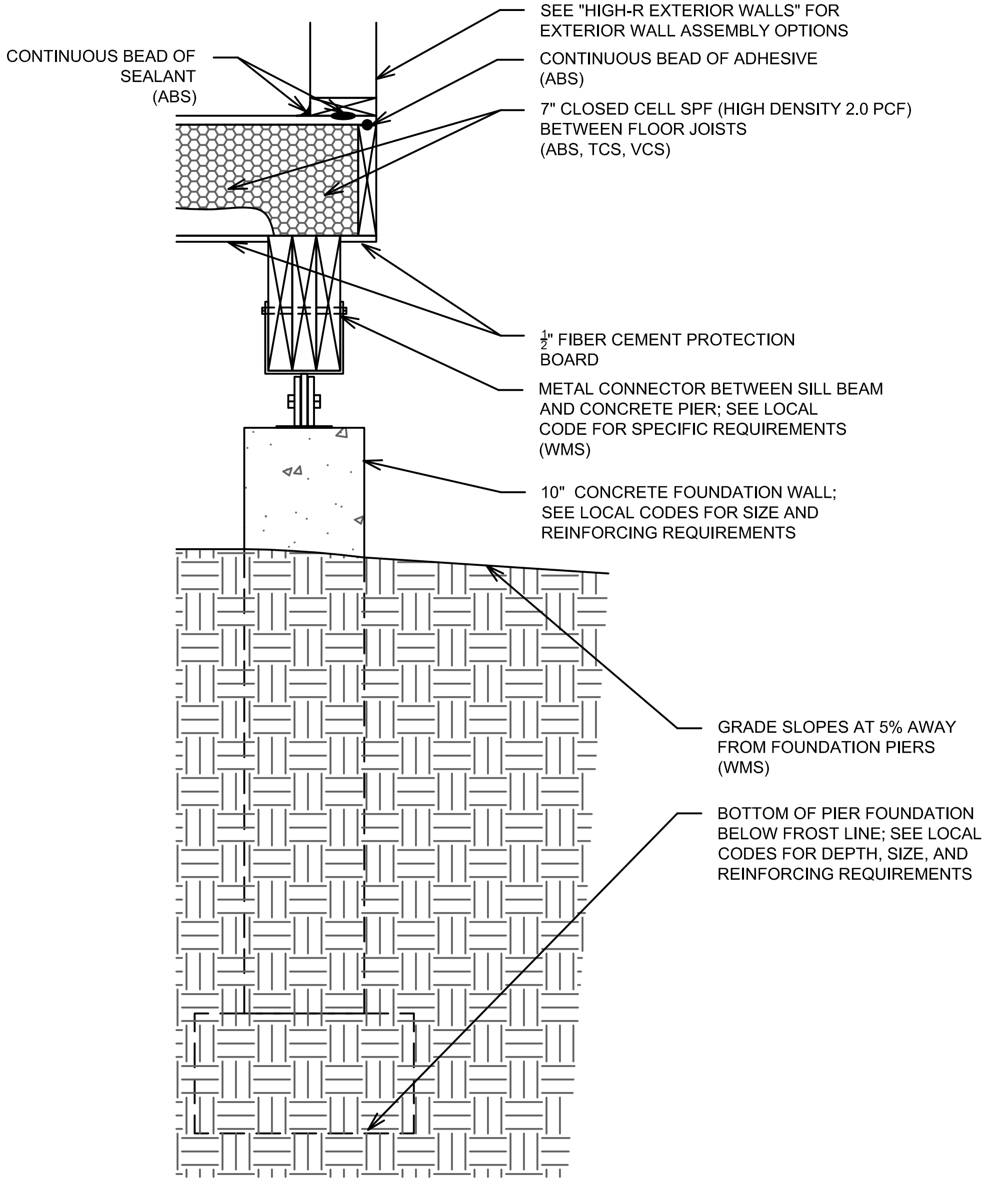


bsc *with* Building America U.S. Department of Energy *Research Toward Zero Energy Homes*

Project:	High-R Foundation Walls	*Sheet Title:*
Date:	2009-06-03 DRAFT	CS Type #3
Drawing Title:	Foundation Walls	
Drawing File:	FoundationDetails.dwg	
Drawing Scale:	3/4" = 1'-0"	

Foundation:	CONCRETE PIERS	
Crawl Space:	VENTED	
Ground Cover:	NONE	
Location of Insulation:	INSIDE FLOOR JOISTS	
Drying:	N/A	
Insulation Type, Insulation R-Value:	7" CLOSED CELL SPF (HIGH DENSITY 2.0 PCF), R-42	

ABS: *Air Barrier System component*
TCS: *Thermal Control System component*
VCS: *Vapor Control System component*
WMS: *Water Management System component*



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Project:	High-R Foundation Walls
Date:	2009-06-03 DRAFT
Drawing Title:	Foundation Walls
Drawing File:	FoundationDetails.dwg
Drawing Scale:	3/4" = 1'-0"

Sheet Title:

CS Type #4

C-280

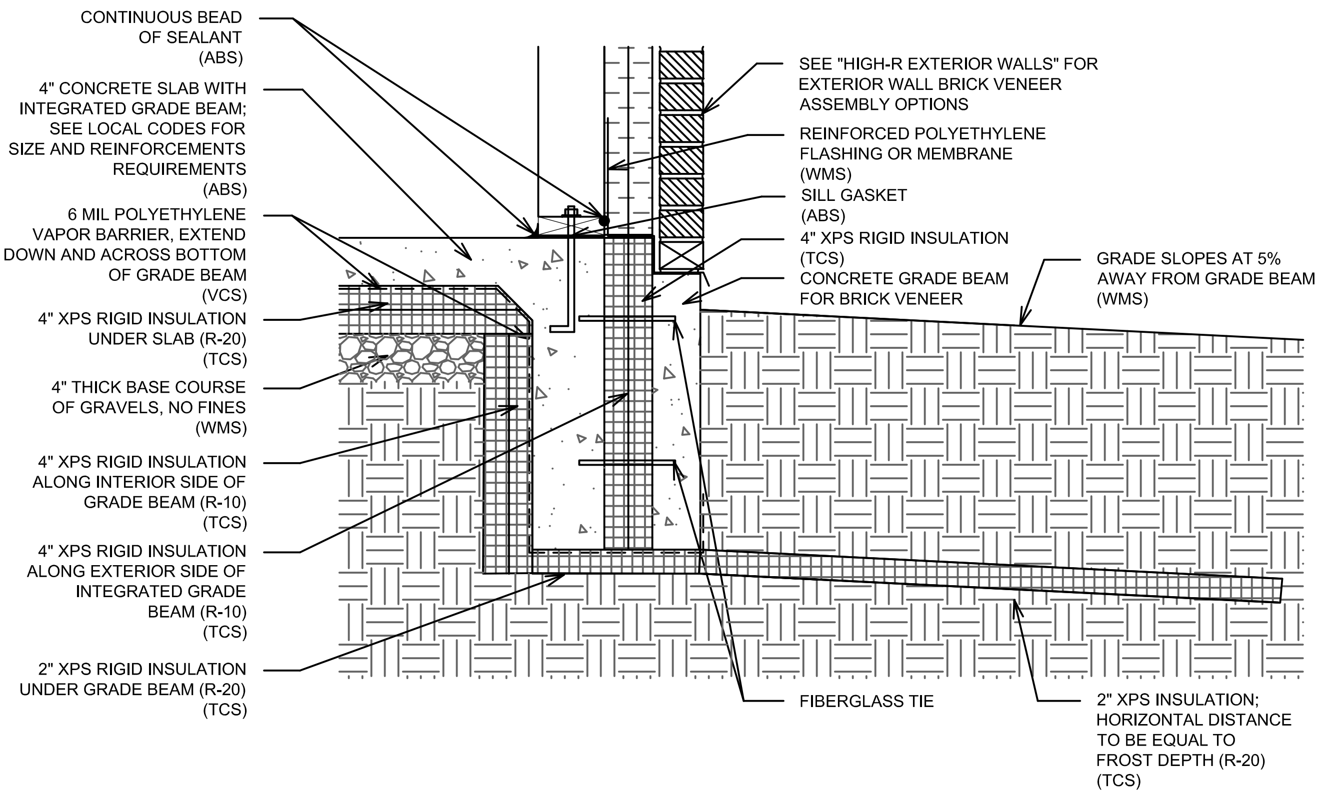
Foundation:	CONCRETE GRADE BEAM INTEGRAL WITH SLAB	
Slab on Grade Type:	MONOLITHIC SLAB	
Location of Insulation:	BELOW SLAB, ENCLOSING GRADE BEAM, AND HORIZONTAL FROST PROTECTION	
Drying:	TO INTERIOR	

Insulation Type, Insulation R-Value:

BELOW SLAB: 4" XPS RIGID INSULATION, R-20
INTERIOR OF GRADE BEAM: 4" XPS RIGID INSULATION, R-20
EXTERIOR OF GRADE BEAM, 4" XPS RIGID INSULATION, R-10
BELOW GRADE BEAM: 2" XPS RIGID INSULATION, R-10
FROST PROTECTION: 2" XPS RIGID INSULATION, R-10

Appropriate for Cold Climates

ABS: *Air Barrier System component*
TCS: *Thermal Control System component*
VCS: *Vapor Control System component*
WMS: *Water Management System component*



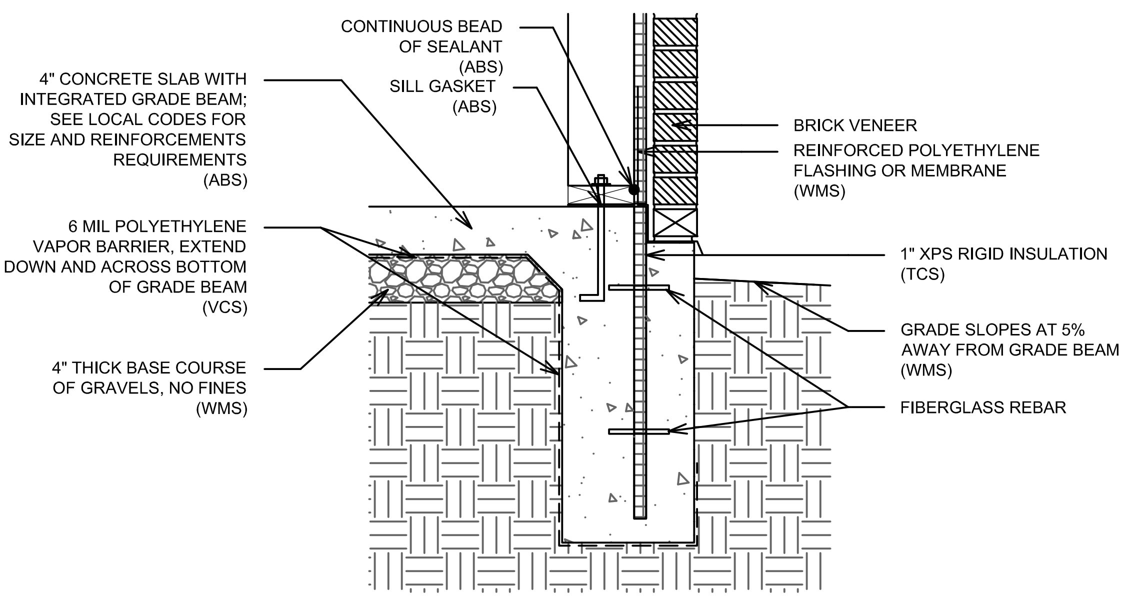
with Building AMERICA U.S. Department of Energy *Research Toward Zero Energy Homes*

Project:	High-R Foundation Walls	*Sheet Title:*
Date:	2009-06-05 DRAFT	SG Type #1A
Drawing Title:	Foundation Walls	
Drawing File:	FoundationDetails.dwg	
Drawing Scale:	3/4" = 1'-0"	

Foundation: CONCRETE GRADE BEAM INTEGRAL WITH SLAB
Slab on Grade Type: MONOLITHIC SLAB
Location of Insulation: WITHIN GRADE BEAM
Drying: TO INTERIOR
Insulation Type, Insulation R-Value:
1" XPS IN GRADE BEAM

Appropriate for Mixed-Humid Climates

ABS: *Air Barrier System component*
TCS: *Thermal Control System component*
VCS: *Vapor Control System component*
WMS: *Water Management System component*



CONTINUOUS BEAD

with

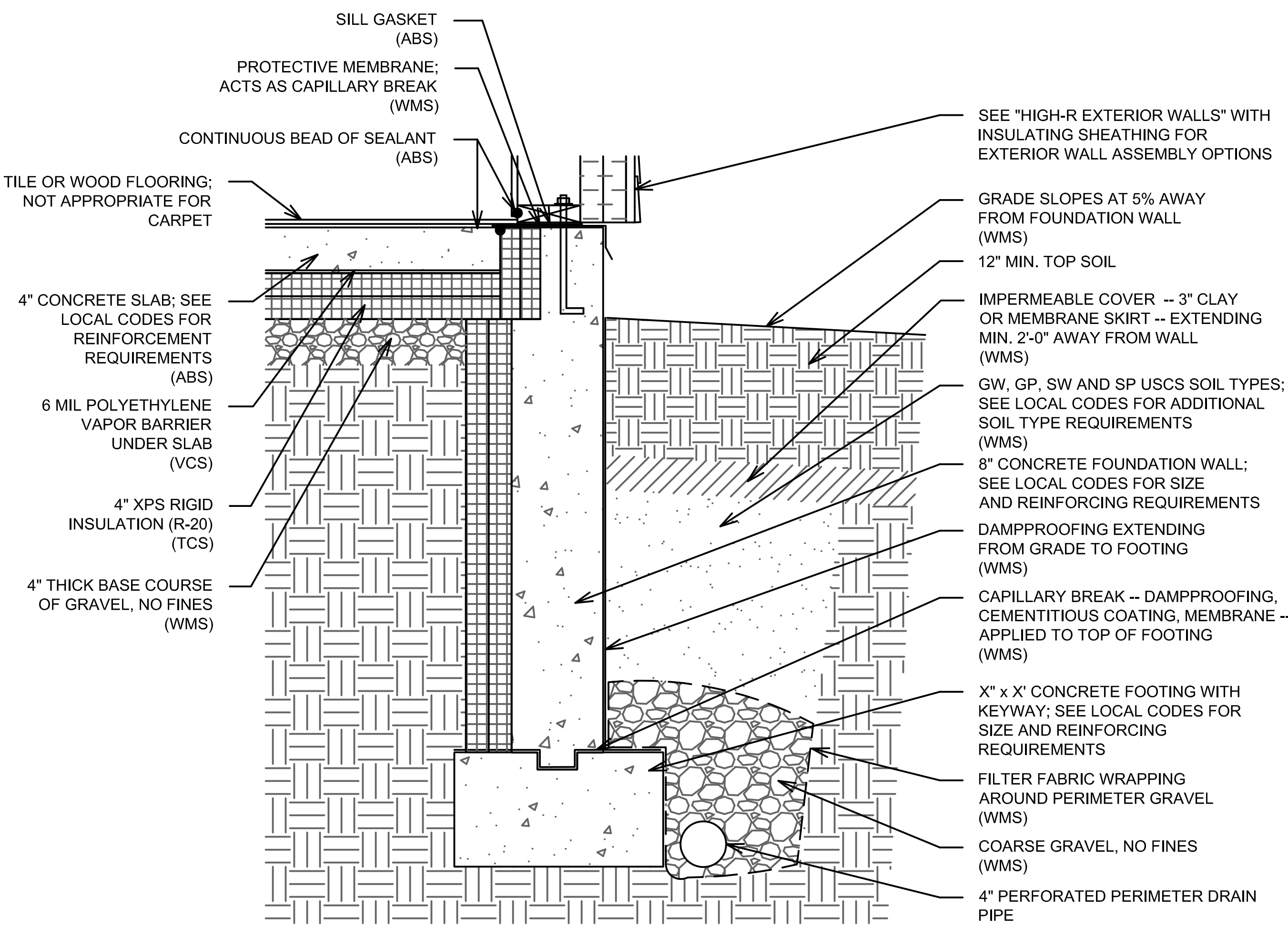
Project: High-R Foundation Walls
Date: 2009-06-05 DRAFT
Drawing Title: Foundation Walls
Drawing File: FoundationDetails.dwg
Drawing Scale: 3/4" = 1'-0"

Sheet Title:

SG Type #1B

Foundation:	CONCRETE	
Slab on Grade Type:	INDEPENDENT 4" SLAB ON GRADE	
Location of Insulation:	BELOW SLAB, ON PERIMETER OF SLAB, AND ON INTERIOR OF FOUNDATION WALL	
Drying:	SLAB: TO INTERIOR; FOUNDATION WALL: TO OUTSIDE (ABOVE GRADE)	
Insulation Type, Insulation R-Value:	BELOW SLAB: 4" XPS RIGID INSULATION, R-20 PERIMETER OF SLAB: 4" XPS RIGID INSULATION, R-20 INTERIOR OF WALL: 4" XPS RIGID INSULATION, R-20	

ABS: *Air Barrier System component*
TCS: *Thermal Control System component*
VCS: *Vapor Control System component*
WMS: *Water Management System component*

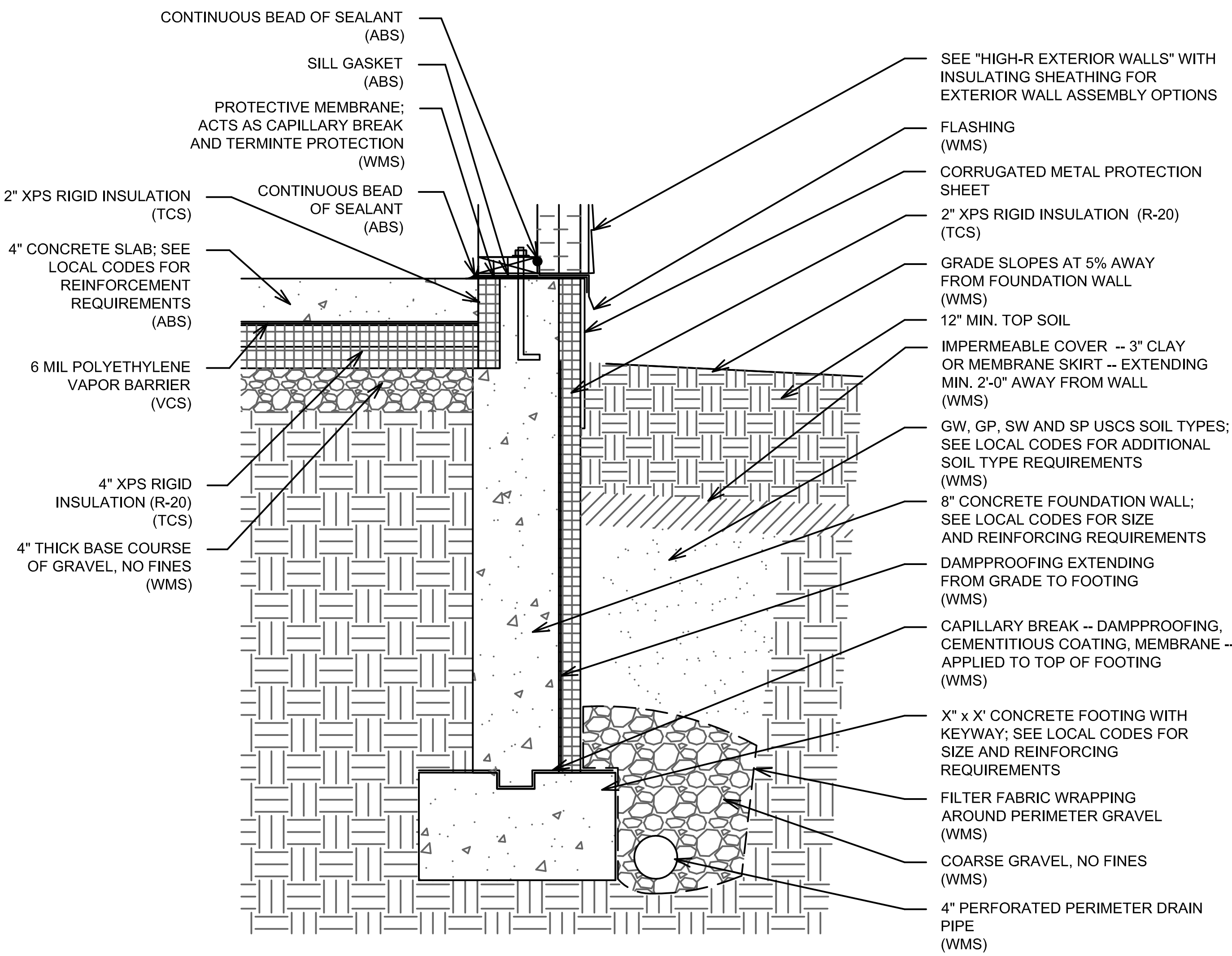


bsc with Building America U.S. Department of Energy Research Toward Zero Energy Homes

Project:	High-R Foundation Walls	*Sheet Title:*
Date:	2009-06-05 DRAFT	SG Type #2
Drawing Title:	Foundation Walls	
Drawing File:	FoundationDetails.dwg	
Drawing Scale:	3/4" = 1'-0"	

Foundation: CONCRETE
Slab on Grade Type: INDEPENDENT 4" SLAB ON GRADE
Location of Insulation: BELOW SLAB AND ON EXTERIOR OF FOUNDATION WALL
Drying: SLAB: TO INTERIOR;
FOUNDATION WALL: TO INSIDE AND OUTSIDE (ABOVE GRADE
Insulation Type, Insulation R-Value:
BELOW SLAB: 4" XPS RIGID INSULATION, R-20
EXTERIOR OF WALL: 2" XPS RIGID INSULATION, R-10

ABS: *Air Barrier System component*
TCS: *Thermal Control System component*
VCS: *Vapor Control System component*
WMS: *Water Management System component*



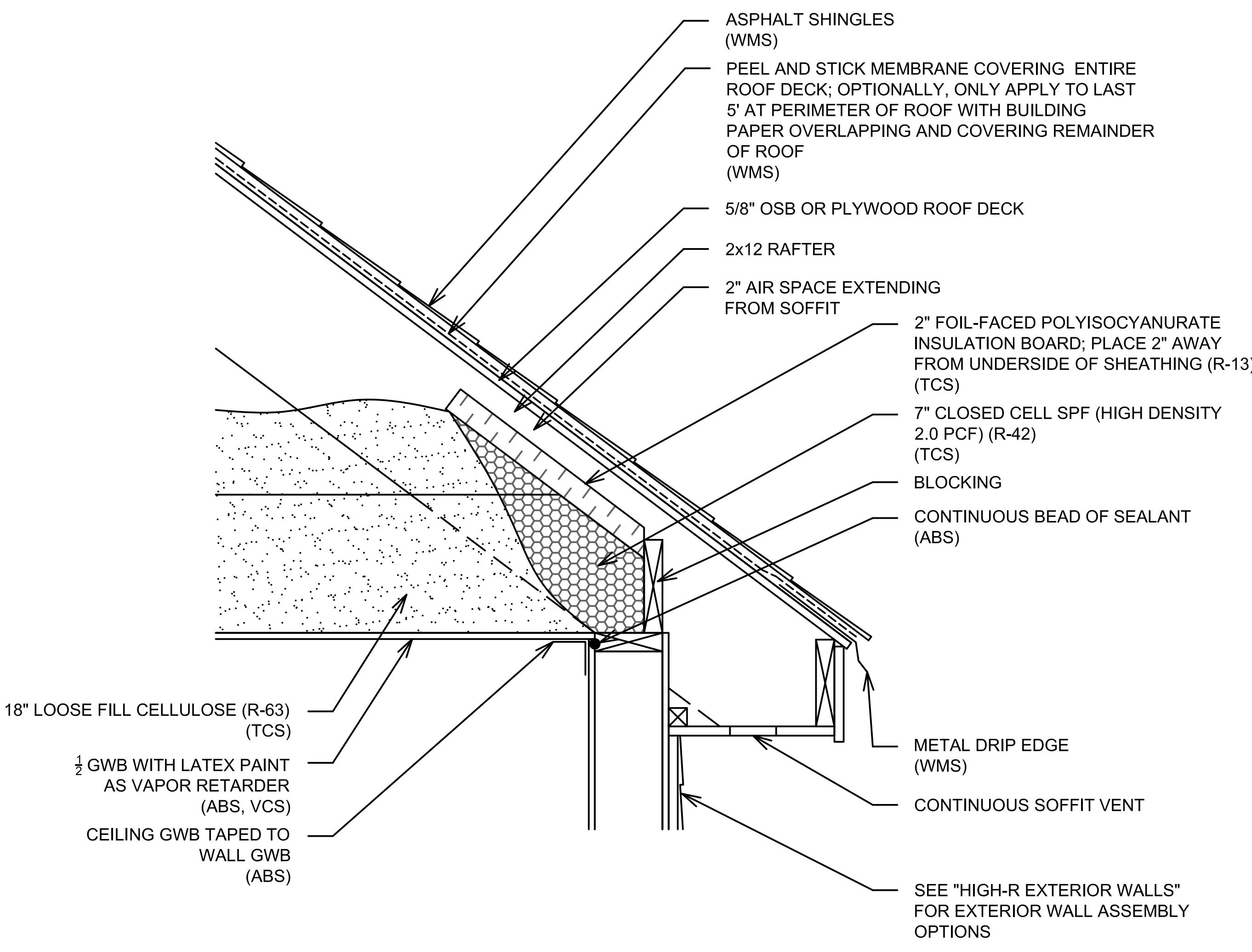
with U.S. Department of Energy
Research Toward Zero Energy Homes

Project: High-R Foundation Walls
Date: 2009-06-05 DRAFT
Drawing Title: Foundation Walls
Drawing File: FoundationDetails.dwg
Drawing Scale: 3/4" = 1'-0"

Sheet Title:
SG Type #3

Roof Structure:	2X12 RAFTER	
Vented or Unvented:	VENTED	
Attic or Cathedral:	ATTIC	
Location of Insulation:	PERIMETER + WITHIN (AND ABOVE) ATTIC FLOOR JOISTS	
Insulation Type, Insulation R-Value:	PERIMETER: 2" FOIL-FACED POLYISOCYANURATE + 7.5" CLOSED CELL SPF (HIGH DENSITY 2.0 PCF) , R-55 ATTIC FLOOR: 18" LOOSE FILL CELLULOSE, R-63	

ABS: *Air Barrier System component*
TCS: *Thermal Control System component*
VCS: *Vapor Control System component*
WMS: *Water Management System component*



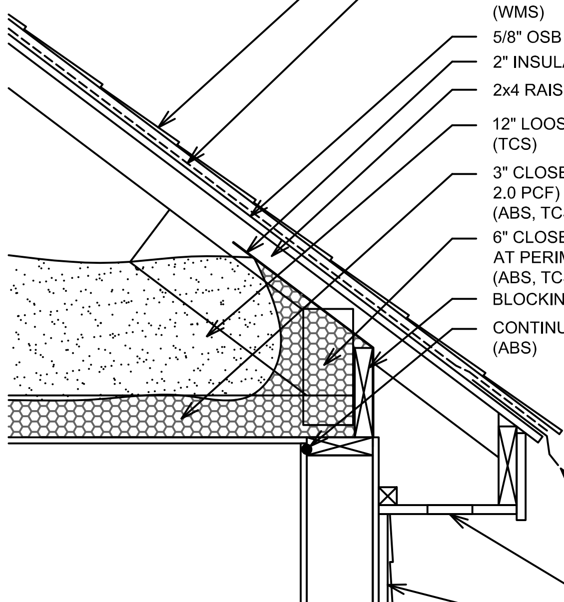
bsc with Building America U.S. Department of Energy Research Toward Zero Energy Homes

Project:	High-R Assemblies
Date:	2009-07-03 DRAFT
Drawing Title:	Roof Assemblies
Drawing File:	RoofDetails.dwg
Drawing Scale:	3/4" = 1'-0"

Sheet Title:

Roof Type #1

Roof Structure:	2X4 RAISED TRUSS	ABS: *Air Barrier System component*
Vented or Unvented:	VENTED	TCS: *Thermal Control System component*
Attic or Cathedral:	ATTIC	VCS: *Vapor Control System component*
Location of Insulation:	PERIMETER + AT ATTIC FLOOR	WMS: *Water Management System component*
Insulation Type, Insulation R-Value:	PERIMETER: 3" CLOSED CELL SPF (HIGH DENSITY 2.0 PCF), R-18 ATTIC FLOOR: 3" CLOSED CELL + 12" LOOSE FILL CELLULOSE, R-60	

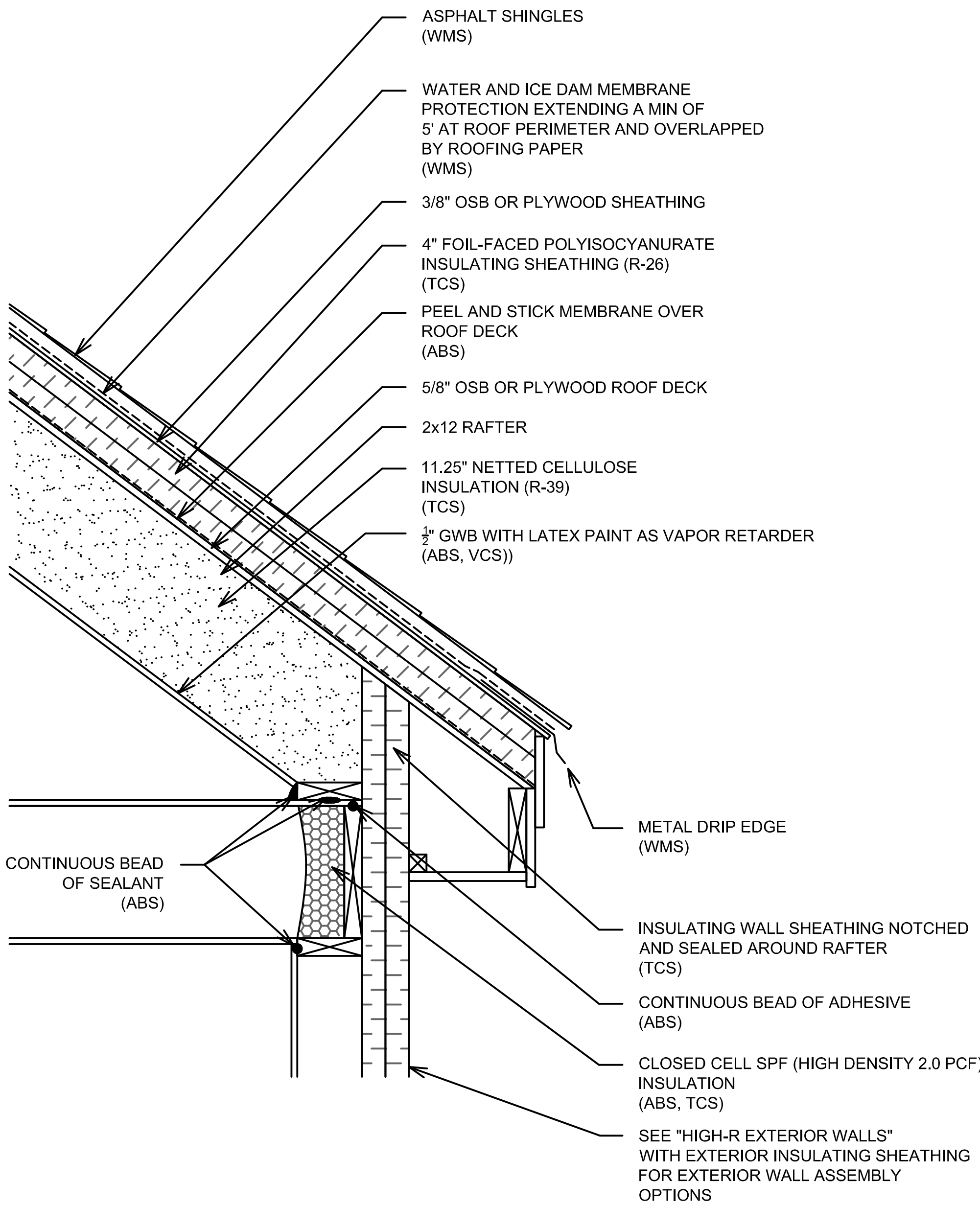


with

Project:	High-R Assemblies	*Sheet Title:*
Date:	2009-07-03 DRAFT	
Drawing Title:	Roof Assemblies	**Roof Type #2**
Drawing File:	RoofDetails.dwg	
Drawing Scale:	3/4" = 1'-0"	

Roof Structure:	2X12 RAFTER
Vented or Unvented:	UNVENTED
Attic or Cathedral:	CATHEDRAL
Location of Insulation:	ABOVE ROOF DECK AND IN RAFTER CAVITY
Insulation Type, Insulation R-Value:	4" FOIL-FACED POLYISOCYANURATE ABOVE ROOF DECK + 11.25" CELLULOSE IN RAFTER CAVITY, R-65
Climate/Zone:	*Cold Climate/up to Zone 6*

ABS: *Air Barrier System component*
TCS: *Thermal Control System component*
VCS: *Vapor Control System component*
WMS: *Water Management System component*



bsc with Building America U.S. Department of Energy *Research Toward Zero Energy Homes*

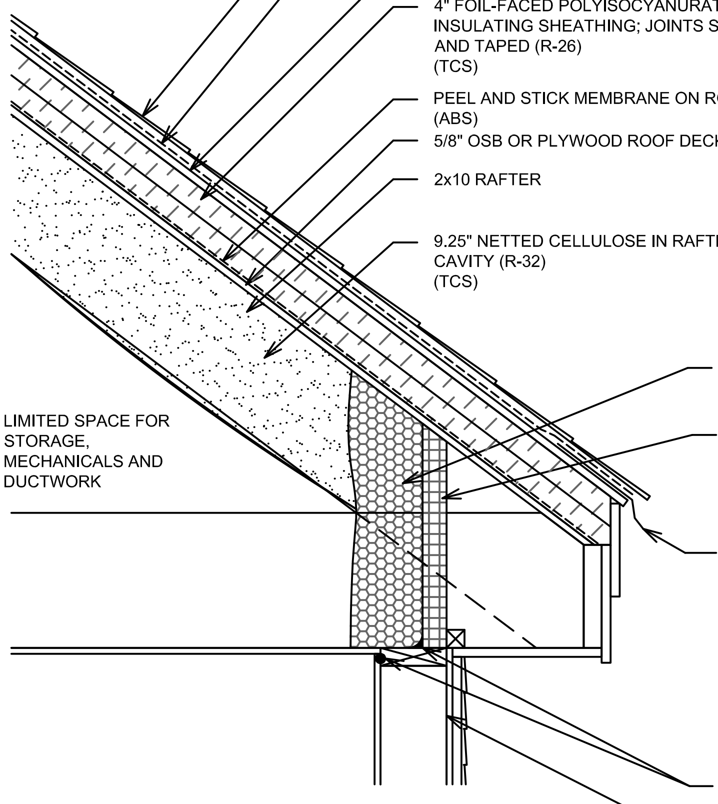
Project:	High-R Assemblies
Date:	2009-07-03 DRAFT
Drawing Title:	Roof Assemblies
Drawing File:	RoofDetails.dwg
Drawing Scale:	3/4" = 1'-0"

Sheet Title:

Roof Type #3

Roof Structure:	2X10 RAFTER
Vented or Unvented:	UNVENTED
Attic or Cathedral:	ATTIC
Location of Insulation:	ABOVE ROOF DECK AND IN RAFTER CAVITY
Insulation Type, Insulation R-Value:	ROOF: 4" FOIL-FACED POLYISOCYANURATE ABOVE ROOF DECK + 9.25" CELLULOSE IN RAFTER CAVITY, R-58 PERIMETER: 6" CLOSED CELL SPF (HIGH DENSITY 2.0 PCF), R-36
Climate/Zone:	Cold Climate/up to Zone 6

ABS: *Air Barrier System component*
TCS: *Thermal Control System component*
VCS: *Vapor Control System component*
WMS: *Water Management System component*



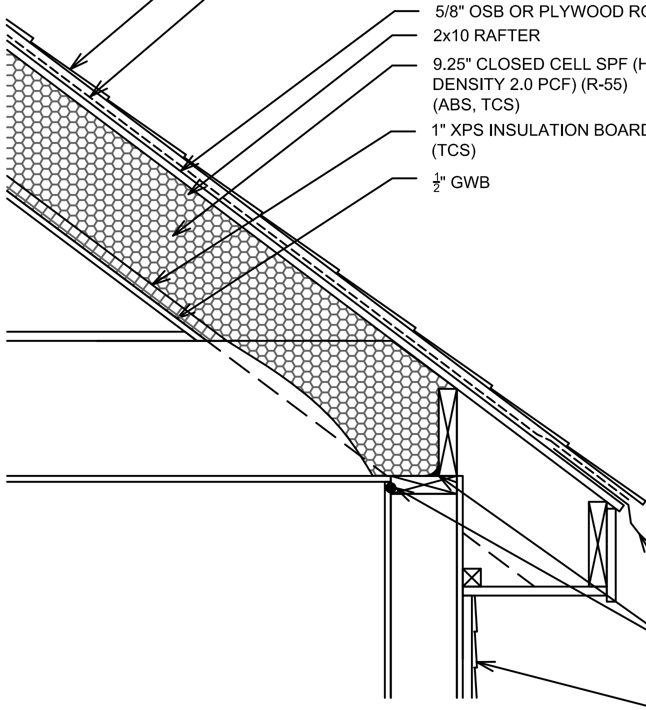
bsc with Building America U.S. Department of Energy Research Toward Zero Energy Homes

Project:	High-R Assemblies
Date:	2009-07-03 DRAFT
Drawing Title:	Roof Assemblies
Drawing File:	RoofDetails.dwg
Drawing Scale:	3/4" = 1'-0"

Sheet Title:

Roof Type #4

Roof Structure:	2X10 RAFTER	ABS:	*Air Barrier System component*
Vented or Unvented:	UNVENTED	TCS:	*Thermal Control System component*
Attic or Cathedral:	CATHEDRAL	VCS:	*Vapor Control System component*
Location of Insulation:	RAFTER CAVITY	WMS:	*Water Management System component*
Insulation Type, Insulation R-Value:	9.25" CLOSED CELL SPF (HIGH DENSITY 2.0 PCF) + 1" RIGID INSULATION UNDER RAFTER, R-60		



Project:	High-R Assemblies	*Sheet Title:*	
Date:	2009-07-03 DRAFT		
Drawing Title:	Roof Assemblies		Roof Type #5
Drawing File:	RoofDetails.dwg		
Drawing Scale:	3/4" = 1'-0"		

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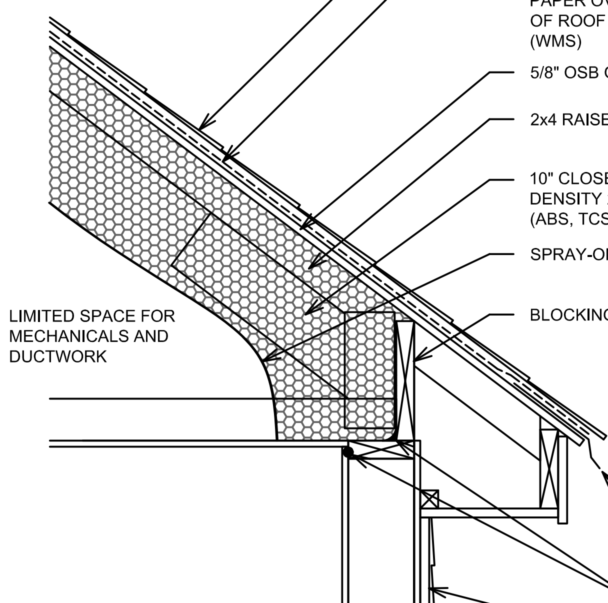
Roof Structure:	2x4 RAISED TRUSS
Vented or Unvented:	UNVENTED
Attic or Cathedral:	ATTIC
Location of Insulation:	BELOW ROOF DECK
Insulation Type, Insulation R-Value:	10" CLOSED CELL SPF (HIGH DENSITY 2.0 PCF), R-60

ABS: *Air Barrier System component*
TCS: *Thermal Control System component*
VCS: *Vapor Control System component*
WMS: *Water Management System component*



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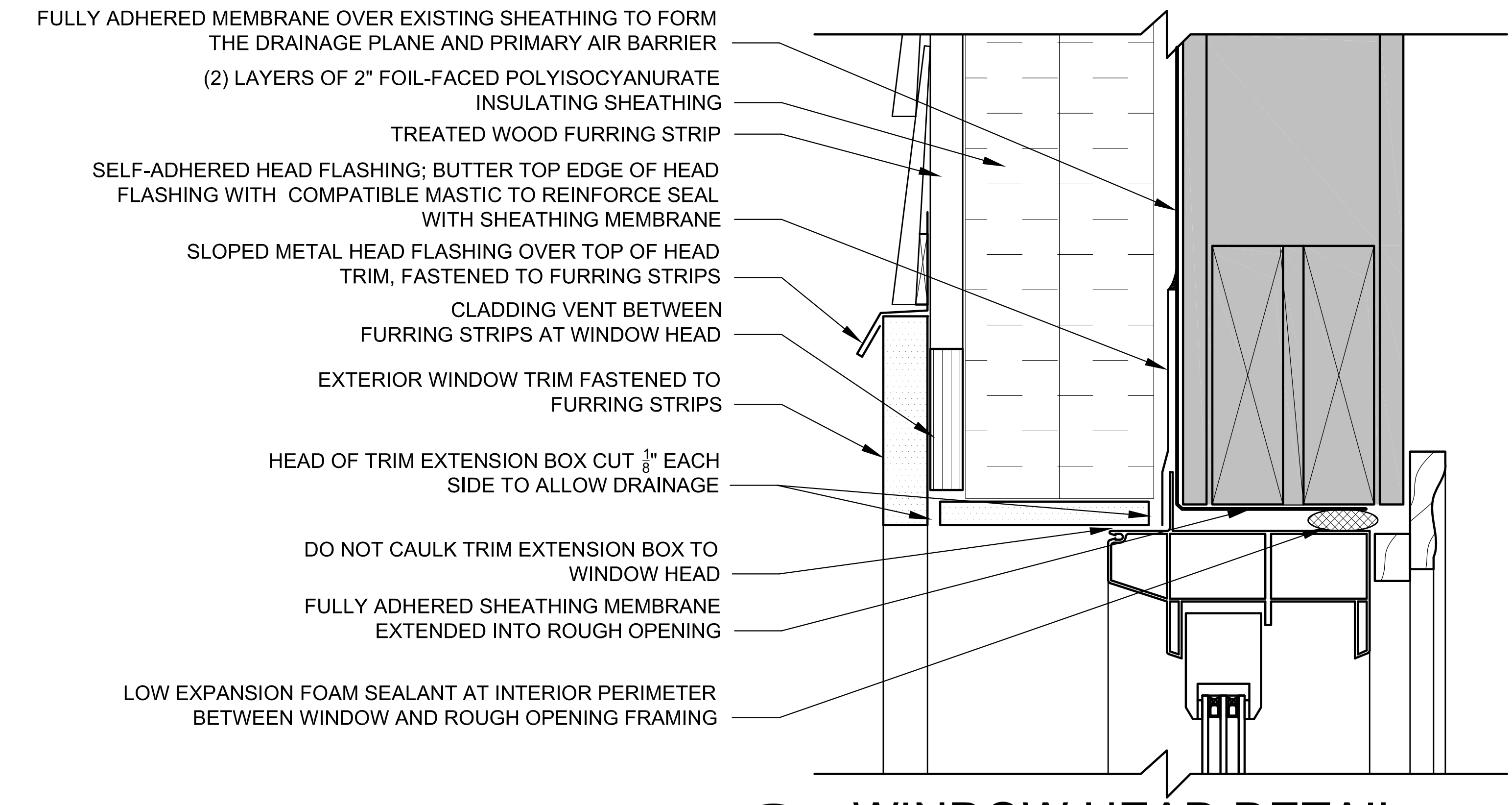
Project:	High-R Assemblies
Date:	2009-07-03 DRAFT
Drawing Title:	Roof Assemblies
Drawing File:	RoofDetails.dwg
Drawing Scale:	3/4" = 1'-0"

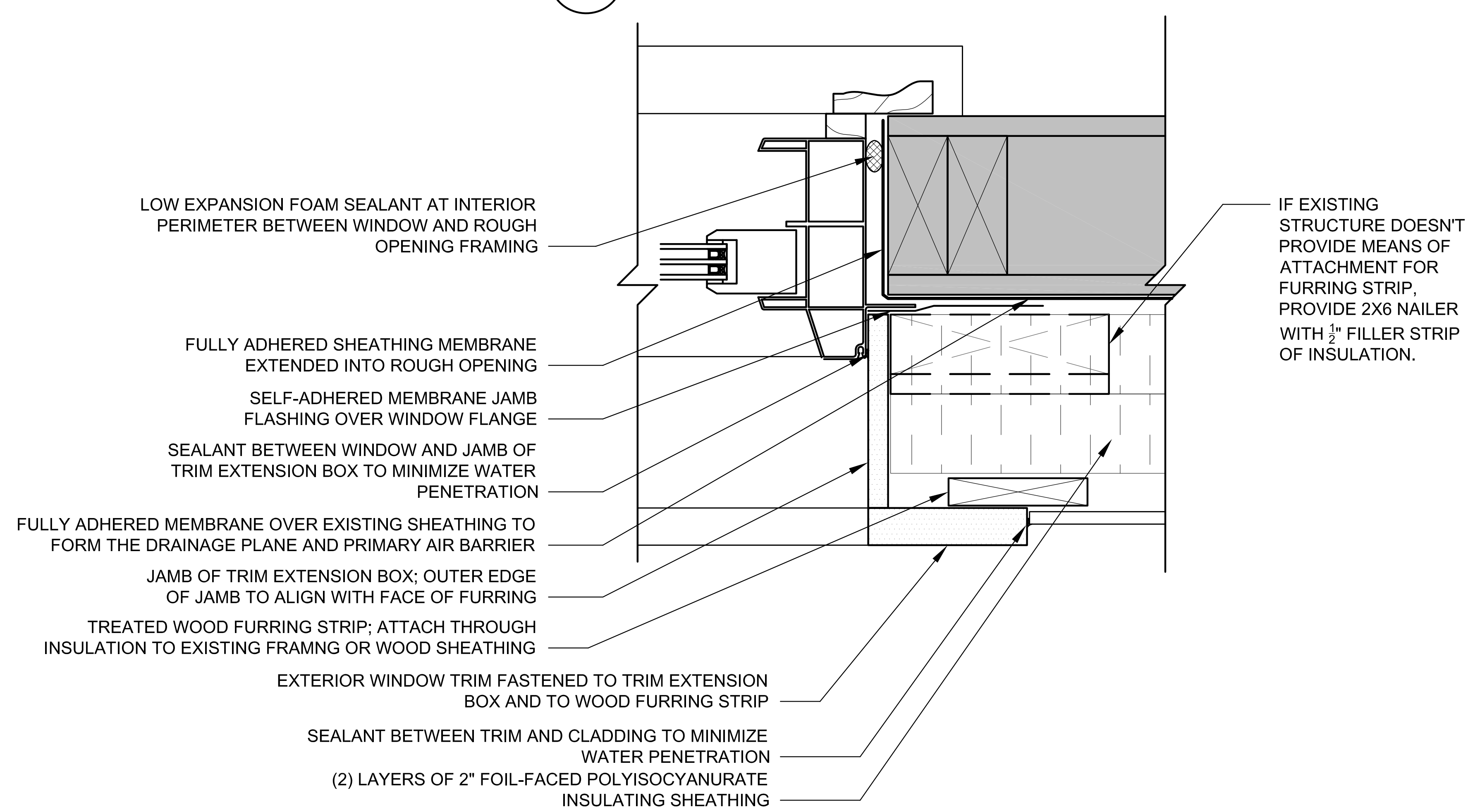
Sheet Title:

Roof Type #6



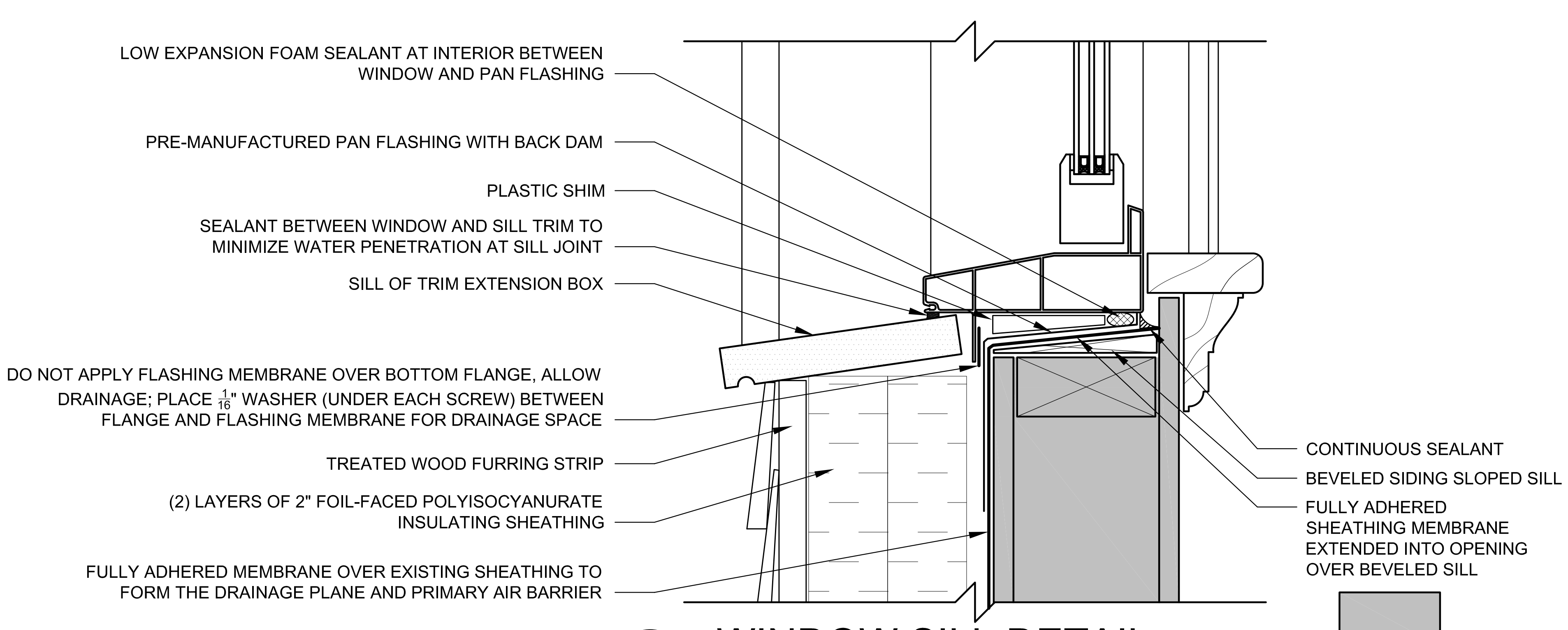
3 WINDOW HEAD DETAIL

SCALE: 3" = 1'-0"



2 WINDOW JAMB DETAIL

SCALE: 3" = 1'-0"



1 WINDOW SILL DETAIL

SCALE: 3" = 1'-0"

GRAY TONE INDICATES EXISTING STRUCTURE

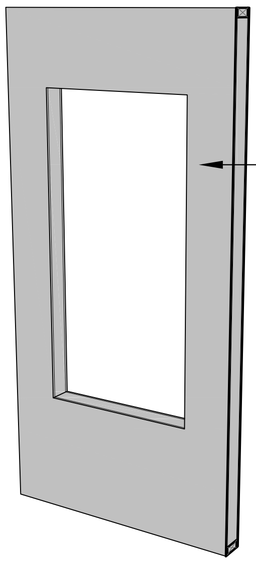
bsc with Building America U.S. Department of Energy Research Toward Zero Energy Homes

Project:	Deep Energy Retrofit
Date:	2009-08-28 DRAFT
Drawing Title:	Window Details
Drawing File:	InnerRetrofitDetails.dwg
Drawing Scale:	3" = 1'-0"

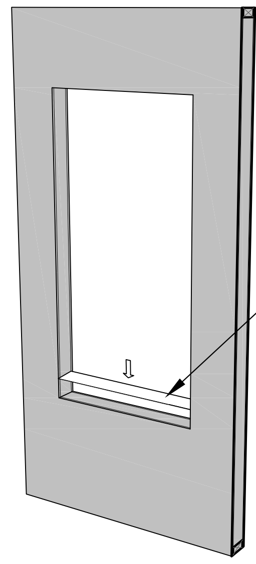
Sheet Title:

Win-1

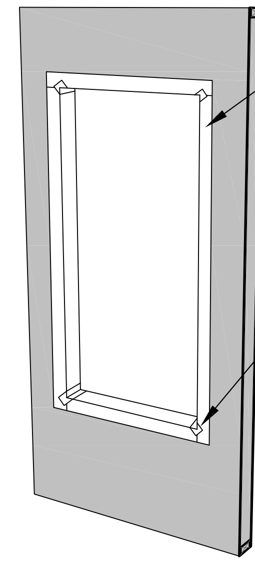
C-231



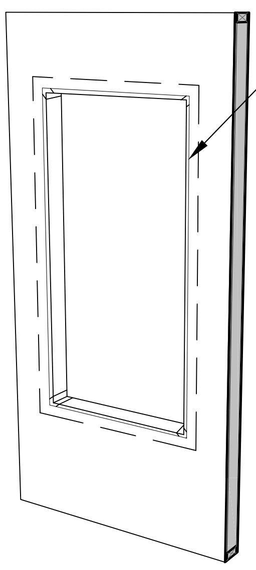
STEP 1



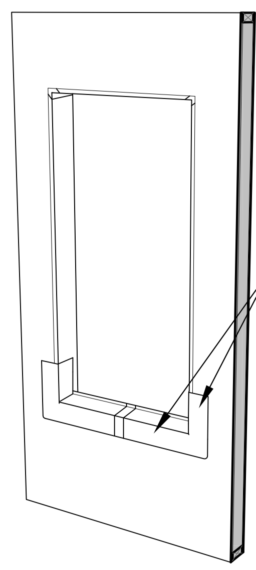
STEP 2



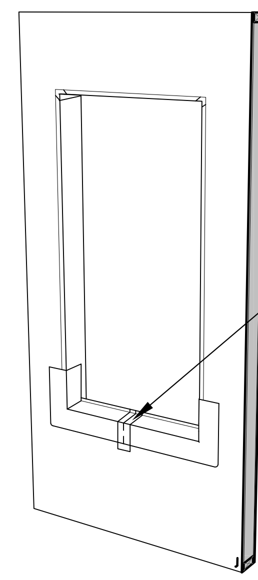
STEP 3



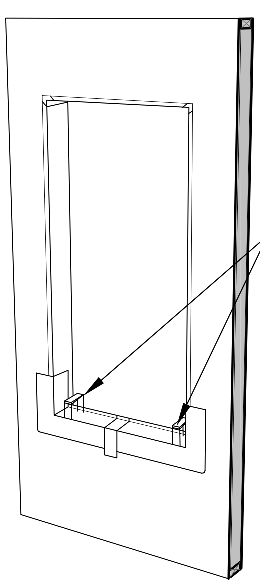
STEP 4



STEP 5



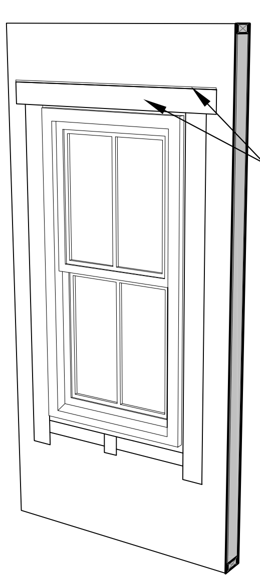
STEP 6



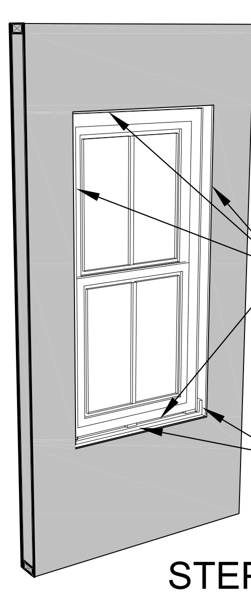
STEP 7

STEP 8

STEP 9



STEP 10



STEP 11

GRAY TONE INDICATES EXISTING STRUCTURE

1 WINDOW INSTALLATION SEQUENCE

N.T.S.

bsc with Building America U.S. Department of Energy Research Toward Zero Energy Homes

Project:	Deep Energy Retrofit
Date:	2009-08-20 DRAFT
Drawing Title:	Window Installation Sequence
Drawing File:	InnerRetrofitDetails.dwg
Drawing Scale:	N.T.S.

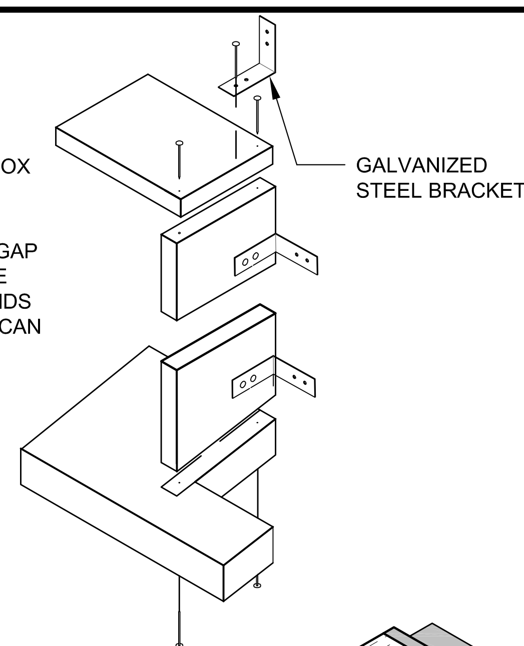
Sheet Title:

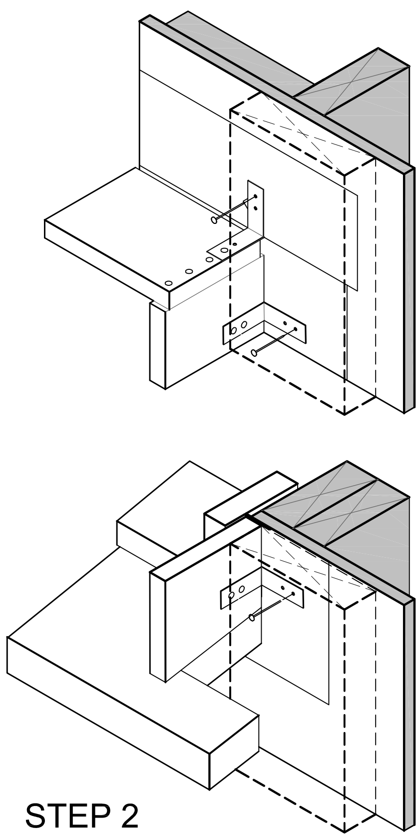
Win-2

C-292

STEP 1

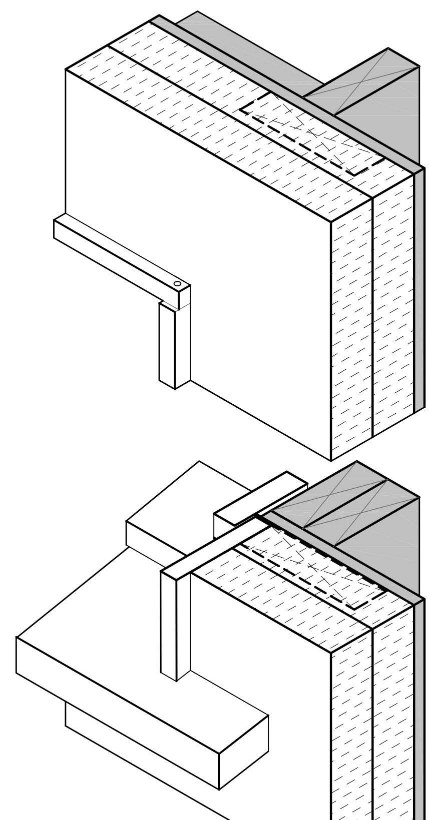
PREASSEMBLE TRIM EXTENSION BOX USING WATER-RESISTANT TRIM MATERIAL; CUT HEAD PIECE $\frac{1}{4}$" NARROW TO ALLOW $\frac{1}{8}$" DRAINAGE GAP TO EITHER SIDE; SLOPE SILL PIECE FOR DRAINAGE; NOTCH SILL AT ENDS SO THAT INSULATING SHEATHING CAN BE PLACED BEHIND IT.





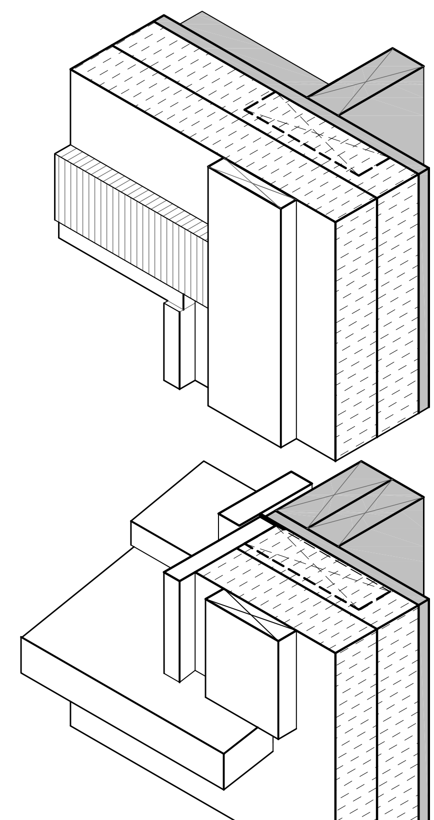
STEP 2

ATTACH TRIM EXTENSION BOX AFTER WINDOW IS INSTALLED AND INTEGRATED INTO DRAINAGE PLANE; IF OPTIONAL NAILER IS NEEDED, ATTACH EXTENSION BOX DIRECTLY TO NAILER



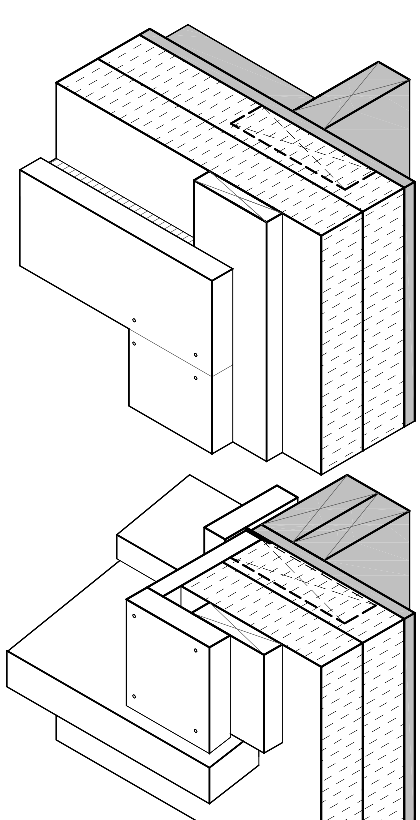
STEP 3

INSTALL INSULATING SHEATHING UP TIGHT TO THE TRIM EXTENSION BOX



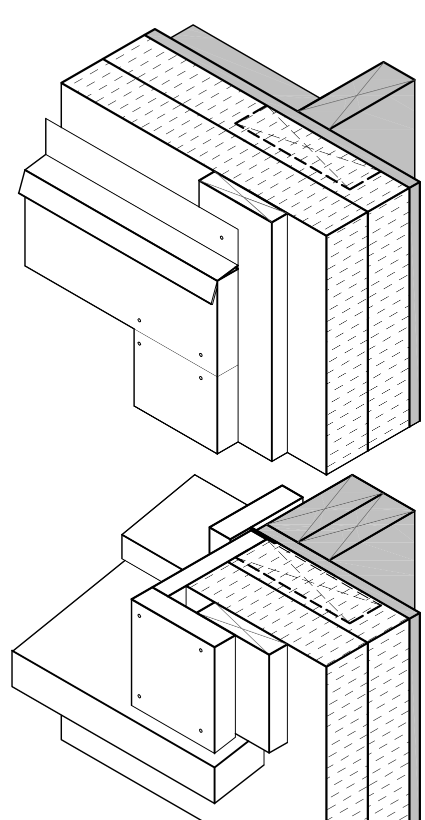
STEP 4

INSTALL 1 x 4 FURRING TO SUPPORT WINDOW TRIM AND CLADDING. INSTALL CLADDING VENT BETWEEN FURRING STRIPS AT WINDOW HEAD



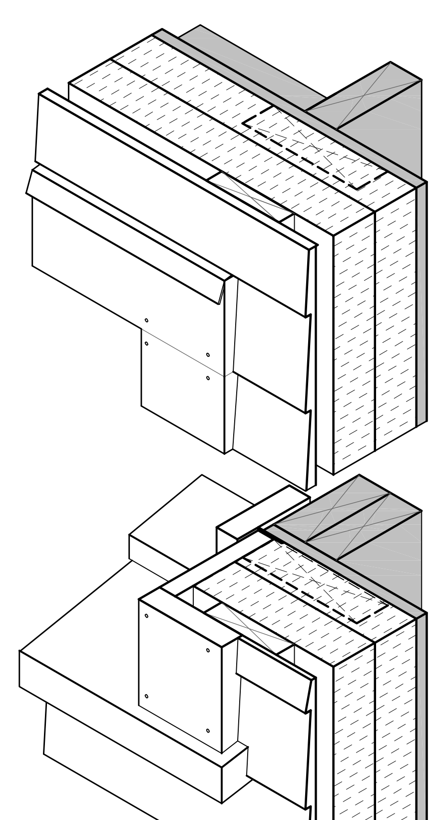
STEP 5

INSTALL WINDOW TRIM; FASTEN TO TRIM EXTENSION BOX AND TO FURRING



STEP 6

INSTALL SLOPED METAL HEAD FLASHING OVER HEAD TRIM, FASTEN TO FURRING STRIPS



STEP 7

INSTALL CLADDING

GRAY TONE INDICATES EXISTING STRUCTURE

1 WINDOW TRIM INSTALLATION SEQUENCE

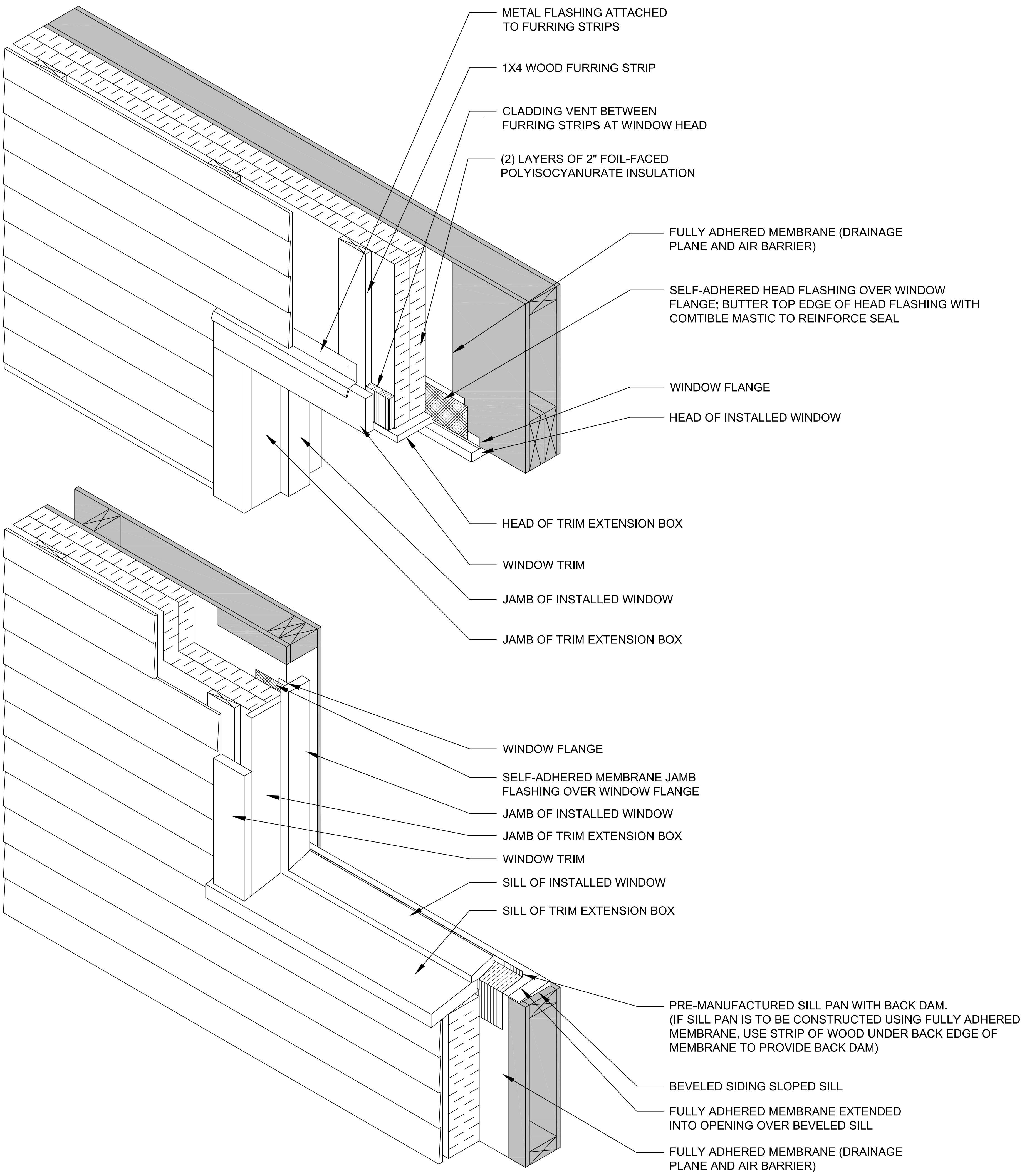
N.T.S.

with

Project:	Deep Energy Retrofit
Date:	2009-08-20 DRAFT
Drawing Title:	Window Trim Installation Sequence
Drawing File:	InnerRetrofitDetails.dwg
Drawing Scale:	N.T.S.

Sheet Title:

Win-3



GRAY TONE INDICATES EXISTING STRUCTURE

1 ENCLOSURE ASSEMBLY WITH WINDOW OPENING

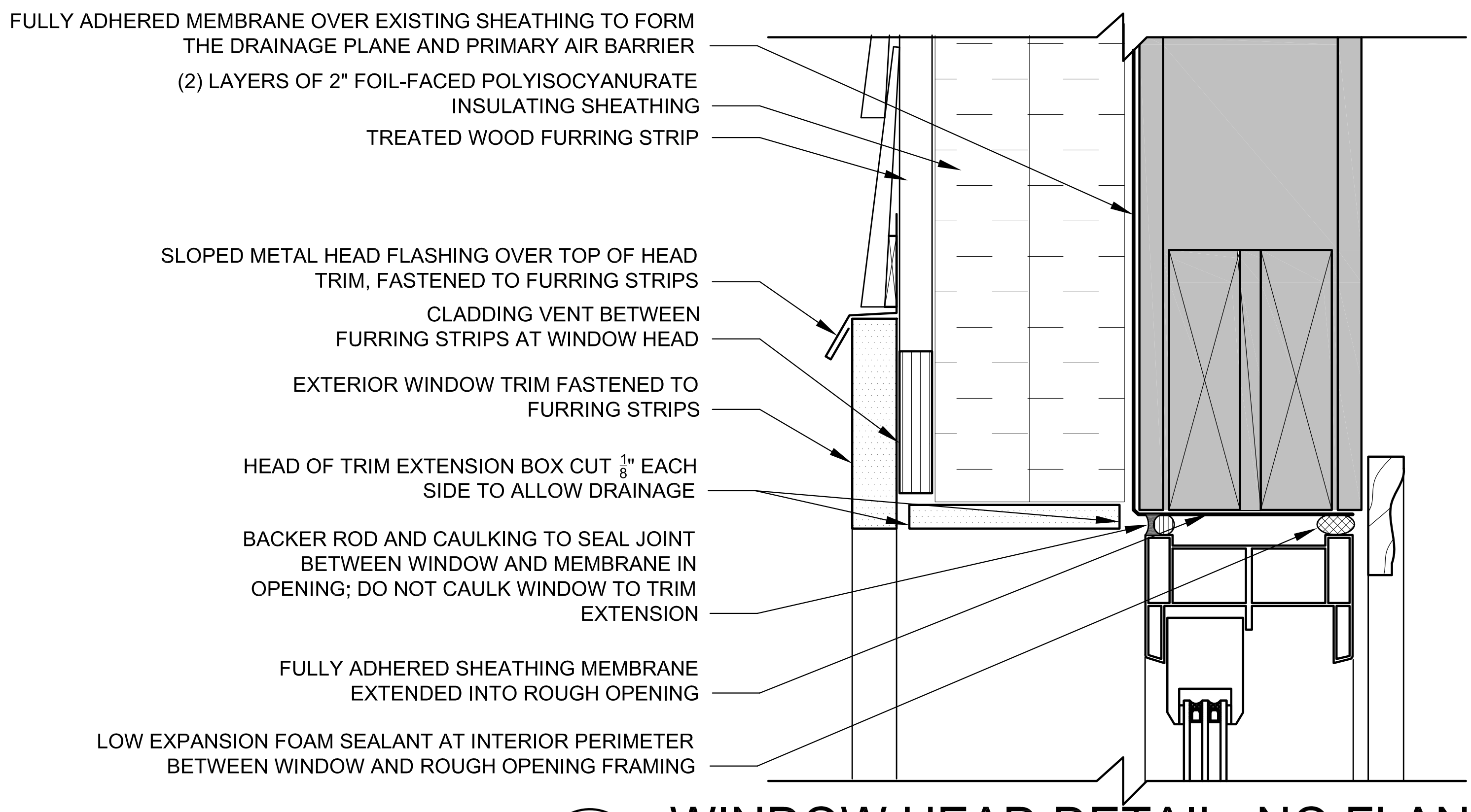
N.T.S.

bsc with Building America U.S. Department of Energy Research Toward Zero Energy Homes

Project: Deep Energy Retrofit
Date: 2009-08-20 DRAFT
Drawing Title: Enclosure Assembly with Window Opening
Drawing File: InnerRetrofitDetails.dwg
Drawing Scale: N.T.S.

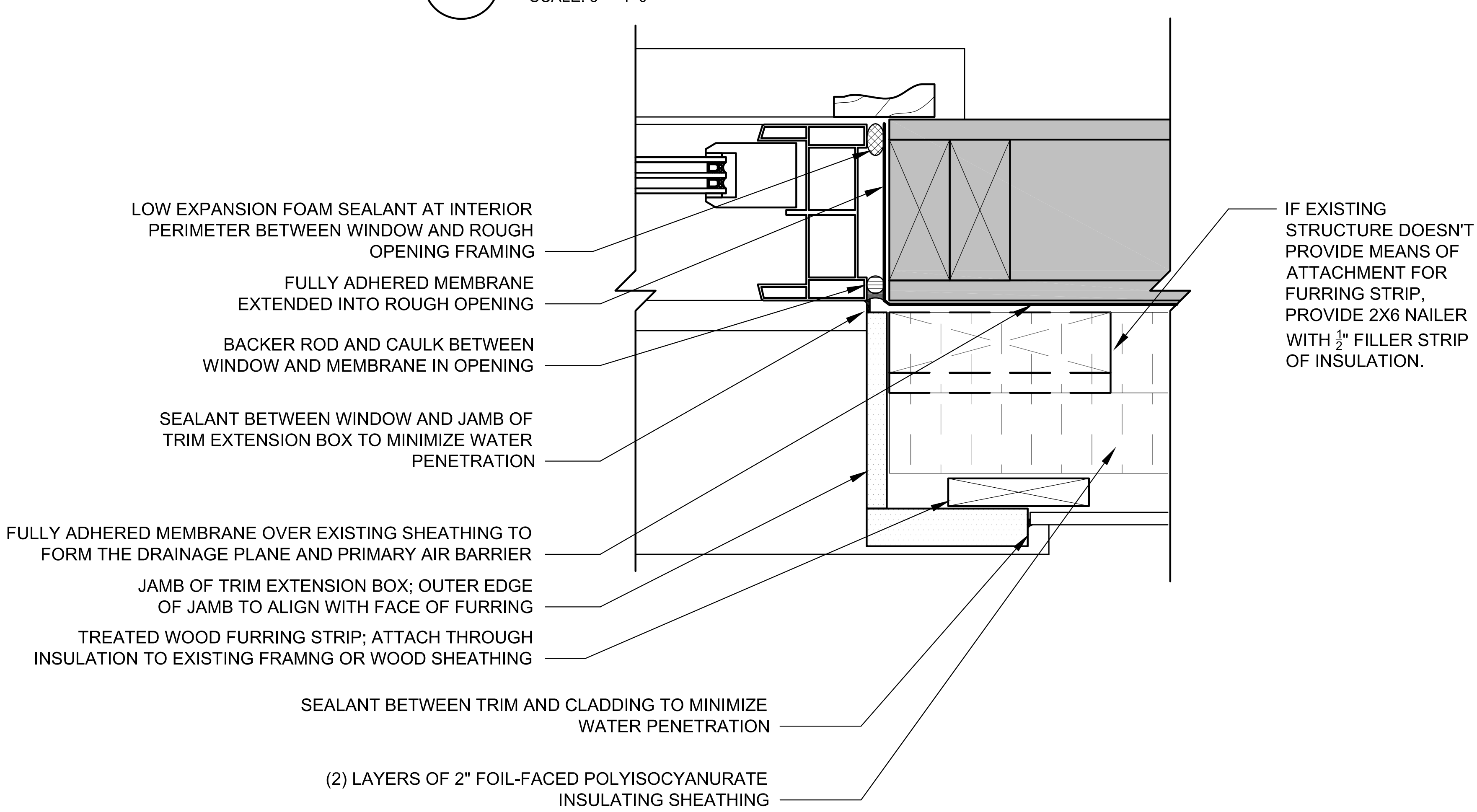
Sheet Title:
Win-4

C-294



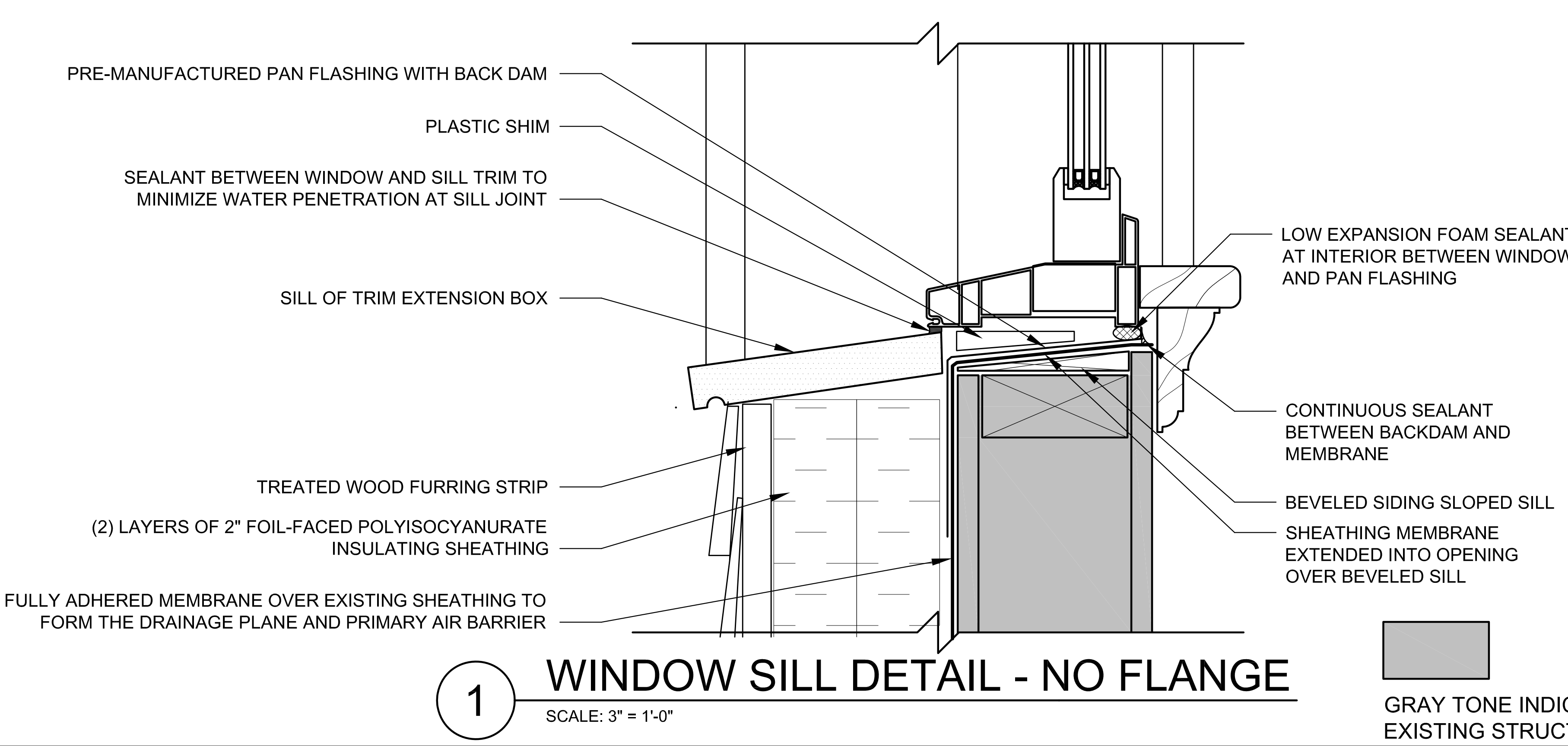
3 WINDOW HEAD DETAIL- NO FLANGE

SCALE: 3" = 1'-0"



2 WINDOW JAMB DETAIL - NO FLANGE

SCALE: 3" = 1'-0"



1 WINDOW SILL DETAIL - NO FLANGE

SCALE: 3" = 1'-0"

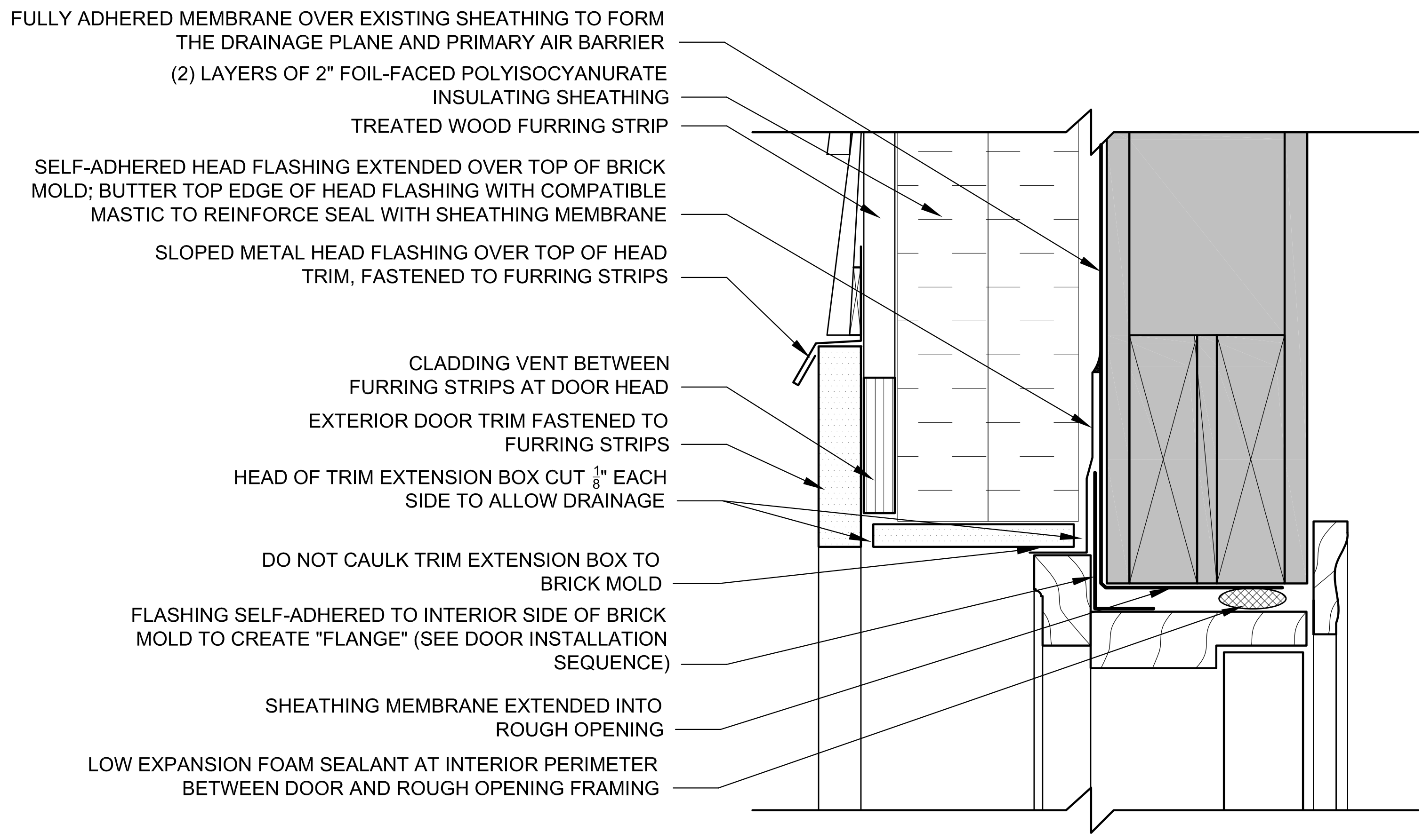
GRAY TONE INDICATES EXISTING STRUCTURE

bsc with Building America U.S. Department of Energy Research Toward Zero Energy Homes

Project:	Deep Energy Retrofit
Date:	2009-08-28 DRAFT
Drawing Title:	Window Details
Drawing File:	InnerRetrofitDetails.dwg
Drawing Scale:	3" = 1'-0"

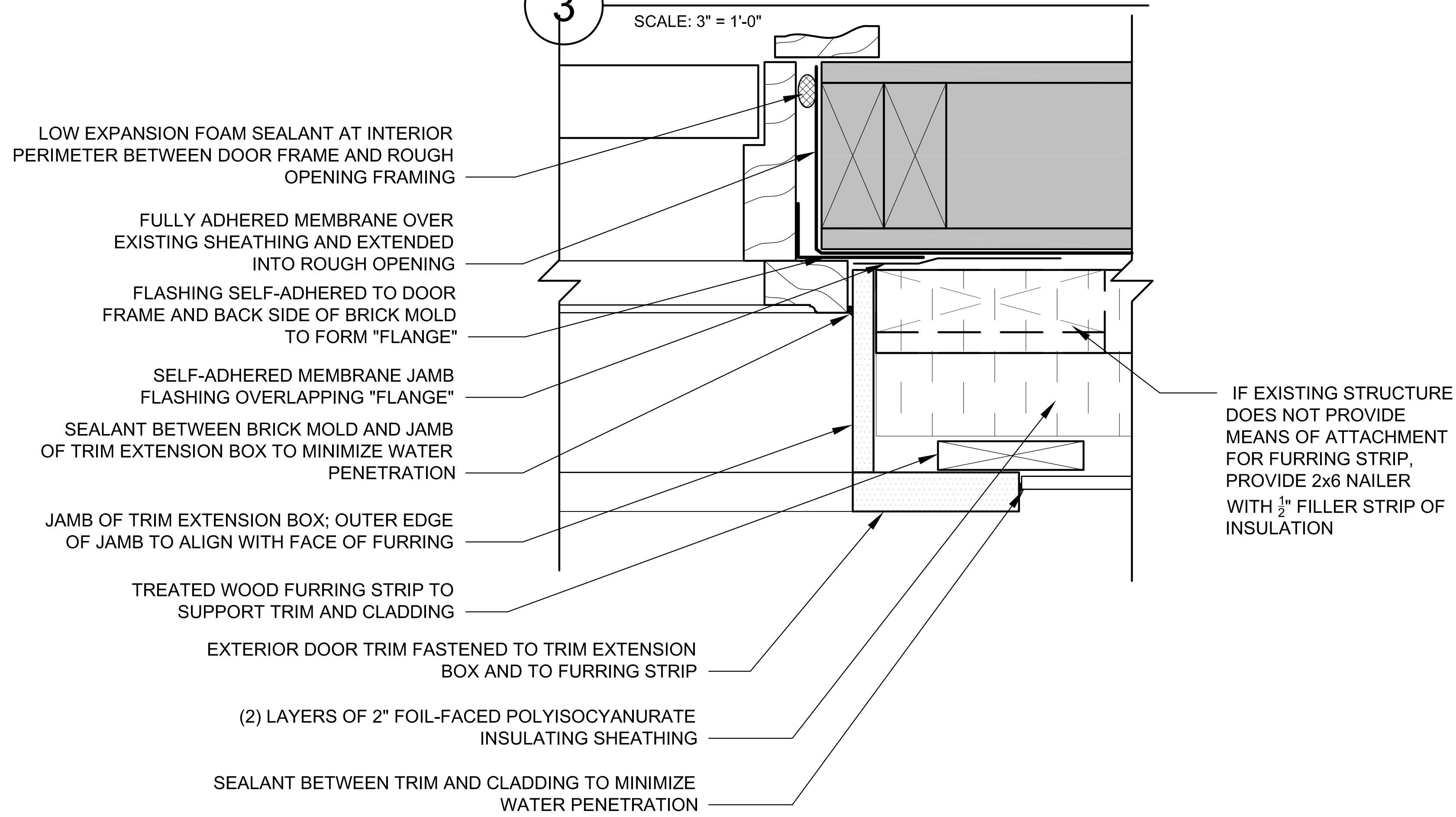
Sheet Title:

Win-1A



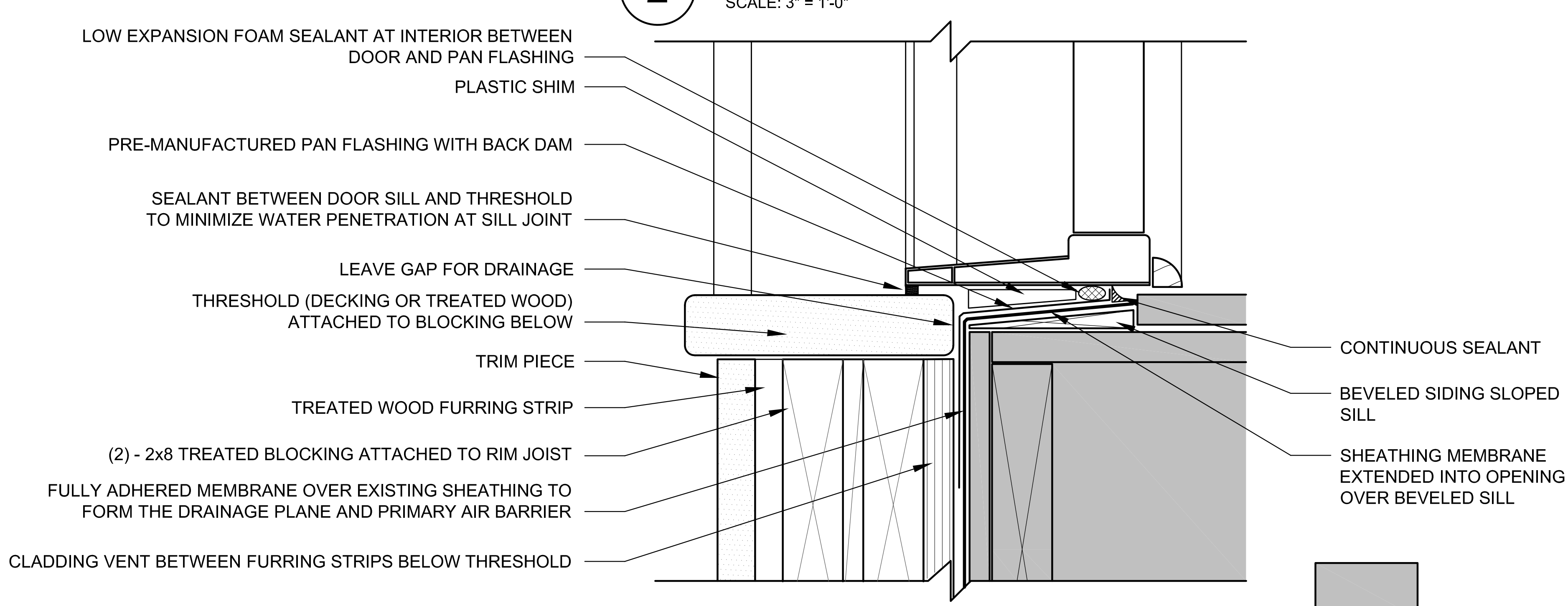
3 DOOR HEAD DETAIL

SCALE: 3" = 1'-0"



2 DOOR JAMB DETAIL

SCALE: 3" = 1'-0"



1 DOOR SILL DETAIL

SCALE: 3" = 1'-0"

GRAY TONE INDICATES EXISTING STRUCTURE

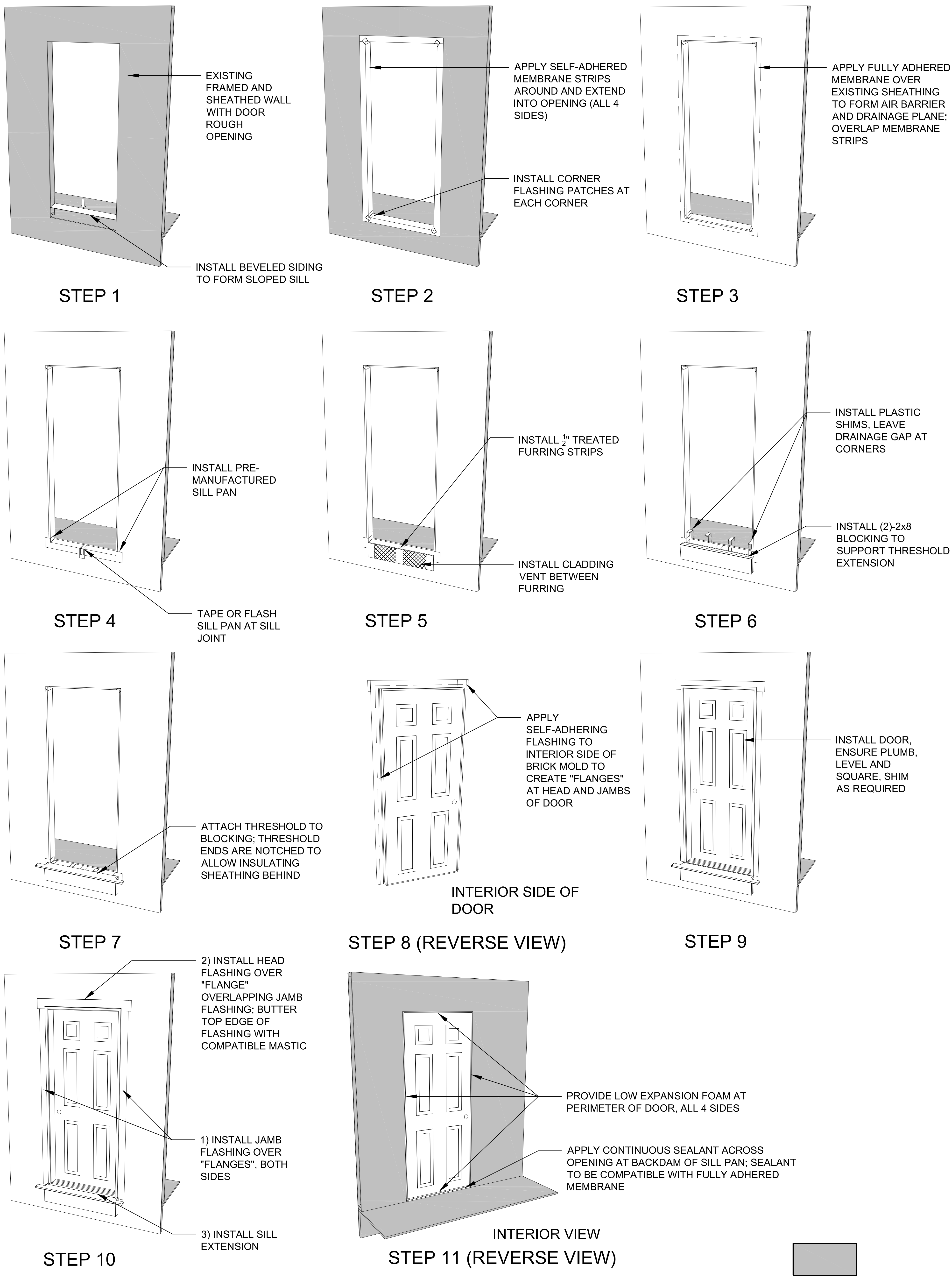
bsc with Building America U.S. Department of Energy Research Toward Zero Energy Homes

Project:	Deep Energy Retrofit
Date:	2009-08-20 DRAFT
Drawing Title:	Door Details
Drawing File:	InnerRetrofitDetails.dwg
Drawing Scale:	3" = 1'-0"

Sheet Title:

Door-1

C-290



GRAY TONE INDICATES EXISTING STRUCTURE

1 DOOR INSTALLATION SEQUENCE

N.T.S.

bsc with Building America U.S. Department of Energy Research Toward Zero Energy Homes

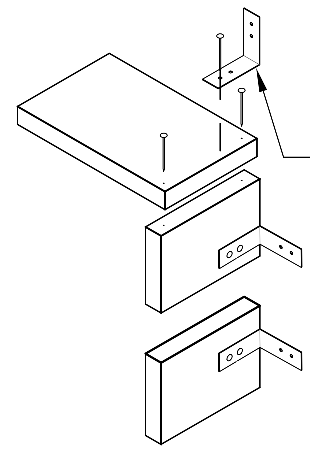
Project:	Deep Energy Retrofit
Date:	2009-08-20 DRAFT
Drawing Title:	Door Installation Sequence
Drawing File:	InnerRetrofitDetails.dwg
Drawing Scale:	N.T.S.

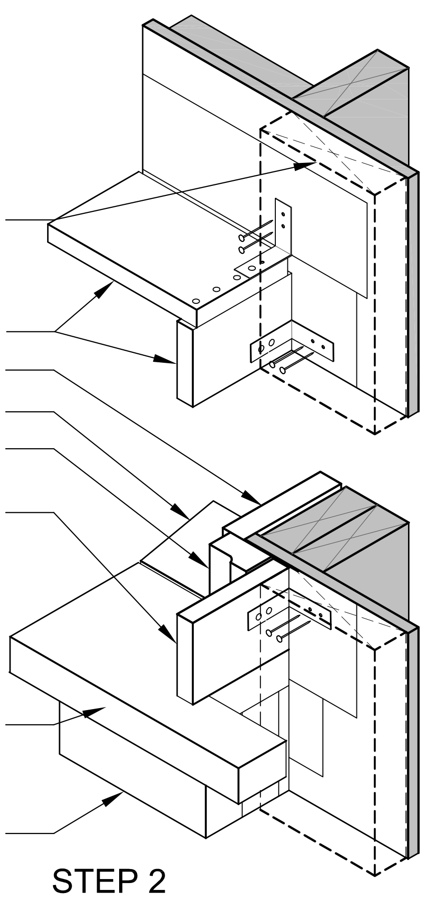
Sheet Title:

Door-2

STEP 1

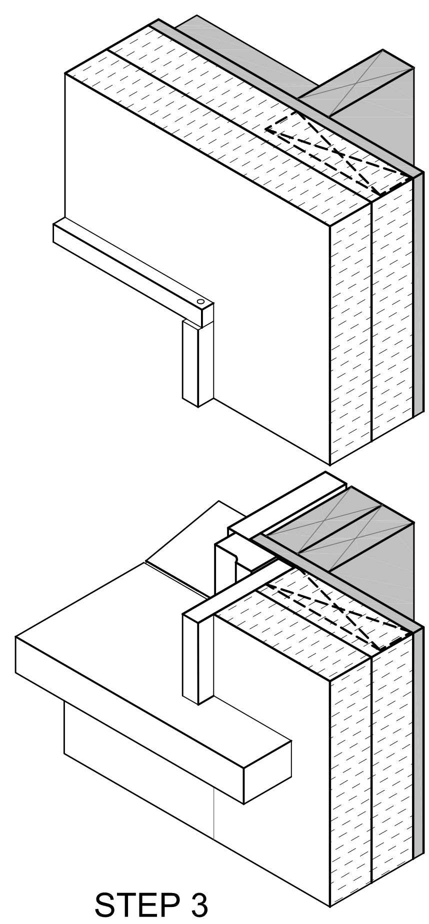
PREASSEMBLE TRIM EXTENSION BOX USING WATER-RESISTANT TRIM MATERIAL; CUT HEAD PIECE ¼" NARROW TO ALLOW ⅛" DRAINAGE GAP TO EITHER SIDE; TRIM EXTENSION BOX CONSISTS OF HEAD AND JAMBS WHICH FIT AROUND THE BRICK MOLD AND REACH DOWN TO THE THRESHOLD. THE THRESHOLD AND THRESHOLD SUPPORT ARE ATTACHED DURING DOOR INSTALLATION.





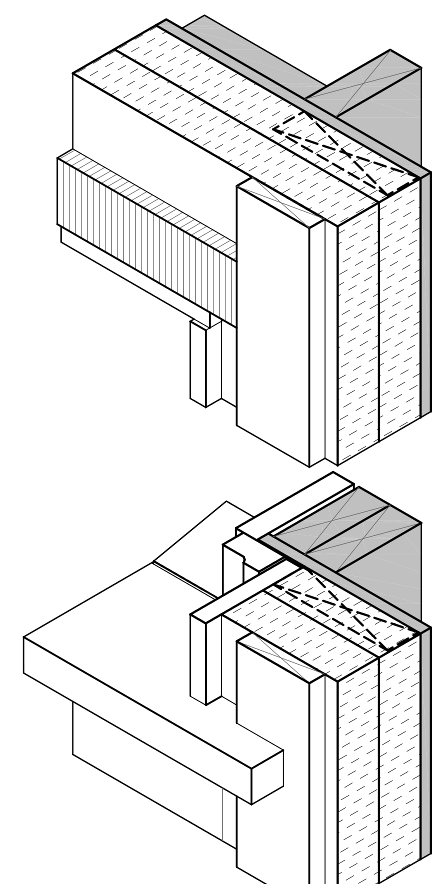
STEP 2

ATTACH TRIM EXTENSION BOX AFTER DOOR IS INSTALLED AND INTEGRATED INTO DRAINAGE PLANE



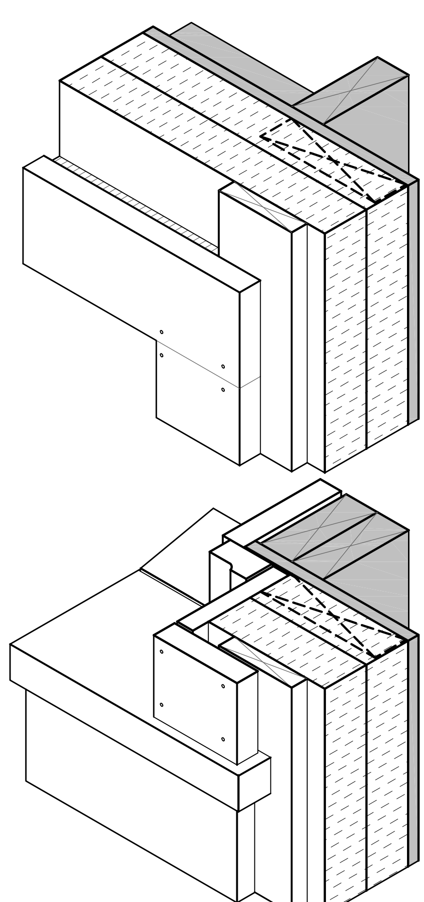
STEP 3

INSTALL INSULATING SHEATHING UP TIGHT TO THE TRIM EXTENSION BOX, THE THRESHOLD, AND THE BLOCKING UNDER THRESHOLD



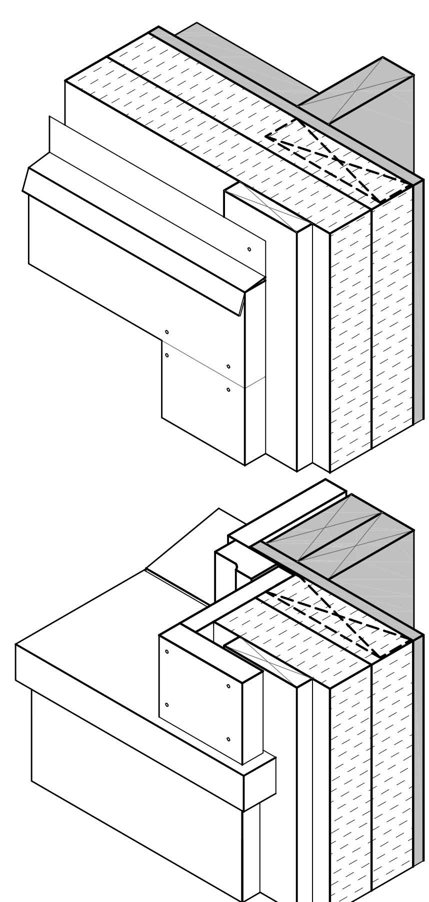
STEP 4

INSTALL 1 x 4 FURRING TO SUPPORT DOOR TRIM AND CLADDING. INSTALL CLADDING VENT BETWEEN FURRING STRIPS AT DOOR HEAD



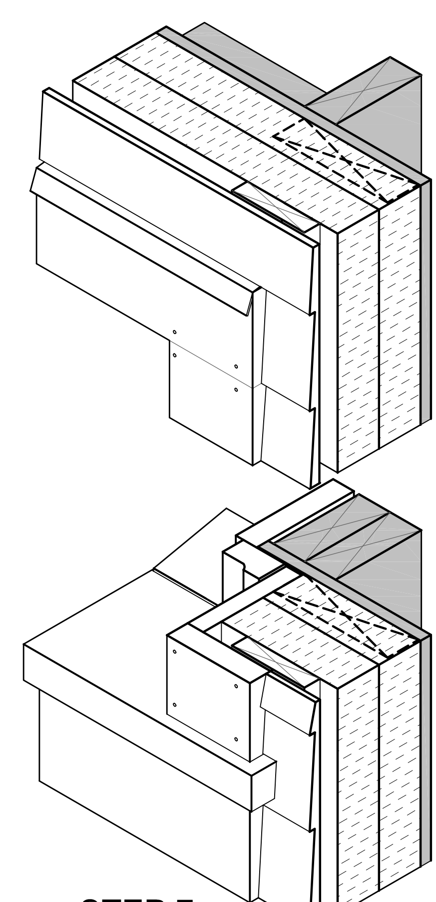
STEP 5

INSTALL DOOR TRIM, FASTEN TO TRIM EXTENSION BOX AND FURRING



STEP 6

INSTALL SLOPED METAL HEAD FLASHING OVER HEAD TRIM, FASTEN TO FURRING STRIPS



STEP 7

INSTALL CLADDING

GRAY TONE INDICATES EXISTING STRUCTURE

1 DOOR TRIM INSTALLATION SEQUENCE

N.T.S.

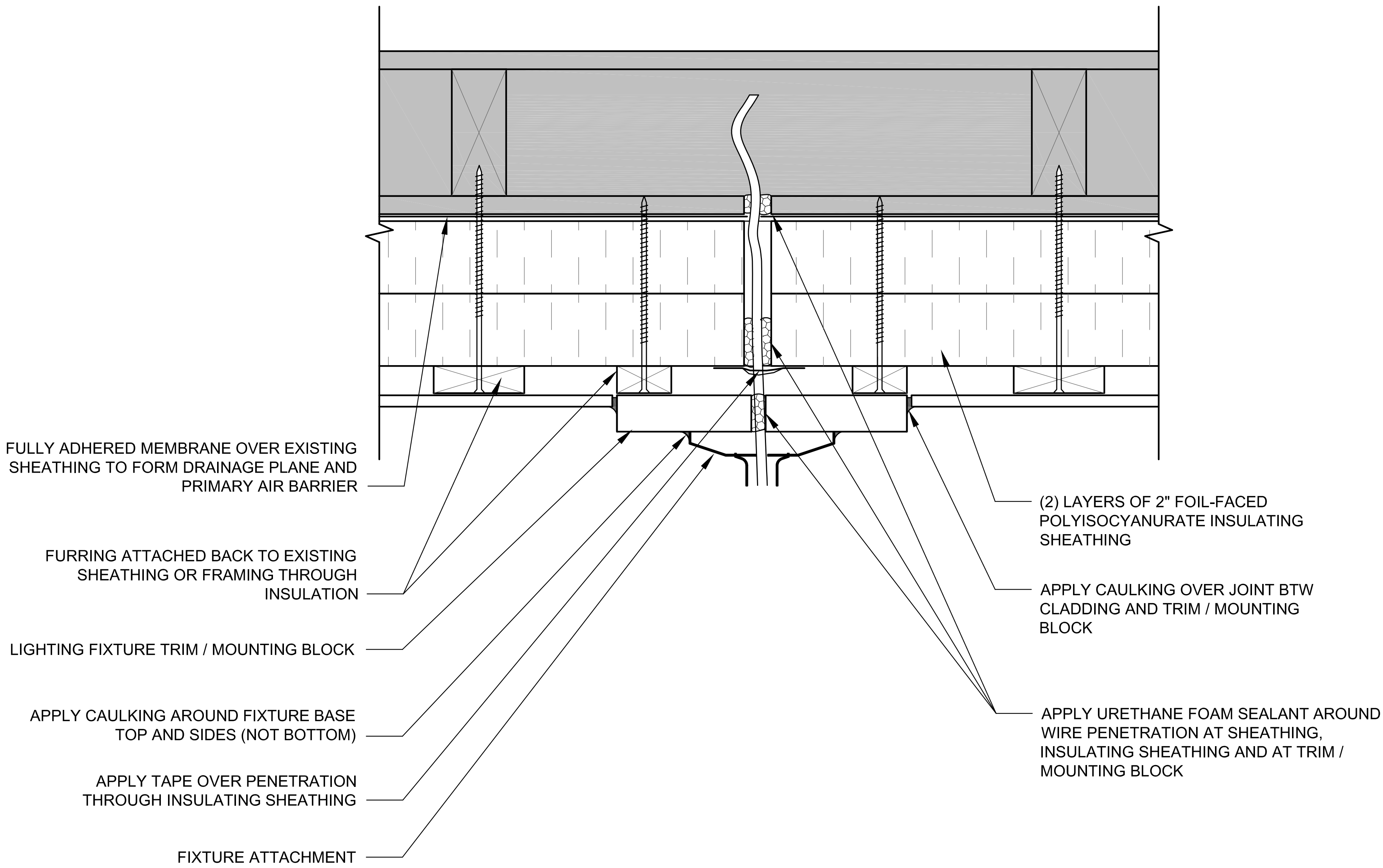
bsc with Building America U.S. Department of Energy Research Toward Zero Energy Homes

Project:	Deep Energy Retrofit
Date:	2009-08-20 DRAFT
Drawing Title:	Door Trim Installation Sequence
Drawing File:	InnerRetrofitDetails.dwg
Drawing Scale:	N.T.S.

Sheet Title:

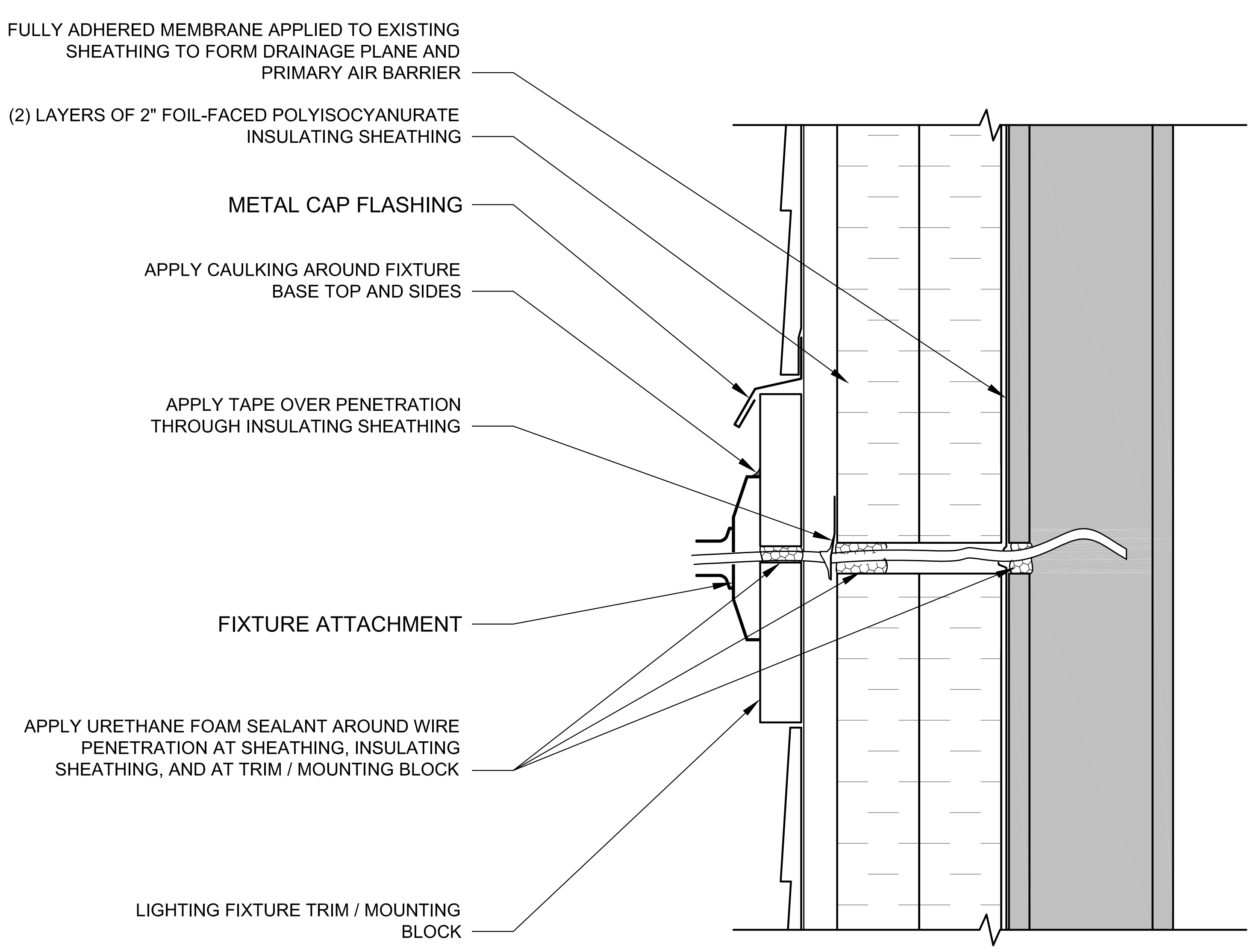
Door-3

C-298



2 EXTERIOR LIGHT FIXTURE PLAN DETAIL

SCALE: 3" = 1'-0"



1 EXTERIOR LIGHT FIXTURE SECTION DETAIL

SCALE: 3" = 1'-0"

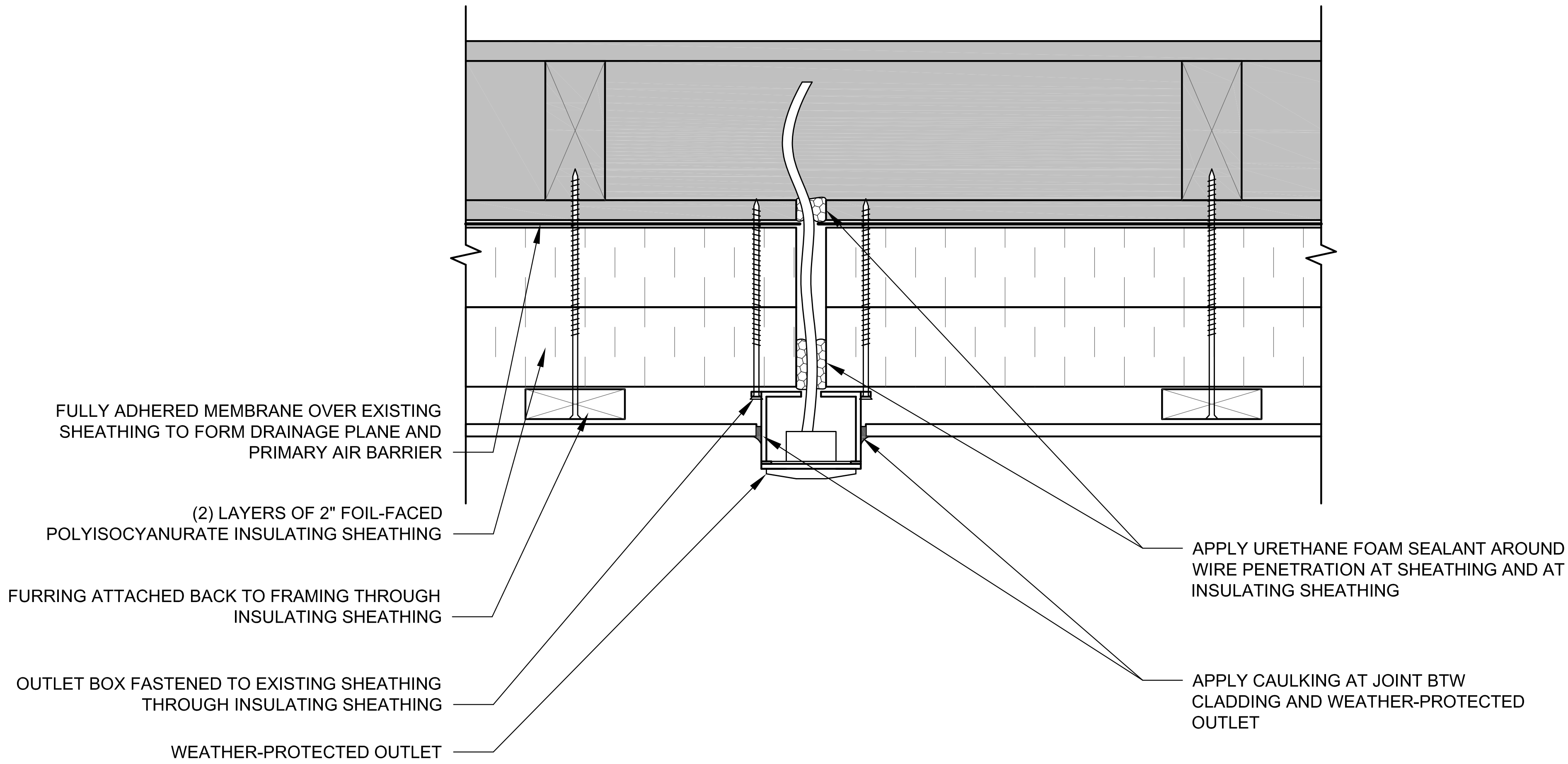
GRAY TONE INDICATES EXISTING STRUCTURE

bsc with Building AMERICA U.S. Department of Energy Research Toward Zero Energy Homes

Project: Deep Energy Retrofit
Date: 2009-08-20 DRAFT
Drawing Title: Penetration Details
Drawing File: InnerRetrofitDetails.dwg
Drawing Scale: 3" = 1'-0"

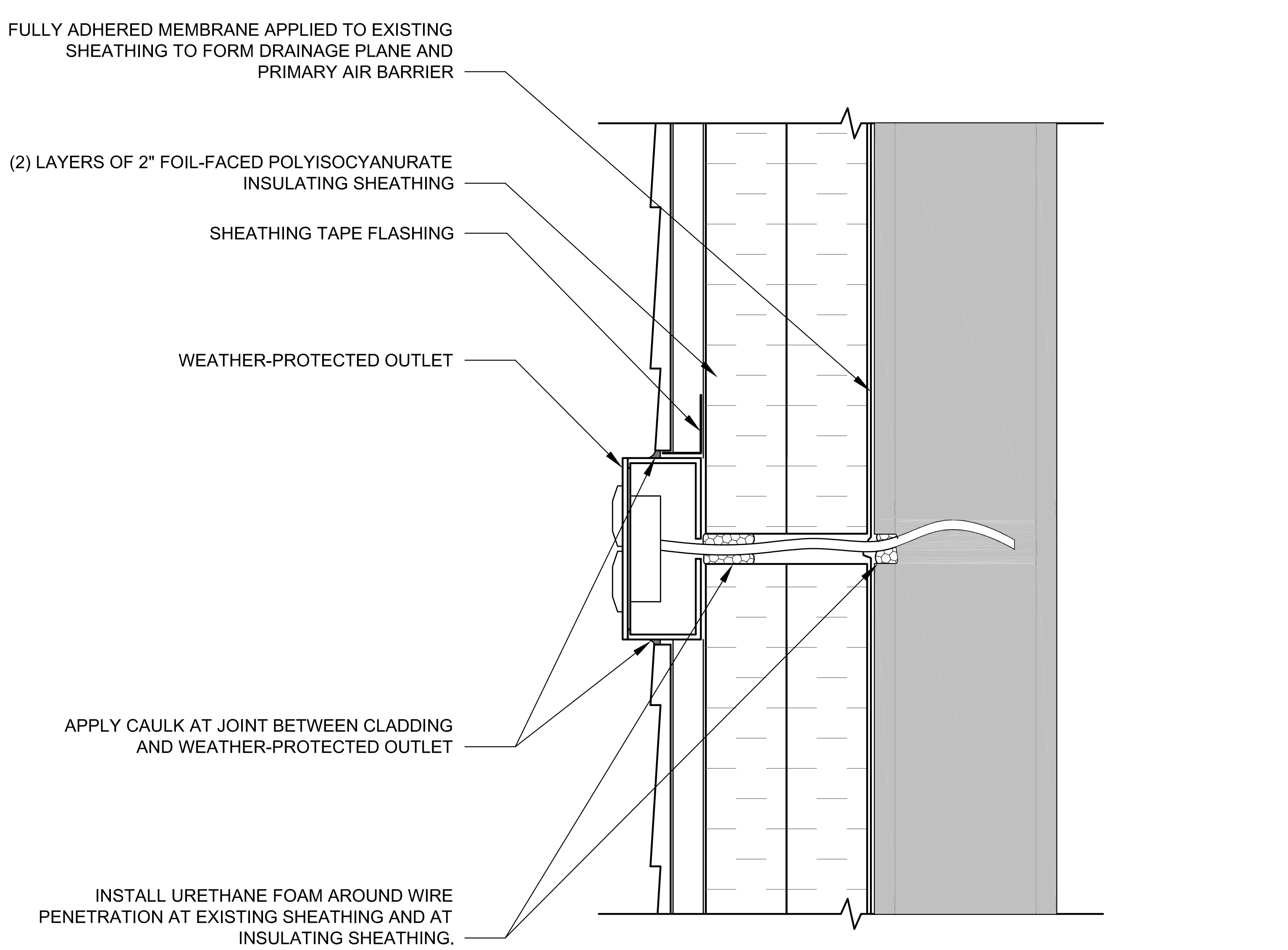
Sheet Title:

Pen-1



2 EXTERIOR ELECTRIC BOX PLAN DETAIL

SCALE: 3" = 1'-0"



1 EXTERIOR ELECTRIC BOX SECTION DETAIL

SCALE: 3" = 1'-0"

GRAY TONE INDICATES EXISTING STRUCTURE

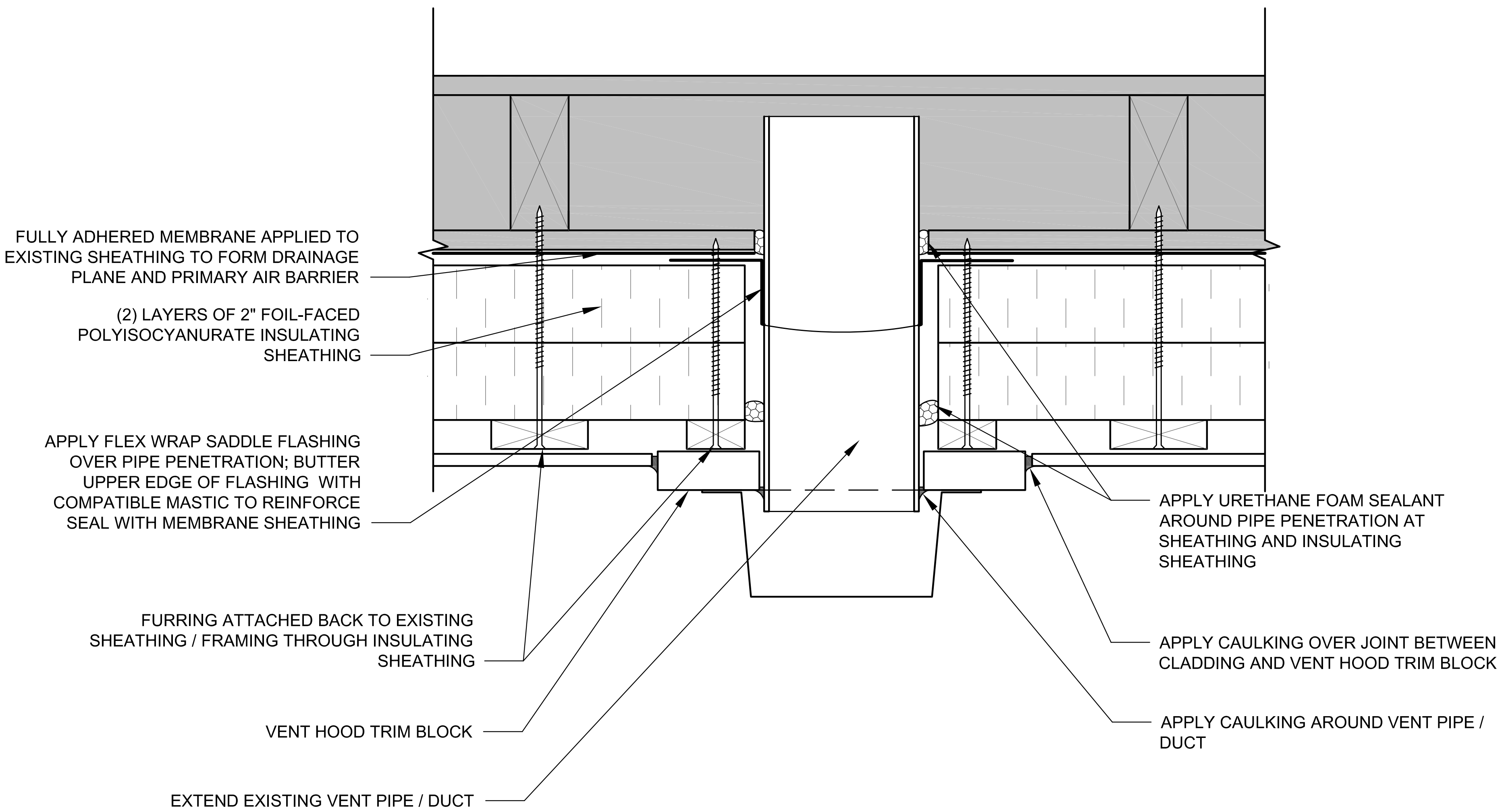
bsc with Building America U.S. Department of Energy Research Toward Zero Energy Homes

Project:	Deep Energy Retrofit
Date:	2009-08-20 DRAFT
Drawing Title:	Penetration Details
Drawing File:	InnerRetrofitDetails.dwg
Drawing Scale:	3" = 1'-0"

Sheet Title:

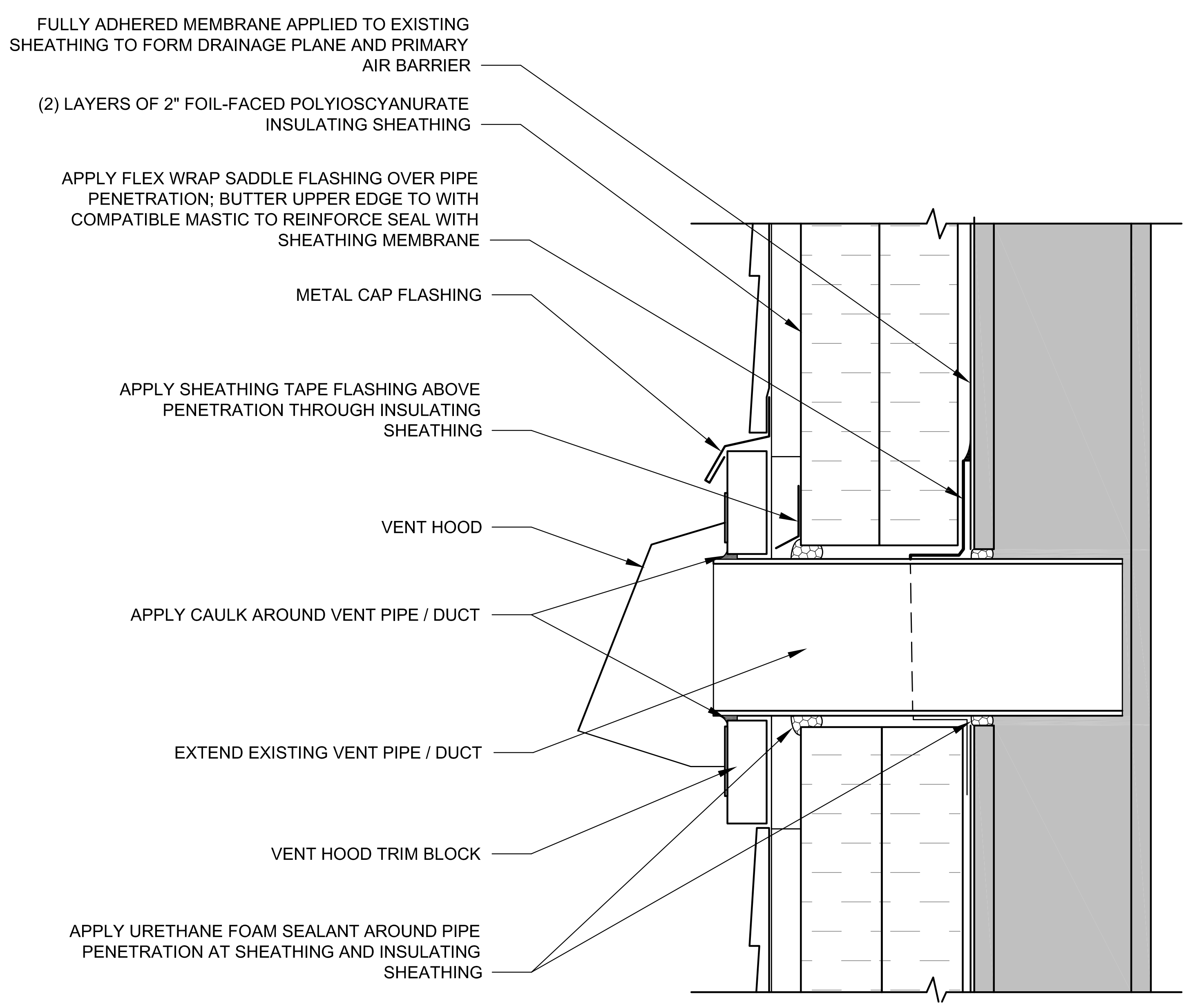
Pen-2

C-300



2 VENT PIPE/DUCT PLAN DETAIL

SCALE: 3" = 1'-0"



1 VENT PIPE/DUCT SECTION DETAIL

SCALE: 3" = 1'-0"

GRAY TONE INDICATES EXISTING STRUCTURE

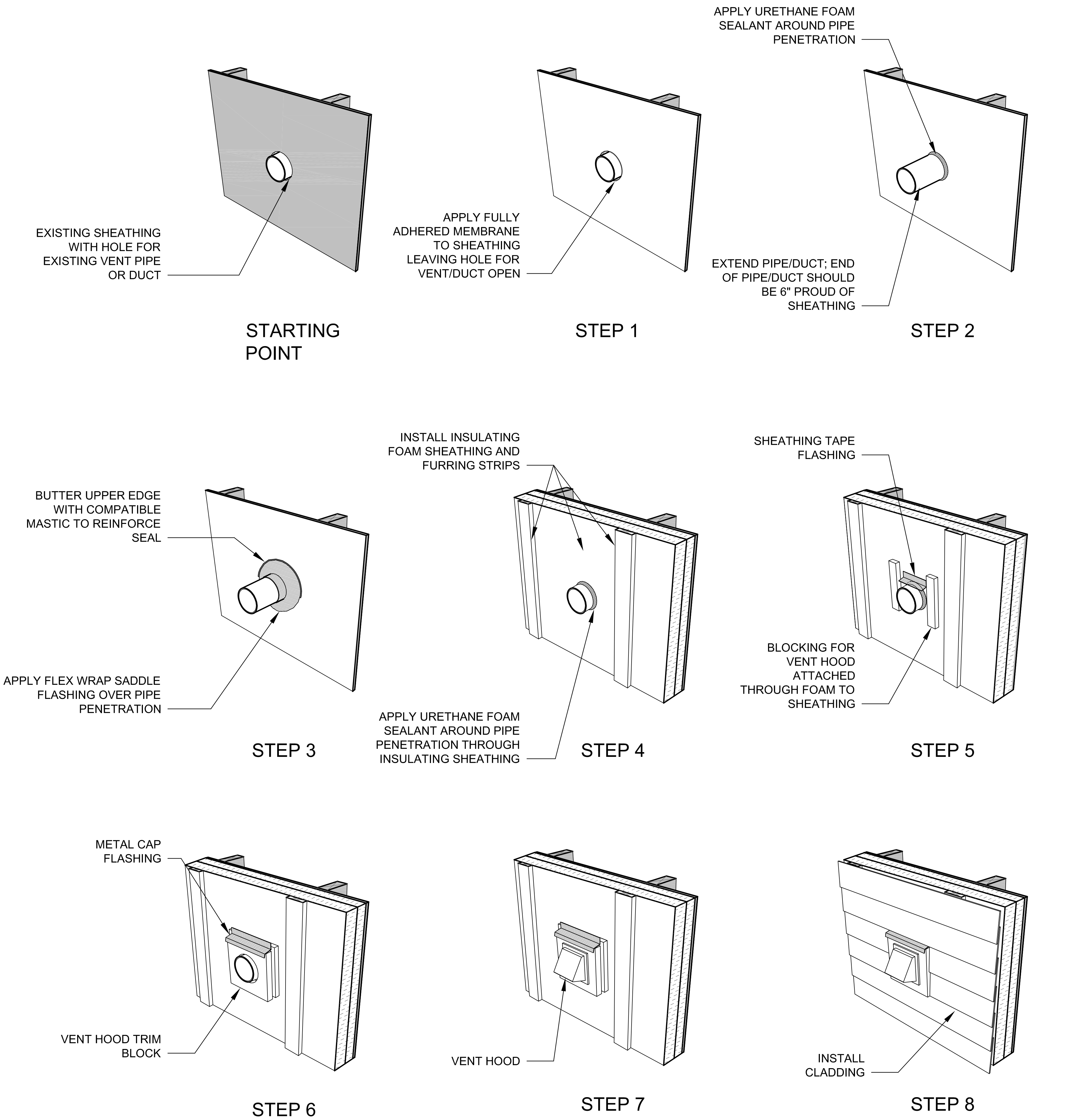
bsc with Building America U.S. Department of Energy Research Toward Zero Energy Homes

Project:	Deep Energy Retrofit
Date:	2009-08-20 DRAFT
Drawing Title:	Penetration Details
Drawing File:	InnerRetrofitDetails.dwg
Drawing Scale:	3" = 1'-0"

Sheet Title:

Pen-3

C-301



1 VENT PIPE/DUCT INSTALLATION SEQUENCE

N.T.S.

GRAY TONE INDICATES EXISTING STRUCTURE

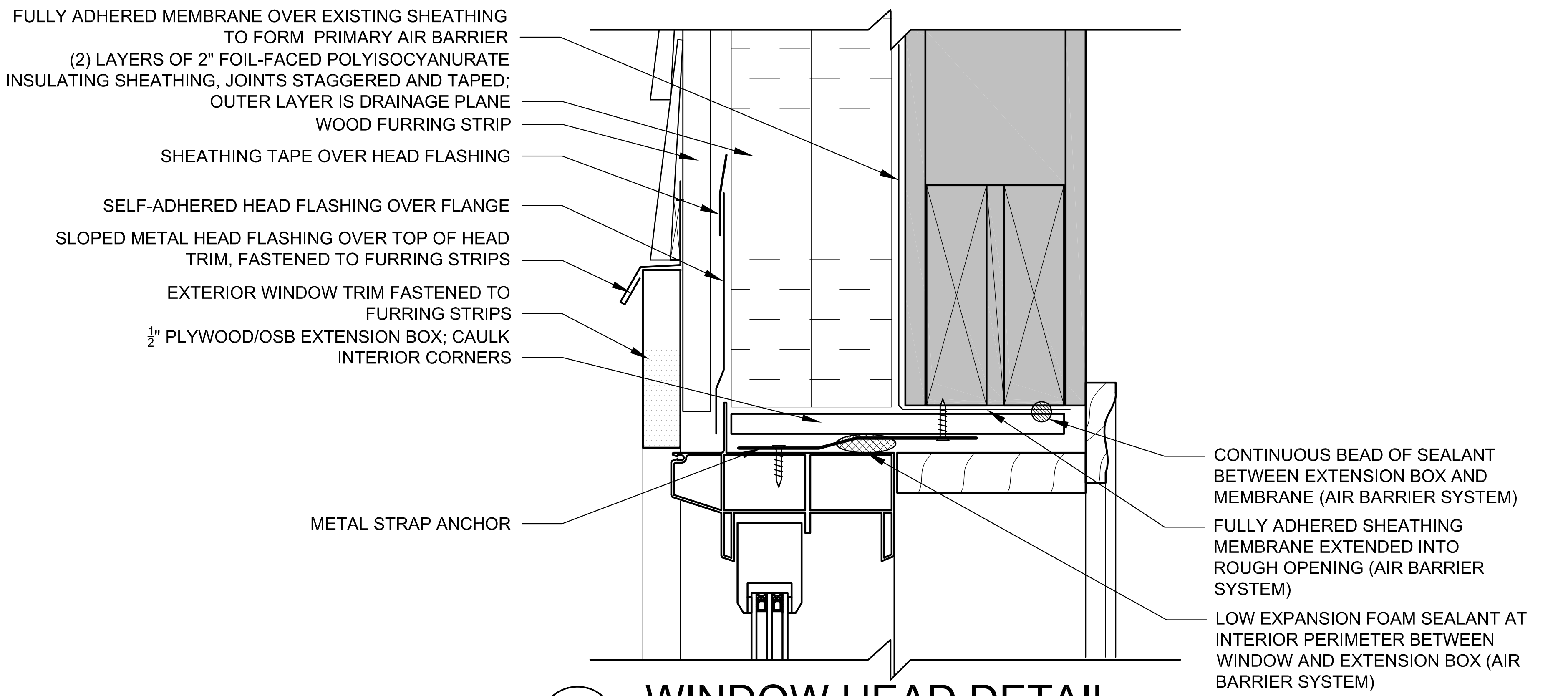
bsc with Building America U.S. Department of Energy Research Toward Zero Energy Homes

Project:	Deep Energy Retrofit
Date:	2009-08-20 DRAFT
Drawing Title:	Penetration Details
Drawing File:	InnerRetrofitDetails.dwg
Drawing Scale:	N.T.S.

Sheet Title:

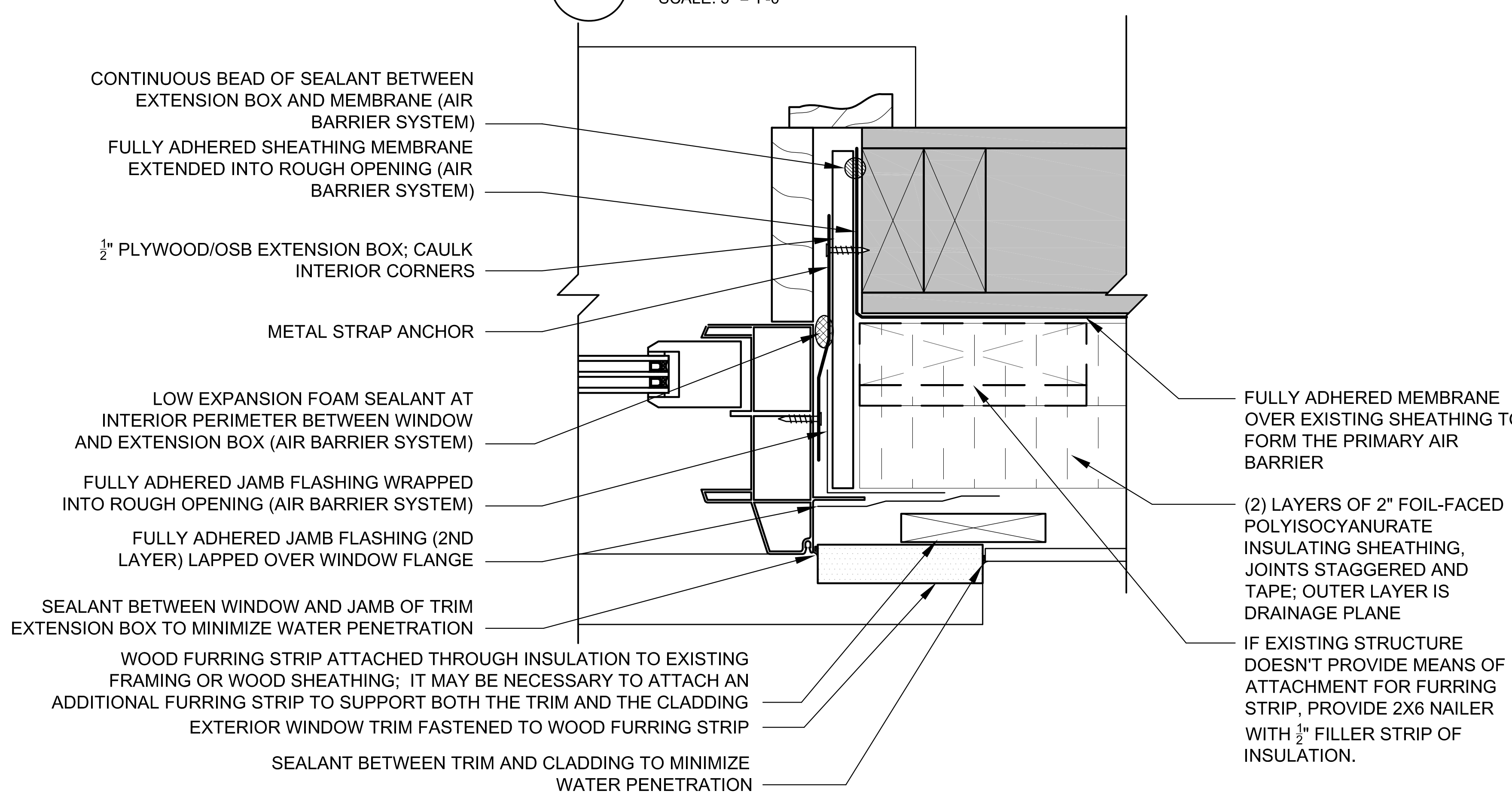
Pen-4

C-302



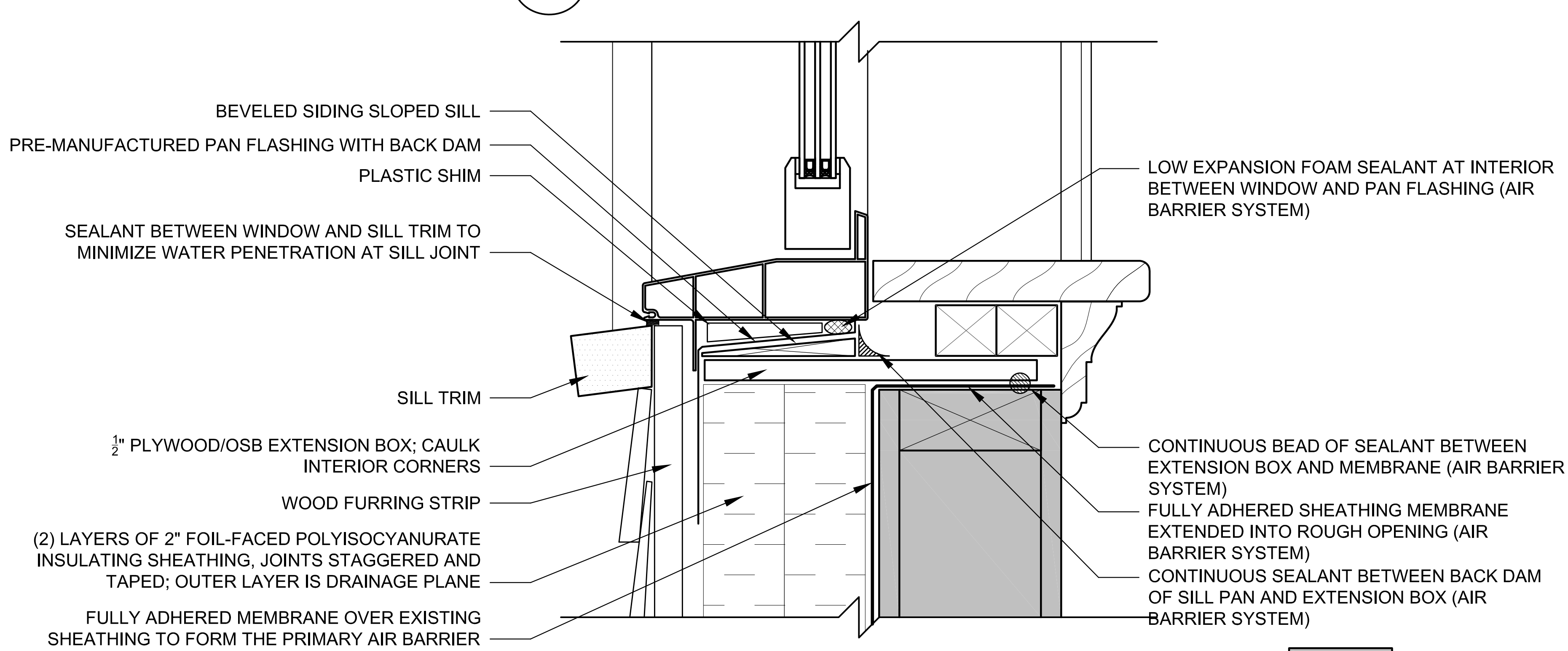
3 WINDOW HEAD DETAIL

SCALE: 3" = 1'-0"



2 WINDOW JAMB DETAIL

SCALE: 3" = 1'-0"



1 WINDOW SILL DETAIL

SCALE: 3" = 1'-0"

GRAY TONE INDICATES EXISTING STRUCTURE

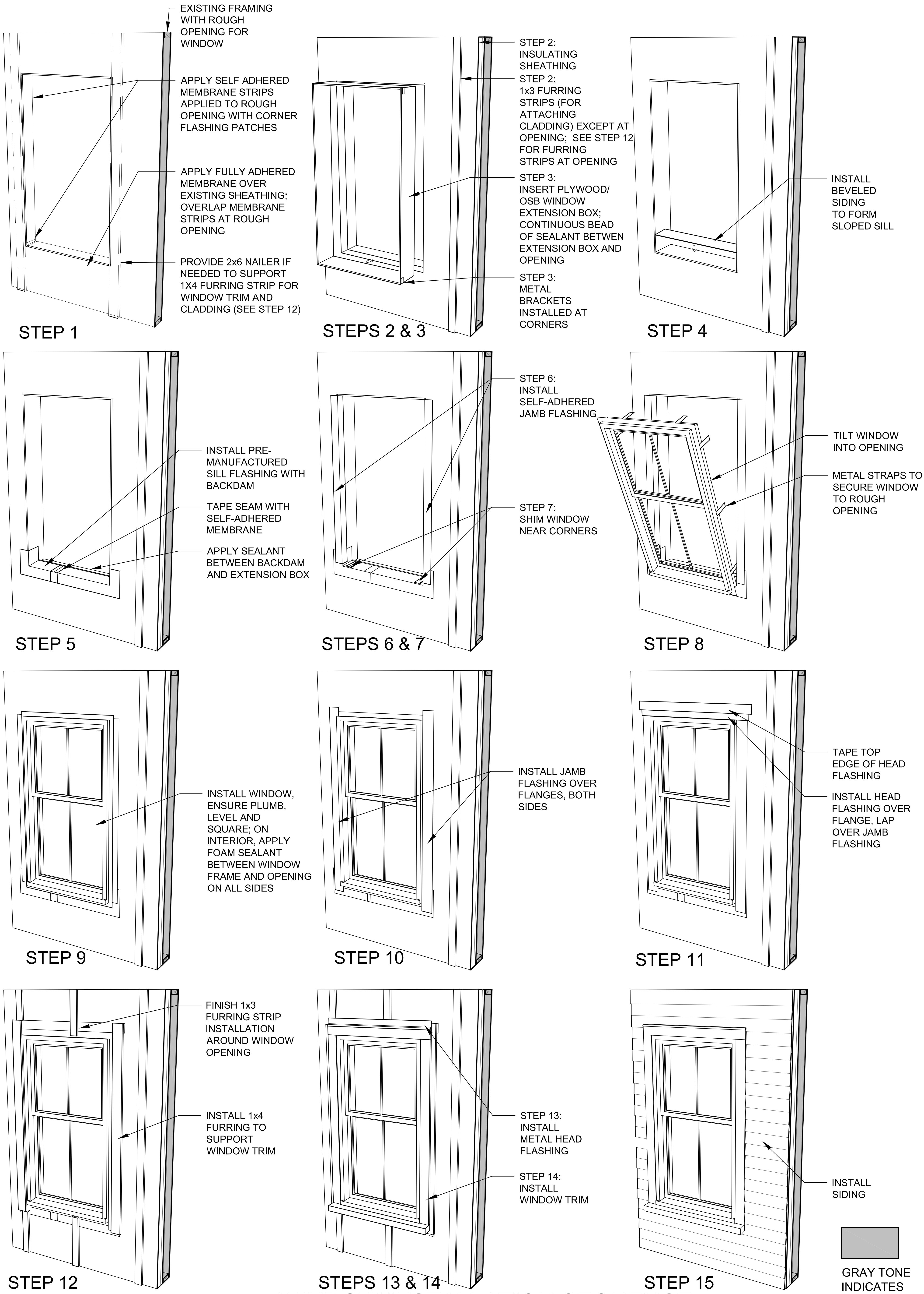
bsc with Building America U.S. Department of Energy Research Toward Zero Energy Homes

Project: Deep Energy Retrofit
Date: 2009-09-01-DRAFT
Drawing Title: Window Details
Drawing File: OuterRetrofitDetails.dwg
Drawing Scale: 3"=1'-0"

Sheet Title:

Win-1

C-303



1 WINDOW INSTALLATION SEQUENCE

N.T.S.

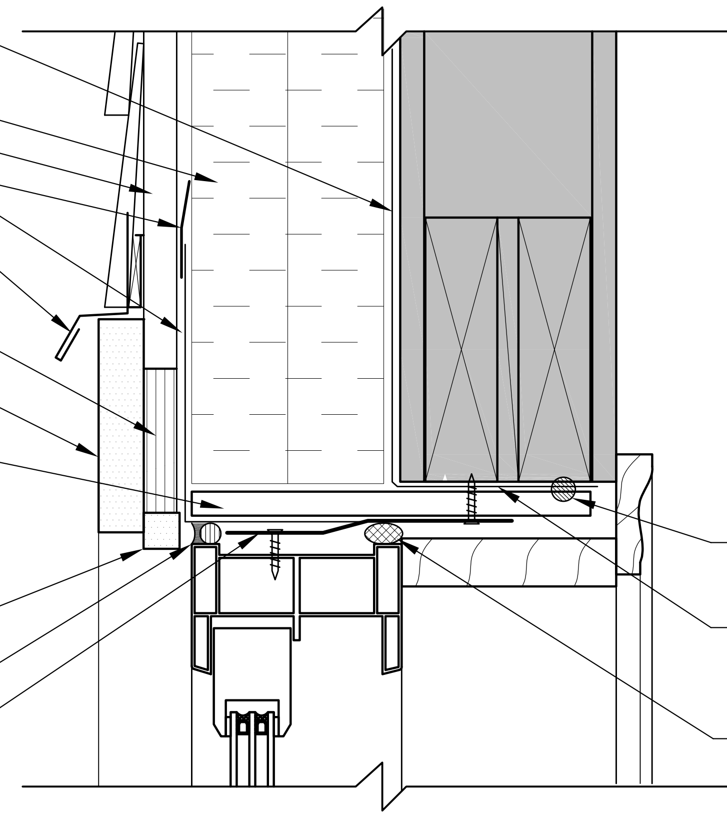
bsc with Building AMERICA U.S. Department of Energy Research Toward Zero Energy Homes

Project:	Deep Energy Retrofit
Date:	2009-09-04-DRAFT
Drawing Title:	Window Installation Sequence
Drawing File:	OuterRetrofitDetails.dwg
Drawing Scale:	N.T.S.

Sheet Title:

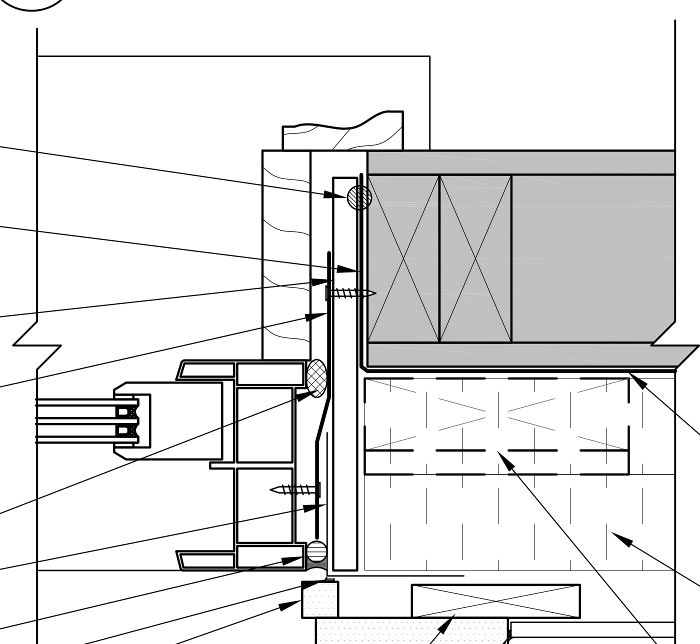
Win-2

C-304



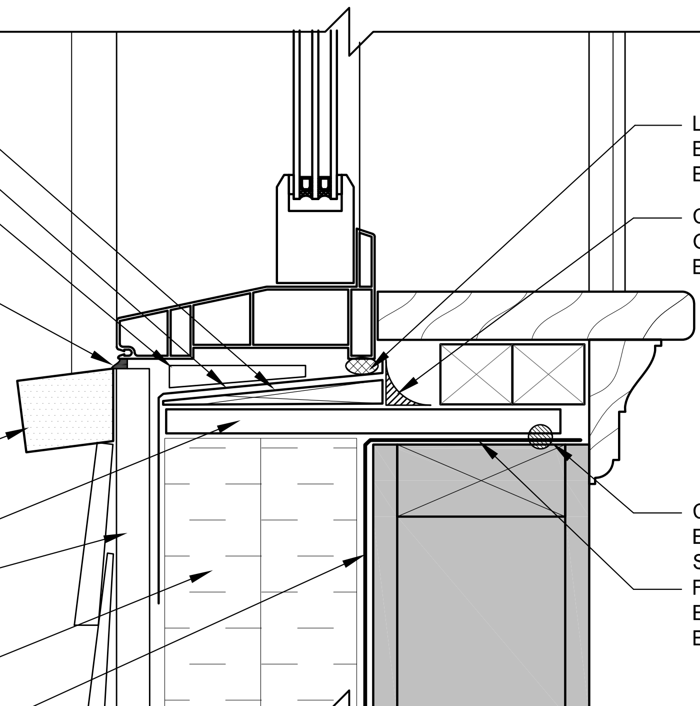
3 WINDOW HEAD DETAIL

SCALE: 3" = 1'-0"



2 WINDOW JAMB DETAIL

SCALE: 3" = 1'-0"



1 WINDOW SILL DETAIL

SCALE: 3" = 1'-0"

GRAY TONE INDICATES EXISTING STRUCTURE

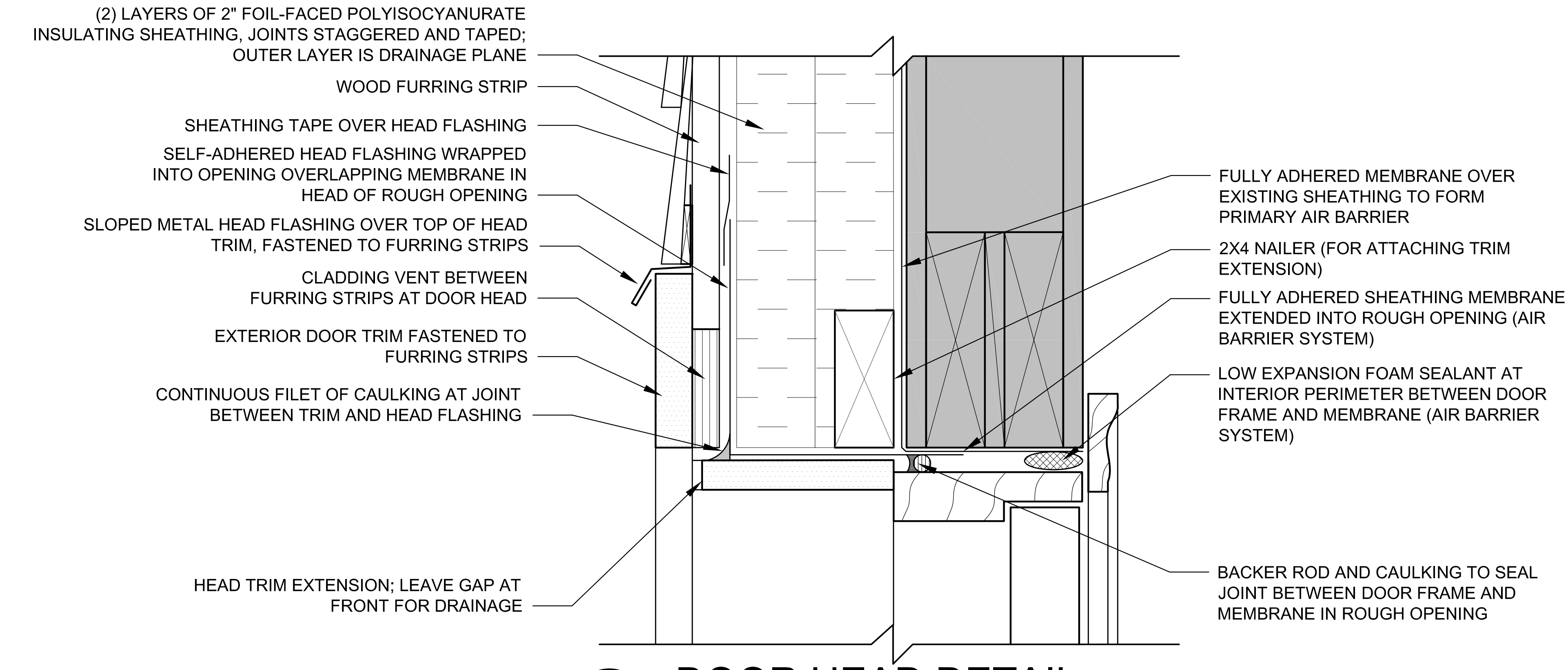
bsc with Building America U.S. Department of Energy Research Toward Zero Energy Homes

Project:	Deep Energy Retrofit
Date:	2009-09-04-DRAFT
Drawing Title:	Window Details
Drawing File:	OuterRetrofitDetails.dwg
Drawing Scale:	3"=1'-0"

Sheet Title:

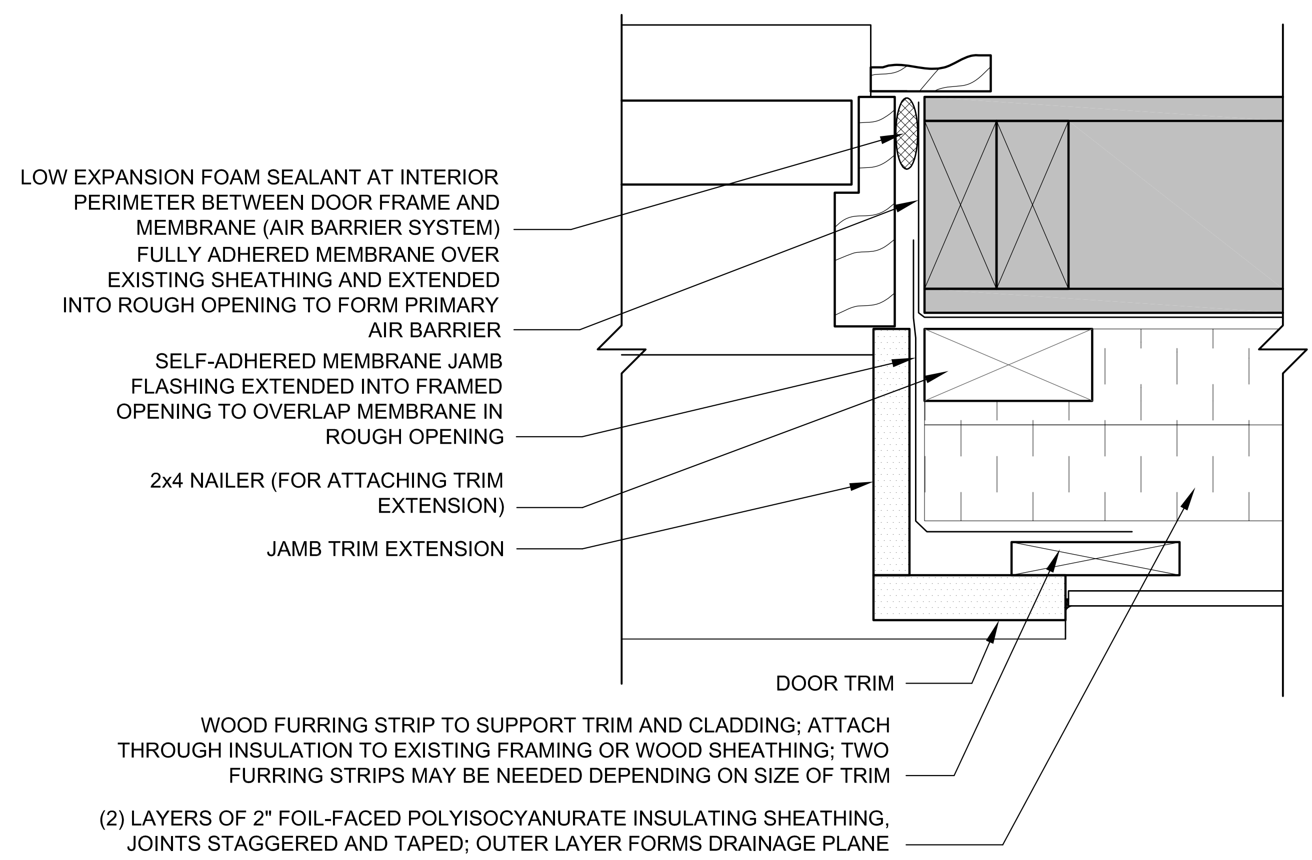
Win-1A

C-303



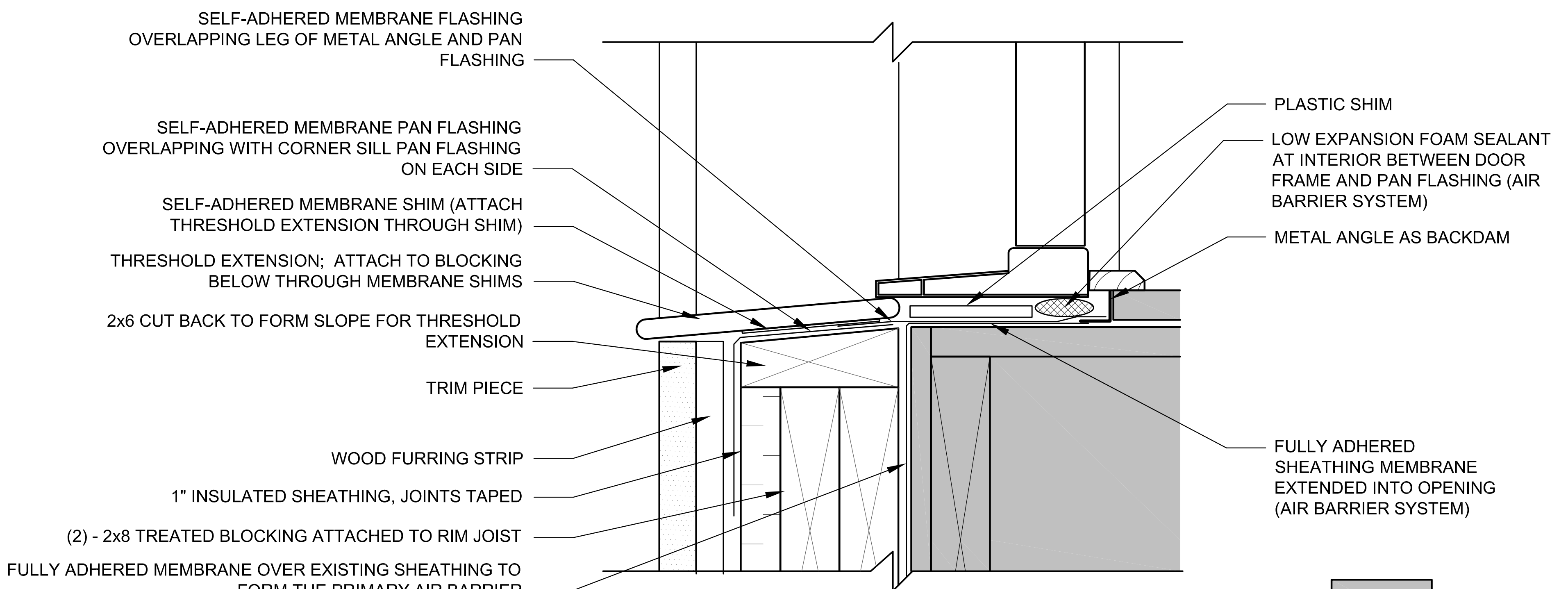
3 DOOR HEAD DETAIL

SCALE: 3" = 1'-0"



2 DOOR JAMB DETAIL

SCALE: 3" = 1'-0"



1 DOOR SILL DETAIL

SCALE: 3" = 1'-0"

GRAY TONE INDICATES EXISTING STRUCTURE

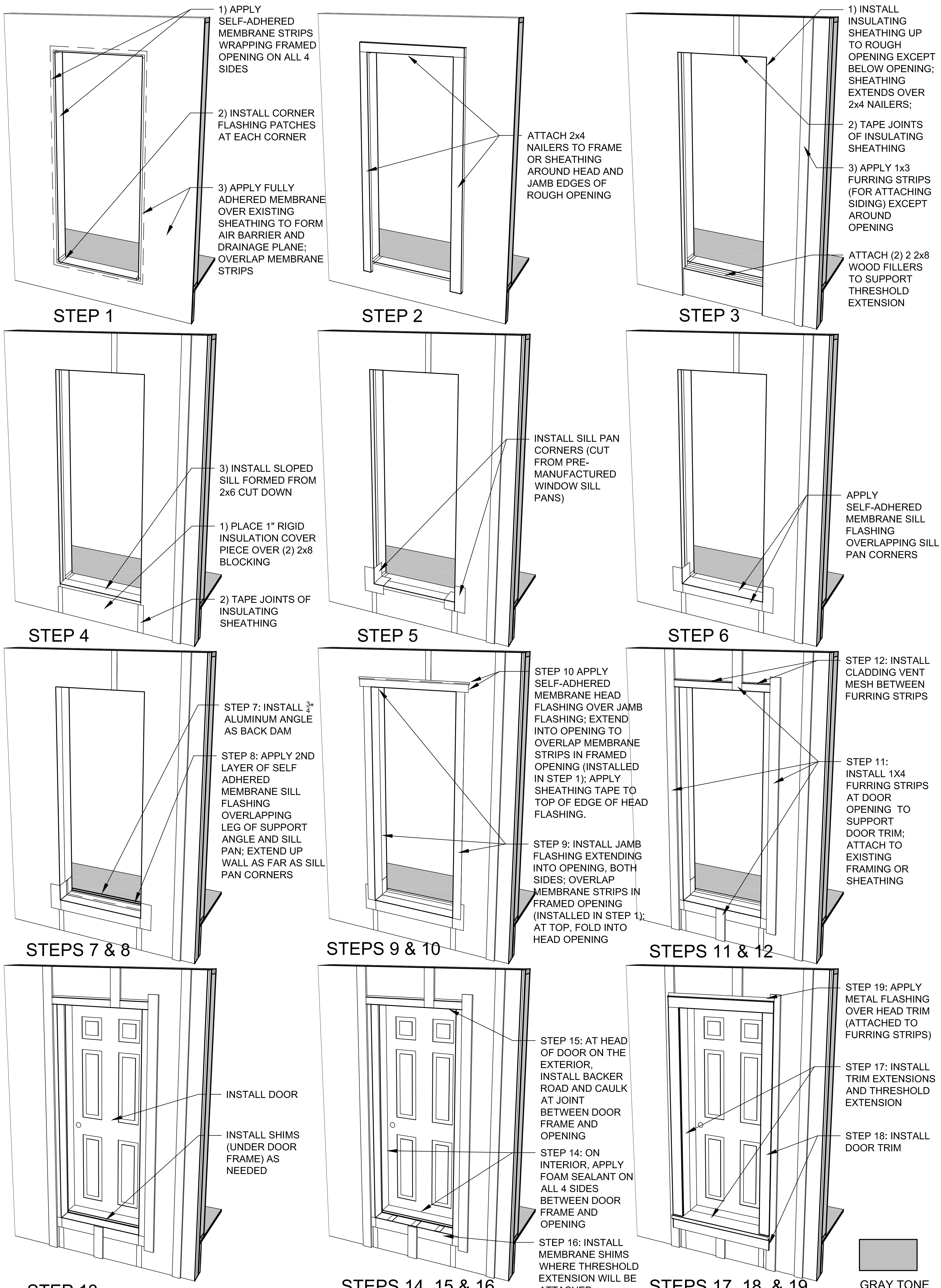
bsc with Building America U.S. Department of Energy Research Toward Zero Energy Homes

Project:	Deep Energy Retrofit
Date:	2009-09-03-DRAFT
Drawing Title:	Door Details
Drawing File:	OuterRetrofitDetails.dwg
Drawing Scale:	3"=1'-0"

Sheet Title:

Door-1

C-300



1 DOOR INSTALLATION SEQUENCE

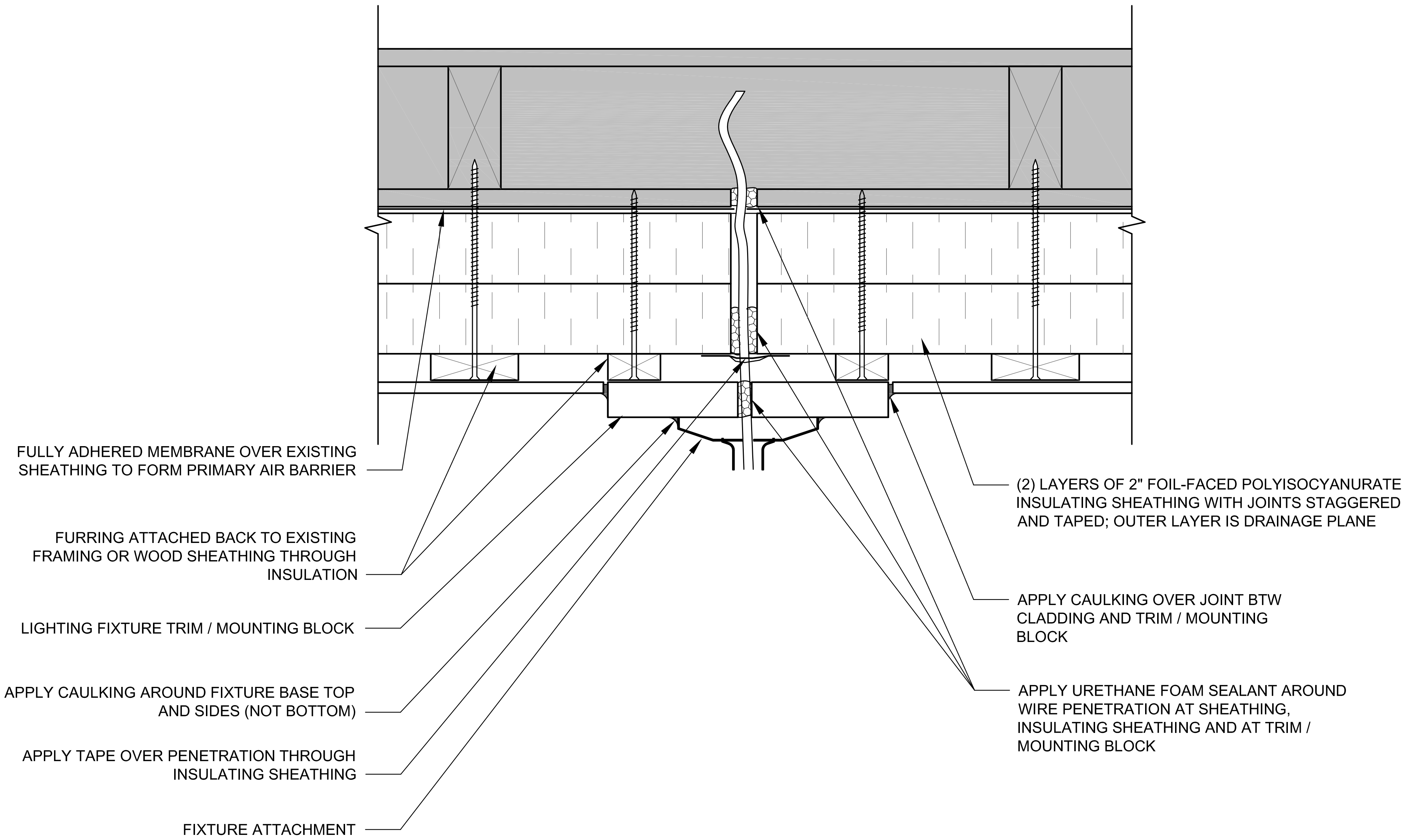
N.T.S.

bsc with Building America U.S. Department of Energy Research Toward Zero Energy Homes

Project: Deep Energy Retrofit
Date: 2009-09-04-DRAFT
Drawing Title: Door Installation Sequence
Drawing File: OuterRetrofitDetails.dwg
Drawing Scale: N.T.S.

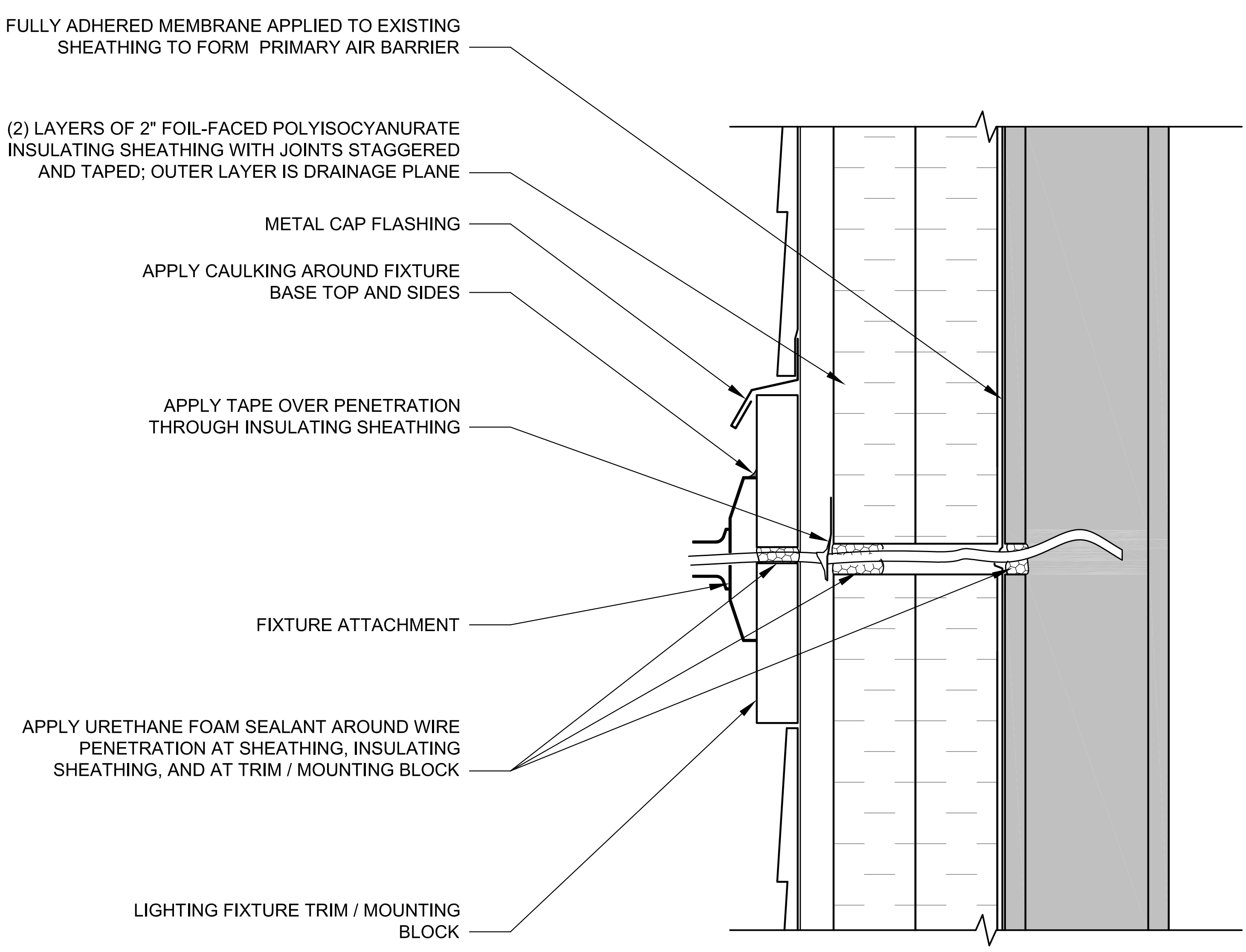
Sheet Title:

Door-2



2 EXTERIOR LIGHT FIXTURE PLAN DETAIL

SCALE: 3" = 1'-0"



1 EXTERIOR LIGHT FIXTURE SECTION DETAIL

SCALE: 3" = 1'-0"

GRAY TONE INDICATES EXISTING STRUCTURE

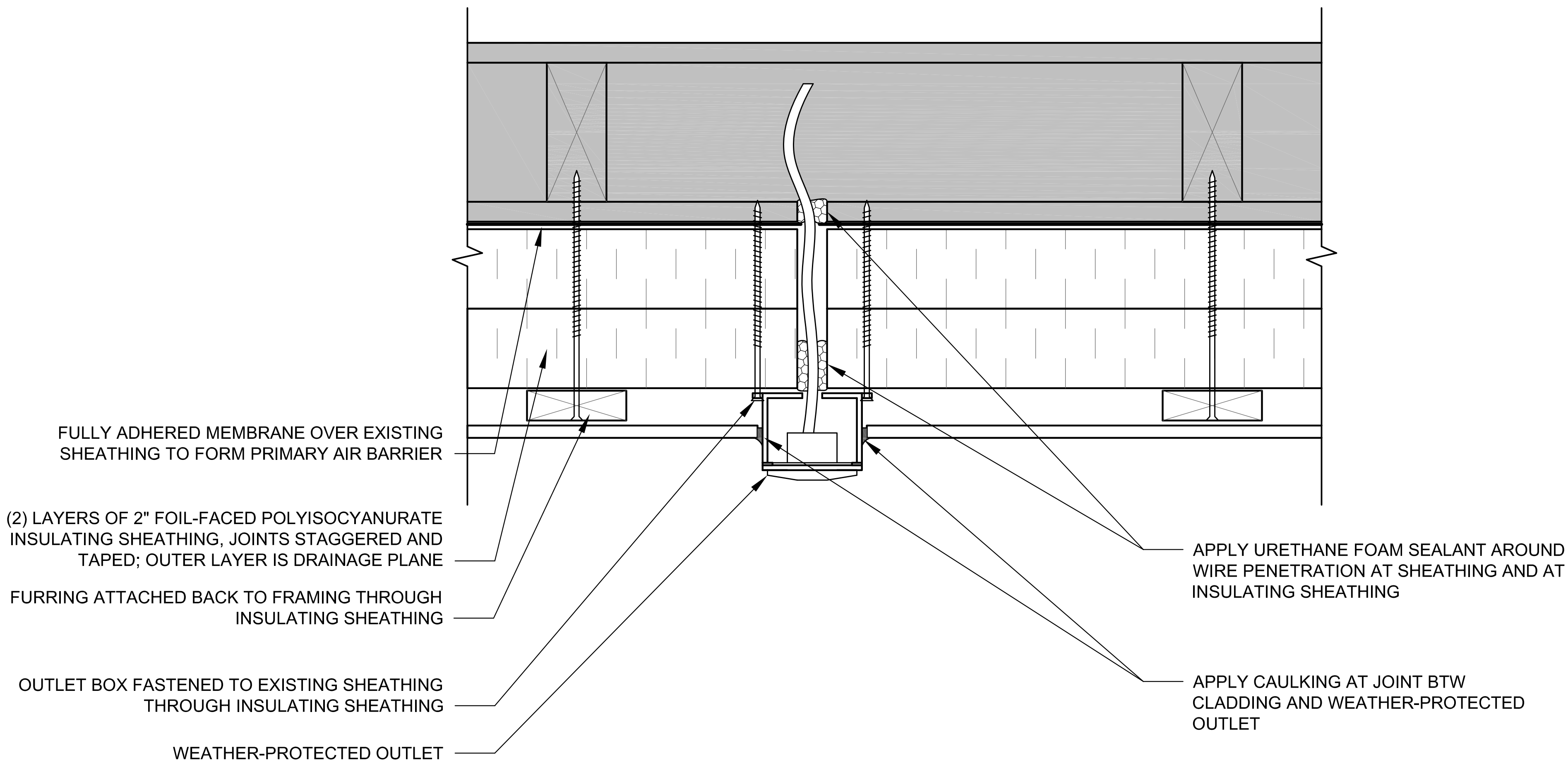
bsc with Building America U.S. Department of Energy Research Toward Zero Energy Homes

Project: Deep Energy Retrofit
Date: 2009-08-20-DRAFT
Drawing Title: Penetration Details
Drawing File: OuterRetrofitDetails.dwg
Drawing Scale: 3"=1'-0"

Sheet Title:

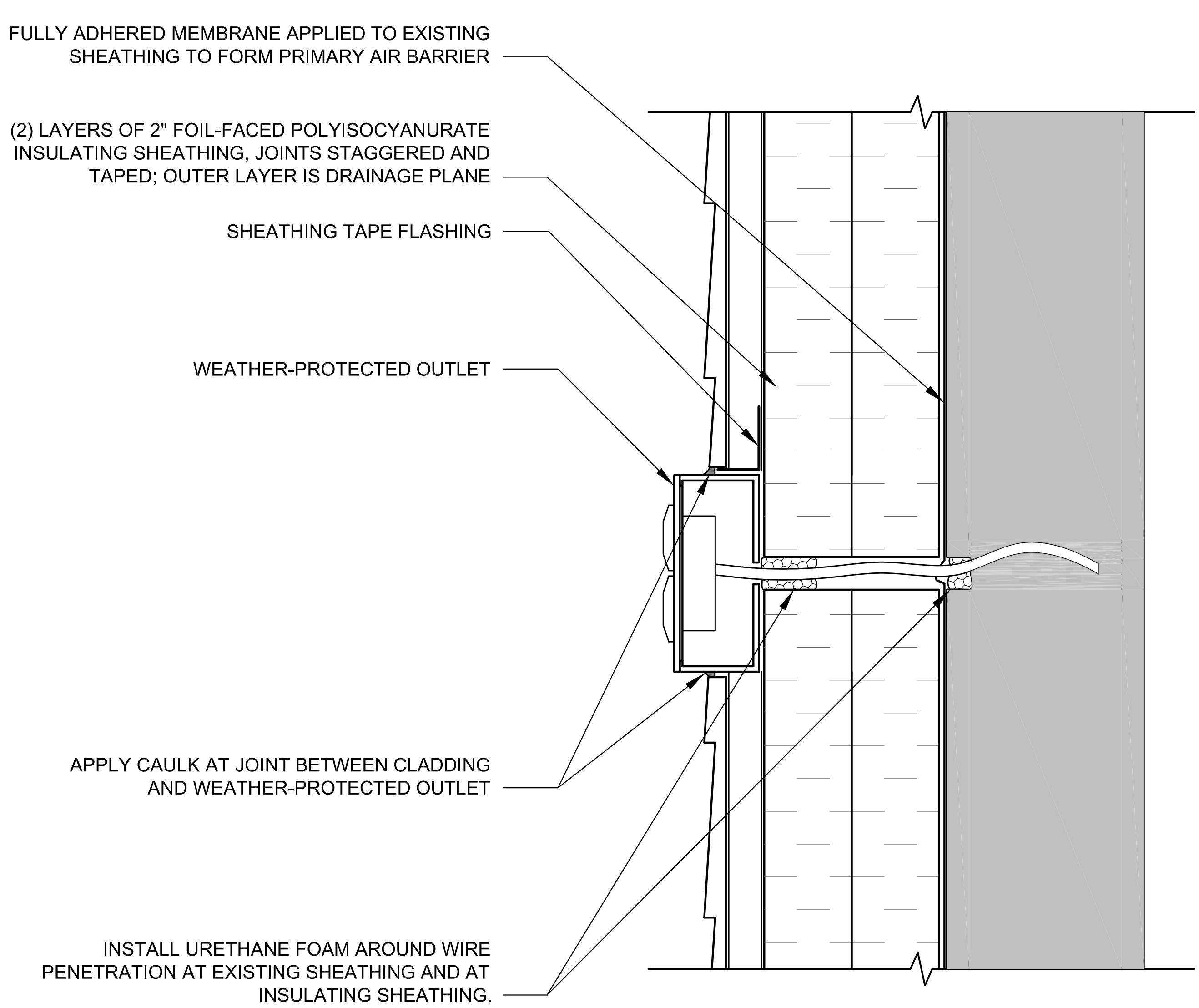
Pen-1

C-308



2 EXTERIOR ELECTRIC BOX PLAN DETAIL

SCALE: 3" = 1'-0"



1 EXTERIOR ELECTRIC BOX SECTION DETAIL

SCALE: 3" = 1'-0"

GRAY TONE INDICATES EXISTING STRUCTURE

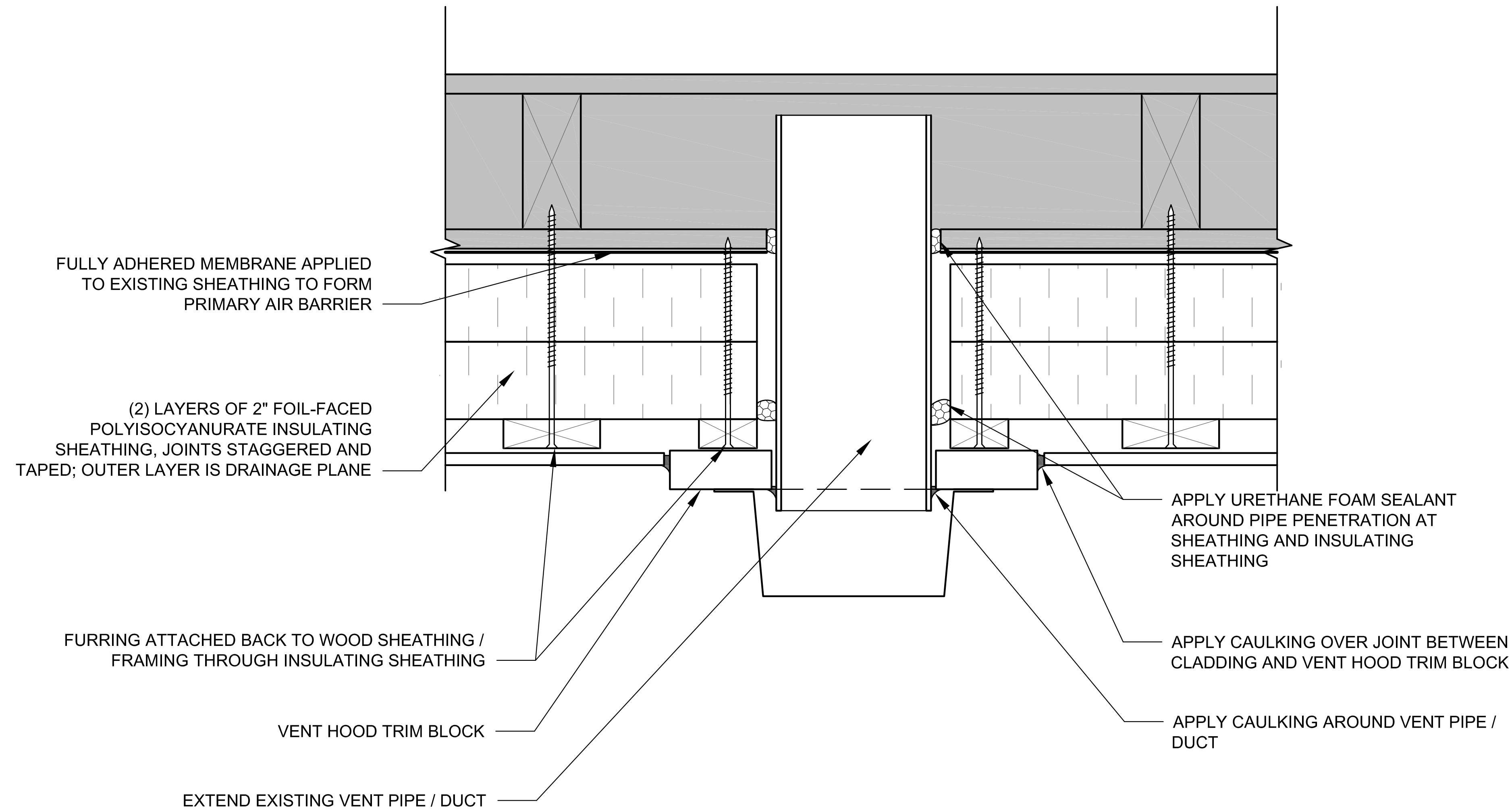
bsc with Building America U.S. Department of Energy Research Toward Zero Energy Homes

Project:	Deep Energy Retrofit
Date:	2009-08-20-DRAFT
Drawing Title:	Penetration Details
Drawing File:	OuterRetrofitDetails.dwg
Drawing Scale:	3"=1'-0"

Sheet Title:

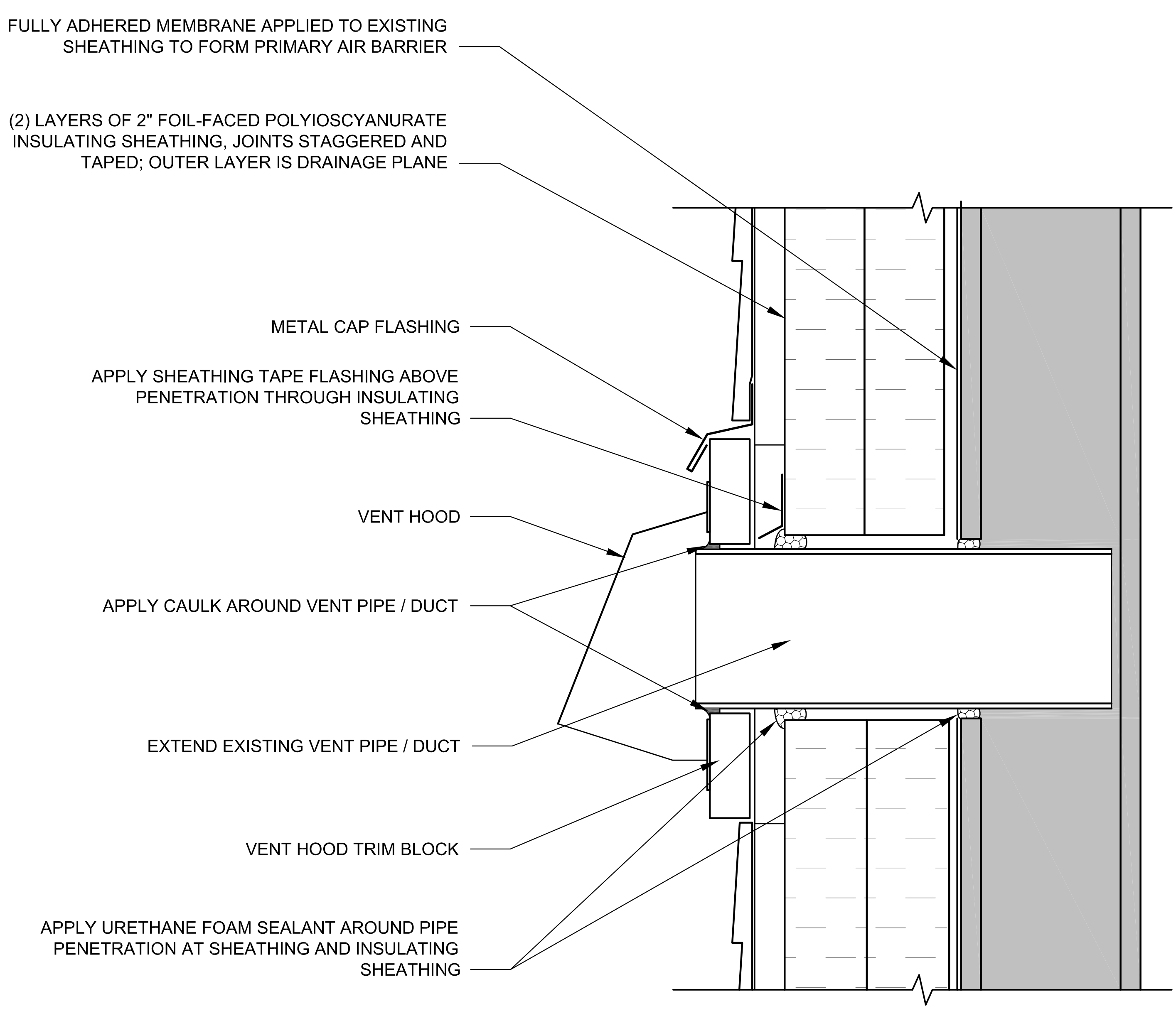
Pen-2

C-309



2 VENT PIPE/DUCT PLAN DETAIL

SCALE: 3" = 1'-0"



1 VENT PIPE/DUCT SECTION DETAIL

SCALE: 3" = 1'-0"

GRAY TONE INDICATES EXISTING STRUCTURE

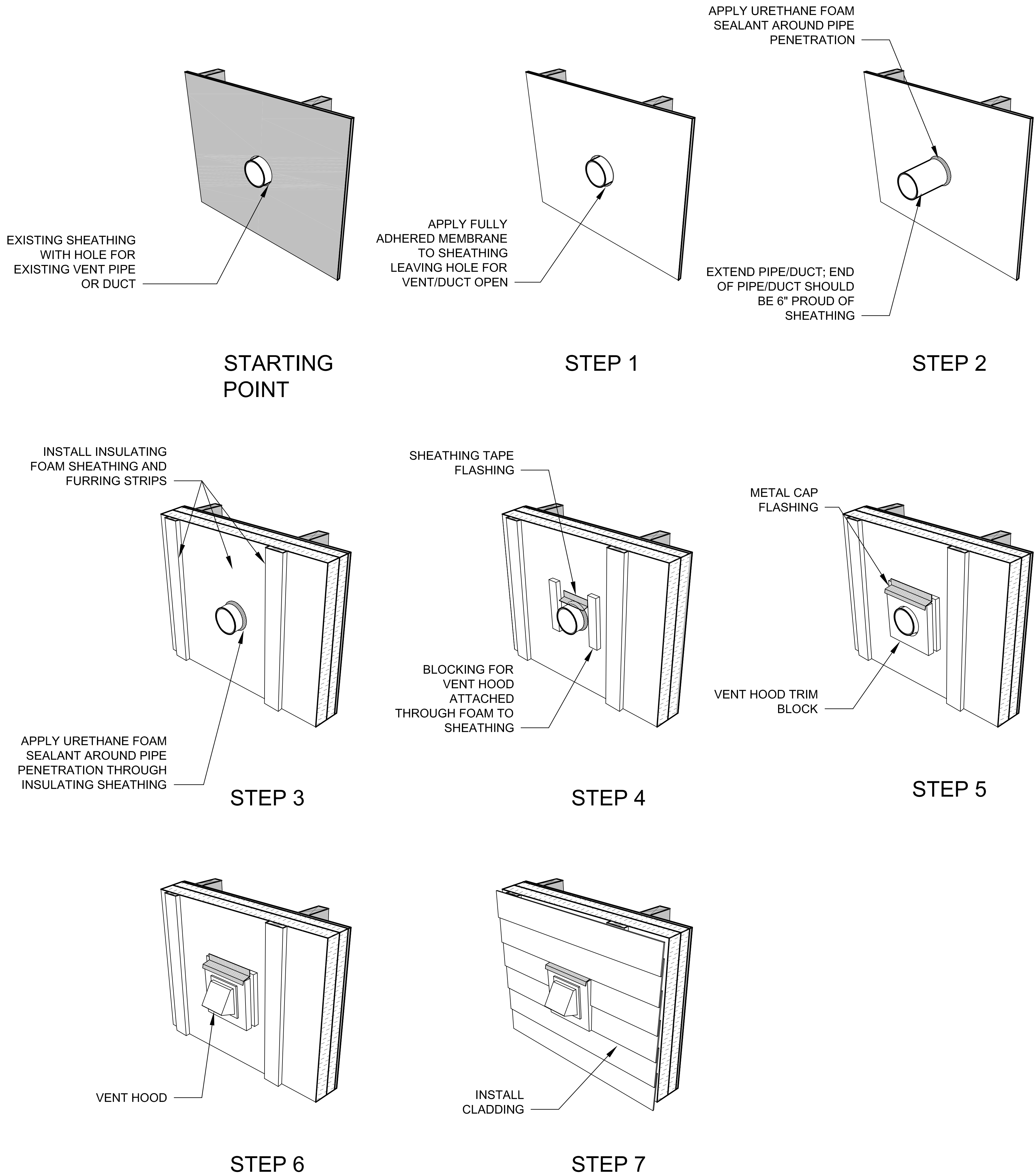
bsc with Building America U.S. Department of Energy Research Toward Zero Energy Homes

Project: Deep Energy Retrofit
Date: 2009-08-20-DRAFT
Drawing Title: Penetration Details
Drawing File: OuterRetrofitDetails.dwg
Drawing Scale: 3"=1'-0"

Sheet Title:

Pen-3

C-310



1 VENT PIPE/DUCT INSTALLATION SEQUENCE

N.T.S.

GRAY TONE INDICATES EXISTING STRUCTURE

with

Project: Deep Energy Retrofit
Date: 2009-08-20-DRAFT
Drawing Title: Penetration Details
Drawing File: OuterRetrofitDetails.dwg
Drawing Scale: N.T.S.

Sheet Title:

Pen-4

C-311

1.5.7. Advanced Framing Deployment – Interim Report

by Joseph Lstiburek and Aaron Grin, December 2009

Building America High R-value Enclosures Research Project:

Advanced Framing Deployment Interim Report

Joseph Lstiburek, Ph.D., P.Eng.
Aaron Grin, M.A.Sc.

Building Science Corporation, Somerville, MA

December 2009

Abstract:

This report investigates the implementation of advanced framing in both production and prototype built homes built in a variety of climate regions across the USA.The current industry standard wall is being replaced by a 2x6 frame at 24 in. centers with single top plates, two-stud corners, no jack studs, no cripples and single headers (and in many cases no headers at all). The advanced framing system is cheaper because it uses 5% to 10% less board feet of lumber, and it is faster because it uses 30% fewer pieces. It saves energy because it provides a 60% deeper cavity (which allows 60% more cavity insulation) and because it reduces the framing factor from 25% to 15%. Advanced framing can save energy, greenhouse gas emissions, and money if properly implemented. Through BSC's experience we have found that builders can save $1000 per house on advanced framing. To maximize cost savings and energy savings for the homeowner, the builder financial savings are best shifted to implementing more energy saving measures. In 2010 BSC will continue deployment of advanced framing wherever possible with its Building America partners.

Advanced Framing Deployment - Interim Report

History and Background

The current industry standard wall—a 2×4 frame at 16 in. (400 mm) centers with double top plates, three stud corners, jack studs, cripples and double headers— is being replaced by a 2×6 frame at 24 in. (600 mm) centers with single top plates, two-stud corners, no jack studs, no cripples and single headers (and in many cases no headers at all). The advanced framing system is cheaper because it uses 5% to 10% less lumber (board-feet), and it is faster because it uses 30% fewer pieces. It saves energy because it provides a 60% deeper cavity (which allows 60% more cavity insulation) and because it reduces the framing factor from 25% to 15%.

The framing elements are farther apart allowing easier installation of services—everything fits easier making the trades happier—the electrician drills fewer holes and the insulator insulates faster because there are fewer cavities, even though the cavities are wider and deeper. Everything lines up so the load paths are direct, leading to fewer but stronger connections. The lines are cleaner, so it just looks and feels better.

Some of the advanced frame technology goes back to the beginnings of framing—"in-line" framing or "stack" framing where everything lines up is not new (Figure 1). But, the real innovations came from a magnificent collaboration between the U.S. Department of Housing and Urban Development (HUD) and the National Association of Home Builders Research Foundation (NAHB Research Foundation) in the 1970s. Out of a HUD initiative called Operation Breakthrough the NAHB Research Foundation delivered "optimum value engineering framing" or OVE framing. Today, this is referred to as "Advanced Framing."

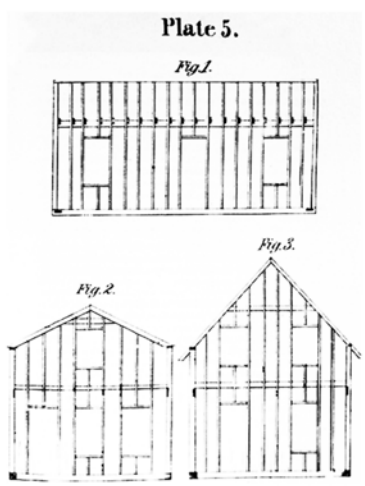


Figure 1 - In-line Framing. (Bullock, 1854)

Figure 2 shows the current expression of advanced framing. Everything lines up so that double top plates are not necessary. No headers in non load-bearing walls. Window openings are clean without jack studs and cripples. Exterior corners have two studs. Gypsum board is supported with drywall clips. And all of this is code accepted by the model building codes because of the foresight of HUD and the NAHB. Although it's in the code, most code officials are not aware of it and even fewer builders.

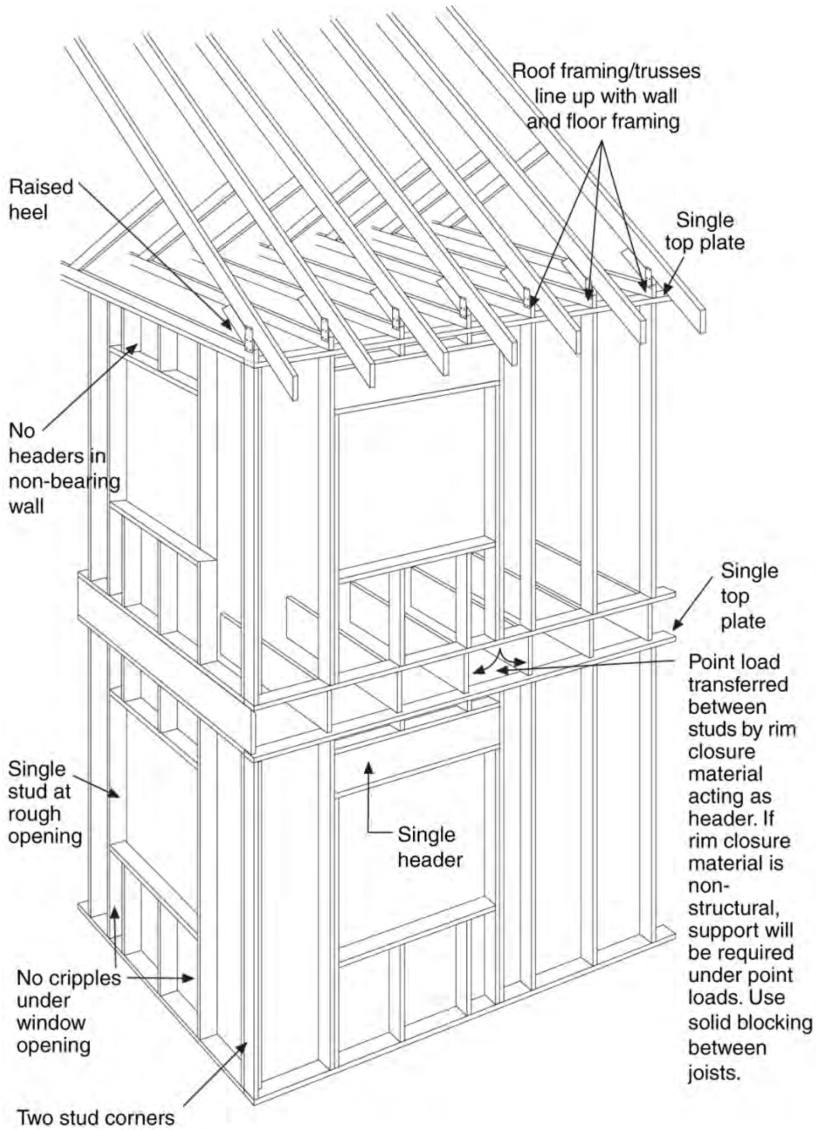


Figure 2: Advanced framing

One of the biggest pushback's from builders and code officials comes from corner support for gypsum board and trim. "Floating corners" reduce drywall cracking and, therefore, are an improvement. Wood always moves because of changing moisture contents. Gypsum board does not want to move. When you attach something that is always moving to something that does not want to move you get cracking. The key to reducing drywall cracking is to attach it less, the easiest drywall clip in the past was to cut a piece of corner bead into 2 in. (51 mm) lengths.

Single top plates seem to be the biggest problem. Not from a structural perspective or from a constructability perspective but from a perception perspective. There are two ways of making a connection: with a metal plate or with a wood splice. The approach taken is purely one based on preference by the framer.

The real change involving single top plates is that when you are framing an 8 ft (2.4 m) wall the studs have to be 1.5 in. (38 mm) longer. Standard "pre-cuts" don't work. You need 94 inches (2.39 m) not

92.5 inches (2.35 m). Load-bearing walls need headers and advanced framing typically involves using single headers with the header pushed to the exterior of the wall. This keeps the header away from the gypsum board so that boarders can't attach to it, therefore, shrinkage in the header does not result in a crack in the drywall.

The most significant change is the fact that the walls are thicker and we have to figure out what to do with the additional 4 in. (100 mm). Do we make the foundation wider? Do we lose 4 in. (102 mm) to the interior? Do we keep the foundation the same, but cantilever the walls? These are not trivial. In production housing interior dimensions are a big deal and can mess up kitchen layouts, hallways and stairs. Site setbacks must be considered as well. It typically means that the drawings have to be redone. Taking existing floor plans and redrawing them is a $1,000 to $1,500 hit per plan for a production builder. This is the biggest knock against advanced framing. Of course, this is not a problem if the plans are drawn up from scratch to be advanced frame.

The floor framing is now on 24 in. (600 mm) centers, and that means the floor sheathing has to be thicker. The savings in the floor framing covers the cost of the thicker floor sheathing. The interior walls are also framed on 24 in. (600 mm) centers using 2×4s. Almost all of them are not load bearing hence the connections are pretty much non-structural.

Things get interesting when we add insulating sheathing, althoughit is not part of advanced framing. Many builders that use advanced framing today also incorporate insulating sheathing. With insulating sheathing the water control layer is the exterior face of the insulating sheathing taped. Insulating sheathing provides no "racking resistance" or "shear" properties. For that OSB or plywood is required creating "braced wall panels" and most builders build them into corners.

Techniques and Components of Advanced Framing

Advanced framing consists of a base set of framing features which allows the builder to use 5% to 10% less board feet of wood, use 30% fewer pieces of wood, creating fewer thermal bridges all while reducing costs. BSC recommends the following features:

- Exterior Walls
  - 2" x 6" Studs
  - 24" Stud Spacing
  - 2-Stud Corners
  - Single Top Plate
  - Stacked Framing
  - Single King Studs
  - Single Jack Studs
  - Non-Load Bearing Headers Removed
- Interior Partitions
  - 24" Stud Spacing
  - Single Top Plate
  - Non-Load Bearing Headers Removed
- Floor Framing
  - 24" Spacing
- Roof Framing
  - 24" Spacing

The following figures are photographs from a variety of homes that have implemented advanced framing measures. These details are also documented the drawings provided in Appendix 1.

Figure: Exterior Walls 2" x 6" Studs 24" Stud Spacing

Figure 3 - Exterior Walls 2-Stud Corners

Figure 4 - Exterior Walls Single Top Plate and Stacked Framing

Figure 5: Exterior Walls Single King Studs without Jack Studs

Figure 6: Exterior Walls Non-Load Bearing Headers Removed

BSC Advanced Framing Research

Building Science Corporation incorporates advanced framing in a large number of its Building America homes. The following table summarizes the number of homes built in various climate regions.

Table 1 - Advanced Framed Homes per Climate Region in 2009

	Number of Homes
Cold, 4A	1
Cold, 5A	9
Hot-Humid, 2A	85
Marine, 3C	1
Mixed-Humid, 3A	29
Mixed-Humid, 4A	1
Grand Total	126

The Hot-Humid and Mixed-Humid regions contain entire communities of advanced framed homes as well as a few prototypes. The other climate regions consist primarily of prototypes and small groups of homes with advanced framing. This can also be presented in terms of builders. Table 2 contains the number of homes built by each BSC BA builder.

Table 2 - Advanced Framed Homes per Builder in 2009

	Number of Homes
Ark Ventures, LLC	1
C.Nelson	7
Colter Construction	1
David Weekley Homes	77
Greencraft LLC.	5
Moser Builders	1
Project Home Again	32
Synergy Companies Construction LLC	1
Zeta Communities	1
Grand Total	126

David Weekley Homes and Project Home Again have taken the lessons learned from early prototypes and have fully embraced advanced framing. David Weekley Homes is in the process of trials and adoption of advanced framing company-wide, in all divisions, in all climate regions. Although the community builders produce the most total square feet, the prototypes also add to the overall total and provide important implementation lessons for the project. Table 3 summarizes the total square feet built per climate region.

Table 3 - Square Feet Built per Climate Region in 2009

	Square Feet Built
Cold, 4A	3782
Cold, 5A	27419
Hot-Humid, 2A	199034
Marine, 3C	1561
Mixed-Humid, 3A	45714
Mixed-Humid, 4A	1280
Grand Total	278790

In total for 2009, over ¼ million square feet of residential floor area have been constructed incorporating advanced framing techniques under the supervision of BSC staff. Many homes include the entire advanced framing package, but some do not include all of the recommended features. This is summarized in Figure 4.

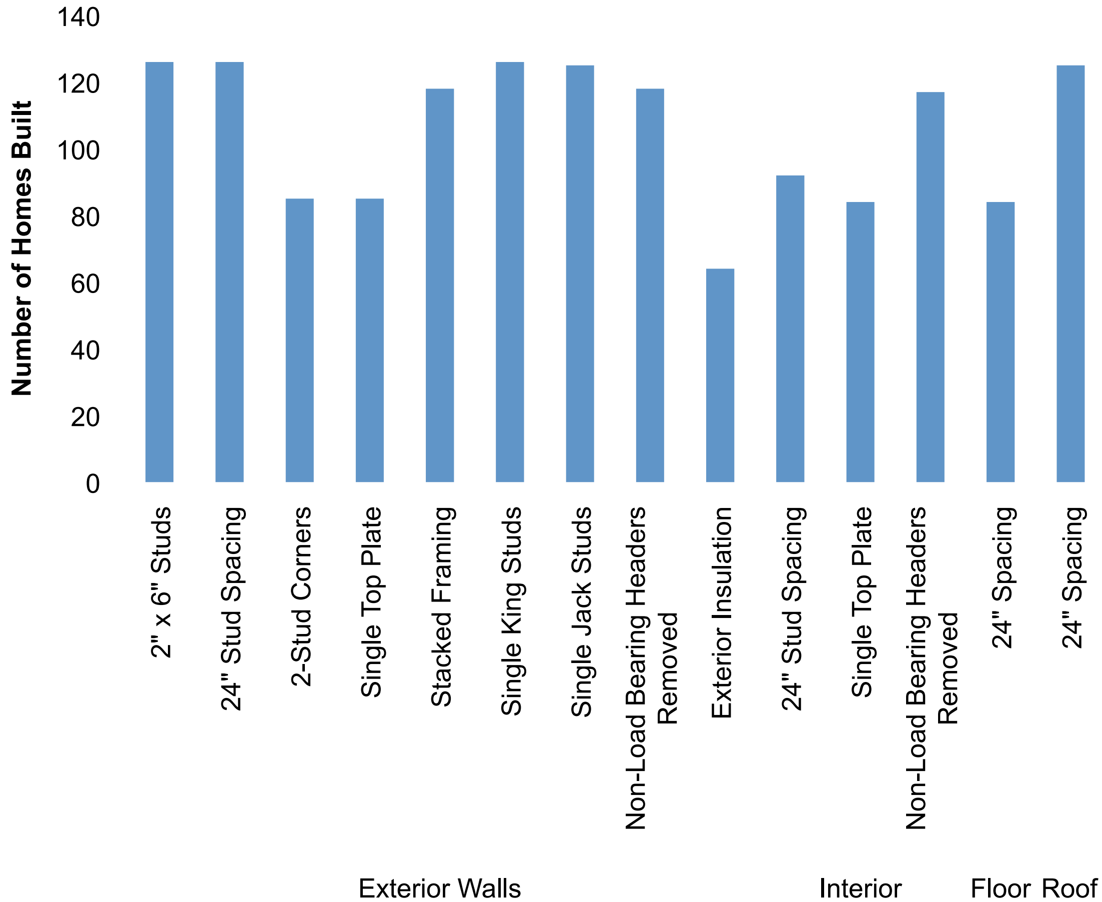


Figure 2 - Advanced Framing Features

The most common advanced framing features adopted are the 2×6 frame at 24 in. (600 mm) centers with stacked framing (where possible), single king studs, single jack studs and removal of non-load bearing headers. Full adoption of advanced framing would include all of the items shown in Figure 4 except the exterior insulation. The exterior insulation data is shown for comparison to demonstrate the high adoption percentage when advanced framing is utilized. It is not always possible to incorporate 24" spacing of the floor joists, which leads to the requirement of using double top plates in the walls because the walls and floors are now framed at different spacing. To realize the full benefits and up-front cost savings of advanced framing, the builder and designer(s) should make the decision to adopt advanced framing early in the design process. Early adoption and acceptance of the full framing package allows the designer to select framing systems (joists, trusses, beams, headers etc) that can be used at 24" O.C. and remain within the relevant building code requirements.

Energy Analysis

Advanced framing has the added benefit of reduced thermal bridging, reduced heat loss and hence energy and cost savings for the occupant. The annual site energy savings associated to adopting advanced framing with and without exterior insulating sheathing are shown in Table 4 and Table 5.

Table 4 - Annual Site Energy Savings with Exterior Insulation

	Avg. Annual Site Energy Savings (MBtu)
Cold, 4A	2.78
Cold, 5A	4.52
Hot-Humid, 2A	unknown
Marine, 3C	0.99
Mixed-Humid, 3A	5.28
Mixed-Humid, 4A	1.19
Average	2.95
	Avg. Annual Energy Savings ($)
Cold, 4A	$43
Cold, 5A	$90
Hot-Humid, 2A	unknown
Marine, 3C	$38
Mixed-Humid, 3A	$180
Mixed-Humid, 4A	$28
Average	$76

Table 5 - Annual Site Energy Savings without Exterior Insulation

	Avg. Annual Site Energy Savings (MBtu)
Cold, 4A	unknown
Cold, 5A	2.50
Hot-Humid, 2A	2.11
Marine, 3C	unknown
Mixed-Humid, 3A	unknown
Mixed-Humid, 4A	unknown
Average	2.31
	Avg. Annual Energy Savings ($)
Cold, 4A	unknown
Cold, 5A	$36
Hot-Humid, 2A	$68
Marine, 3C	unknown
Mixed-Humid, 3A	unknown
Mixed-Humid, 4A	unknown
Average	$52

The data presented in Table 5 is that of a smaller sample than that in Table 4. This is due to the fact that a large number of BSC BA builders adopting advanced framing also adopt exterior insulating sheathing. The exterior insulation significantly improves the performance of the building enclosure. This can be seen in the annual energy savings as well as annual energy cost savings. On average the advanced framing package saves approximately $60 annually. Although the greenhouse gas emissions are not modeled, because less energy is being used, fewer emissions are being released at the power plants. The site energy savings and cost savings are greatly affected by the climate region. Increased thermal performance only reduces annual energy costs associated to heating and cooling. If the heating and cooling loads are very small, as they would be in a mild climate such as Marine 3C, only a small savings is realized both in terms of energy and cost. Some of the data necessary to complete these tables was left as 'unknowns' for 2009 as this data was not available. It is anticipated that homes built in 2010 will have this data available and it will be included in the final report.

Cost and Constructability

Regardless of the energy and green house gas emissions savings, construction is a business, and businesses must be run based on the financials. There is little incentive for builders to incorporate advanced framing measures based on the annual energy savings values alone. Since the builders do not operate the houses for any significant period of time, the builders themselves to do not receive the financial energy savings benefit from incorporating these measures. In certain instances with prototype homes these financial values are very difficult to determine. This is because most trade crews must learn on at least 5 homes before proficiency with advanced framing is realized and most prototype homes do not cost analyze and compare each step. Only when a plan has been built a number of times to a base standard and then changes are made to that plan and built a number of times again incorporating advanced framing can the true value of the savings be estimated. In a production based build, the cost of engineering can also be spread over a large sample of homes instead of just one prototype. In 2010, BSC will provide additional information about these cost savings.

Incorporating the advanced framing design changes from the inception of a design does not generally require additional design fees, but re-drawing existing drawings can be costly. For the builder the cost savings of building with advanced framing is associated to reduced board feet of lumber, increased speed of framing (after a brief learning period), increased speed of other trades such as plumbers, electricians and insulators, and simplified construction. The combination of these time savings in conjunction with a well planned and executed construction schedule can significantly reduce the required build time. If each trade can spend less time in a home, more homes can be built in a given time period.

There are many cost trade-offs associated to upgrading to advanced framing. For instance increasing the spacing from 16" to 24" of floor joists requires that the floor sheathing be thicker. In BSC's experience this increase in sheathing thickness has an associated cost that roughly matches the cost savings in reducing the board feet of floor joists required. Due to code requirements, some locations also require different sheathing for the exterior shear panels in walls if 24" stud spacing is used. Again, the associated cost increase of additional, rearranged or thicker sheathing is taken away from the savings associated with fewer board feet of exterior wall studs. Interior partitions can be framed at 24" O.C. and with single top and bottom plates can have a net positive material and cost savings. In certain circumstances, as with the David Weekley Homes Charleston division, a cost savings associated with insulating to R19 over R14 was found. The R19 fiberglass insulation package actually cost less than the R14 insulation package. Upgrading only the exterior walls to 24" O.C. is a step in the correct direction, but likely will not yield significant savings. The largest savings can be seen if all features of the advanced framing package are utilized. BSC's past experience shows that a builder can save $1,000 per home by implementing advanced framing.

Advanced framing has the possibility to be a cost shifting advantage. The energy savings is relatively low, but the upfront cost savings is relatively high for the builder. The savings from advanced framing can be used to fund other efficiency options, increasing energy efficiency even further. The cost shifting creates a home that costs the same, but is significantly more energy efficient.

Although framing at 24" OC is not new, there are still hurdles to overcome for it to be implemented nationally. There are issues getting stucco installed over 7/16" OSB on advanced framing, this is not a code compliance or structural issue, it is a matter of completing testing to prove that it is possible. Recently another advanced framing hurdle was overcome in recent Baltimore code hearings. The code for allowing the use of single headers passed the committee stage. Many other perceived issues are code compliant. Appendix A contains a summary of the compliance of advanced framing to the IRC of 2000 and 2003. Currently 24" 2x6" stud spacing, single top plates, removal of headers in non-load bearing walls and drywall clips are all code approved with specified application stipulations.

Preliminary Conclusions and Future Research Plans

Advanced framing can save energy, greenhouse gas emissions, and money if properly implemented. Through BSC's experience we have found that builders can save $1000 per house on advanced framing. To maximize cost savings and energy savings for the homeowner, the builder financial savings are best shifted to implementing more energy saving measures. The cost shifting creates a home that costs the same, but is significantly more energy efficient. Code compliance hurdles, in the few cases they actually exist, have been or are in the process of being overcome. Further testing is required in many cases, although code approved, to demonstrate that advanced framing is possible and functional.

In 2010 BSC will continue deployment of advanced framing wherever possible with its Building America partners. David Weekley Homes is to continue production and this will allow BSC to gather both energy and cost data from production levels of construction. Smaller scale implementation will be completed with other BA builders in a variety of other climate zones. The data gathered from BSC's production and prototype builders will allow further cost and energy savings analysis during 2010. We expect that this information will be included in the FY2010 final report.

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Appendix 1 – BSC Advanced Framing Detail Drawings and Code Review

2. PROJECT 2: VENTILATION EFFECTIVENESS ADVANCED SYSTEM RESEARCH

2.1 Executive Summary

Overview

ASHRAE Standard 62.2–2007 — Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings sets recommended ventilation rates for residential dwelling units. Many jurisdictions are considering adopting it into their building codes, yet it currently contains a critical flaw. The Standard in effect tells the designer or builder how much ventilation air to provide, yet does not give any guidance on where or how to provide that air. The amount of ventilation air is determined by the size of the dwelling and the number of occupants, typically determined from the number of bedrooms. No attempt is made to distinguish between the effectiveness of different ventilation systems, although the ventilation community widely agrees that different systems provide very different performance.

The purpose of this research is to provide quantitative information regarding the performance of broad classes of ventilation systems on the market. Currently, many homes are built without ventilation systems, and of those that do have ventilation systems, many are systems that are relatively ineffective at removing contaminants. This creates a situation where the homes may have poor indoor air quality and high contaminant concentrations. Evidence of such occurrences was found in a recent study commissioned by the California Air Resources Board. Due to incomplete knowledge regarding the failure of these ventilation systems, there may be political pressure to increase ventilation rates in building codes and standards such as ASHRAE Standard 62.2, which would unnecessarily penalize systems that are effective at the current rates. Increasing ventilation rates would increase energy consumption for space conditioning loads and may not improve indoor air quality. One of the outcomes of this work is expected to be a modification to the ASHRAE Standard 62.2 to account for the effectiveness of different types of ventilation systems. The modification would result in an equation of the form shown in the equation below:

$Q_{fan} = C_D * Q_{vent}$,

where

Q_{fan} = required ventilation system flow rate,

C_D = coefficient of distribution (assigned based on the type of ventilation system selected), and

Q_{vent} = the current ventilation flow rate recommended by Standard 62.2-2007.

In this manner, ineffective ventilation systems will have their required ventilation rates increased while higher-performing systems will not.

Key Results

In 2009 BSC has made major efforts to promote the acceptance of a proposed addendum to ASHRAE Standard 62.2 to account for the effect of system types and operation. A supermajority of the SSPC committee agrees with the approach. The public review process for the proposed addendum is proceeding and will continue into 2010. Further work may be needed in areas not yet identified.

Gate Status

1. Source Energy Savings and Whole Building Benefits ("must meet")

This project meets the Gate 1B "must meet" requirement for source energy savings. The modifications to ASHRAE Standard 62.2 will address the current need for effective ventilation and good indoor air quality, while encouraging high-performing ventilation systems including those that often incorporate heat or energy recovery. This will have the net effect of reducing the amount of energy needed to condition homes.

2. Performance-Based Code Approval ("must meet")

This project meets both the Gate1B "must meet" requirement for performance-based and "should meet" requirement for prescriptive-based safety, health and building code requirements for new homes. Commercially-available ventilation systems that comply with ASHRAE Standard 62.2 will be products that meet this requirement.

3. Prescriptive-Based Code Approval ("should meet")

This project meets both the Gate1B "must meet" requirement for performance-based and "should meet" requirement for prescriptive-based safety, health and building code requirements for new homes. Commercially-available ventilation systems that comply with ASHRAE Standard 62.2 will be products that meet this requirement.

4. Cost Advantage ("should meet")

This project meets the Gate 1B "should meet" requirement for strong potential to provide cost benefits relative to current systems. Because the net effect of this change to the standard would be to encourage high-performing ventilation systems including those that often incorporate heat and energy recovery, it will encourage greater market penetration of these systems and innovation with other ventilation systems, resulting in a price advantage to the builder and consumer.

5. Reliability Advantage ("should meet")

This project meets the Gate 1B "should meet" requirement to meet reliability, durability, ease of operation, and net added value requirements for use in new homes. The change to the standard will not affect the products' reliability, durability, or ease of operation, and should add net value to new homes through improved indoor air quality and lower energy consumption and bills.

6. Manufacturer/Supplier/Builder Commitment ("should meet")

This project meets the Gate 1B "should meet" requirement of manufacturer/supplier/builder commitment. Manufacturers are eager to sell more ventilation equipment, and builders are beginning to install more ventilation systems. The ASHRAE Standard 62.2 Committee has engaged with BSC in this issue, and progress is being made.

7. Gaps Analysis ("should meet")

Previously identified gaps for this project have been overcome. A future research gap to overcome includes addressing the technical knowledge needed to accurately account for the source of outside air on occupant exposure. The impact on indoor air quality should be assessed for systems when the source of outside air is either unknown or expected to come from undesirable locations (such as garage, attic, crawl space, or below grade soil). There are no major market barriers to implementing this change to the standard.

Conclusions

In 2009 BSC has made major efforts to promote the acceptance of a proposed addendum to ASHRAE Standard 62.2 to account for the effect of system types and operation. A supermajority of the SSPC committee agrees with the approach. The public review process for the proposed addendum is proceeding and will continue into 2010. Further work may be needed in areas not yet identified.

2.2 Sacramento Tracer Gas Testing

In January 2006 BSC (in conjunction with the National Renewable Energy Laboratory (NREL)) performed tracer-gas testing of two new Building America homes near Sacramento, California. NREL performed testing on one house and BSC performed testing on the second. The field testing involved several multi-zone tracer gas tests in each house over the course of two weeks. The results of this testing were written up by Bob Hendron at NREL and were published in a draft NREL report (Hendron 2006) and an ASHRAE paper (Hendron 2007).

2.2.1. Description of House

This work looks only at the house tested by BSC. The house is two-story, approximately 2600 ft^2, with four bedrooms and three bathrooms. The first floor consists of one bedroom, one bathroom, a laundry room, the living room area, and a kitchen and dining room. The second floor consists of the master bedroom and bathroom, two additional bedrooms, an additional bathroom, and a small common area at the top of the stairway which overlooks the living room below. Figure 2.1 contains a drawing of the floor plan of the house, and Figure 2.2 contains a photograph of the front elevation.

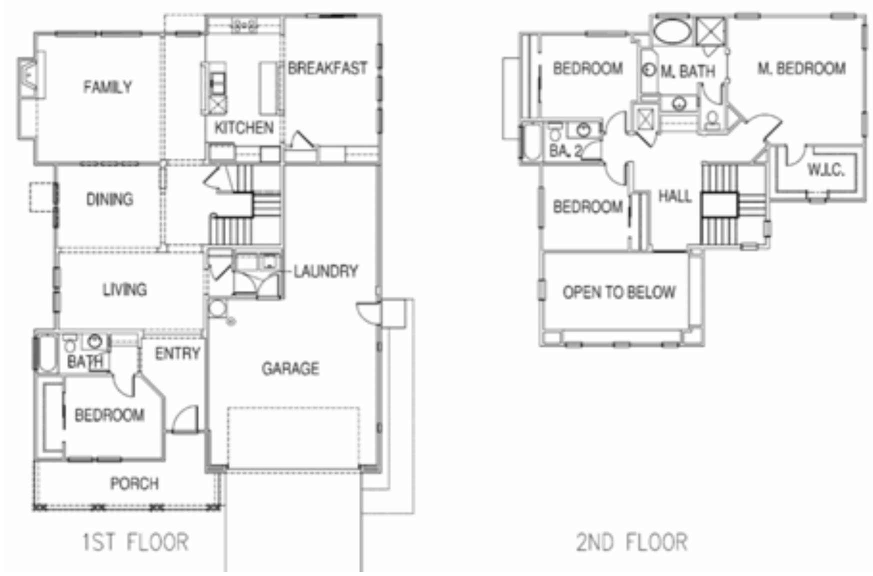


Figure 2.1: Floor plan of the house tested

Figure 2.2: Front elevation of the house tested

2.2.2. Description of Test Method

The two houses were tested using tracer gas decay techniques. In these tests, a tracer gas was injected into the house and the central air handler (AHU) was operated continuously in order to mix the house to a uniform tracer gas concentration. The test was initiated by deactivating the mixing systems and activating the ventilation system as appropriate for the test, and leaving the house in that state for a period of 2 to 14 hours. Three ventilation systems were tested. The first ventilation system tested was the central-fan-integrated supply (CFIS) ventilation system, which consists of an outside-air duct to the return side of the AHU and a controller that operates the AHU on a minimum duty cycle. The outside-air duct contains a damper that remains closed except when the CFIS system is activated. The duty cycle of the AHU and CFIS system varied from test to test. This ventilation system was operated at different ventilation rates using a variable-speed fan installed in line with the outside air duct, as described in Table 2.1. The second and third ventilation systems were upgraded exhaust fans located in the laundry room and master bedroom, respectively. The exhaust fans were tested only at 100% of the ASHRAE Standard 62.2-2003 ventilation rate, and were tested with and without simultaneous operation of the AHU for mixing. In addition to the ventilation tests, natural infiltration and air handler bump (natural infiltration with the AHU running) tests were also conducted. During the tracer gas tests, the bedroom doors were either open or closed. The house was built with transfer grills, which are passive openings above the doorways that allow a return air path when the bedroom doors are closed. The transfer grills were also either open or closed (taped over) during the tracer gas tests. The doors to the bathrooms and laundry room were always open. All exterior doors and windows were always closed.

2.2.3. Test Performed

In the tracer gas testing, two common ventilation systems were tested: an upgraded bathroom exhaust fan and a central-fan-integrated supply (CFIS) system. Tests were performed with the interior doors in the houses open and closed, with the transfer grills open and closed, and with and without mixing via the AHU. In total, seventeen ventilation tests were performed on the house using tracer gas decay methods. Table 2.1 lists the tracer gas tests performed.

Table 2.1: List of tracer gas tests

Test Number	Description
CFIS Tests With Mixing (All have AHU 20 min off/10 min on)	
1	Doors Closed, Transfer Grills Open, 95% of the 62.2 Ventilation Rate*
2	Doors Closed, Transfer Grills Open, 60% of the 62.2 Ventilation Rate
3	Doors Closed, Transfer Grills Open, 33% of the 62.2 Ventilation Rate
4	Doors Closed, Transfer Grills Closed, 60% of the 62.2 Ventilation Rate
Laundry Exhaust Tests With Mixing (All at 100% of the 62.2 ventilation rate)	
5	Doors Closed, Transfer Grills Open, AHU 20 min off/10 min on
6	Doors Closed, Transfer Grills Open, AHU 25 min off/5 min on
7	Doors Closed, Transfer Grills Closed, AHU 25 min off/5 min on
Laundry Exhaust Tests Without Mixing (All at 100% of the 62.2 ventilation rate)	
8	Doors Open, Transfer Grills Open
9	Doors Closed, Transfer Grills Open
10	Doors Closed, Transfer Grills Closed
Master Bathroom Exhaust Tests With Mixing (All at 100% of the 62.2 ventilation rate)	

11	Doors Closed, Transfer Grills Open, AHU 25 min off/5 min on
Master Bathroom Exhaust Tests Without Mixing (All at 100% of the 62.2 ventilation rate)	
12	Doors Closed, Transfer Grills Open
13	Doors Closed, Transfer Grills Closed
Natural Infiltration Tests (No ventilation or AHU operation)	
14	Doors Open, Transfer Grills Open
Air Handler Bump Tests (No ventilation, AHU on)	
15	Doors Open, Transfer Grills Open
16	Doors Closed, Transfer Grills Open
17	Doors Closed, Transfer Grills Closed

*Test 1 was 95% instead of 100% of the 62.2 ventilation rate due to hardware limitations.

2.2.4. Results

The results from these tests showed that the two ventilation systems had substantially different room-to-room difference in tracer gas concentration and therefore different efficacy at distributing ventilation air to each of the rooms in the houses. Figure 2.3 shows the decay in tracer gas concentration for one of the exhaust-only tests, and Figure 2.4 shows the decay in tracer gas concentration for one of the CFIS tests. The difference in uniformity is clear, and convinced BSC that an effort should be made to address the differences between different types of ventilation systems.

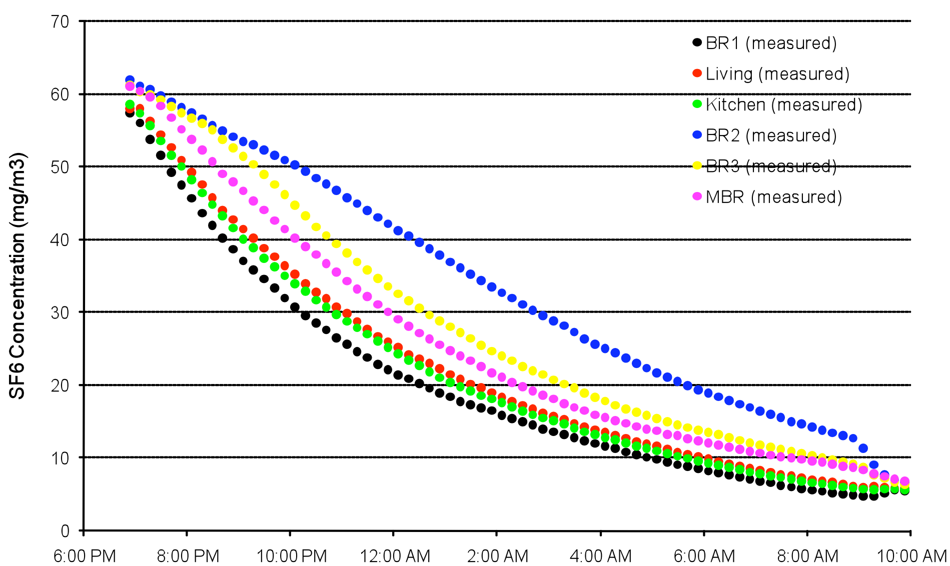


Figure 2.3: Tracer gas measurement results for Test 1 (exhaust from laundry room)

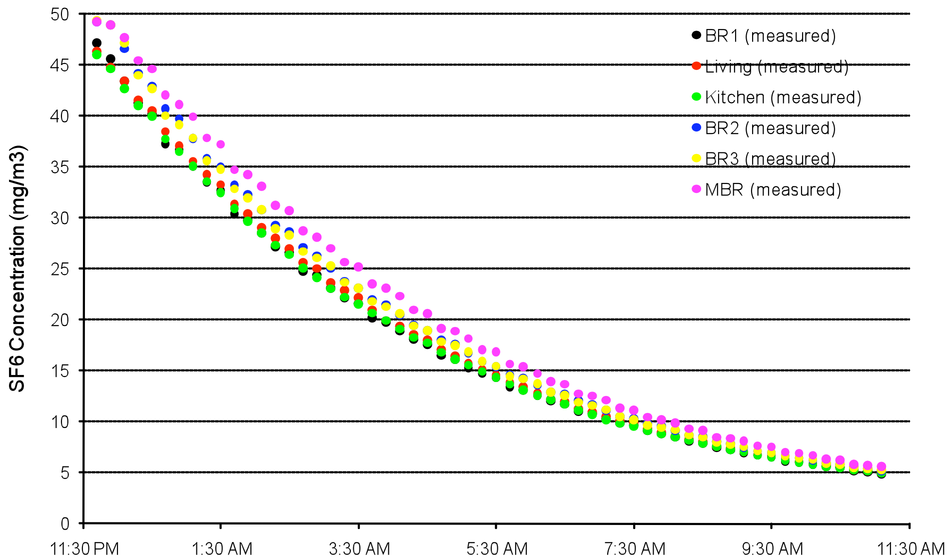


Figure 2.4: Tracer gas measurement results for Test 3 (CFIS)

2.2.5. Conclusions

The tracer gas tests showed clear differences in the efficacy of the two different ventilation systems tested at removing pollutants from all zones in the house. It was decided that a computer model should be constructed in order to determine the efficacy of ventilation systems not tested in the tracer gas testing.

2.3 Calibration of First Model

In order to extend the results obtained during the physical testing to ventilation systems not present in the two houses tested, a computer program was used to create a calibrated model which could accurately recreate the physical testing results and therefore could be expected to predict the performance of other types of ventilation systems.

2.3.1. Introduction to CONTAM

The computer program used for the model was CONTAM. CONTAM is a multi-zone air flow network modeling software developed by the National Institute of Standards and. It is commonly used in ventilation research to model buildings, ventilation systems, and contaminants in indoor and outdoor air. In CONTAM, the user specifies attributes of the building's zones, air flow pathways between zones (such as leaks or fans and ducts), contaminant sources and sinks, and other relevant inputs. The software performs the simulation and the results are available for visualization or export.

2.3.2. Testing of Substitute House

The results from CONTAM are very dependent on having realistic inputs for the attributes of the building in terms of air flow pathways; however at the time of the tracer gas testing described above the only diagnostic test that was performed on the house was an enclosure air leakage test. No further diagnostics were performed on the house enclosure or interior demising walls because further work was not planned at that time. Later, when the decision was made to create a calibrated computer model, much more detailed information about the enclosure and interior airflow paths was needed in order to provide a reasonable starting point for the calibration process. The original house was no longer available for testing, so another house of the same floor plan was tested instead. While two houses of the same floor plan can certainly have different leakage characteristics, these two houses were built within a few months of each other, by the same builder and likely the same subcontractors, and the overall enclosure leakage testing results were similar. The original house had a leakage rate of 1346 cfm50, and the substitute house had 1608 cfm50. The substitute house was slightly larger due to an option that added two additional bedrooms and an additional bathroom; after subtracting the leakage in the additional bedrooms, the substitute house was 1411 cfm50. As the substitute house was simply a starting point for calibrating the model, differences between the houses were of minor consequence and were remedied during the calibration process.

Air leakage characterization on the substitute house was performed to quantify both house-to-exterior and room-to-room leakage characteristics. The testing also included tests of zone pressures and central forced-air system airflow to each room. The testing procedure was able to quantify the leakage characteristics of each room to the exterior and to neighboring zones, but no attempt was made to identify the specific locations of leakage within each room. Further details of the testing at the substitute house are included in Appendix A.

2.3.3. Calibration Procedure

The goal of the calibration procedure was to produce a set of inputs for the house enclosure and zone-to-zone leakage pathways that, when simulated with CONTAM, would produce the same results as the tracer gas tests when the ventilation systems were operated in the same manner as each of the tracer gas tests.

As a starting condition, leakage values calculated from the leakage testing in the substitute house were used for the exterior enclosure and the interior partition walls. Because the actual leakage locations within each room were not determined by the testing, leakage within each room was initially distributed proportional to the wall and ceiling area. Wall leakage was broken into leakage for each wall orientation and into five vertical locations on each wall, with equal vertical separation between the locations. Each leakage location on a wall had the same leakage coefficient and exponent. Initial test runs with simplified models showed the vertical spacing chosen (5 leaks per wall, equally spaced on a 9 ft (2.7 m) wall) approximated diffuse wall leakage, while still maintaining a manageable number of leakage elements in the model. The temperature in each room and the outdoor temperature and wind speed had been recorded during the tracer gas testing, and were used as inputs to the model. Wind direction was not recorded during the tracer gas testing, so meteorological data from the nearest airport (Auburn, CA, approximately 10 miles away) was obtained and the wind direction data was used as an input to the model. Drawings and specifications for the AHU and duct system were obtained from the subcontractor, which were used to create a full duct and AHU model. The AHU and all ductwork in this house are located within conditioned space, greatly simplifying the need to characterize duct leakage. For each test simulated, a schedule was created that controlled the ventilation systems, AHU operation, and transfer grill and bedroom door status to replicate operation as performed in the tracer gas tests. Results from the model were compared to the tracer gas data and the leakage inputs were modified via trial-and-error to decrease the error between the model output and the tested data. No formal method was used to obtain a minimized error function, only visual comparison of the measured and simulated tracer gas decay curves, so there is no reason to assume that the final inputs represent a unique or optimized solution.

During the initial comparisons of measured and simulated data, it became clear that the most difficult tests to replicate were the tests with large differences in tracer gas decay rates between the different rooms. Stated differently, it is easier to replicate the decay rate in a well-mixed house (which might be approximated as a single well-mixed zone) than it is to replicate the decay rates of six interconnected zones. Consequently, a single test was used for the calibration, and the remaining tests were used after the calibration was complete in order to evaluate the results. The test used to calibrate the model was one which utilized the continuously-operating laundry room exhaust fan as the ventilation system, did not have mixing via the AHU, and had the bedroom doors closed and the transfer grills open.

2.3.4. Calibration Results

Overall, good agreement between the modeling and tracer gas results was obtained. The best agreement was obtained for cases with mixing and the least agreement was obtained for the natural infiltration case. Tracer gas concentration decay plots are presented below for several tests.

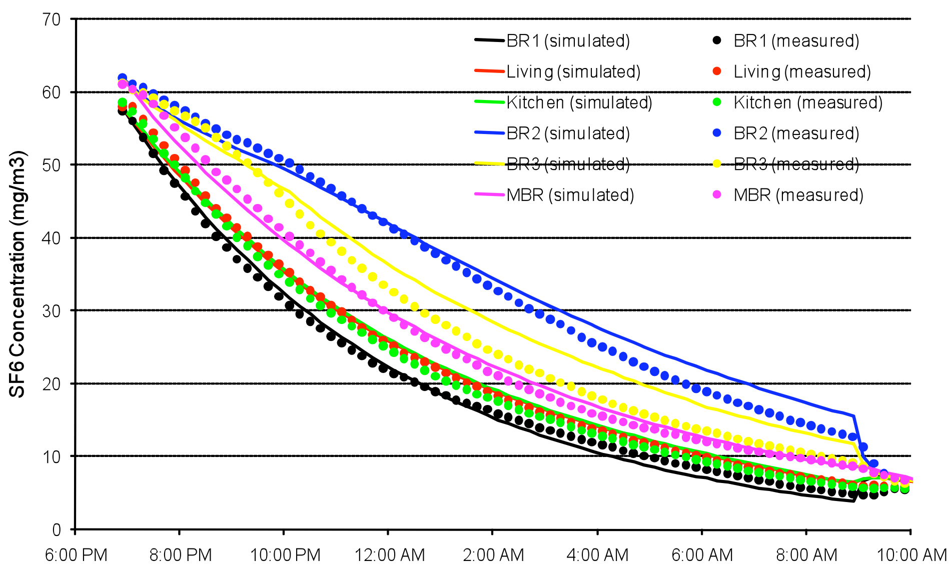


Figure 2.5: Comparison of results for the laundry exhaust test without mixing (test 1)

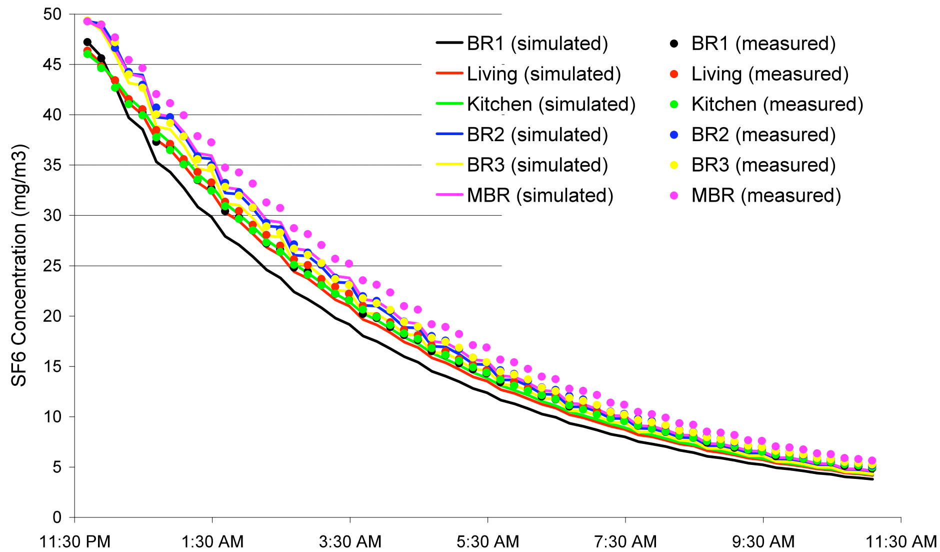


Figure 2.6: Comparison of measured results for the CFIS test (test 3)

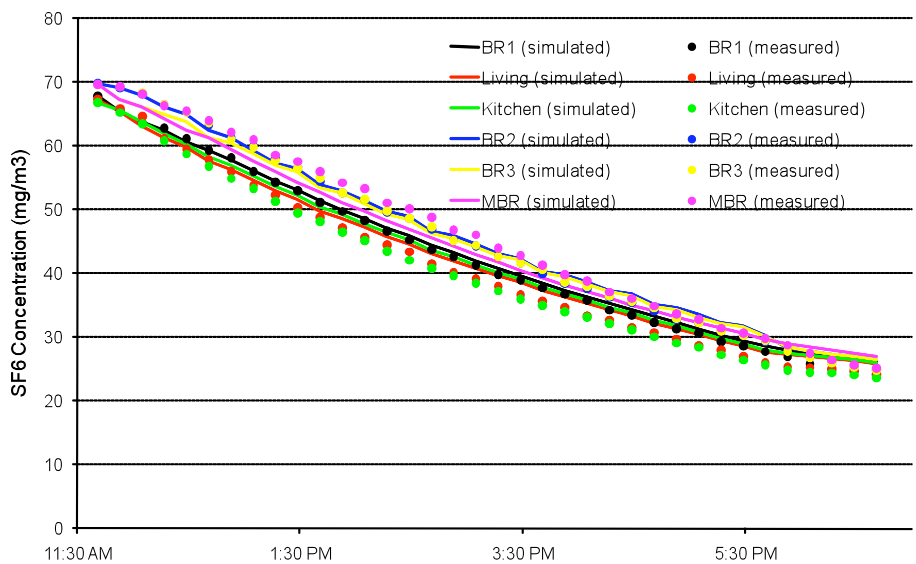


Figure 2.7: Comparison of results for the laundry exhaust test with mixing (test 6)

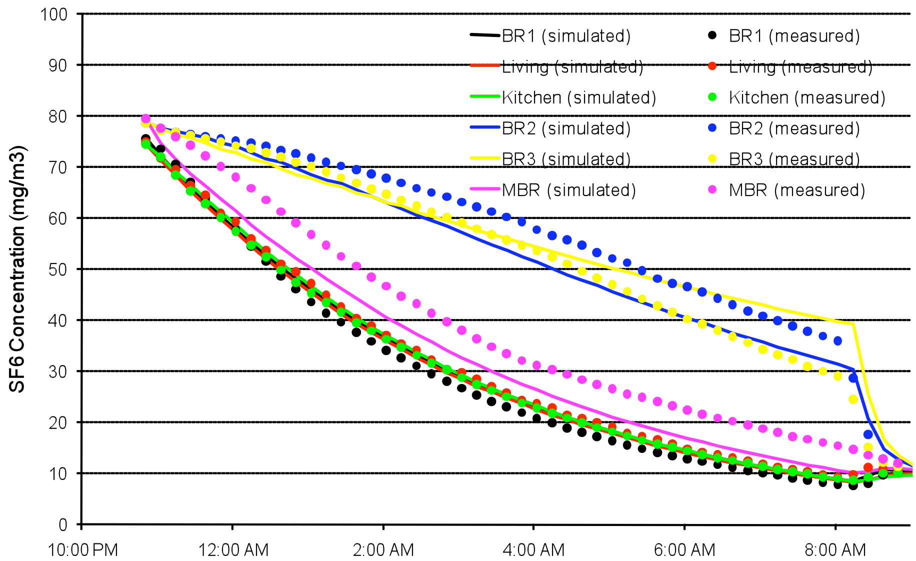


Figure 2.8: Comparison of results for the master bathroom exhaust test without mixing (test 15)

A technical paper describing the calibrated model and results was written and published in ASHRAE Transactions (Townsend 2009).

Because all of the simulations necessary for modeling ventilation systems necessarily have ventilation, the model was deemed sufficiently accurate to enable simulations of systems not tested in the tracer gas tests.

2.3.5. Use of Calibrated Model for Other Ventilation Systems

Six different ventilation systems were simulated using the calibrated model. The ventilation systems compared using the calibrated model were:

1. Exhaust ventilation, without central duct system
2. Supply ventilation, without central duct system
3. Exhaust ventilation, with central ducts, AHU controlled by standard thermostat
4. Exhaust ventilation, with central ducts, AHU controlled by thermostat with timer
5. Supply ventilation, with central ducts, AHU controlled by thermostat with timer
6. Fully ducted balanced ventilation system, without central duct system

For the extension, a single day was examined. During this day, the outdoor temperature varied between 10 and 24 °C and the indoor temperature was constant at 22 °C as shown in Figure 2.10.

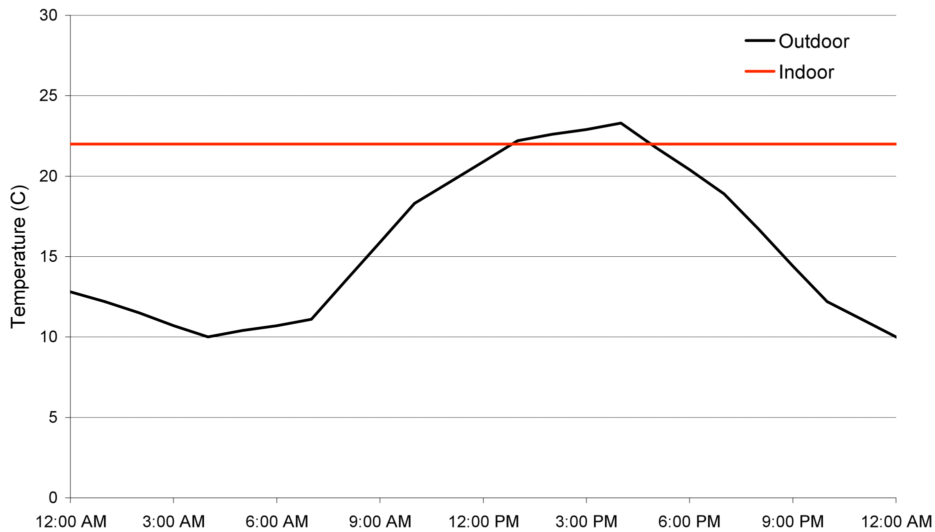


Figure 2.10: Indoor and outdoor temperatures used in extension cases

The tracer gas decay curves for each of these systems are shown in Figure 2.11 through Figure 2.16.

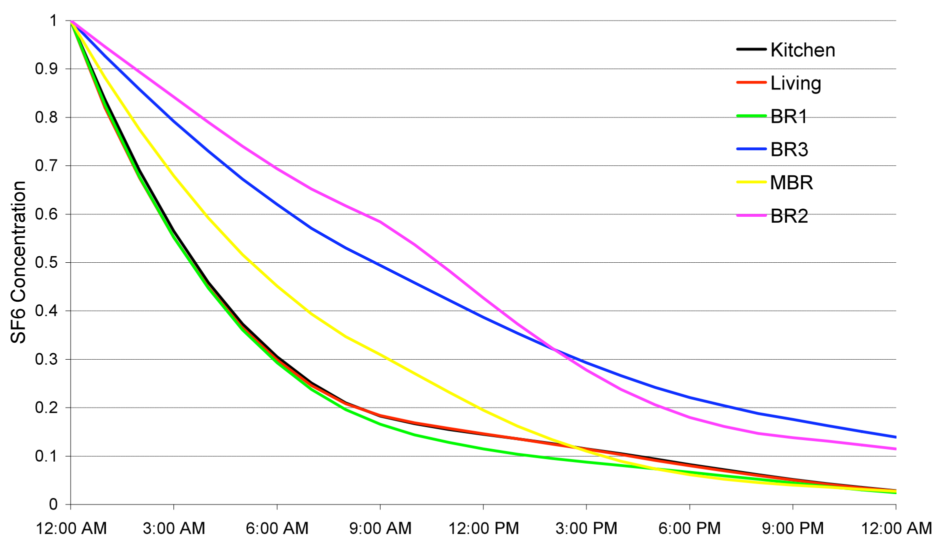


Figure 2.11: Extension case—exhaust ventilation without central AHU

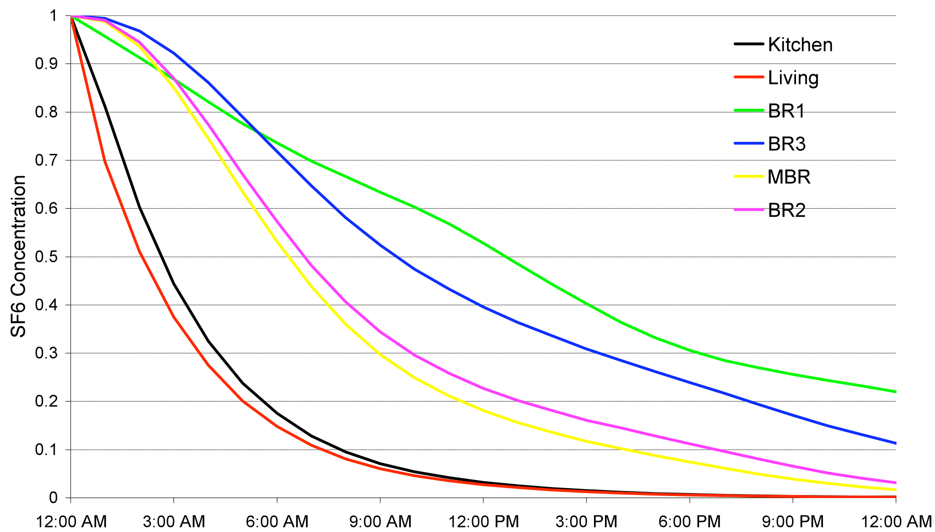


Figure 2.12: Extension case—supply ventilation without central AHU

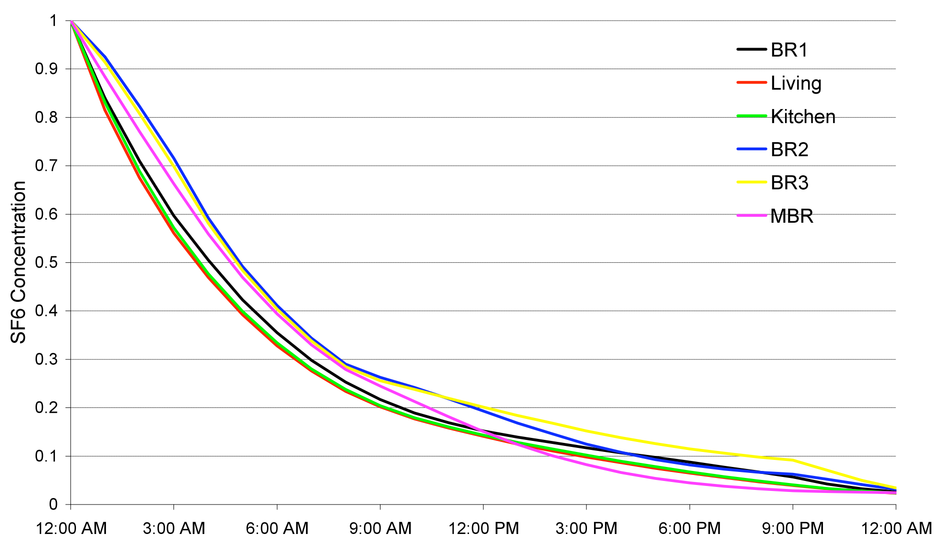


Figure 2.13: Extension case—exhaust ventilation with central AHU and standard thermostat

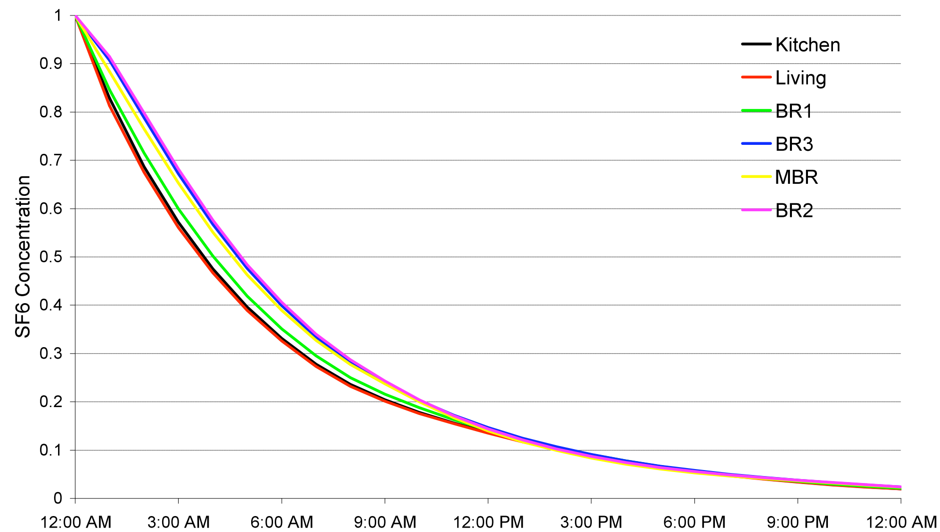


Figure 2.14: Extension case—exhaust ventilation with central AHU and minimum run timer

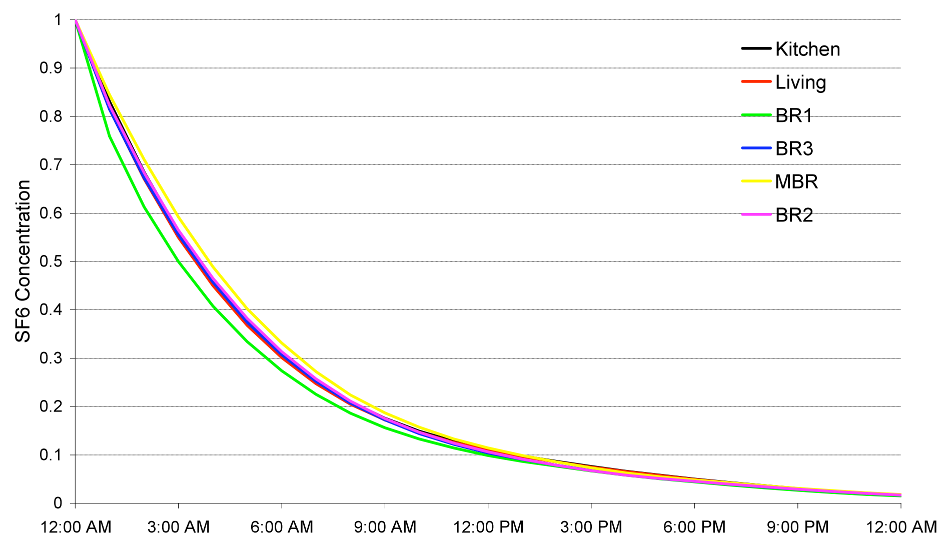


Figure 2.15: Extension case—CFIS ventilation with minimum run timer

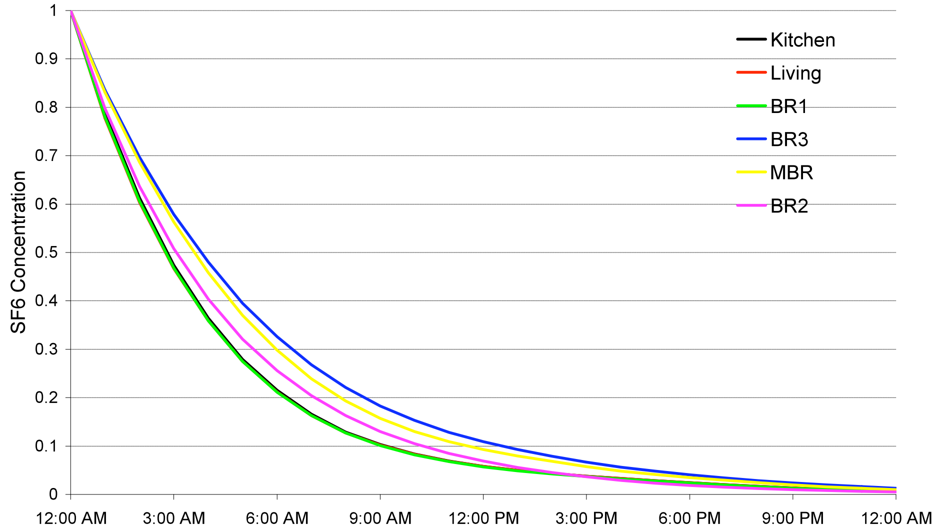


Figure 2.16: Extension case—balanced ventilation system without AHU

The results of these simulations indicated that the worst performance of any of the systems simulated was the exhaust system without an AHU. Therefore the average decay rate of this system was established as a minimum performance criterion, and the other systems were compared to this system to determine if the airflow rates could be modified while still meeting the minimum performance criterion. Figure 2.17 shows the established minimum performance criterion as an average of what the occupants of the house would experience as they moved from zone to zone over the course of a day.

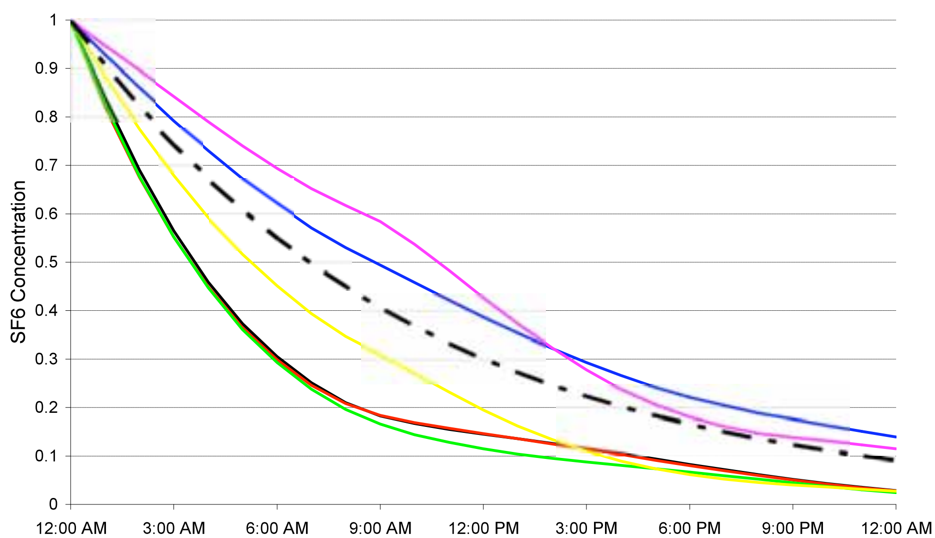


Figure 2.17: Establishing the reference decay rate using the exhaust ventilation system without and AHU

Figure 2.18 shows the same minimum performance criterion and the decay curves for the balanced ventilation system at 100% of the 62.2 ventilation rate. It is clear that the balanced ventilation system exceeds the minimum decay rate criterion, and therefore it may be possible to reduce the airflow somewhat and still meet the minimum decay rate criterion.

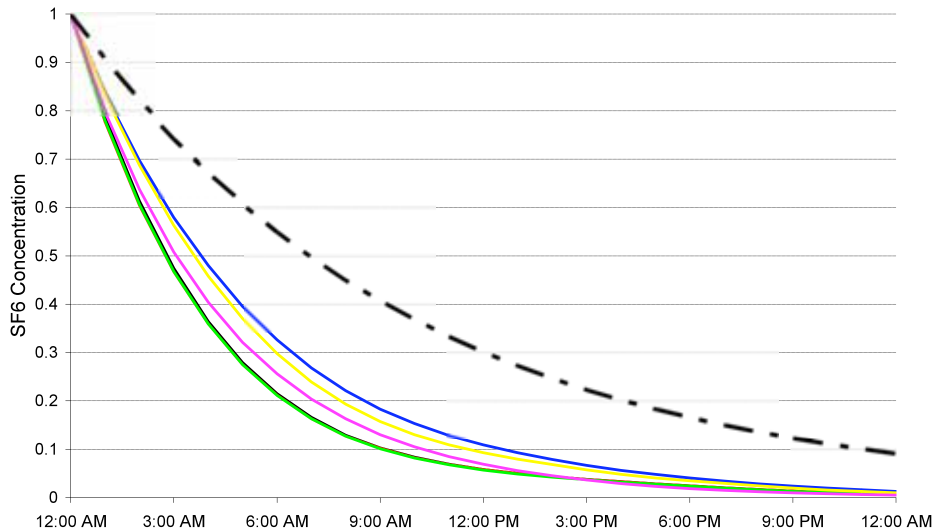


Figure 2.18: Comparison of reference decay rate with decay rates of house with balanced ventilation at 100% of the 62.2 rate

Figure 2.19 shows the same minimum performance criterion and the decay curves for the balanced ventilation system at 50% of the 62.2 ventilation rate. The figure shows that even at 50% of the airflow the tracer gas decay curves are below the established minimum performance criterion. This suggests that the balanced ventilation system could provide only half as much air as the exhaust system and still provide faster decay rates.

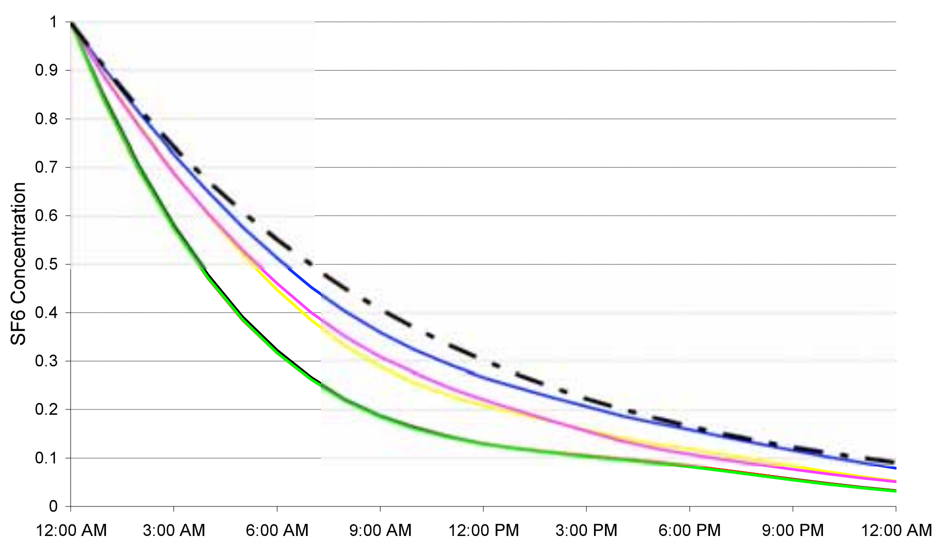


Figure 2.19: Comparison of reference decay rate with decay rates of house with balanced ventilation at 50% of the 62.2 rate

Based on this very limited set of simulations, distribution coefficients for these systems would be:

1. Exhaust ventilation, without central duct system C_D=1.25
2. Supply ventilation, without central duct system C_D =1.25
3. Exhaust ventilation, with central ducts, AHU controlled by standard thermostat C_D =1
4. Exhaust ventilation, with central ducts, AHU controlled by thermostat with timer C_D =0.75
5. Supply ventilation, with central ducts, AHU controlled by thermostat with timer C_D =0.75
6. Fully ducted balanced ventilation system, without central duct system C_D =0.5

2.4 ASHRAE Meeting—January 2007, Dallas

2.4.1. Building America Expert Meeting

BSC presented the results from the tracer gas testing, model calibration, and extension cases at a Building America Expert Meeting in January 2007 in Dallas, just before the ASHRAE Standard 62.2 meeting. Speakers during this meeting were Ren Anderson of NREL, Bjarne Olesen of the Technical University of Denmark, Max Sherman of Lawrence Berkeley National Laboratory, and Aaron Townsend of Building Science Corporation. The expert meeting summary is included in Appendix B.

2.4.2. SSPC 62.2 Meeting

BSC also presented our work to the ASHRAE SSPC 62.2 committee during their normal meeting. In general, the committee engaged with BSC's presentation and was receptive to the idea of modifying airflow rates in order to achieve equivalent performance, but wanted to see the effect of different assumptions in the model before agreeing to any change to the standard. In particular, they wanted to see the effect of these assumptions:

1. Full-year calculation of exposure
2. Climate
3. Enclosure air tightness
4. AHU location
5. Duct leakage
6. Ventilation system duty cycle

In addition to identifying these areas of concern, several members of the committee offered advice and suggestions on how to approach the task of modeling this many combinations of parameters.

2.5 Preparation for First Round of Simulations

In order to determine the effects of the assumptions listed above, a larger batch of simulations was performed. In order to execute these simulations, a test plan was created; weather files were prepared; operational schedules were prepared for the AHU and other equipment; AHU sizes were determined; CONTAM automation tools were gathered; and the necessary post-processing tools were created.

2.5.1. Weather Files

CONTAM uses a custom text format for its climate input files, so TMY2 data files for each climate in the test plan were used to create CONTAM weather files.

2.5.2. Schedule Files

CONTAM also allows the user to specify the operation schedule for many components of the model using custom text files. These files specify a multiplier that is applied to the component, such that the component is between 0 and 100% of its input value.

For basic AHU operation in each climate, the operation schedule was derived from the TMY2 outdoor temperature data. Under either heating or cooling conditions, the AHU was assumed to operate 80% of the hour under design conditions and 0% of the hour at the balance point. Points between the balance point and design conditions were linearly interpolated between 0 and 80%. Points between the heating and cooling balance points had no operation.

Schedules were also created that layered an additional requirement on top of the above schedule. These schedules imposed a minimum runtime of 10 minutes out of every 30 minutes.

Schedules were also prepared for bedroom door operation. The doors were closed at night and open during the day.

2.5.3. AC Sizes

For each of the climates in the simulation plan, an ACCA Manual J calculation was performed to determine the proper size air conditioner for this house in the climate. The AHU airflow was set at 400 cfm per ton.

2.5.4. CONTAM Automation Tools

NIST personnel provided a parametric automation tool called CONTAM Factorial. This program requires the user to create a base CONTAM file, then open the file in a text editor and insert wildcard characters where the Factorial program will insert different values as specified in a separate text file. The Factorial program can change any number of variables with up to eight values per variable. The Factorial program creates a CONTAM file for every combination of value for each variable, and a .BAT file for executing the files in a batch process.

2.5.5. Post-Processing Tools

The output of CONTAM is a text file with contaminant concentrations in each zone for each time step. In order to convert these concentrations into an occupant exposure, the text file must be processed. An Excel macro program was written to perform this conversion.

2.6 First Round of Simulations

2.6.1. Model Description

In order to model a larger subset of the housing stock as requested by the 62.2 committee, the model necessarily became less specific and more general. In this case it means the model was detuned from its calibrated state (where it was calibrated to match one particular house) in order to predict general behavior over a larger population of houses.

The model was expanded from a single day to cover an entire year. The model was also enhanced to include the effects of wind, pollutant generation within the house, and occupants moving around within the house.

Wind speed and direction data were taken from the TMY2 data for each climate. The local wind shielding model and modifiers from ASHRAE Fundamentals 2005 Chapters 16 and 27 for typical suburban surroundings were used.

In previous simulations, the house was first loaded to a uniform concentration of pollutant, and the performance metric of interest was how fast the concentration decayed. For these year-long simulations, constant pollutant sources were inserted in each zone in the model and CONTAM calculated the pollutant concentration in each zone each time step. The net result is that the pollutant concentration does not decay, but varies up or down according to the amount of air exchange between the building and the outdoors.

The enclosure leakage was assumed to be distributed as reported in ASHRAE Fundamentals Chapter 27. Walls, windows, and doors made up 62% of the total leakage, ceilings and non-operating exhaust vents 23%, and ducts 15%.

The model layout in this round of simulations is shown in Figure 2.20 below.

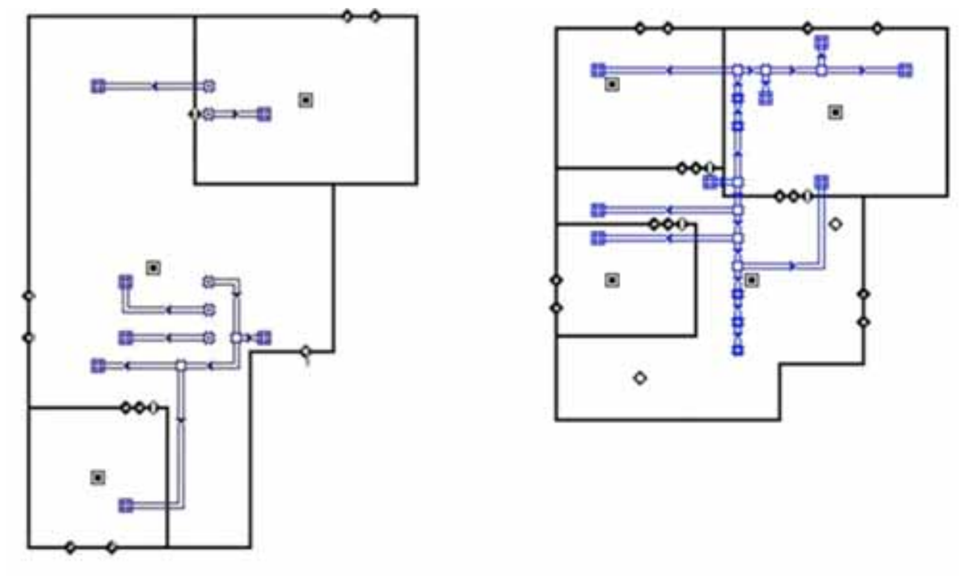


Figure 2.20: CONTAM layour during the first round of simulations

2.6.2. Parameters Varied

The parameters varied in this round of simulations were the presence and location of the central system, the amount of duct leakage, the AHU operation, the enclosure leakage rate, the ventilation system, the ventilation rate, and the climate.

2.6.2.1. Presence and location of central system

The AHU and central duct system is either absent, present but outside of the conditioned space, or present and inside the conditioned space.

2.6.2.2. Duct leakage

If a central system was present, duct leakage was either 6% or 12% of the nominal AHU flow.

2.6.2.3. AHU operation

The AHU, if present, operates either with a standard thermostat or with a thermostat with a minimum of 10 minutes runtime every 30 minutes.

2.6.2.4. Enclosure leakage

Total enclosure leakage rates included 1.5, 3.5, and 7.0 ACH50.

2.6.2.5. Ventilation system

Four ventilation systems were modeled, included a single-point exhaust system, a single-point supply system, a two-point balanced system, and a balanced system with a fully-ducted supply and a single-point exhaust.

2.6.2.6. Ventilation rate

The ventilation rate was 0%, 50%, 100%, or 150% of the ASHRAE Standard 62.2-2003 rate for this house (which was 63 cfm).

2.6.2.7. Climate

Three climates were modeled: Phoenix, Seattle, and Minneapolis (DOE climate zones 2B, 4C, and 6, respectively).

2.6.3. Occupant Exposure as Metric Comparison

The metric for the calibration round of simulations was tracer gas decay rate. This is useful for short time periods, however for longer time periods it is not useful. Instead, pollutant sources are located within the model and CONTAM calculates the pollutant concentration in each zone each time step. The metric for this round of simulations and all rounds after this is exposure to the occupants, which is expressed as an average concentration of pollutant in the air the occupant is breathing. The average can be taken over any time period of interest, for example an hour, a day, or a year. In this round of simulations, averages were taken over three-hour, eight-hour, and one-year time periods.

Exposures were calculated assuming a volume-weighted pollutant source. This type of source simulates pollutants from building materials and finishes such as paint, OSB, carpet, etc.

2.6.4. Post-Processing

An Excel macro program was created to reformat the output from CONTAM and provide the output in a human-readable format.

A different approach was used to determine the airflow ratios. In this round, the “best” system was assumed to be the balanced system with fully ducted supply. Other systems were compared to this system in order to determine how much air they need to supply or exhaust to achieve equivalent performance.

2.6.5. Results

This round of analysis showed that other ventilation systems had airflow ratios in the range of 0.9 to 2.6, with approximate medians in the range of 1.0 to 2.0 for each group.

System Type	**Range**	**Approximate Median**
Fully ducted balanced ventilation system, with or without central duct system	1.0	1.0
Non-fully ducted balanced ventilation, with central duct system, and central air handler unit controlled to a minimum runtime of at least 10 minutes per hour	0.9 to 1.1	1.0
Supply ventilation, with central duct system, and central air handler unit controlled to a minimum runtime of at least 10 minutes per hour	1.1 to 1.7	1.25

Exhaust ventilation, with central duct system, and central air handler unit controlled to a minimum runtime of at least 10 minutes per hour	1.1 to 1.9	1.25
Exhaust ventilation, with central duct system, and central air handler unit not controlled to a minimum runtime of at least 10 minutes per hour	1.0 to 1.8	1.5
Supply ventilation, without central duct system	1.4 to 1.9	1.75
Exhaust ventilation, without central duct system	1.3 to 2.6	2.0

2.7 ASHRAE Meeting—June 2007, Long Beach

2.7.1. Building America Expert Meeting

BSC held a second expert meeting before the June 2007 ASHRAE meeting in Long Beach to discuss further developments in the ventilation field. The meeting was again held the same day as the ASHRAE 62.2 committee meeting, allowing greater participation by the committee members. Speakers during this meeting were Max Sherman and Iain Walker of Lawrence Berkeley National Laboratory, Bob Hendron of NREL, and Aaron Townsend of Building Science Corporation. The expert meeting summary is included as Appendix C.

2.7.2. SSPC 62.2 Meeting

BSC again presented our work to the ASHRAE SSPC 62.2 committee during their normal meeting. The committee remained engaged with BSC's work, but wanted further explanation of the effect of each parameter varied, and comparison with other work presented. Their questions are summarized as:

1. How do the cases BSC examined fit with the work LBL presented?
2. What happens if the air conditioner is not sized by ACCA Manual J?
3. What is the effect of each of the varied parameters?
4. Are these consistent with other climates?

2.8 Second Round of Simulations

In order to expand the number of climates and extend the results to 200% of the 62.2 rate, further simulations were performed. The climates added were Daytona Beach, FL, and Raleigh, NC (DOE climate zones 2A and 4A, respectively).

2.8.1. Changes from Previous Modeling

Minimal changes were made to the model. This round was primarily an expansion of the previous results in terms of number of climates and higher ventilation rates. The largest change to the model was to increase the number of leakage points on each wall from two to five, in order to better approximate diffuse leakage over the height of the wall. The other change was to a separate set of simulations that fully mixed the house in order to replicate some of the metrics that LBL presented in the previous expert meeting.

2.8.2. Model Description

The only change to the model for the main group of simulations was the change from two leakage points per wall, located at the top and bottom of the wall, to five leakage points per wall, spaced equally over the wall's height. For a small subset, the house was fully mixed in order to provide a baseline comparison similar to one metric presented by LBL.

2.8.3. Parameters Varied

The only change to the parameters varied from the first round of simulations was the number of climates and the ventilation rates.

2.8.3.1. Presence of central system

The AHU and central duct system is either absent, present but outside of the conditioned space, or present and inside the conditioned space.

2.8.3.2. Duct leakage

If a central system was present, duct leakage was either 6% or 12% of the nominal AHU flow.

2.8.3.3. AHU operation

The AHU, if present, operates either with a standard thermostat or with a thermostat with a minimum of 10 minutes runtime every 30 minutes.

2.8.3.4. Enclosure leakage

Total enclosure leakage rates included 1.5, 3.5, and 7.0 ACH50.

2.8.3.5. Ventilation system

Four ventilation systems were modeled, included a single-point exhaust system, a single-point supply system, a two-point balanced system, and a balanced system with a fully-ducted supply and a single-point exhaust.

2.8.3.6. Ventilation rate

The ventilation rate was 0%, 50%, 100%, 150%, or 200% of the ASHRAE Standard 62.2-2003 rate for this house (which was 63 cfm).

2.8.3.7. Climate

Five climates were modeled: Daytona Beach, Phoenix, Raleigh, Seattle, and Minneapolis (DOE climate zones 2A, 2B, 4A, 4C, and 6, respectively).

2.8.4. Exposure Calculation Method and Scenarios

Exposures were calculated in several different ways in order to compare BSC's results with LBL's results. These included different source locations and different assumptions about occupancy. The following methods were examined:

1. Everybody Everywhere
    a. Equal source in each zone (source strengths independent of zone sizes)

    b. Occupants spend equal time in each zone
    c. Exposure each hour is average of all zones
2. Volume Weighted Sources
    a. Source strengths proportional to volume of each zone (meets age of air assumptions)
    b. Occupants spend equal time in each zone
    c. Exposure each hour is average of all zones
3. Worst Case Age of Air
    a. Source strengths proportional to volume of each zone (meets age of air assumptions)
    b. Varying degrees of worst case:
        i. Case A: Occupant in worst zone each hour
        ii. Case B: Occupant always in zone with worst yearly average
        iii. Case C: Occupant has worst exposure of all occupants in the house, assuming a daily schedule
4. I Stink
    a. Single source in same zone as occupant
    b. Occupant stays in worst zone
5. You Stink
    a. Single source different zone than occupant
    b. Worst combination of source zone and occupied zone

2.8.5. Post-Processing

An Excel macro program was created to perform most of the calculations and post-processing for this round of simulations.

2.8.6. Results

This round of simulations and analysis focused on answering several specific questions posed by the 62.2 committee. These questions were:

1. How do the cases BSC examined fit with the work LBL presented?

2. What happens if the air conditioner is not sized by ACCA Manual J?

3. What is the effect of each of the varied parameters?

4. Are these consistent with other climates?

To answer the first question, BSC replicated the cases LBL had previously presented in order to determine if there were any inconsistencies between the two sets of data. Table 2.2 through Table 2.6 compare the results of the BSC and LBL analyses. The results are remarkably close given the different approaches taken by the two research teams, and there are no results that suggest that the two sets of data are inconsistent.

Table 2.2: Comparison of BSC and LBL results for Everybody Everywhere case

Simple Exhaust

	BSC	LBL
Leaky House	1.22 to 1.27	1.06 to 1.64
Tight House	1.22 to 1.44	1.37 to 2.43

CFI

	BSC	LBL
Leaky House	1.16 to 1.20	1.16 to 1.36
Tight House	0.96 to 1.06	1.01 to 1.10

Exhaust with Mixing

	BSC	LBL
Leaky House	1.12 to 1.16	1.13 to 1.18
Tight House	1.00 to 1.07	1.03 to 1.05

Table 2.3: Comparison of BSC and LBL results for Volume Weighted Sources case

Simple Exhaust

	BSC	LBL
Leaky House	0.91 to 1.01	0.95 to 1.14
Tight House	0.90 to 1.10	1.05 to 1.20

CFI

	BSC	LBL
Leaky House	0.98 to 1.00	1.01 to 1.04
Tight House	0.92 to 1.02	1.00 to 1.00

Exhaust with Mixing

	BSC	LBL
Leaky House	0.99 to 1.00	0.99 to 1.00
Tight House	0.99 to 1.06	0.99 to 1.00

Table 2.4: Comparison of BSC and LBL results for Worst-Case Age-of-Air case

Simple Exhaust

	BSC			LBL
	Case A	Case B	Case C	
Leaky House	1.30 to 1.44	0.98 to 1.33	1.01 to 1.17	1.05 to 1.59
Tight House	1.22 to 1.50	1.00 to 1.42	0.98 to 1.23	1.09 to 1.83

CFI

	BSC			LBL
	Case A	Case B	Case C	
Leaky House	1.14 to 1.22	1.02 to 1.18	1.07 to 1.09	1.06 to 1.18
Tight House	1.05 to 1.12	1.05 to 1.11	0.93 to 1.03	1.01 to 1.03

Exhaust with Mixing

	BSC			LBL
	Case A	Case B	Case C	
Leaky House	1.10 to 1.13	1.02 to 1.10	1.05 to 1.06	1.05 to 1.06
Tight House	1.05 to 1.11	1.05 to 1.09	1.00 to 1.07	1.01 to 1.02

Table 2.5: Comparison of BSC and LBL results for I Stink case

Simple Exhaust

	BSC	LBL
Leaky House	9.09 to 10.05	3.25 to 10.85
Tight House	8.47 to 10.44	4.25 to 24.80

CFI

	BSC	LBL
Leaky House	6.14 to 7.68	2.96 to 7.22
Tight House	3.21 to 3.70	1.94 to 2.83

Exhaust with Mixing

	BSC	LBL
Leaky House	4.62 to 5.94	3.14 to 5.19
Tight House	2.17 to 2.45	1.88 to 2.21

Figure 2.6: Comparison of BSC and LBL results for You Stink case

Simple Exhaust

	BSC	LBL
Leaky House	1.44 to 2.05	1.04 to 1.88
Tight House	1.72 to 2.43	2.53 to 2.95

CFI

	BSC	LBL
Leaky House	1.13 to 1.22	0.90 to 2.04
Tight House	1.02 to 1.13	1.16 to 1.20

Exhaust with Mixing

	BSC	LBL
Leaky House	1.1 to 1.19	0.94 to 1.28
Tight House	1.02 to 1.09	1.13 to 1.14

In order to answer the second question, BSC analyzed the effect of doubling the size of the air conditioner and AHU. For a system using a standard thermostat, this has minimal effect because the heating or cooling load will be met in half the time, resulting in the same amount of mixing in the house. Figure 2.21 below shows this effect.

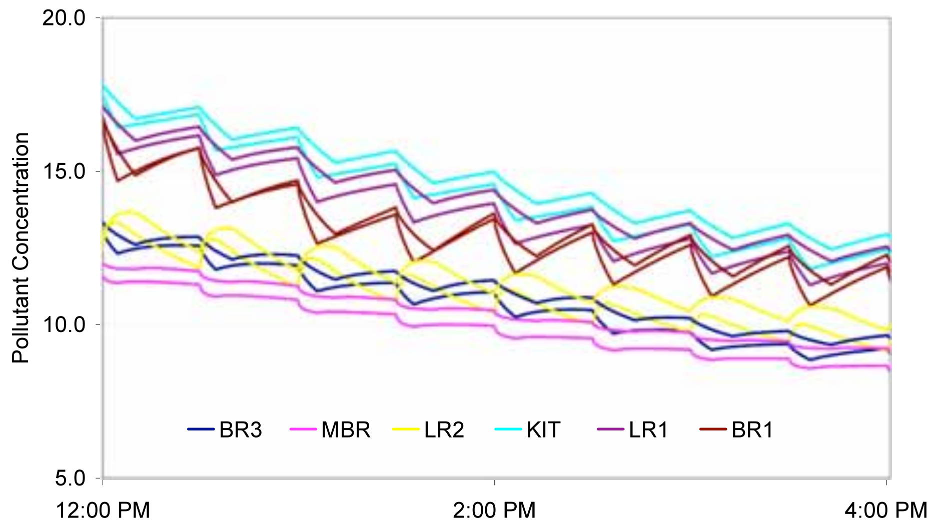


Figure 2.21: Difference between 1X and 2X Manual J sizing

In the cases where a minimum runtime is used, oversizing does result in more mixing; however at the level of a minimum of 10 minutes per 30 minute period the house is well mixed already and further mixing does little to increase the uniformity of pollutant concentrations in the house.

In order to answer the third question, the data set was analyzed one variable at a time, holding the other variables constant or averaging over all values of the other variables. The effects of climate, central system presence, duct leakage, central system minimum runtime, and envelope tightness were examined.

Figure 2.22 shows the effect of climate (as represented by infiltration degree days) on the calculated yearly average exposure. The results show that for no or low ventilation, mild climates have higher exposures than severe climates; however this effect is greatly reduced at the 62.2 ventilation rate and is nearly gone at twice the 62.2 rate. The effect of enclosure is similar: climate matters more with leakier houses than with tight houses.

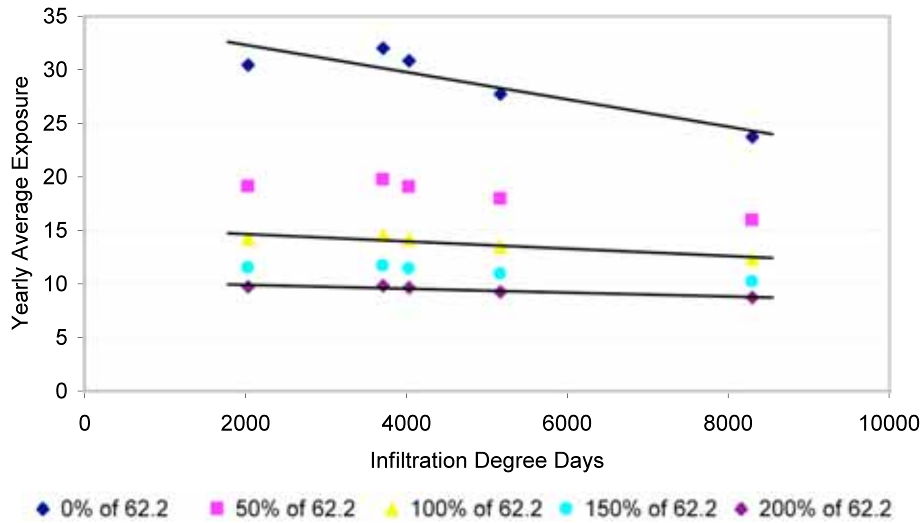


Figure 2.22: Effect of climate on yearly average exposure

Figure 2.23 shows the effect of central system presence and location on yearly average exposure. The results show that duct leakage in unconditioned space results in rejecting indoor pollutants to those locations and therefore lowers the exposure in this analysis. This may not be true in reality, particularly if the ducts are located in spaces with poor air quality such as unconditioned crawlspaces. Additionally, the graph shows that the difference is fairly consistent from 50% to 200% of the 62.2 rate.

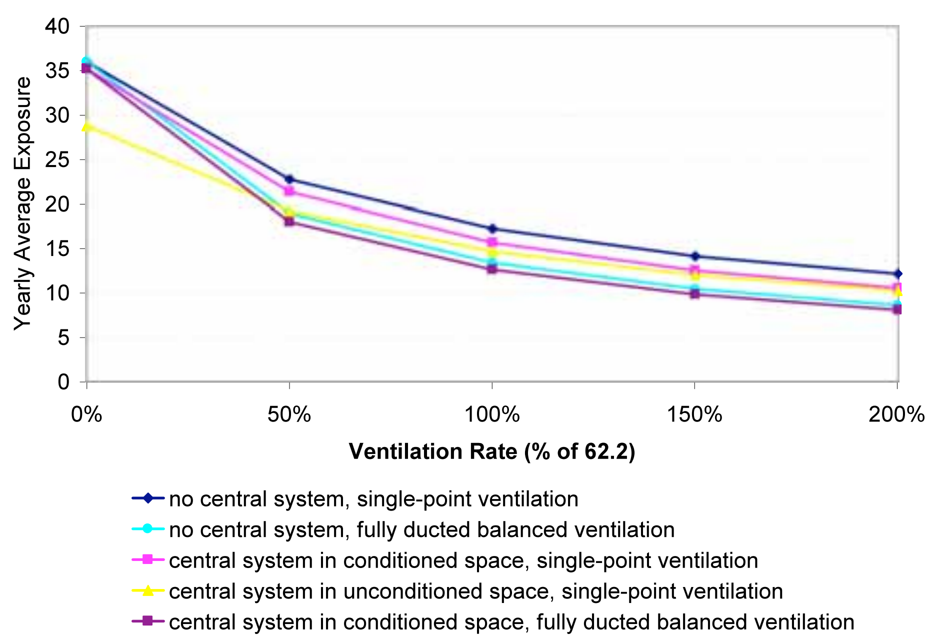


Figure 2.23: Effect of central system on yearly average exposure

Figure 2.24 shows the effect of duct location and leakage rate on the yearly average exposure. The graph shows that when ducts are located inside conditioned space, the leakage rate does not affect the pollutant concentration, as all the leakage is to the interior. However, when the ducts are located outside the conditioned space, more duct leakage leads to more air exchange with the exterior and therefore lower pollutant levels in the home, unless the leakage results in air being pulled in from a zone with poor air quality such as an unconditioned crawlspace.

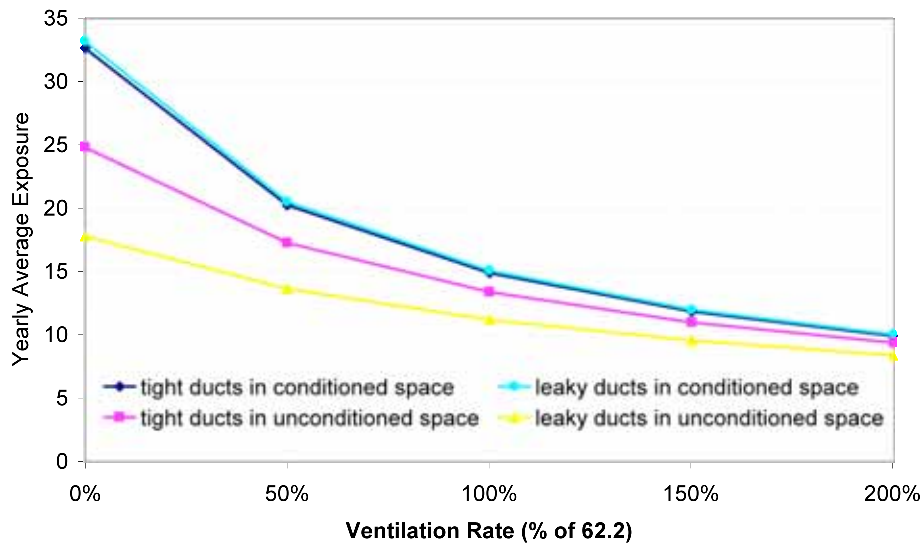


Figure 2.24: Effect of duct location and leakage level on yearly average exposure

Figure 2.25 shows the effect of minimum runtime on yearly average exposure. The graph shows that minimum runtime reduces the yearly average exposure both when ducts are in conditioned space and when they are in unconditioned space.

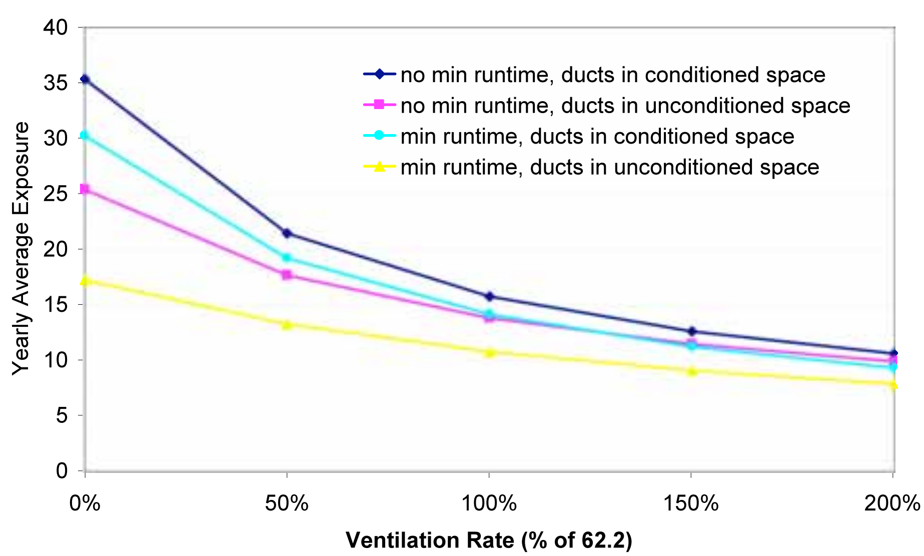


Figure 2.25: Effect of minimum runtime on yearly average exposure

Figure 2.26 shows the effect of envelope leakage rate on yearly average exposure. The graph shows that there is a large dependence on the envelop leakage rate at low ventilation levels, but that the difference becomes smaller at the 62.2 rate and much smaller at twice the 62.2 rate.

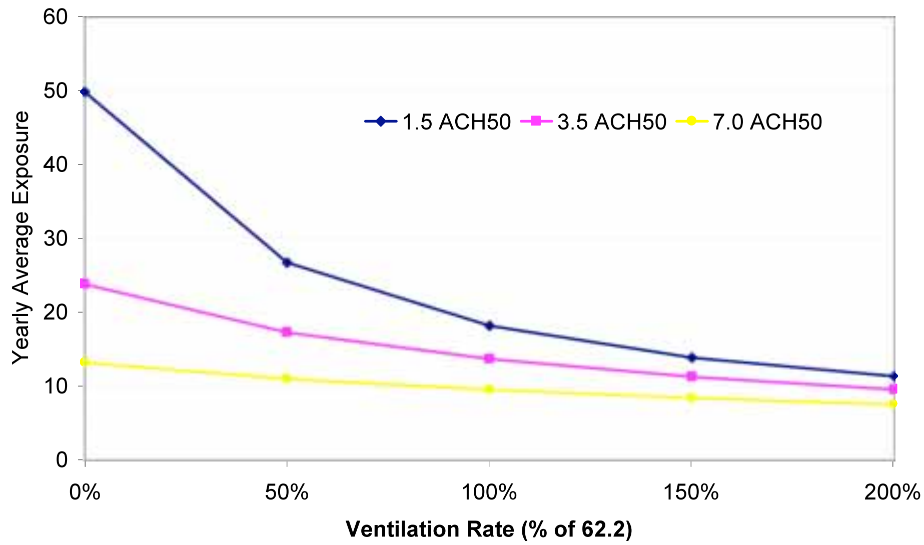


Figure 2.26: Effect of envelope leakage rate on yearly average exposure

Finally, the last question from the June 2007 meeting was whether the results were consistent if we examined additional climates. The two additional climates added (Daytona Beach and Raleigh) confirmed that the results were consistent.

2.9 ASHRAE Meeting – January 2008 – New York City

2.9.1. Building America Expert Meeting

BSC hosted a Building America Expert Meeting before the ASHRAE SSPC 62.2 meeting in January 2008. Speakers at this meeting were Bud Offerman of Indoor Environmental Engineering, Bill Rittleman of Ibacos, and Aaron Townsend of BSC. The summary report for the Expert Meeting is included in Appendix D.

2.9.2. SSPC 62.2 Meeting

BSC again presented to the SSPC 62.2 committee. The presentation covered the results of the simulations and analysis performed since the June 2007 meeting. The committee remained engaged and open to the change proposal but wanted to see results from more climates, a wider variety of ventilation systems, no duct leakage, slight changes to the leakage distribution over the enclosure, additional detail in the occupant schedules, and different source locations.

2.10 Third Round of Simulations

In order to provide the requested data, a third round of simulations was planned and executed.

2.10.1. Model Description

Several substantial changes were made to the model for this round of testing.

Duct leakage was eliminated. The committee felt that duct leakage in the model provided a benefit, whereas several members of the committee were concerned that duct leakage in unconditioned areas with poor air quality (such as crawlspaces) would lead to contaminants being introduced from those areas and therefore should not be rewarded.

Enclosure leakage previously assigned to the ducts was assigned to the ceiling. Enclosure distribution was distributed as follows: 55% walls, 45% ceilings.

An additional enclosure leakage rate was added to represent a typical existing leaky house (20 ach50).

The minimum runtime criterion for the AHU was changed to a minimum turnover requirement, in order to remove the effect of sizing and more truly represent the amount of mixing that occurs.

Four additional zones were added to the house. On the first floor a bathroom and the laundry room were added, and on the second floor the master bathroom and a secondary bathroom were added. In previous rounds of simulations these rooms were lumped within the room that contains them. Figure 2.27 shows the location of the new zones in the CONTAM model layout.

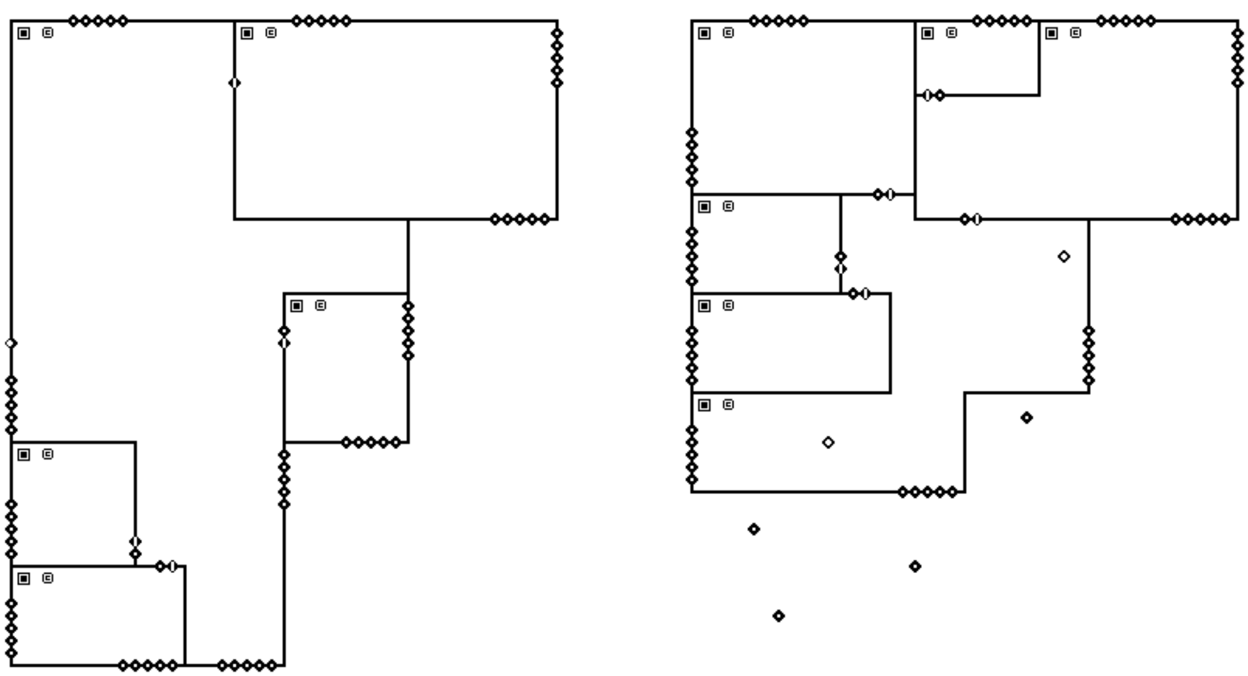


Figure 2.27: CONTAM model layout with added zones

2.10.2. Parameters Varied

The parameters varied for this round of simulations were the presence of the AHU, the AHU operation, the enclosure leakage rate, the ventilation system, and the ventilation rate.

2.10.2.1. Presence of central system

The AHU and central duct system is either absent or present and inside the conditioned space.

2.10.2.2. AHU operation

The AHU, if present, operates either with a standard thermostat or with a thermostat with a minimum runtime to achieve at least 0.7 turnovers of air per hour. (One turnover is the equivalent of passing the same amount of air through the AHU as the house volume.)

2.10.2.3. Enclosure leakage

Total enclosure leakage rates included 1.5, 3.5, 7, and 20 ACH50.

2.10.2.4. Ventilation system

Ten different ventilation systems were modeled:

1. Single-point exhaust from common area
2. Single-point exhaust from master bathroom
3. Single-point supply to common area
4. Central-fan-integrated supply
5. Three-point exhaust, 1/3 from each bathroom continuously
6. Four-point exhaust, 1/4 from kitchen and each bathroom continuously
7. Two-point balanced (supply into common area, exhaust from family bathroom)
8. Two-point balanced combined with central system (supply into supply ducts, exhaust from return plenum, interlock with central system operation)
9. Fully-distributed balanced (independent ventilation duct system, supply into the common area and each bedroom, single exhaust from the common area)
10. Fully-distributed balanced (independent ventilation duct system, supply into the common area and each bedroom, exhaust from each bathroom, utility room, and kitchen)

2.10.2.5. Ventilation rate

The ventilation rate was 0%, 50%, 100%, 150%, or 200% of the ASHRAE Standard 62.2-2003 rate for this house (which was 63 cfm).

2.10.2.6. Climate

Seven climates were simulated in this round. These were Houston (DOE climate zone 2A), Phoenix (2B), Sacramento (3B), San Diego (3B), Seattle (4C), Raleigh (4A), and Minneapolis (6).

2.10.3. Exposure Scenarios

For this round of simulations, a unique pollutant was generated in each zone. In post-processing, the pollutants were weighted in different combinations to create different source scenarios. In this way, four scenarios were examined:

1. Generation rate in each zone proportional to the zone volume, with new occupant schedule described below

2. Generation rate in each zone proportional to the zone volume, assuming occupants spend equal time in each zone each hour ("Everybody Everywhere" scenario)

3. 1/3 of pollutants generated in master bathroom and 2/3 in kitchen (no pollutants generated anywhere else), with new occupant schedule described below

4. 1/3 of pollutants generated in master bathroom and 2/3 in kitchen (no pollutants generated anywhere else), assuming occupants spend equal time in each zone each hour ("Everybody Everywhere" scenario)

The previous occupant schedule was modified to include time spent in the bathrooms. The schedule is the same for all occupants:

1. 10 PM to 7 AM: in bedroom with door closed

2. 7 AM to 7:30 AM: in the bathroom nearest to occupant's bedroom

3. 7:30 AM to 9 AM: in kitchen

4. 9 AM to 12 PM: in living room

5. 12 PM to 1 PM: in kitchen

6. 1 PM to 5 PM: in living room

7. 5 PM to 7 PM: in kitchen

8. 7 PM to 9:30 PM: in other bedrooms

9. 9:30 PM to 10:00 PM: in the bathroom nearest to occupant's bedroom

2.10.4. Post Processing

An Excel macro program was created to perform the calculations and post-processing for this round of simulations.

2.10.5. Results

The results of this set of simulations are a set of airflow ratios for each climate, enclosure leakage level, and exposure scenario. Figure 2.28 through Figure 2.31 show these results in graphical format for the four exposure scenarios described above, respectfully.

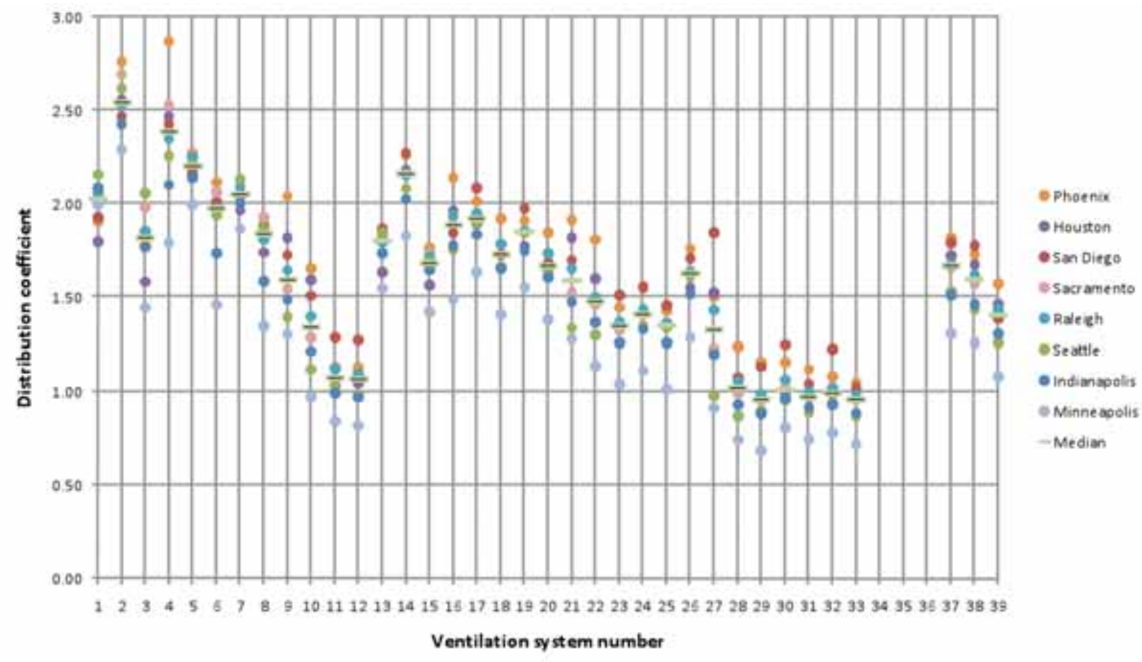


Figure 2.28: System coefficients for 3.5 ach50 enclosure, exposure scenario 1

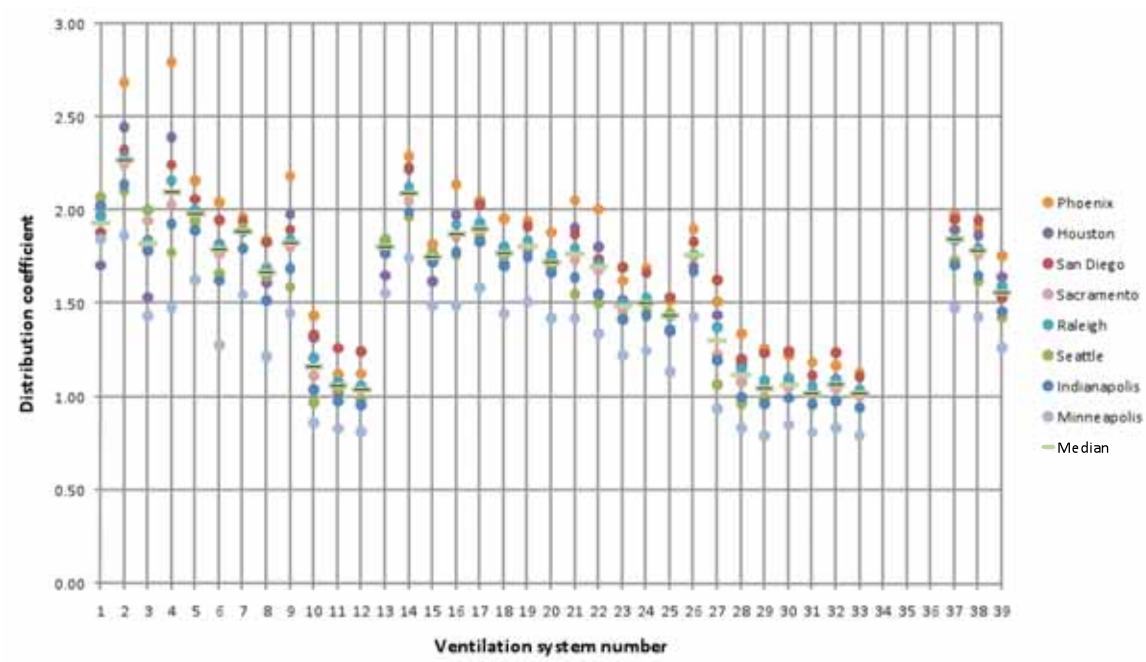


Figure 2.29: System coefficients for 3.5 ach50 enclosure, exposure scenario 2

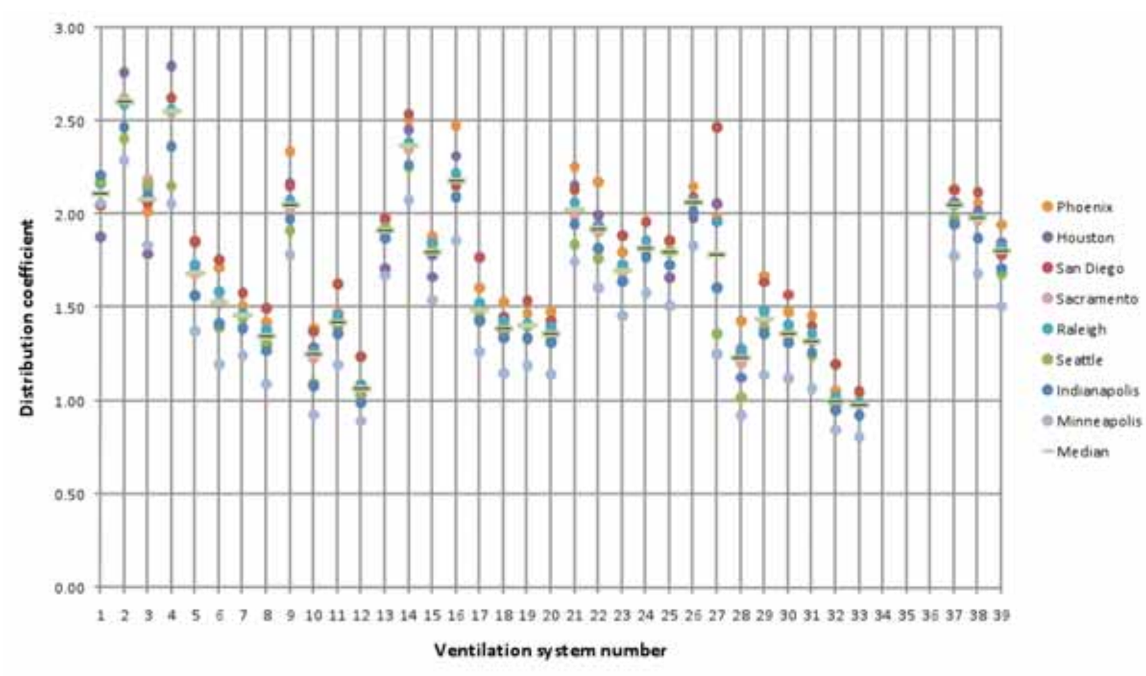


Figure 2.30: System coefficients for 3.5 ach50 enclosure, exposure scenario 3

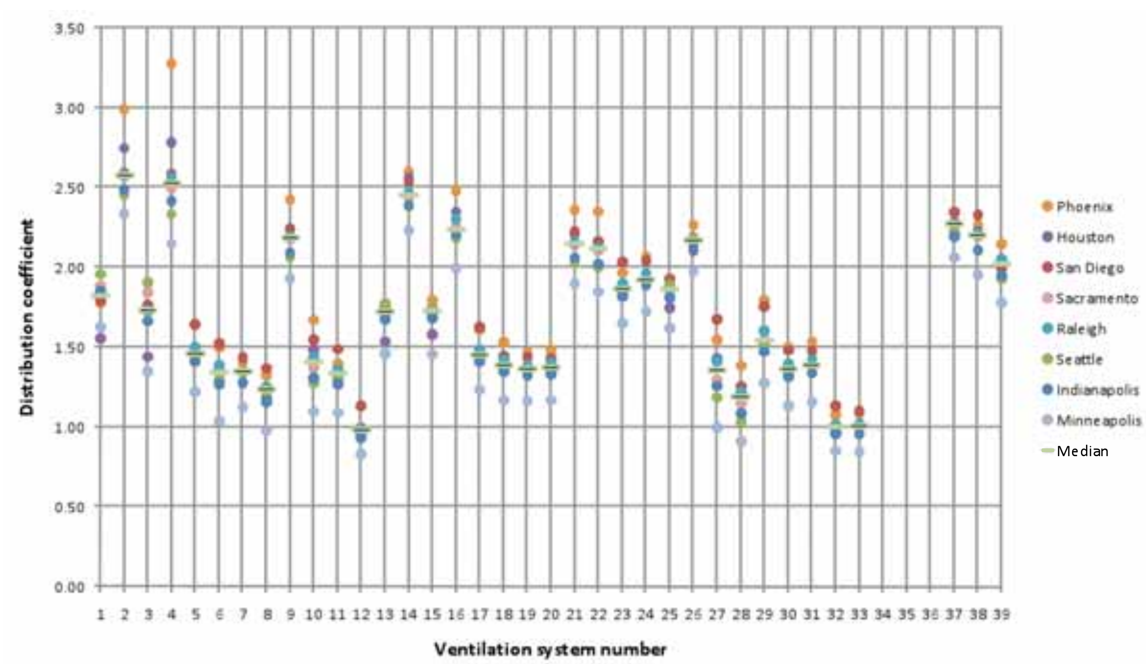


Figure 2.31: System coefficients for 3.5 ach50 enclosure, exposure scenario 3

When grouped into categories of systems and averaged across all the climates, these scenarios produce the system coefficient tables in Table 2.7 through Table 2.8.

Table 2.7: System coefficients for 3.5 ach50 enclosure, exposure scenario 1

Ventilation type	Ventilation ducting	With AHU		Without AHU
		With Min Turnover	Without Min Turnover	
Supply	fully ducted	1.35	1.65	1.65
	not fully ducted	1.35	1.65	1.65
Exhaust	fully ducted	1.65	2	2
	not fully ducted	1.65	2	2
Balanced	fully ducted	1	1	1
	not fully ducted	1	1.35	1.35

Table 2.8: System coefficients for 3.5 ach50 enclosure, exposure scenario 3

Ventilation type	Ventilation ducting	With AHU		Without AHU
		With Min Turnover	Without Min Turnover	
Supply	fully ducted	1.65	2	2
	not fully ducted	2	2	2
Exhaust	fully ducted	1.35	1.65	1.65
	not fully ducted	2	2	2
Balanced	fully ducted	1.35	1.35	1.35
	fully ducted + exhaust in wet rooms	1	1	1
	not fully ducted	1.35	1.65	2

2.11 ASHRAE Meeting – June 2008 – Salt Lake City

2.11.1. SSPC 62.2 Committee Meeting

At the SSPC 62.2 committee meeting at the June 2008 ASHRAE meeting, BSC presented the results from the latest round of simulations in a working group format (no official presentation, simply working from Excel spreadsheets). The committee was in general agreement with several of BSC's proposals, such as using the 3.5 ach50 enclosure tightness as the reference case and using the annual average exposure. In other areas there was disagreement between committee members as to the proper approach to take, particularly regarding the exposure scenario to select, and whether or not to exempt very leaky houses from the system coefficient. In order to help address the issue, BSC agreed to perform additional simulations at an enclosure tightness level of 5 ach50. One additional important issue that was raised was the desire to see the effect of pollutants generated by the occupants themselves.

2.12 Fourth Round of Simulations

In order to see the effect of pollutants generated by the occupants themselves, another round of simulations had to be performed.

2.12.1. Model Description

The model was substantially the same as the previous round of simulations, except that in addition to the stationary pollutant sources in each zone, the occupants also emitted pollutants at a constant rate. As before, weighting factors were applied in post-processing to create the different exposure scenarios.

2.12.2. Parameters Varied

The parameters varied in the fourth round of simulations were the same as in the third round of simulations.

2.12.3. Exposure Scenarios

For this round of simulations, a unique pollutant was generated in each zone and by each occupant. In post-processing, the pollutants were weighted in different combinations to create different source scenarios. In this way, six scenarios were examined. The first four are identical to the previous round of simulations; the last two are the new scenarios:

1. Generation rate in each zone proportional to the zone volume, with the occupant schedule described below

2. Generation rate in each zone proportional to the zone volume, assuming occupants spend equal time in each zone each hour ("Everybody Everywhere" scenario)

3. 1/3 of pollutants generated in master bathroom and 2/3 in kitchen (no pollutants generated anywhere else), with the occupant schedule described below

4. 1/3 of pollutants generated in master bathroom and 2/3 in kitchen (no pollutants generated anywhere else), assuming occupants spend equal time in each zone each hour ("Everybody Everywhere" scenario)

5. All pollutants generated by the occupants, with the occupant schedule as described below.

6. Half of the pollutants generated by the occupants and the other half generated proportional to zone volumes, with the occupant schedule as described below.

The occupant schedule is the same for all occupants:

1. 10 PM to 7 AM: in bedroom with door closed

2. 7 AM to 7:30 AM: in the bathroom nearest to occupant's bedroom

3. 7:30 AM to 9 AM: in kitchen

4. 9 AM to 12 PM: in living room

5. 12 PM to 1 PM: in kitchen

6. 1 PM to 5 PM: in living room

7. 5 PM to 7 PM: in kitchen

8. 7 PM to 9:30 PM: in other bedrooms

9. 9:30 PM to 10:00 PM: in the bathroom nearest to occupant's bedroom

2.12.4. Post Processing

Due to the additional exposure scenarios, another Excel macro program was created to perform post-processing of the data.

2.12.5. Results

In addition to the results produced in the third round of simulations, the fourth round of simulations produced airflow ratios for the added exposure scenarios. Graphs of these results are shown in Figure 2.32 and Figure 2.33.

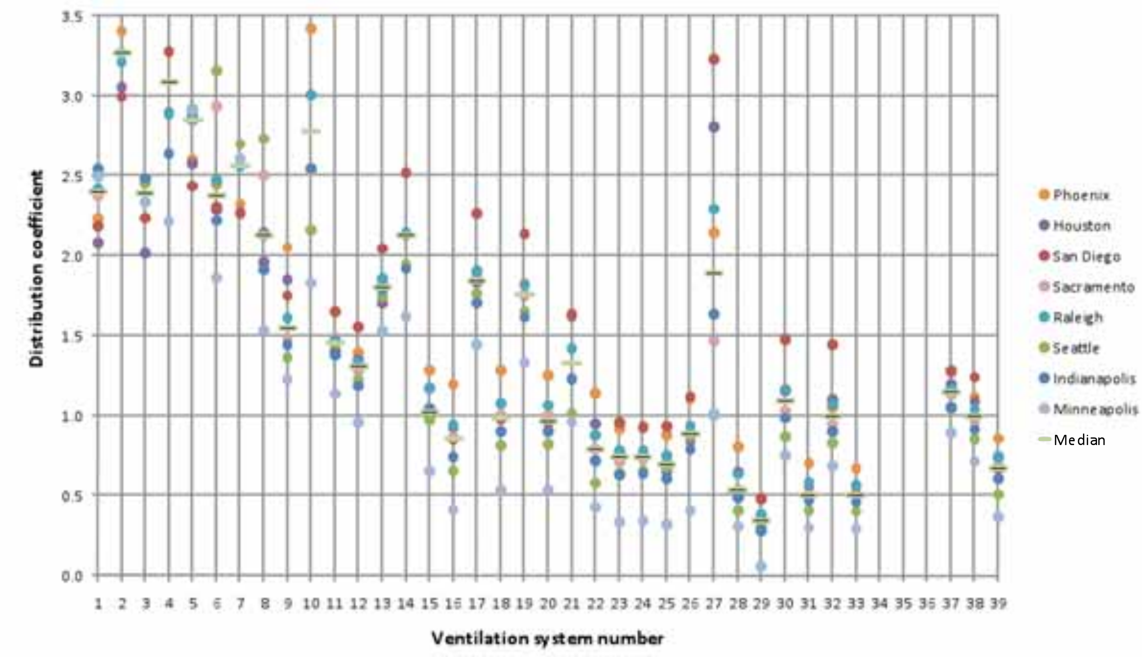


Figure 2.32: System coefficients for 3.5 ach50 enclosure, exposure scenario 5

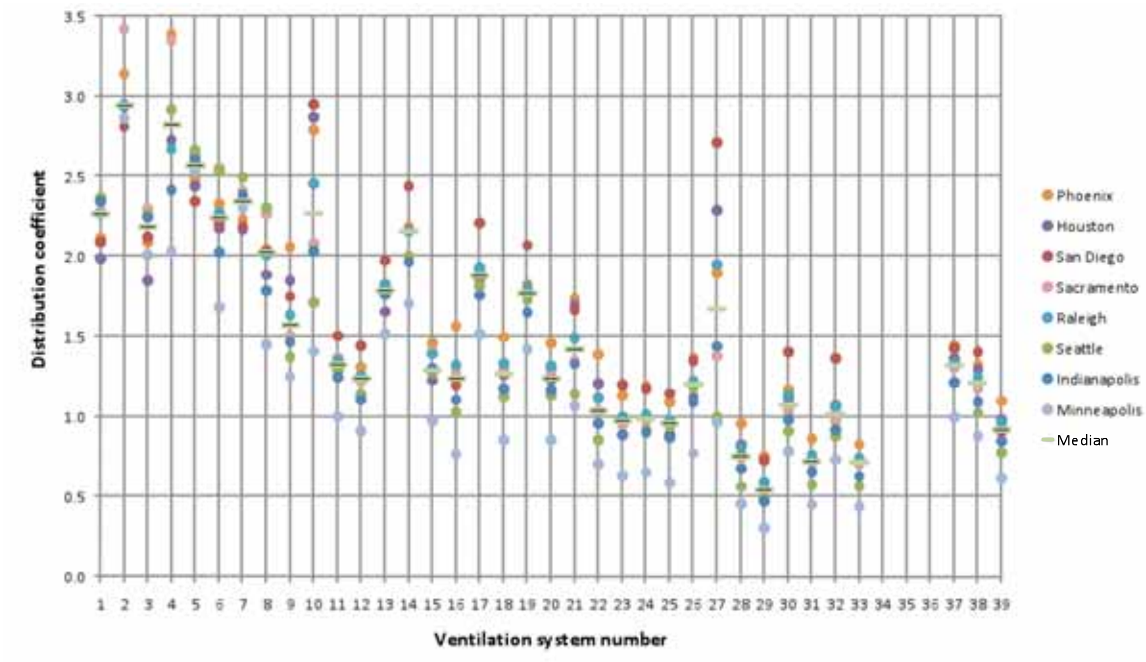


Figure 2.33: System coefficients for 3.5 ach50 enclosure, exposure scenario 6

When grouped into categories of systems and averaged across all the climates, these scenarios produce the system coefficient tables in Table 2.9 and Table 2.10.

Table 2.9: System coefficients for 3.5 ach50 enclosure, exposure scenario 5

Ventilation type	Ventilation ducting	With AHU		Without AHU
		With Min Turnover	Without Min Turnover	
Supply	fully ducted	1	1	1
	not fully ducted	1	1.35	1.65
Exhaust	fully ducted	1	1.65	2
	not fully ducted	1	2	2
Balanced	fully ducted	1	1	1.35
	not fully ducted	1	2	2

Table 2.10: System coefficients for 3.5 ach50 enclosure, exposure scenario 6

Ventilation type	Ventilation ducting	With AHU		Without AHU
		With Min Turnover	Without Min Turnover	
Supply	fully ducted	1	1.35	1.35
	not fully ducted	1	1.35	1.65
Exhaust	fully ducted	1.35	2	2
	not fully ducted	1.35	2	2
Balanced	fully ducted	1	1	1.35
	not fully ducted	1	1.65	2

2.12.6. Sensitivity Analysis

In order to help move the committee nearer a decision on the exposure scenario, BSC performed a sensitivity study on the ratio of pollutant sources. The following cases were examined to determine where the tipping points occurred in the tables. Exposure scenarios 1, 3, 5, and 6 were previously done. Exposure cases 7-12 were added for the sensitivity analysis. All of these exposure cases use the occupant schedules.

Table 2.11: Pollutant source cases for sensitivity study

Scenario	1	3	5	6	7	8	9	10	11	12
Volume Weighted	100	0	0	50	40	30	50	50	33	20
Kitchens & Baths Only	0	100	0	0	10	20	10	20	33	20
Occupants Only	0	0	100	50	50	50	40	30	33	60

When grouped into categories of systems and averaged across all the climates, these scenarios produce the system coefficient tables in Table 2.12 through Table 2.17. The tables show minor differences, but predominantly indicate that the coefficients are heavily influenced by the presence of occupant-emitted pollutants.

Table 2.12: System coefficients for 3.5 ach50 enclosure, exposure scenario 7

Ventilation type	Ventilation ducting	With AHU		Without AHU
		With Min Turnover	Without Min Turnover	
Supply	fully ducted	1	1.35	1.35
	not fully ducted	1	1.35	1.65
Exhaust	fully ducted	1.35	1.65	2
	not fully ducted	1.35	2	2
Balanced	fully ducted	1	1	1.35
	not fully ducted	1	1.65	2

Table 2.13: System coefficients for 3.5 ach50 enclosure, exposure scenario 8

Ventilation type	Ventilation ducting	With AHU		Without AHU
		With Min Turnover	Without Min Turnover	
Supply	fully ducted	1	1.35	1.35
	not fully ducted	1	1.35	1.65
Exhaust	fully ducted	1	1.65	2
	not fully ducted	1.35	2	2
Balanced	fully ducted	1	1	1.35
	not fully ducted	1	1.65	2

Table 2.14: System coefficients for 3.5 ach50 enclosure, exposure scenario 9

Ventilation type	Ventilation ducting	With AHU		Without AHU
		With Min Turnover	Without Min Turnover	
Supply	fully ducted	1	1.35	1.35
	not fully ducted	1	1.35	1.65
Exhaust	fully ducted	1.35	1.65	2
	not fully ducted	1.35	2	2
Balanced	fully ducted	1	1	1.35
	not fully ducted	1	1.65	2

Table 2.15: System coefficients for 3.5 ach50 enclosure, exposure scenario 10

Ventilation type	Ventilation ducting	With AHU		Without AHU
		With Min Turnover	Without Min Turnover	
Supply	fully ducted	1	1.35	1.35
	not fully ducted	1.35	1.65	1.65
Exhaust	fully ducted	1.35	1.65	2
	not fully ducted	1.35	2	2
Balanced	fully ducted	1	1	1
	not fully ducted	1	1.65	2

Table 2.16: System coefficients for 3.5 ach50 enclosure, exposure scenario 11

Ventilation type	Ventilation ducting	With AHU		Without AHU
		With Min Turnover	Without Min Turnover	
Supply	fully ducted	1	1.35	1.35
	not fully ducted	1.35	1.65	1.65
Exhaust	fully ducted	1.35	1.65	2
	not fully ducted	1.35	2	2
Balanced	fully ducted	1	1	1
	not fully ducted	1	1.65	2

Table 2.17: System coefficients for 3.5 ach50 enclosure, exposure scenario 12

Ventilation type	Ventilation ducting	With AHU		Without AHU
		With Min Turnover	Without Min Turnover	
Supply	fully ducted	1	1	1.35
	not fully ducted	1	1.35	1.65
Exhaust	fully ducted	1	2	2
	not fully ducted	1	2	2
Balanced	fully ducted	1	1	1.35
	not fully ducted	1	2	2

2.13 ASHRAE Meeting – January 2009 – Chicago

2.13.1. Building America Expert Meeting

Before the ASHRAE meeting in January 2009, BSC held a Building America Expert Meeting. The focus of this meeting was gathering information about what exposure scenarios were most appropriate. Presenters were Jeff Siegel and Atila Novoselac from the University of Texas at Austin, and Aaron Townsend from BSC. The summary meeting report is included in Appendix E.

2.13.2. SSPC 62.2 Committee Meeting

At the SSPC 62.2 committee meeting, BSC presented an overview of the whole process of discovery and learning since the Sacramento tracer gas testing and capped it off with the results of the latest simulations and the sensitivity study. The committee was processing the information and seemed prepared to accept the change, but got bogged down in the mechanics of how to reduce the top end of the system coefficients into a politically viable range.

2.14 Post January 2009 meeting

2.14.1. Rescaling Coefficient Range

After the January 2009 meeting, BSC worked with the committee to rescale the coefficient range into an acceptable range. Figure 2.34 shows one example of this process. First, the actual average air flow ratios as calculated from the simulation post-processing are rescaled into the desired range. Then, thresholds are applied to assign each system into a coefficient bin. Bin sizes from 0.1 to 0.35 were examined, with a recommended value of 1/6 (0.1666).

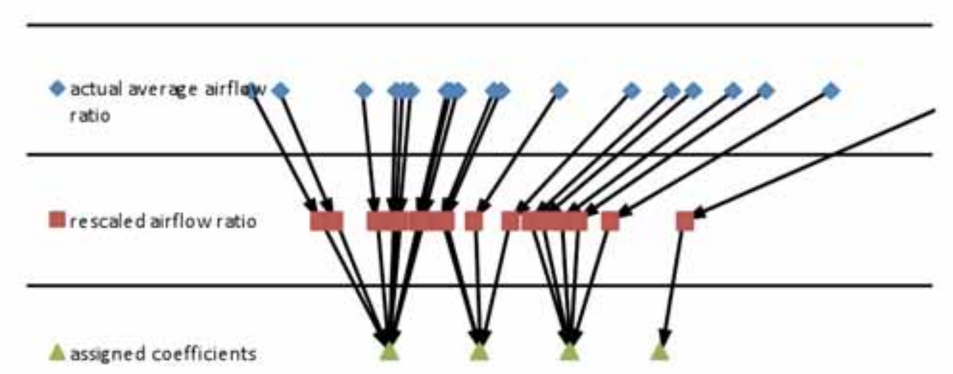


Figure 2.34: Example illustration of the process of rescaling the coefficients

2.14.2. Average Exposures Instead of Highest Occupant Exposures

One vocal member of the committee objected to choosing the highest occupant exposure in the house as the basis for the standard. His opinion was that this would lead to skewed results and might possibly results in increased average exposures. This issue mostly revolves around the question of if mixing via an AHU could actually increase exposures by bringing pollutants from a remote zone into the zone where the occupants are located. In order to answer this question, BSC performed an analysis of the average exposure as well as the maximum exposure with three systems: exhaust only, CFIS, and fully-ducted balanced. Figure 2.35 through Figure 2.37 illustrate the results of this analysis. The exhaust-only ventilation system consistently results in higher occupant exposures. This is true even in the kitchens and bathrooms source scenario, where all of the pollutants are generated in rooms other than the rooms where the occupants spend most of their time.

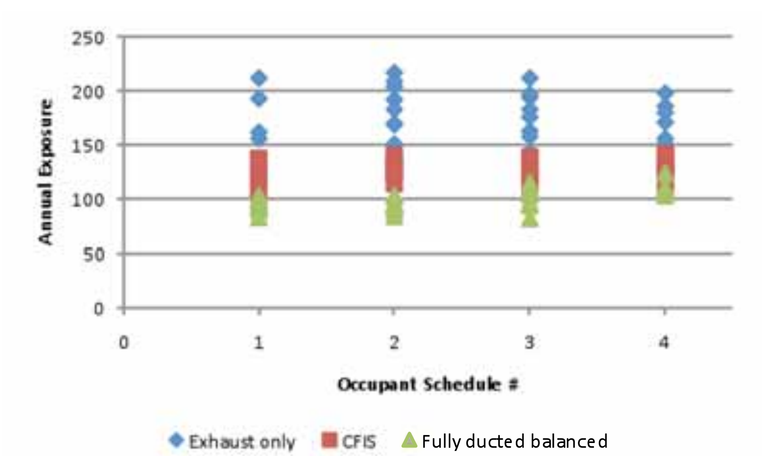


Figure 2.35: Results of average exposure analysis for volume-weighted source scenarios

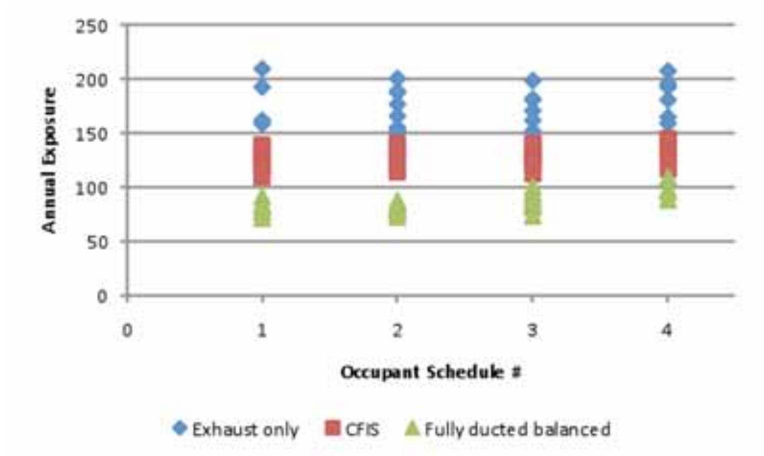


Figure 2.36: Results of average exposure analysis for kitchen & bathrooms source scenarios

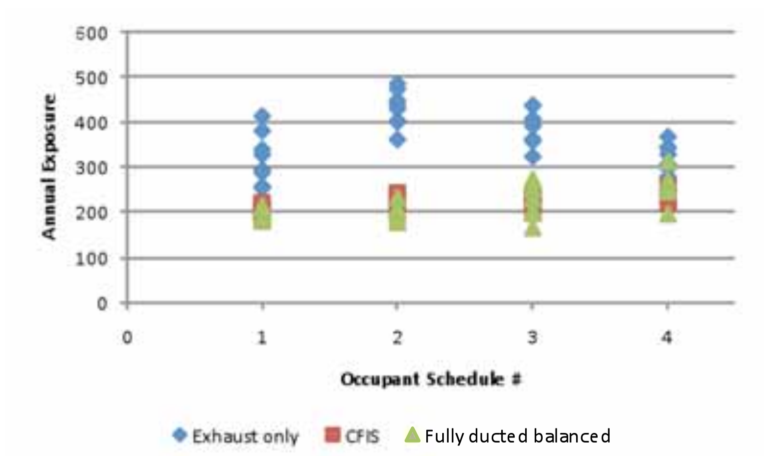


Figure 2.37: Results of average exposure analysis for occupant-generated source scenario

2.15 ASHRAE Meeting – June 2009 – Louisville

2.15.1. SSPC 62.2 Committee Meeting

At the SSPC 62.2 meeting in June 2009, BSC put forward a change proposal to the envelope subcommittee. The change proposes coefficients to account for the effect of system types and operation. The subcommittee voted to forward the change proposal to the full committee with a recommendation to publish the change proposal for public review. The full committee considered the change proposal and voted to do so.

The change proposes coefficients to account for the effect of system types and operation. The proposed system coefficients are based on three factors: the difference between balanced and unbalanced systems; the difference between fully ducted and not fully ducted systems; and the effect of mixing.

The change increases mechanical ventilation system flow rates for systems that are unbalanced and not fully ducted. The motion does not increase mechanical ventilation system flow rates for systems that are balanced and fully ducted or systems that are balanced and not fully ducted that have a provision for mixing and systems that are unbalanced and fully ducted that have a provision for mixing.

The change assigns a system coefficient of 1.0 for a balanced and fully ducted system. Systems that are balanced but not fully ducted and systems that are not balanced but fully ducted have a system coefficient of 1.25. An unbalanced not fully ducted system has a system coefficient of 1.5. These system coefficient values assume no provision for mixing. If mixing is provided then the systems that had coefficients of 1.25 without mixing have coefficients reduced to 1.0 and the systems that had coefficients of 1.5 without mixing have coefficients reduced to 1.25.

The analysis supporting the coefficients values is based on annual average exposure and assumes that contaminants are distributed in houses roughly 1/3 for occupants, 1/3 for furnishings and materials uniformly distributed throughout the house and 1/3 split between the kitchen and the bathrooms.

The change contains definitions for "fully-ducted ventilation system"; for "balanced ventilation system"; and for "minimum turnover" or mixing. Minimum turnover is defined as whole-building air mixing such that at least 50 percent of the house air volume is moved through a forced air distribution system each hour.

The change excludes buildings that have leakage rates of 7 ach @ 50 Pa or greater; the change excludes systems in building enclosures other than single family detached; and the change excludes systems installed according to the Existing Building Appendix.

2.15.2. Presentation of Technical Papers

Aaron Townsend of BSC presented two technical papers arising from this work during the June 2009 ASHRAE meeting (Townsend 2009a, Townsend 2009b). The presentation slides are given in Appendices F and G, respectively.

2.16 Post June 2009 Meeting

2.16.1. Progress and current status of change proposal

Because not all of the voting members of the committee were able to attend the meeting, the change proposal was sent out on a letter ballot to all voting members of the full committee. In the letter ballot vote, the committee voted to publish the change proposal for public review. The ASHRAE Standards Committee then also voted to publish the change proposal as a proposed addendum for public review. After public review, the SSPC 62.2 committee will have to address all public comments received. If all comments are acceptably addressed, the change could be incorporated into the 2010 version of the ASHRAE 62.2 Standard.

2.17 References

Hendron, B., Anderson, R., Barley, D., Hancock, E. 2006. Building America Field Test and Analysis Report. Draft NREL report.

Hendron, R., A. Rudd, R. Anderson, D. Barley, A. Townsend. 2007. Field Test of Room-to-Room Distribution of Outside Air with Two Residential Ventilation Systems. IAQ 2007: Healthy & Sustainable Buildings Conference Proceedings. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Townsend, A., A. Rudd, and J. Lstiburek. 2009a. Extension of Ventilation System Tracer Gas Testing Using a Calibrated Multi-Zone Airflow Model. ASHRAE Transactions 115(2).

Townsend, A., A. Rudd, and J. Lstiburek. 2009b. A Method for Modifying Ventilation Airflow Rates to Achieve Equivalent Occupant Exposure. ASHRAE Transactions 115(2).

2.18 APPENDICES

2.18.1. Substitute House Testing Trip Report

2.18.2. January 2007 Expert Meeting Summary Report

2.18.3. June 2007 Expert Meeting Summary Report

2.18.4. January 2008 Expert Meeting Summary Report

2.18.5. January 2009 Expert Meeting Summary Report

2.18.6. 2009 ASHRAE Transactions 11, Paper #1 Presentation

2.18.7. 2009 ASHRAE Transactions 12, Paper #2 Presentation

2.18.1. Substitute House Testing Trip Report

To: Memo of Record

From: Aaron Townsend

Date: November 17, 2006

Subject: Ventilation air flow measurements in Augustus

On Tuesday and Wednesday, November 14 and 15, 2006, I performed air flow and pressure measurements at a house in DR Horton's Augustus development in Lincoln, CA. These measurements are intended to assist in providing inputs to the CONTAM modeling of the tracer-gas testing Armin and I performed in January 3-10, 2006 in the same development. This report summarizes the measurements.

The house I tested was 1664 Markdale Lane, which is the same plan as the 2-story house located at 1117 Montague Lane that was tested in January. The only difference is that 1664 Markdale Lane has two additional bedrooms and an additional bathroom located over the garage, where 1117 Montague Lane did not. The floor plan comparison is shown in Figure 1 and Figure 2. 1117 Montague Lane has a total of 2961 square feet of living space, and 1664 Markdale Lane has a total of 3440 square feet of living space.

I intended to perform automated Zone Pressure Diagnostics (ZPD) tests using a program developed by Dave Bohac of the Minnesota Center for Energy and the Environment (MNCEE) and Colin Olson of the Energy Conservatory (TEC); however this program requires the use of TEC's Automated Performance Testing (APT) system, and the APT was damaged during shipping. Instead I performed several manual tests, as described in Table 1.

The furnace, air handler, and condenser are Goodman equipment. The furnace is rated at 93 AFUE. The condenser is model number CLQ48-1B, rated at 4 tons and 14 SEER.

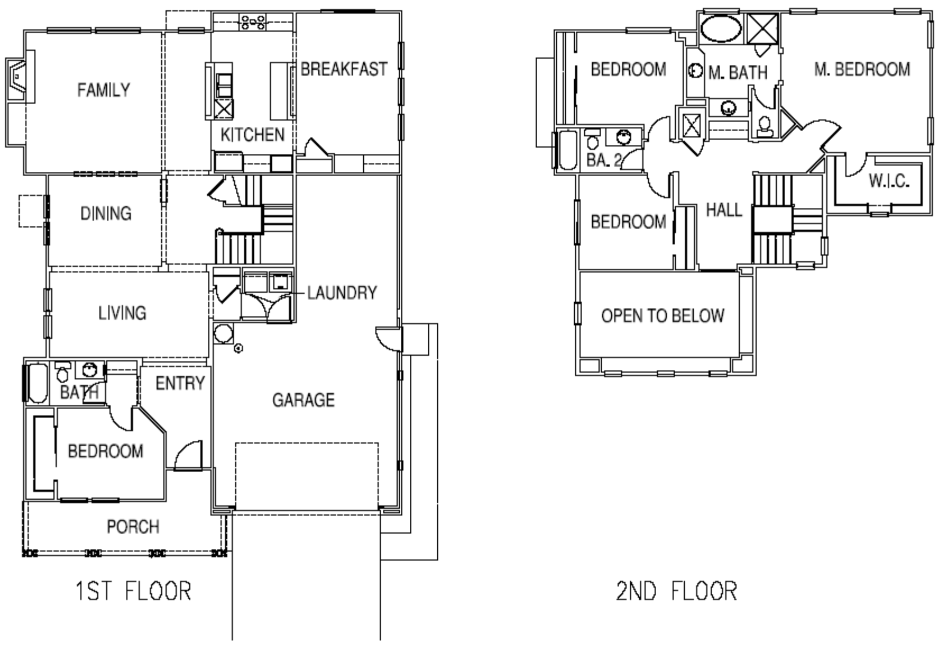


Figure 1: Floor plan of 1117 Montague Lane

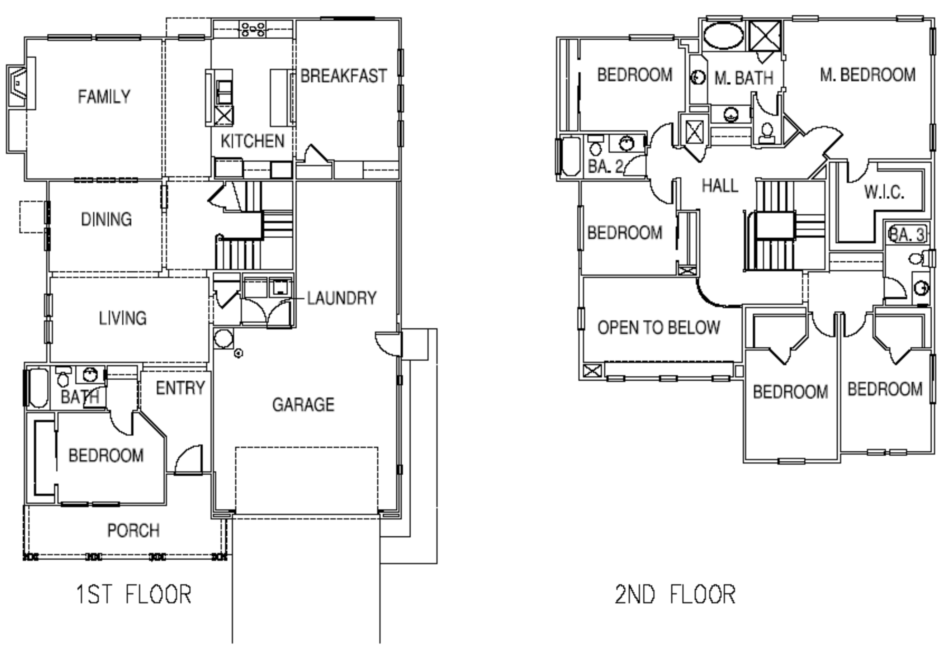


Figure 2: Floor plan of 1664 Markdale Lane

Table 1: Tests Performed This Trip

Test #	Test Description	Ducts	Transfer Grills	Bedroom Doors
1	Overall envelope leakage	Open	Open	Open
2	Room-by-room envelope leakage	Closed	Closed	Open
3	Room-by-room leakage to other rooms	Closed	Closed	Closed
4	Room-by-room leakage to main living space	Closed	Closed	Closed
5	Characterization of transfer grills	NA	NA	NA
6	Measure pressure field with laundry exhaust running	Closed	Closed	Closed
7	Measure pressure field with laundry exhaust running	Open	Closed	Closed
8	Measure pressure field with MBR exhaust running	Closed	Closed	Closed
9	Measure pressure field with MBR exhaust running	Open	Closed	Closed
10	Measure pressure field and supply flows with AHU on	Open	Closed	Closed
11	Measure pressure field and supply flows with AHU on	Open	Open	Closed
12	Overall duct leakage	Closed	NA	Open
13	Duct leakage to outside	Closed	NA	Open
16	Measure pressure field and duct and transfer grill flows with laundry exhaust running	Open	Open	Closed

Test Results

Test #1

Overall envelope leakage. This was measured by performing a standard multipoint blowerdoor test using TECTITE and a DG-700. The blower door was located in the door between the laundry room and the garage. The roll-up garage door was open. The following results were obtained: 1608 CFM50, C=124.4 (+/-1.8%), n=0.654 (+/-0.005), EqLA=165 square inches, ELA=87 square inches. Figure 3 shows the graph of the multipoint blowerdoor test.

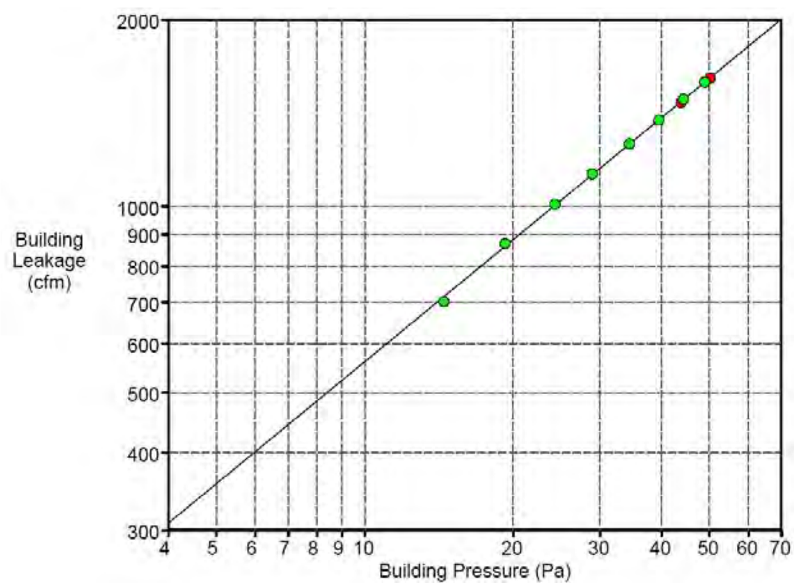


Figure 3: TECTITE building leakage graph

Test #2
Room-by-room envelope leakage. This test was performed similar to a duct-leakage-to-outside test. The house was brought to -50 Pa using the blower door, then one-by-one the zone leakages were measured using the duct blaster and a blower door frame and shroud in the door to that zone. For this test, all ducts and transfer grills were closed, and all doors except the zone being tested were opened.

Room	Pressure wrt living space (Pa) with shroud installed, no ductblaster flow	Ductblaster flow (cfm) required to zero pressure wrt living space
Master BR	(not recorded)	256
Bedroom 1	(not recorded)	65
Bedroom 2	+5.4	57
Bedroom 3	+6.2	60
Bedroom 4	+9.6	88
Bedroom 5	+9.0	87

For this test the baseline house pressure was -1.5 Pa. The house was taken to -50 Pa wrt outside. The sum of the leakage measured in the bedrooms is 613 cfm50 or 38% of the total leakage of 1608 cfm50. The remainder of the leakage is assumed to be to the main living area of the house. Therefore, the total leakage area of the building is distributed as below:

Room	Envelope leakage (cfm50)	Percentage of total leakage area	Flow Coefficient
Master BR	256	16%	20
Bedroom 1	65	4%	5
Bedroom 2	57	4%	4
Bedroom 3	60	4%	5
Bedroom 4	88	5%	7
Bedroom 5	87	5%	7
Main Living Space	995	62%	77
Total	1608	100%	124

Test #3
Room-by-room opening window to outside with all doors, ducts, and transfers closed and house at -50 Pa (originally). The blower door controller was not adjusted during this test. The results of the test show that each zone is isolated from the other zones. No two zones show correlation greater than 5%. This shows that the zones will leak primarily to the main living space when the ducts are not considered.

		With this zone open to outside:						
		None	MBR	BR1	BR2	BR3	BR4	BR5
Pressure wrt main living space	MBR	15.4	42.1	11.4	12.7	13	13.3	12.4
	BR1	3.7	3.1	40.6	3.1	3	3.2	3.1
	BR2	5.9	4.8	4.6	43.6	5.9	5.3	4.9
	BR3	5.5	5.1	4.2	5.1	44.8	4.8	4.4
	BR4	13.1	11.1	11.1	11.5	11.8	44.9	12.8
	BR5	8.1	6.7	6.3	7.1	7.2	8	42.7
Pressure wrt outside	Main living space	-51	-42.1	-40.5	-43.9	-43.6	-44.9	-43.4

		With this zone open to outside:						
		None	MBR	BR1	BR2	BR3	BR4	BR5
Pressure wrt outside	MBR	-35.6	0	-29.1	-31.2	-30.6	-31.6	-31
	BR1	-47.3	-39	0.1	-40.8	-40.6	-41.7	-40.3
	BR2	-45.1	-37.3	-35.9	-0.3	-37.7	-39.6	-38.5
	BR3	-45.5	-37	-36.3	-38.8	1.2	-40.1	-39
	BR4	-37.9	-31	-29.4	-32.4	-31.8	0	-30.6
	BR5	-42.9	-35.4	-34.2	-36.8	-36.4	-36.9	-0.7

		With this zone open to outside:						
		None	MBR	BR1	BR2	BR3	BR4	BR5
Percent of way to outside	MBR	30%	100%	28%	29%	30%	30%	29%
	BR1	7%	7%	100%	7%	7%	7%	7%
	BR2	12%	11%	11%	99%	14%	12%	11%
	BR3	11%	12%	10%	12%	103%	11%	10%
	BR4	26%	26%	27%	26%	27%	100%	29%
	BR5	16%	16%	16%	16%	17%	18%	98%

		With this zone open to outside:						
		None	MBR	BR1	BR2	BR3	BR4	BR5
Difference from no zones open	MBR	0%	70%	-2%	-1%	0%	-1%	-2%
	BR1	0%	0%	93%	0%	0%	0%	0%
	BR2	0%	0%	0%	88%	2%	0%	0%
	BR3	0%	1%	0%	1%	92%	0%	-1%
	BR4	0%	1%	2%	1%	1%	74%	4%
	BR5	0%	0%	0%	0%	1%	2%	83%

Test #4
Room-by-room leakage to main living space with doors, ducts, transfers closed. In this test, the house was taken to two different depressurization levels, with the doors, ducts, and transfer grills closed, and the pressure of the bedrooms with respect to the living space was recorded. The measured values are below:

	Pressure wrt living space (Pa)	
Room	with house at -15 Pa	with house at -51 Pa
Master BR	+3.4	+15.4
Bedroom 1	+0.8	+3.7
Bedroom 2	+1.2	+5.9
Bedroom 3	+1.1	+5.5
Bedroom 4	+3.2	+13.1
Bedroom 5	+1.7	+8.1

In this test, each room has a flow into it (from outdoors) and out of it (to the main living space), and these two flows are assumed to be equal. By using the flow equation twice (once for each flow), and using values previously established for the flow coefficient (C) (established in test #2) and pressure exponent (n) (established in test #1), the following system of equations results:

General flow equation: $Q = C * (\Delta P)^n$, where

- Q = flow rate of air (cfm)
- C = flow coefficient (cfm/Pa^n)
- ΔP = pressure difference along the flow path (Pa)
- n = pressure exponent for the flow path (unitless)

Apply the general flow equation to the exterior wall of a zone (the wall between the zone and the outdoors):

$Q_o = C_o * (\Delta P_o)^\wedge n_o$, where the subscripts indicate that the value is for the flow from the *outside*.

Now apply the general flow equation to the interior wall of a zone (the wall between the zone and the main living space):

$Q_i = C_i * (\Delta P_i)^\wedge n_i$, where the subscripts indicate that the value is for the flow to the *inside*.

Assuming these two flows are equal, and by using previously-established values of C and n for the exterior wall, we can then rearrange the equation to get:

$C_i = (\Delta P_o)^\wedge n_o / (\Delta P_i)^\wedge n_i * C_o$

In this equation we have two unknowns: C_i and n_i. By running the test at two different pressures (ΔP_o and ΔP_o'), we have two equations with two unknowns, and can solve the system of equations for n_i and then plug the value into the equation above to solve for C_i.

$n_i = n_o * \ln(\Delta P_o' / \Delta P_o) / \ln(\Delta P_i' / \Delta P_i)$, and

By applying this system to each of the bedrooms, the flow coefficient and pressure exponent were found for leakage between the zone and the main living space. The table below shows the results. The pressure exponents are near 0.5, which is the value for orifice flow. This makes sense, since the dominant leakage path between the bedrooms and main living space is usually the door, particularly the door undercut. The differences between the flow coefficients are due to the door size, undercut amount, and flooring type present under each door. The master bedroom has a 3080 door, where the other bedrooms have 2668 doors. Additionally, all of the bedrooms have carpet flooring, but bedroom 1 is adjacent to a living space with wood flooring, which allows more air to flow through the door undercut.

Room	Flow Coefficient	Pressure Exponent
Master BR	54.3	0.485
Bedroom 1	32.0	0.514
Bedroom 2	22.5	0.486
Bedroom 3	24.8	0.482
Bedroom 4	18.2	0.541
Bedroom 5	28.2	0.491

Test #5

Transfer grill characterization. This test was intended to determine the pressure-flow characteristics of the transfer grills. The transfer grills consist of a louvered grill on either side of the wall above the bedroom door. The grill on each side of the wall are offset, with one being higher than the other. The gross area of each grill is approximately 5.5" by 9.5", with approximately 50% open area.

In order to determine the flow characteristics, a cardboard box was fixed on one side of a transfer grill, with the duct blaster duct exhausting air out of the box. The pressure and flow measurements are listed in Table 2 below. Figure 4 shows the results and provides a fit of the equation Q=C*(dP)^n, where for this case C=27 cfm/(Pa^n) and n=0.53. In hindsight I should have tested higher pressure differences, as later tests showed that the rooms were pressurized up to ten Pascals. Figure 5 shows the effect of the exponent at higher differential pressures. It is clear from Figure 6 that the flow exponent is definitely less than 0.65 and closer to 0.5.

Table 2: Bedroom 3 Transfer Grill Pressure-Flow Characteristics

Pressure difference (Pa)	Measured flow (cfm)
0.6	21
0.8	24
0.9	26
1.4	32
1.8	38

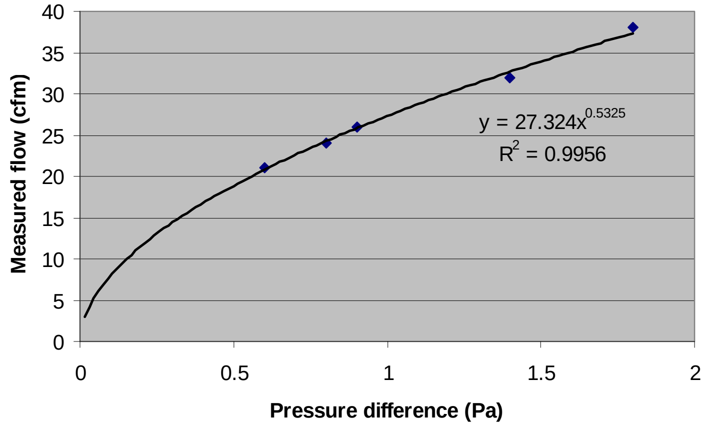


Figure 4: Curve-fit of tested data for transfer grill to bedroom 3

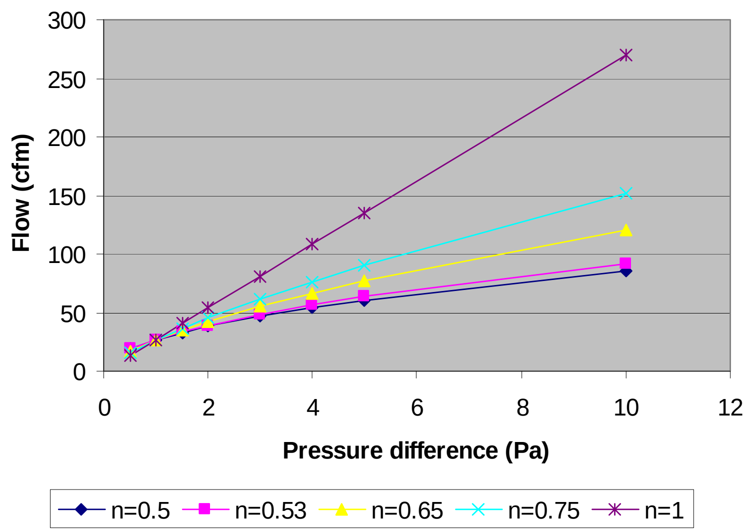


Figure 5: Extrapolation of flow to 10 Pa for different values of the flow exponent n

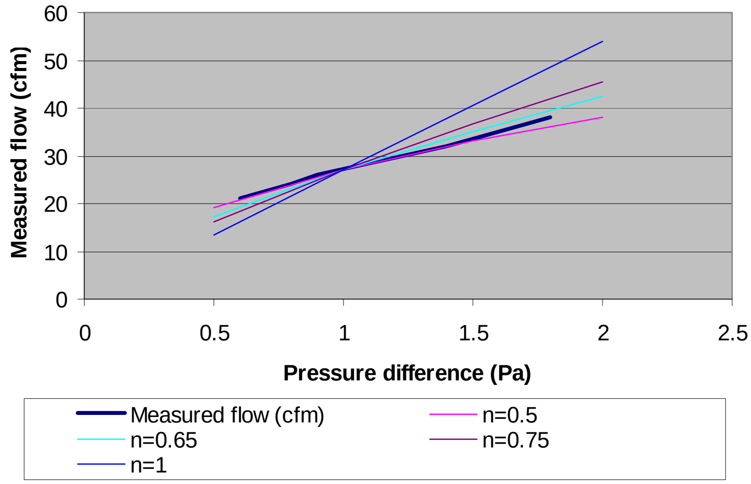


Figure 6: Comparison of measured flow to flow with several different flow exponents

The master bedroom transfer grill was also tested, as it is significantly different than the other bedroom transfer grills. The master bedroom transfer grill is in a chase that extends the full height of the wall. The gross grill size is approximately 13.5" by 9.5", with approximately 50% open area.

The same procedure as described above was performed, yielding the results described in the table and figure below. For this case, C=61 cfm/(pa^n) and n=0.62.

Table 3: Master Bedroom Transfer Grill Pressure-Flow Characteristics

Pressure difference (Pa)	Measured flow (cfm)
0.2	21
0.4	38
1.0	60
1.5	76

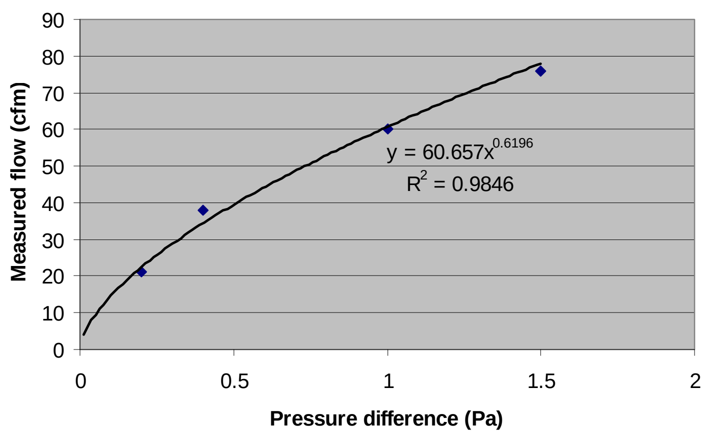


Figure 7: Curve-fit of tested data for transfer grill to master bedroom

The value of the flow exponent is significantly higher than the value for the previous test. Upon examination, it is clear that the first measurement, at 0.2 Pa, heavily influences the resulting curve-fit. Removing the 0.2 Pa measurement, which is the least accurate since the accuracy of the manometer is only 0.1 Pa, results in a flow exponent very close to the value found in the first test. After this step, C=61 cfm/Pa^n, and n=0.52.

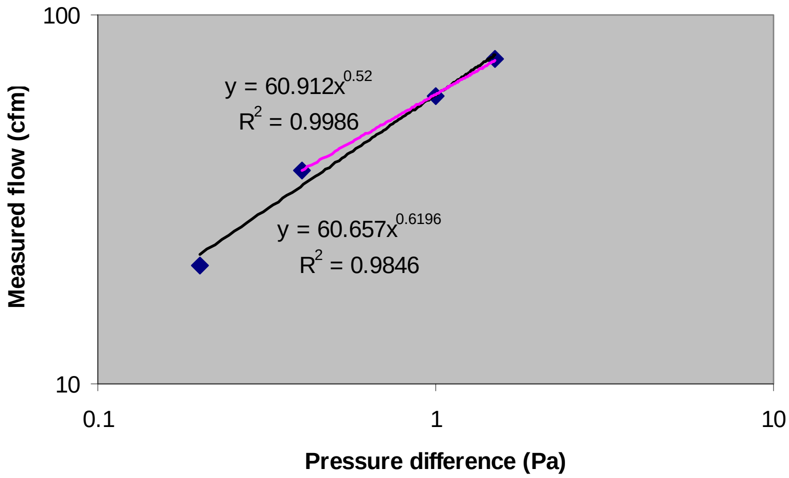


Figure 8: Log-log plot of pressure versus flow

Tests #6, 7, 16

The pressure field in the house was measured with laundry exhaust running, and the doors, ducts, and transfers closed or opened as described in the table. The results are below:

Test Number	6	7	16
Doors	Closed	Closed	Closed
Transfer grills	Closed	Closed	Open
Ducts	Closed	Open	Open
House Pressure wrt outside (Pa)	-0.5	Not recorded	-2.3
Baseline House Pressure wrt outside (Pa)	-0.1	-1.6	-1.6
Measured exhaust flow rate (cfm)	53	Not recorded	56
Room pressure wrt living space (Pa)			
Master BR	+0.1	0.0	0.0
Bedroom 1	+0.1	+0.2	+0.2
Bedroom 2	+0.1	0.0	+0.1
Bedroom 3	0.0	0.0	0.0
Bedroom 4	+0.2	0.0	0.0
Bedroom 5	+0.1	0.0	+0.1

Test 6 was conducted during the day, with relatively little stack effect present (baseline pressure -0.1 Pa). During this test, the bedrooms were more or less at the same pressure as the outside, to the accuracy of the manometer.

Tests 7 and 16 were conducted about 9:00 PM, with a higher indoor-outdoor temperature difference and therefore greater stack pressure (baseline pressure -1.6 Pa). During both of these tests, bedroom 1 (on the ground floor) was at +0.2 Pa, indicating that there was airflow from outside, through bedroom 1, to inside. Since bedroom 1 did not have a transfer grill in this house, tests 7 and 16 are nearly identical for this room (duct open but no transfer grill). The only difference between the tests is in the secondary or tertiary flow paths through the ducts to other bedroom and their transfer grills. Since the pressures changed very little in the other bedrooms, and these paths are not the primary airflow paths, these differences can be ignored.

For bedrooms 2 and 5, the results from tests 7 and 16 are counterintuitive. The results suggest that the bedrooms are more closely linked to outside when the transfer grills are open, which is not true. The measurements are within the uncertainty of the manometers (0.15 Pa in this range).

During test 16, the duct and transfer flows were measured with the Alnor Lo-Flow Hood. The Lo-Flow hood can measure flows only down to 10 cfm. These results are below:

Room	Pressure wrt living space (Pa)	Measured duct flow (cfm)	Measured transfer flow (cfm)
Master BR	0.0	0	0
Bedroom 1	+0.2	0	(no transfer grill present)
Bedroom 2	+0.1	0	0
Bedroom 3	0.0	0	0
Bedroom 4	0.0	0	0
Bedroom 5	+0.1	0	0
Bath 1	NA	0	NA
Bath 2	NA	0	NA
Bath 3	NA	0	NA
Breakfast	NA	0	NA
Family	NA	11 (supplying)	NA
Dining	NA	0	NA
Living	NA	0	NA
Laundry	NA	0	NA

Test #9
Pressure field in house with master bathroom exhaust fan running and AHU off, bedroom doors closed, transfer grills closed, and ducts open. The exhaust flow rate was measured with the Alnor Lo-Flow Hood.

Room	Pressure wrt living space (Pa)
Master BR	-0.9
Bedroom 1	+0.2
Bedroom 2	0.0
Bedroom 3	0.0
Bedroom 4	0.0
Bedroom 5	0.0
Bath 1	NA
Bath 2	NA
Bath 3	NA
Breakfast	NA
Family	NA
Dining	NA
Living	NA
Laundry	NA

During this test the pressure of the main living space wrt outdoors was -2.5 Pa with the master bathroom exhaust fan running. The measured exhaust flow rate was 85 cfm. Baseline pressure of the main living space wrt outdoors was approximately 2 Pa, estimated from baseline measurements for test 11 (1 hr before this test) and test 10 (10 minutes after this test).

The exhaust rate of 85 cfm would be expected to cause a pressure drop of about 1.25 Pa, given the flow parameters for the master bedroom calculated in test 4 (C=54.3, n=0.5, mainly via leakage past the bedroom door). Given the measured pressure drop of 0.9 Pa, the duct system is clearly providing an air flow path, which reduces the flow rate past the bedroom door and therefore the pressure drop. At 0.9 Pa, the door flow path would be expected to give approximately 52 cfm airflow, leaving approximately 33 cfm of airflow through the duct system.

Tests #10 and 11

Pressure field and supply flows in house with AHU on (cooling mode), bedroom doors closed, and transfer grills closed or open. Supply and transfer flows were measured with the Alnor Lo-Flow Hood.

Test Number	10		11		
Doors	Closed		Closed		
Transfer grills	Closed		Open		
Ducts	Open		Open		
House Pressure wrt outside (Pa)	-2.2		-1.9		
Baseline House Pressure wrt outside (Pa)	(not recorded)		-1.6		
Room	Pressure wrt living space (Pa)	Supply flow(s) (cfm)	Pressure wrt living space (Pa)	Supply flow(s) (cfm)	Transfer flow (cfm)
Master BR	+1.9	16, 18, 18, 14	+0.55	16, 19, 21, 14 (total 70)	36
Bedroom 1	(not recorded)	(not recorded)	+1.1	22	(no transfer)
Bedroom 2	+8.6 Pa	69	+3.6	76	38
Bedroom 3	+10.2 Pa	90	+5.1	100	39
Bedroom 4	+5.0	46	+1.5	49	31
Bedroom 5	+1.8	27	+0.4	26	18

In comparing tests 10 and 11, some reduction in supply flow is seen due to closing of the transfer grills. Significant pressurization of bedrooms 2, 3, and 4 is seen with the transfer grills closed, and even with the transfer grills open bedrooms 2 and 3 are pressurized above BSC's 3 Pa criteria.

During test 11, all of the supply flows in the house were measured with AHU on (cooling mode), bedroom doors closed, and transfer grills open.

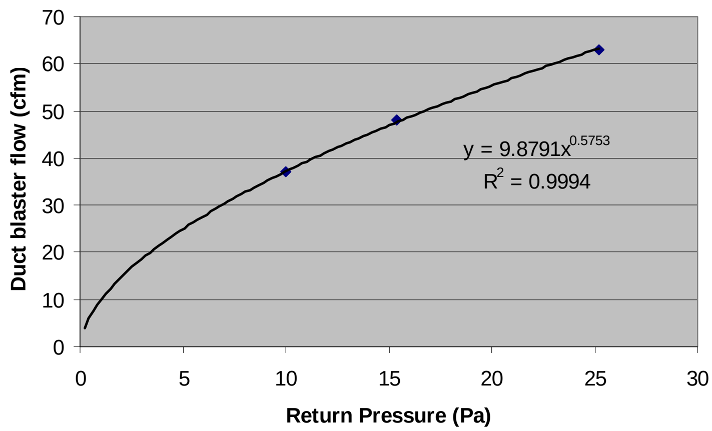
Room	Supply flow(s) (cfm)
Master BR	16, 19, 21, 14 (total 70)
Bedroom 1	22
Bedroom 2	76
Bedroom 3	100
Bedroom 4	49
Bedroom 5	26
Bath 1	26
Bath 2	21
Bath 3	17
Breakfast	207
Family	181
Dining	47
Living	133
Laundry	35

The total measured supply flow is 1010 cfm, only 63% of the design flow of 1600 cfm. Significant air flow through the door undercuts was observed in bedrooms 2 and 3.

Test #12

Overall duct leakage. Overall duct leakage was measured using the duct blaster exhausting from the return grill. The results are summarized in the table and figure below. The total leakage at 25 Pascals was 63 cfm, approximately 4% of design air handler flow (1600 cfm) and 6% of measured supply flow (1010 cfm).

Return Pressure (Pa)	Ductblaster flow (cfm)
0	0
-10.0	37
-15.4	48
-25.2	63



Test #13

Duct leakage to outside. A duct leakage to outside test was performed by depressurizing the house to -25 Pa. With the duct blaster off, the pressure in the return wrt the house was only +0.2 Pa. The duct leakage to outside was significantly below 20 cfm, the lowest measurable flow of the Ductblaster.

2.18.2. January 2007 Expert Meeting Summary Report

SYSTEMS ENGINEERING APPROACH TO DEVELOPMENT OF ADVANCED RESIDENTIAL BUILDINGS

<u>13.B.2 FINAL EXPERT MEETING PLANS</u>

RE: TASK ORDER NO. **KAAX-3-32443-13**
UNDER
TASK ORDERING AGREEMENT NO. **KAAX-3-32443-00**

MIDWEST RESEARCH INSTITUTE,
NATIONAL RENEWABLE ENERGY LABORATORY DIVISION,
1617 COLE BOULEVARD,
GOLDEN, CO
80401-3393

CONSORTIUM LEADER:
BUILDING SCIENCE CORPORATION
70 MAIN STREET, WESTFORD, MA
(978) 589-5100 / (978) 589-5103 FAX
CONTACT: BETSY PETTIT, AIA
BETSY@BUILDINGSCIENCE.COM

CONSORTIUM MEMBERS:

ANDERSON SARGENT HOMES
ARTISTIC HOMES
BURLINGAME RANCH, LLC/SHAW CONSTRUCTION
CHRIS MILES
CHUCK MILLER CONSTRUCTION, INC.
COASTAL HABITATS
DAVID WEEKLEY HOMES
D.R. HORTON
EBSCO
FERRIER HOMES
FIREMAN'S FUND
GLOBAL GREEN
HAYMOUNT, LLC
ICI HOMES
ISM CONSTRUCTION, INC.
IDEAL HOMES
MCSTAIN COMMUNITIES
OAKLAND HOUSING
PULTE HOME CORPORATION / DEL WEBB
VENTURE, INC.

ANDERSEN WINDOWS
CARDINAL GLASS CO.
PANASONIC
THE DOW CHEMICAL COMPANY
CERTAINTEED
DUPONT NONWOVENS
FORTIFIBER
GEORGIA PACIFIC
HONEYWELL
HUBER ENGINEERED WOOD PRODUCTS
ICYNENE, INC.
JAMES HARDIE BUILDING PRODUCTS
LIPIDEX CORPORATION
JOHN MANSVILLE
MASCO
U. S. GREENFIBER, LLC
TAMLYN
RESEARCH PRODUCTS CORPORATION/APRILAIE

FEBRUARY 15, 2007

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AGENDA

Building America Expert Meeting

VENTILATION AIR DISTRIBUTION EFFECTS IN HOMES

Meeting Manager:	Joseph Lstiburek, Building Science Corporation
Date/Time:	**Friday, 26 January 2007, 8 am to 12 pm**
Location:	Dallas, TX, **Adam's Mark, Houston Ballroom** (ASHRAE Winter Meeting hotel)

Featured Speakers:

- Max Sherman, Lawrance Berkeley National Laboratory
- Bjarne Olesen, International Center for Indoor Environment and Energy, Denmark
- Ren Anderson, National Renewable Energy Laboratory
- Aaron Townsend, Building Science Corporation

Invitees:
Participants will be key people working in the indoor air quality field. Participants are invited from the following groups: Building America teams, ASHRAE Standard 62.2 committee members and participants, residential HVAC and construction industry, national and state government laboratories and agencies, university researchers, energy efficiency organizations, and building consultants.

Meeting Agenda:

- 8:00 am to 8:15 am, Welcome and Meeting Introduction – Joseph Lstiburek

- Presentations

    - 8:15 to 8:45, (30 min) Max Sherman, "Development of Metrics for Ventilation Distribution"
    - 8:45 to 8:55, (10 min) Questions and discussion

    - 8:55 to 9:25, (30 min) Bjarne Olesen, "Exposure and Risk"
    - 9:25 to 9:35, (10 min) Questions and discussion

    - 9:35 to 9:45 (10 min) Break/refreshments

    - 9:45 to 10:15, (30 min) Ren Anderson, "Contaminants and Control Strategies"

    - 10:15 to 10:25, (10 min) Questions and discussion

    - 10:25 to 10:55, (30 min) Aaron Townsend, "Field Measurements and Simulations"
    - 10:55 to 11:05, (10 min) Questions and discussion

- General discussion, 11:05 to 11:55 (50 min), Joseph Lstiburek-discussion moderator

- Whole-house ventilation air distribution is important to achieve reliable ventilation performance.
- What are the metrics that can be used to quantify the effective differences between systems?
- How can those metrics be applied to ASHRAE Standard 62.2?

• Wrap up, action items, and follow-up plan, 11:55 to 12:00

Key questions regarding this meeting:

Mechanical ventilation is becoming an increasingly larger portion of the total space conditioning load in high-performance buildings. Where contaminant sources are managed (for example, closed combustion) and ventilation air distribution is assured, reduced ventilation requirements may be acceptable and advantageous. Hot-humid climates may benefit the most.

1. What does the latest research tell us about ventilation effectiveness due to spatial air distribution?

2. Should not ventilation systems with better spatial distribution be credited for having more reliable whole-house performance relative to indoor air quality?

3. What are the best metrics to account for ventilation air distribution in determining appropriate minimum residential ventilation rates?

References/Supporting Documents

Hendron, R, Rudd, A., Anderson, R., Barley, D., Hancock, E., Townsend, A., 2006. “Field test of room-to-room uniformity of ventilation air distribution in two new houses.” Submitted for publication to IAQ 2007, ASHRAE, December.

Lstiburek, J., Townsend, A., Rudd, A., 2006. “Engineering based guidelines for effective ventilation in new homes.” Final report submitted to USDOE, December.

Table 1. List of confirmed attendees (not including speakers and BSC staff)

#	Last name	First name	Company	Email	Y/N response as of 1/5/07	62.2 status
1	Baxter	Van	ORNL	baxtervd@ornl.gov	Y	
2	Bloemer	John	Research Products Corp.	jb@aprilaire.com	Y	
3	Brennan	Terry	Camroden Associates	terry@camroden.com	Y	SSPC 62.2 vote
4	Chandra	Subrato	Florida Solar Energy Center	subrato@fsec.ucf.edu	Y	
5	Crawford	Roy	Trane	roy.crawford@trane.com	Y	SSPC 62.2 vote
6	Davis	John	Research Products Corp.	jgd@aprilaire.com	Y	
7	Drumheller	Craig	NAHB Research Center	cdrumheller@nahbrc.org	Y	SSPC 62.2 non-vote
8	Emmerich	Steve	NIST	steven.emmerich@nist.gov	Y	SSPC 62.2 vote
9	Fairey	Philip	FSEC	pfairey@fsec.ucf.edu	Y	
10	Ferris	Rob	Fantech	rofe@fantech.net	Y	
11	Forest	Daniel	Venmar Ventilation	forestd@venmar.ca	Y	
12	Francisco	Paul	University of Illinois-UC	pwf@uiuc.edu	Y	SSPC 62.2 vote
13	George	Marquam	Blu Spruce Construction	marquam.george@uas.alaska.edu	Y	SSPC 62.2 vote
14	Grimsrud	David		grimsrud@earthlink.net	Y	SSPC 62.2 vote
15	Heidel	Tom	Broan-Nutone	theidel@broan.com	Y	
16	Henderson	Hugh	CDH Energy	henderson@cdhenergy.com	Y	
17	Holton	John		jholton1@verizon.net	Y	SSPC 62.2 vote
18	Kosar	Douglas	University of Illinois-Chicago	dkosar@uic.edu	Y	
19	Lubliner	Mike	Washington State University	lublinerm@energy.wsu.edu	Y	
20	Olson	Collin	Energy Conservatory	colson@energyconservatory.com	Y	
21	Proctor	John	Proctor Engineering	john@proctoreng.com	Y	SSPC 62.2 vote
22	Rittelmann	Bill	IBACOS	brittelmann@ibacos.com	Y	
23	Ryan	William	University of Illinois-UC	wryan@uic.edu	Y	
24	Stevens	Don	Stevens & Associates	don.t.stevens@wavecable.com	Y	SSPC 62.2 vote
25	Stroud	Thomas	Health Patio & Barbeque Assoc	stroud@hpba.org	Y	SSPC 62.2 vote
26	Talbot	John		jmtalbott@comcast.net	Y	
27	Uselton	Dutch	Lennox	dutch.uselton@lennoxInd.com	Y	
28	Walker	Iain	LBNL	iswalker@lbl.gov	Y	SSPC 62.2 vote
29	Wilcox	Bruce		bwilcox@lmi.net	Y	SSPC 62.2 vote
30	Williams	Ted	AGA	twilliams@aga.org	Y	SSPC 62.2 vote

Appendices

METRICS

What do we need to know in order to add air distribution into ASHRAE Standard 62.2?

Max Sherman

OBJECTIVES

- To define some potential metrics that can be used to evaluate air distribution
  - But, first we need to look at implied metrics for acceptable Indoor Air Quality
- Suggest some approaches to evaluate metrics
  - Simulation
  - Experiment

Max's Metric Mantra:

Metrics must be meaningful and measurable

Pre-Metric: Acceptable IAQ

- Frames discussion of metrics
- Won't discuss this quantitatively, but operationally it should
  - Limit **damage**
  - Caused by **contaminants** of concern
  - To which people are exposed over some **time** period

Types of "DAMAGE"

- Comfort
  - Unpleasant Odors, Irritation *(covered by 62.2)*
  - Acoustics, lighting, thermal, etc. *(not covered)*
- Health
  - Reduced physiological functioning
  - Tissue damage
  - Increased susceptibility to disease

Contaminants of Concern

- Compounds and specifics: ***Bjarne***
- Whole-house ventilation looks at what?
  - Acute Mortality/Morbidity: No
    - E.g. we don't control phosgene with 62.2
  - Reduction in life-expectancy: Yes
    - E.g. carcinogenesis, mutagenesis, toxic loads
  - Reduction in quality of life: Yes
    - E.g. hours of discomfort, minor disease etc.

Timed Exposure

- Delay in absorption of contaminant
  - Important for short-term exposure
- Body can repair/adapt sometimes; e.g.
  - 10 ppm CO for 400 hours: small impact
  - 400 ppm CO for 10 hours: death
- But not others; e.g.
  - Irreparable tissue damage
  - Risk increases during exposure

Damage Equation:

- Linear (n=1) for many cumulative risks
  - Most cancer, metals, stable (e.g. DDT)
- n=3 for Chlorine
  - Typical of oxidants, poisons
- n>>1 represents a threshold
  - Time above threshold is important
- Linear approximation good if little variation

IAQ METRICS

- Peak concentration of contaminant
  - Good for high exposure levels/acute effects
  - Good for threshold-dominated contaminants
  - Focus on short-term dose
- Average concentration (e.g. linearized)
  - Good for cumulative exposures
  - Good for steady exposures above thresholds
  - Focus on long-term dose

Average Concentration It is

- Highly variable emission rates
  - Not well controlled by continuous ventilation
  - Need source control (e.g. exhaust ventilation)
- Contaminants of concern
  - Must be above thresholds to be “of concern”
  - Are the ones we expect to control with whole-house ventilation
- Metric is then long-term average concentration: DOSE

How Do We Get Concentration

- Depends on
  - Sources & sinks
  - Volumes
  - Ventilation & air transport
- Linked by Continuity Equation
- Need to proceed generically
  - No pollutant specifics (i.e. a tracer gas)
  - Ignore species-specific interactions

CONTINUITY EQUATION

- Locally Covariant Derivation
  - Good everywhere
  - Even near black holes
- Steady state, single zone expression:
  - S=emission rate (e.g. cfm)
  - Q= ventilation (e.g. cfm)

Getting Back to Distribution

- Air distribution is only relevant when it is not a single well-mixed zone.
  - Can't get too crazy (e.g. CFD)
  - Need to relate it to the simple result
- We use a multizone continuity equation
  - But we can assume the zones are well mixed
  - Need matrix formulation of continuity equation

MATRIX EQUATION

- Local Zonal Description
  - Matrix of flows
  - Independent sources
  - Zonal concentrations
- Psuedo-Steady State
  - Matrix inverse
  - Represents averages

MATRIX NOTATION

- For N zones: N rows & N columns
- Sum of all entries gives single zone value
- Diagonal element is total for zone
- Off-diagonal elements of Q matrix are (negative of) flow between zones
  - Ask about Volume matrix if you dare

Dose is our IAQ Metric

- A person can only be in one zone at a time
  - So, we define an activity variable.
- Source strength may vary zonally.
  - So, we define a source fraction for each zone
- Distribution impacts are relative
  - So, we define a relative dose v. perfect mixing

How Should We Use Metric

1. Evaluate Metric for distribution system of interest
2. Evaluate Metric for distribution in reference case (e.g. 62.2 default)
3. Adjust total rate by ratio to increase or decrease depending on system
   - Could be tabulated like in 62.1

DOSE

- *d* is dose
- ***s*** is fractional source strength
- ***a*** is fractional time spent in each zone
- **D** is Distribution Matrix

DISTRIBUTION MATRIX

- Couples emission in one zone to exposure in all other zones; e.g.
  - All entries the same (1) for fully mixed
  - Matrix diagonal for isolated zones
- ***Independent*** of sources, activities, etc
- So, we could base final metric on it
  - If we define activity/source distribution

3-Zone Example (PFT data)

- Q Matrix=>
  - m^3/hr
  - Q_o=726 m^3/hr

653	-291	0
-130	448	-206
-17	-23	292

- D Matrix =>
  - Dimensionless
  - D_o=9.54

1.30	0.88	0.62
0.43	1.97	1.39
0.11	0.21	2.63

Metric Choices

- Need to determine how to use the Distribution Matrix in a way that does not depend on knowing activity/sources.
- What is appropriate for a standard?
  - Best case?
  - Worst case?
  - Typical case?
    - What is that??

Extreme Metrics

- The best and worst cases of the metric will be when the contaminant of concern is emitted in a single zone
- Worst case: Highest value in matrix; e.g. someone generates contaminants and lives in same zone: 2.63 in example
- Best case: lowest value: e.g. live in most isolated room: 0.11 in example

Distributed Distribution

- Assume sources are fully dispersed and activity is spread between all zones
- d=1.06 in example
- Tends toward perfect mixing result because of source distribution and activity patterns

Inactivity Patterns

- Suppose sources were distributed but someone spent all their time in the worst zone
- Relative dose would then be from the row of Distribution Matrix with highest sum.
- From example
  - 0.93, 1.26, 0.98
  - RMS mean=1.07

Deviation from Perfection

- Suppose we have no clue on activity patterns or source distributions
- We can measure the "distance" from perfect mixing using RMS deviation
- d=1.80 for example case

Which Metric Option?

- Fully distributed sources & activities (1.06)
  - Air distribution effect will be minimal
- Worst zone; distributed sources (1.26)
  - Is reasonable? (RMS=1.07)
- Clueless: (1.80)
  - Robust, but semi-empirical; conservative
- Worst case: (2.63)
  - Appropriate for minimum standard?

METRICS ARE WORTHLESS

Unless you can measure them, of course

- Direct Field Measurement
  - Measure response in real configuration
  - Can really only be done with tracer gas
- Simulation
  - More practical; allows parametrics
  - But must be believable
    - See "Direct Field Measurement" above

HOW TO MAKE THE MEAUSURMENTS

The diagnostics necessary to measured air distribution effects

TWO TRACER APPROACHES

- Simplified for the Metric of Choice; e.g.
  - Inject tracer in reference source pattern
  - Sample in reference activity pattern
- Complete Characterization
  - Measure all flows to/from zones
  - Can be used to compare metrics
    - And derive simplified approach
  - Can be used to verify simulations

TRACER CONTINUITY

- Same Continuity equation, but
  - this time we know concentrations
  - and are looking to determine the flows
- Unfortunately, no direct solution
  - N^2 unknowns, but only N equations
  - Need to get more information

THREE APPROACHES

- Time Series in Non-steady State
  - Fit time series data over changing conditions (e.g. decay) to solve differential equation
- Series (Single-Tracer) Steady-state Tests
  - N tests are done one at a time
- Simultaneous Multi-Tracer Tests
  - Use N tracer gases to run simultaneous tests (e.g. inject one in each zone)

TIME SERIES

- Fit data to=>
- To find eigenvalues
- "A"s are relevant air change rates
  - N of the them; C_{ij} are their eigenvectors
  - Slowest is whole-building air change rate
  - Quickest determines uncertainty
- This approach never works in real buildings
  - Mixing issues obscure vital information
  - KIDS: DON'T DO THIS AT HOME

MIXING KILLS

- In all real experiments mixing will obscure short-term information with noise
- Don't differentiate---INTEGRATE
- Even in single-zone situations, fitting decay data is inferior to integrating under the curve
- In multizone situations it is much worse
  - Alternative approaches are needed

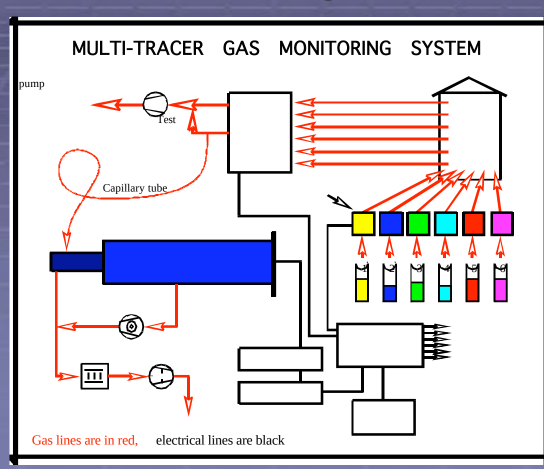
MULTIPLE EXPERIMENTS

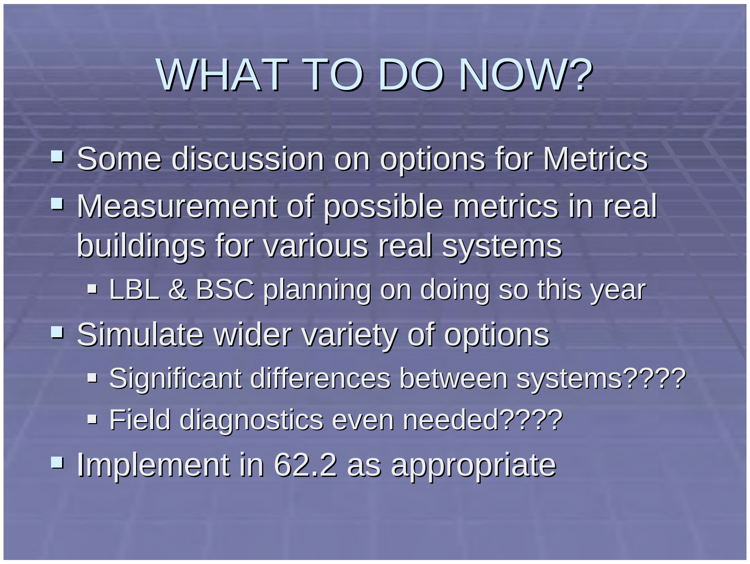
- Do N different experiments & integrate/average
  - inject in N independent ways
    - E.g. in 1 zone different zone each experiment
- Add to Matrix equation
  - Can be inverted now

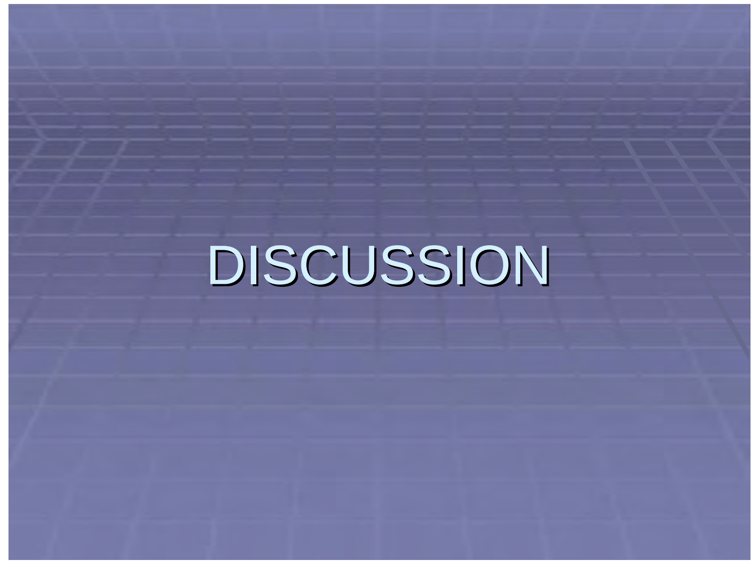
SERIES OR PARALLEL

- Series Option
  - Can be done with one tracer gas
  - Very sensitive to changes in air flows
- Parallel (MultiTracer) Option
  - Can accurately find average flow
  - Takes less time
  - LBL's MTMS uses this approach

MTMS




WHAT TO DO NOW?
Some discussion on options for Metrics
Measurement of possible metrics in real buildings for various real systems
LBL & BSC planning on doing so this year
Simulate wider variety of options
Significant differences between systems????
Field diagnostics even needed????
Implement in 62.2 as appropriate


DISCUSSION

International Centre for Indoor Environment and Energy

VENTILATION AIR DISTRIBUTION EFFECTS IN HOMES
Indoor Air Quality-Exposure and Risk

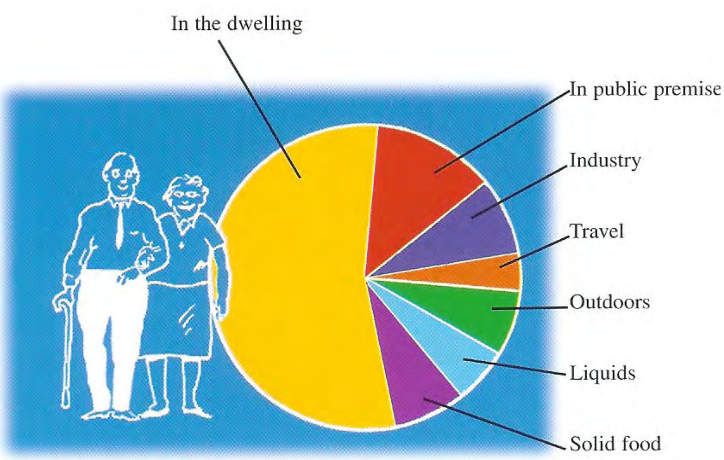
Professor Bjarne W. Olesen, Ph.D.

www.ie.dtu.dk

Technical University of Denmark

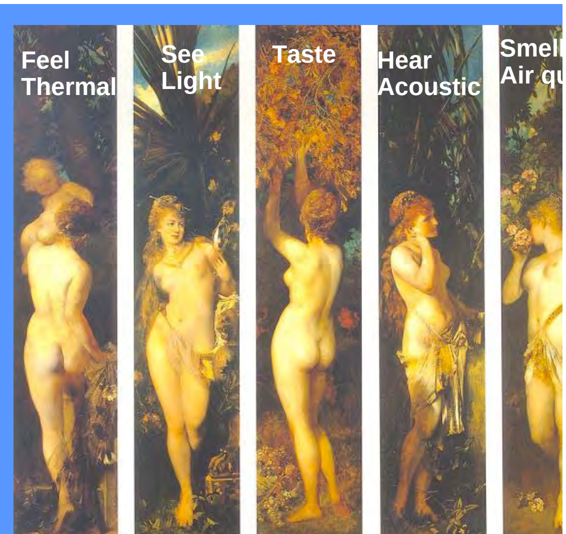
INDOOR - OUTDOOR

- Highest exposure to the indoor environment
- People spend ~90 % of the time indoors during work, during transportation and at home



Relative exposure of air during a normal life.

5 SENSES



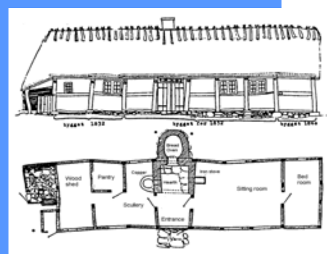
HEALTH

In developing regions 5000 persons die per day due to poor IAQ

(WHO)

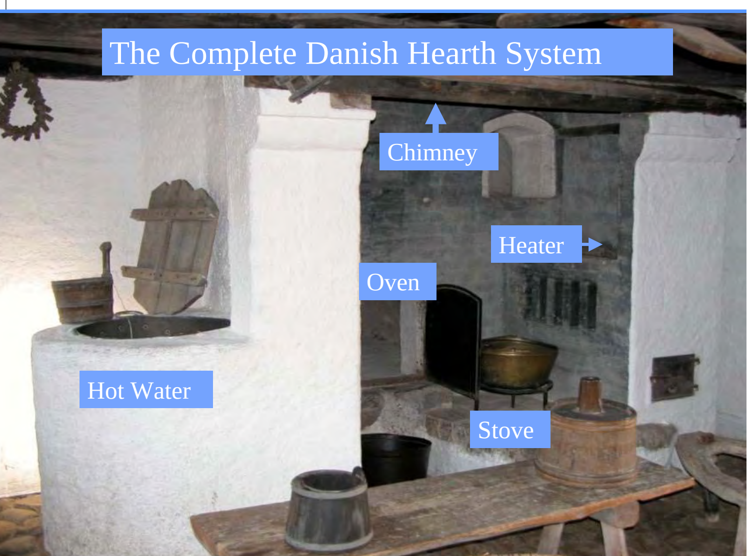
Experiments in two houses at Lejre Experimental Centre for Archaeolog
Professor Kirk Smith, UC-Berkeley

- How does the Danish hearth system perform?
- Will the system be useable in developing countries, e.g. Nepal, so that peoples exposure to smoke from indoor fireplaces can be reduced?



Not so long ago, Denmark was a low-technology wood-burning society
not able to afford much metal.

How did its people solve the smoke problem?

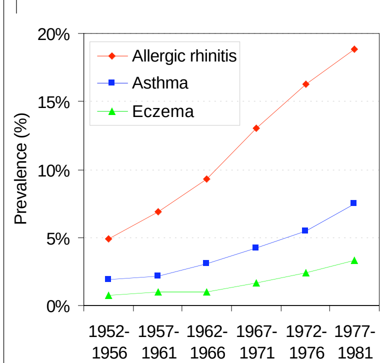


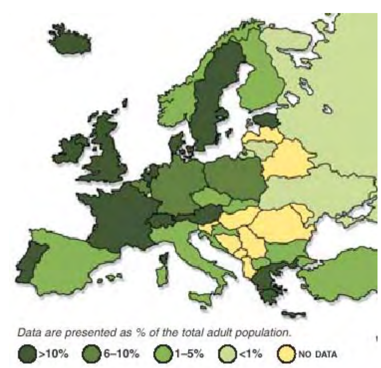
Monitoring of CO and fine particles in house during use of fireplace (cooking, heating, boiling water)

Asthma and Allergy

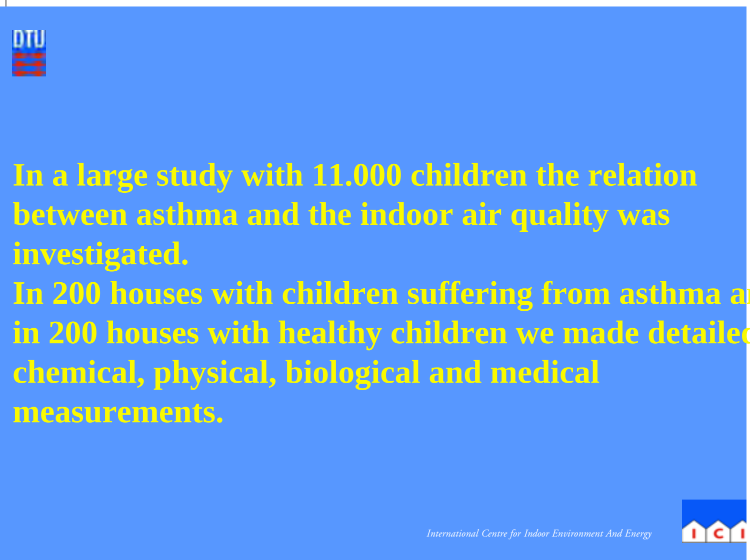
In several industrial countries 50% of school children is suffering from Asthma or Allergy. This number has doubblet within the last 20 years

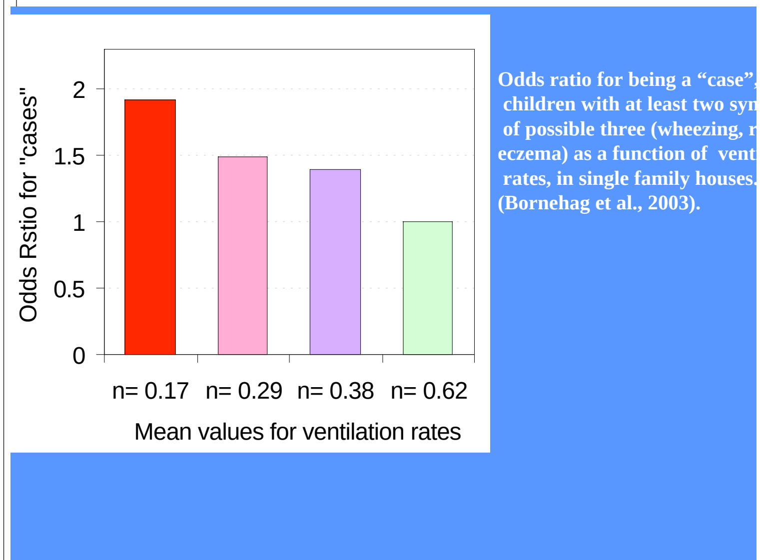
International Centre for Indoor Environment And Energy

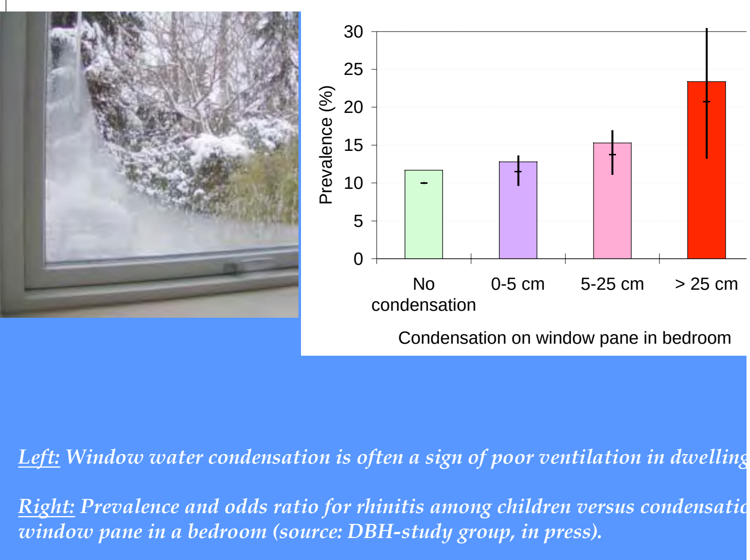


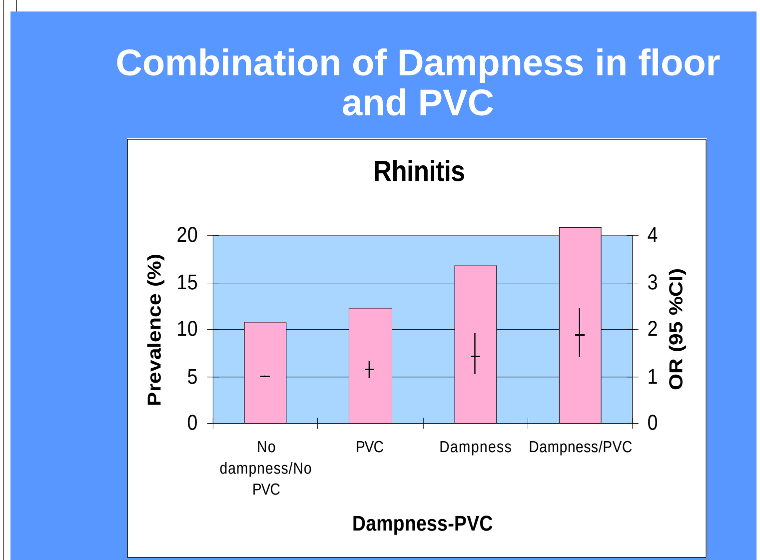


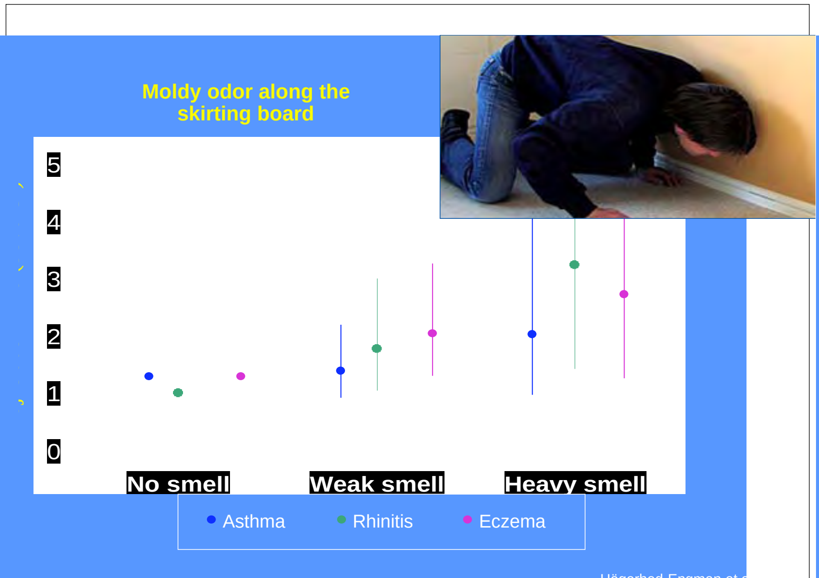
Left: Trends for allergic rhinitis, asthma and eczema among male conscripts (17-20 years age) in Sweden (Bråbäck et al., 2004).
Right: Current data on prevalence of asthma in adults in Europe (Loddenkemper et al., 2


DTU
In a large study with 11.000 children the relation between asthma and the indoor air quality was investigated.
In 200 houses with children suffering from asthma and in 200 houses with healthy children we made detailed chemical, physical, biological and medical measurements.
International Centre for Indoor Environment And Energy

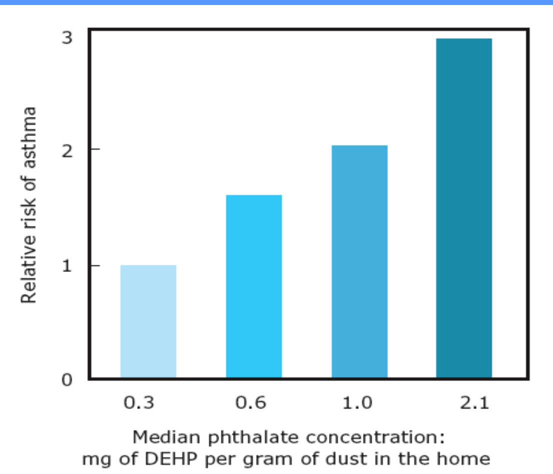

Odds Rstio for "cases"
2
1.5
1
0.5
0
n= 0.17
n= 0.29
n= 0.38
n= 0.62
Mean values for ventilation rates
Odds ratio for being a "case", children with at least two sym of possible three (wheezing, r eczema) as a function of vent rates, in single family houses. (Bornehag et al., 2003).


Prevalence (%)
30
25
20
15
10
5
0
No condensation
0-5 cm
5-25 cm
> 25 cm
Condensation on window pane in bedroom
Left: Window water condensation is often a sign of poor ventilation in dwelling
Right: Prevalence and odds ratio for rhinitis among children versus condensatio window pane in a bedroom (source: DBH-study group, in press).


Combination of Dampness in floor and PVC
Rhinitis
Prevalence (%)
20
15
10
5
0
4
3
2
1
0
OR (95 %CI)
No dampness/No PVC
PVC
Dampness
Dampness/PVC
Dampness-PVC


Moldy odor along the skirting board
5
4
3
2
1
0
No smell
Weak smell
Heavy smell
Asthma
Rhinitis
Eczema
Hägerhed-Engman et a


THE RIDDLE OF ALLERGIES
• ALLERGIES ARE INCREASING!
• Up to 50% of children has or have had symptoms of allergic disease
• IN SWEDEN more in the north!
• IN EUROPE more in the west!
• IN USA more among the poor!
• MOST in countries that speak ENGLISH (UK, New Zeeland, Australia
• Also high in Peru...
THE ROLE OF INDOOR AIR?



Plasticizers fro polyvinyl chlor in dwellings increase the ri of asthma amo children.

Each column represents abo 90 dwellings.

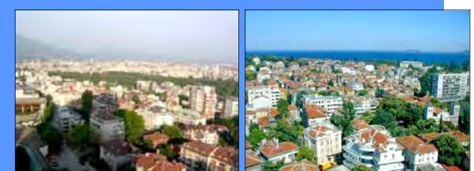
DEHP: di(2-ethylhexyl) phthalate.

The ALLHOME study

Objectives

•To map the housing conditions regarding indoor environment in two representative urban areas of Bulgaria (Sofia and Burgas).

•To explore the associations between housing condition and symptoms in airways, eyes, nose and skin in children age 2 to 7.

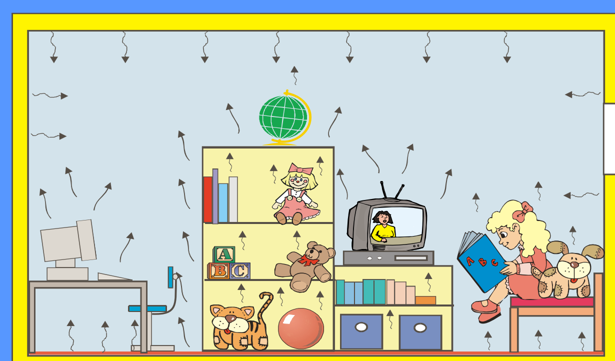


The ALLHOME-2 study

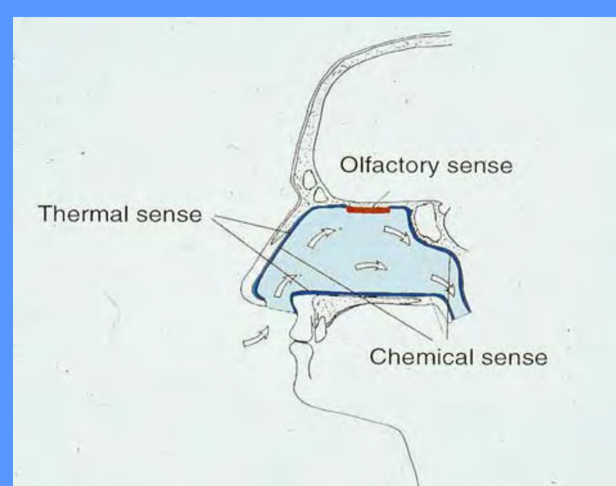
- Nested case-control study, including medical and engineering measurements
- Case and control children selected based on the ALLHOME-1 study
- December-March 2005
- Medical and engineering measurements:
    - Building inspection, 24h-CO_2, RH, T; dust samples,
    - Examination, Skin Prick Test (10 allergens), urine
- Collected data: 215 children (111 cases, 114 controls), 211 houses

Analyses are ongoing

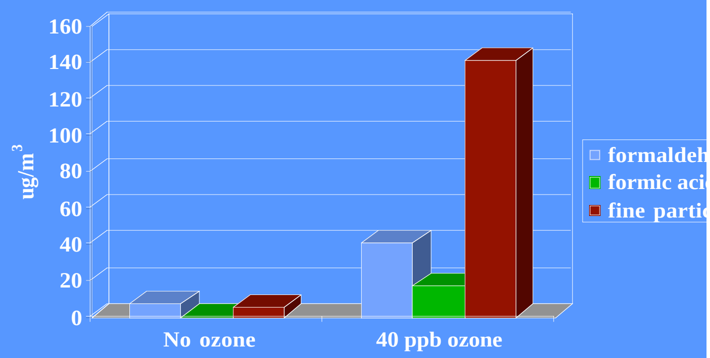
Homes



List of 350 common volatile organic compounds in indoor air



Mixture of 23 VOCs (including d-limonene and α-pinene)

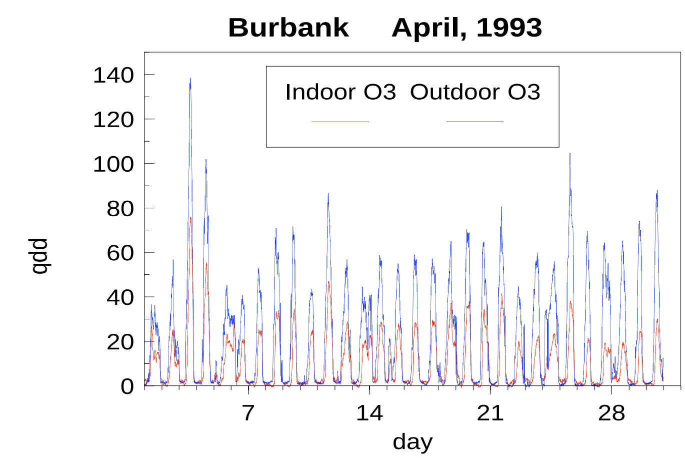


Indoor Chemistry

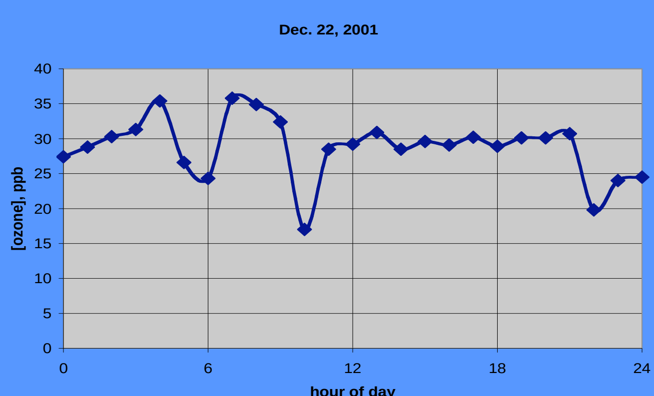
- Indoor chemistry can influence the kind and concentration of organic chemicals in indoor air

Ozone

- Sources
  - outdoor to indoor transport
  - photocopiers
  - laser printers
  - ozone generators
- Indoor levels normally smaller than outdoor
- Large variations with time of day, day of week and season

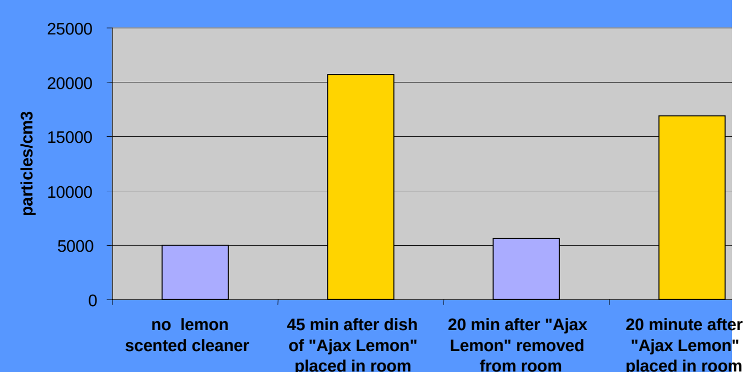


Even in Scandinavia During the Winter Outdoor Ozone Can Exceed 35 ppb



Office in Copenhagen; Dec. 19, 2001

[outdoor ozone] = 28 ppb



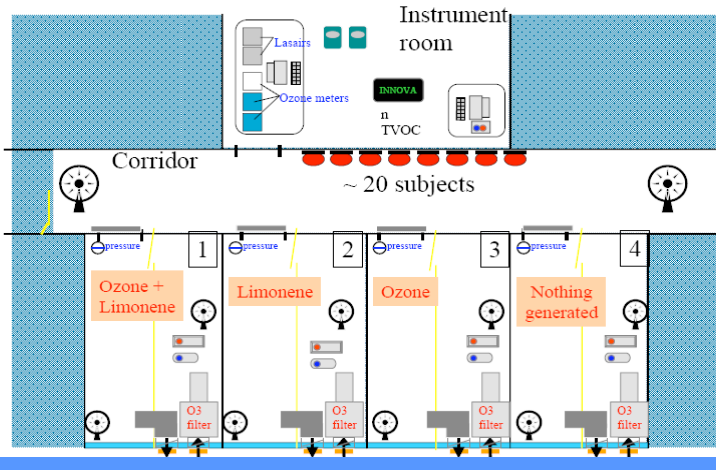
Examples of common indoor pollutants that react with ozone in the air

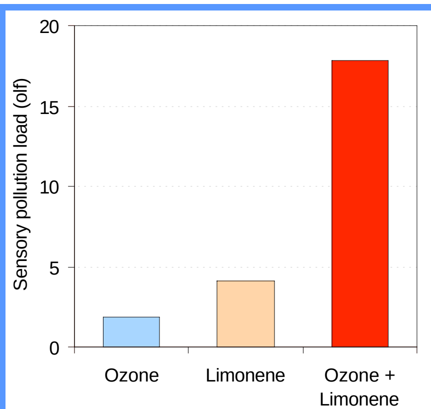
- Nitric oxide, nitrogen dioxide

- Terpenoids (e.g., d-limonene, α-pinene, linalool)

- Unsaturated fatty acids (e.g., oleic, linoleic)

Sensory effects from ozone + limonene





The sensory pollution load in an office where either ozone (15 ppb) or limonene (83 pp were present separately or both ozone and limonene (15 ppb+83 ppb respectively) we mixed in the office air (Tamás et al., 2005); the increased sensory pollution load is due to the presence of reaction products in the office air.

When is Indoor Chemistry Most Likely to Happen

- When indoor ozone levels are elevated (oxidation)
- When the humidity is elevated (hydrolysis)
- When temperatures are elevated
- When ventilation rates are low (gas phase)
- When terpene levels are high
- When surfaces are "dirty"

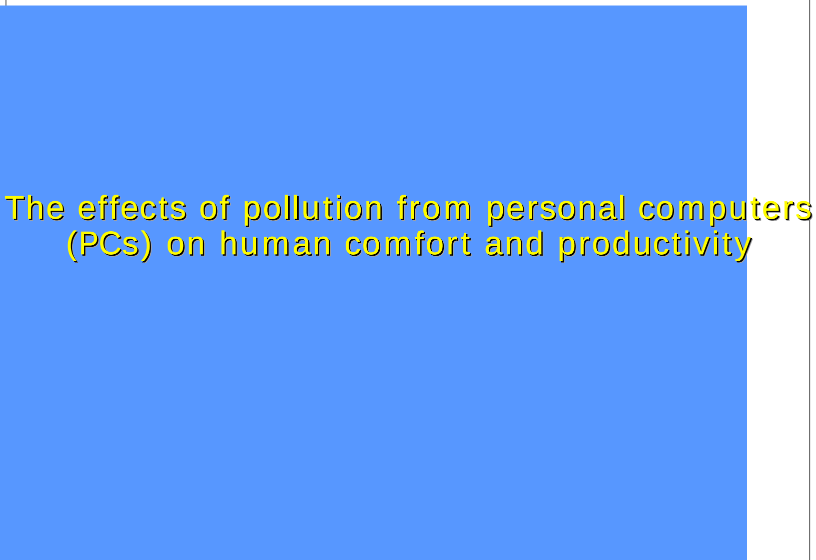
Generation of pollution from occupants

	Sensory pollution load olf/ occupant	Carbon dioxide l/(h· occupant)	Carbon monoxide 1) l/(h· occupant)	Water vapour 2) g/(h· occupan
Sedentary, 1-1.2 met				
0% smokers	1	19		50
20% smokers 3)	2	19	$11 \cdot 10^{-3}$	50
40% smokers 3)	3	19	$21 \cdot 10^{-3}$	50
Physical exercise				
Low level, 3 met	4	50		200
Medium level, 6 met	10	100		430
high level (athletes), 10 met	20	170		750
Children				
Kindergarten, 3-6 years, 2,7 met	1,2	18		90
School, 14-16 years, 1-1,2 met	1,3	19		50

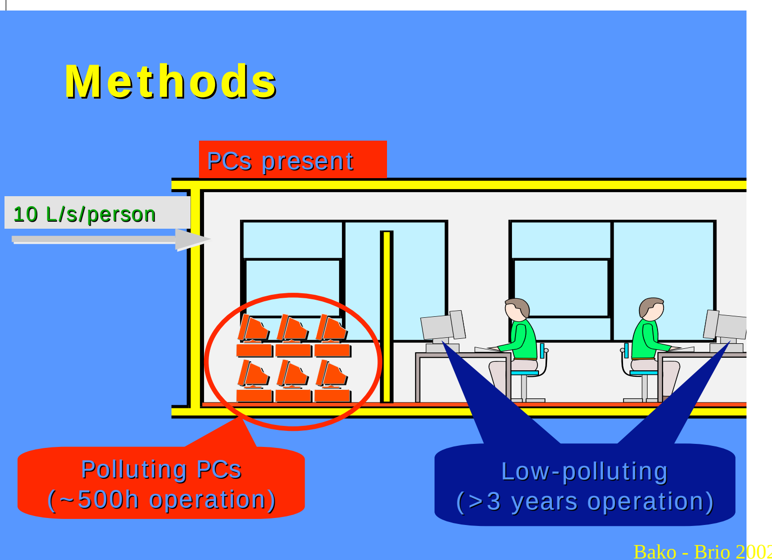
1) from tobacco smoking
2) applies for persons close to thermal neutrality
3) average smoking rate 1,2 cigarettes/hour per smoker, emission rate 44 ml CO/cigarette

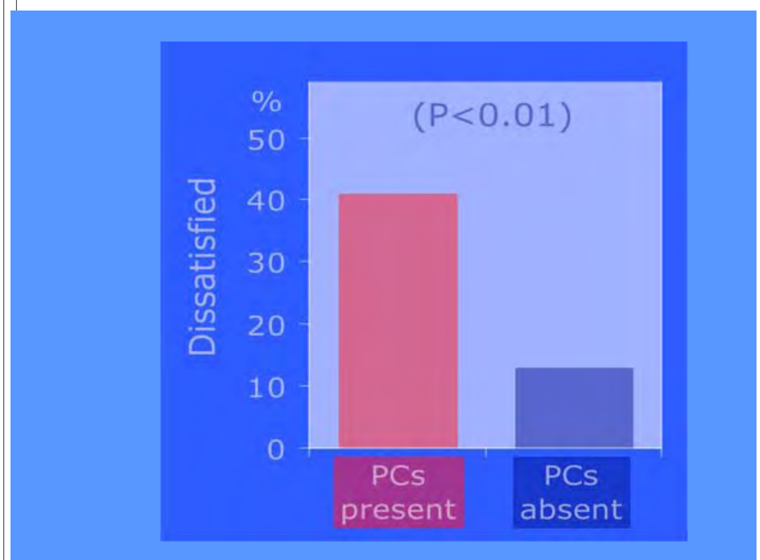
POLLUTANT FROM BUILDING, FURNISHING AND SYSTEM	Sensory pollution lo olf/m_	
	Average	Range
Existing buildings		
Offices a)	0,3 d)	0,02-0,9
Offices b)	0,6 c)	0 - 3
Class rooms a)	0,3	0,12-0,5
Kindergarten a)	0,4	0,20-0,7
Auditorium a)	0.3 d)	0,13-1,3
New buildings (No-smoking)		
Low polluting buildings	0,1	
Not-low polluting buildings	0,2	
Very low polluting buildings	0.02	

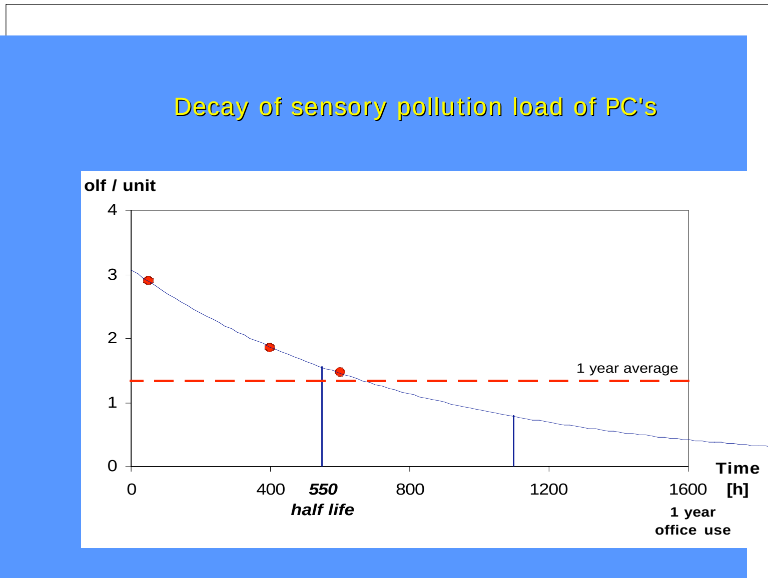
a) Data from more than 40 mechanical ventilated buildings in Denmark.
b) Data from an European Audit program, 1992-1995.
c) Includes pollutant load from smokers
d) Includes pollutant from earlier smoking.

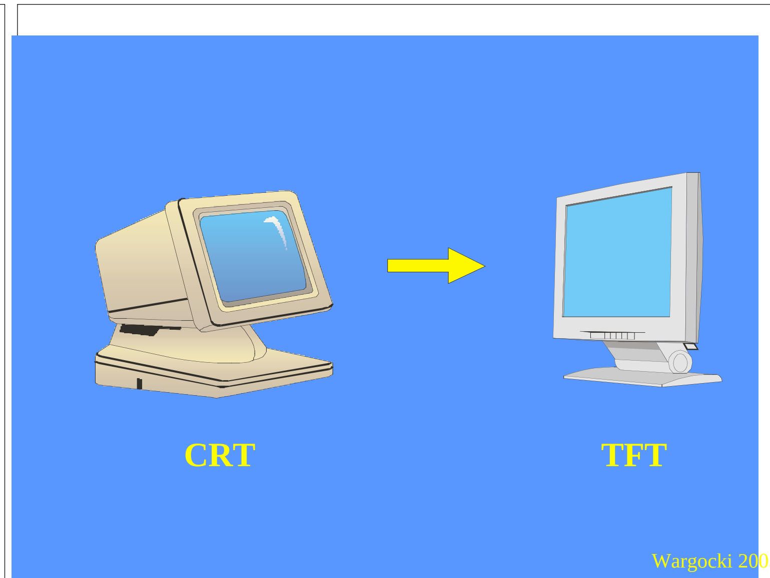

The effects of pollution from personal computers
(PCs) on human comfort and productivity

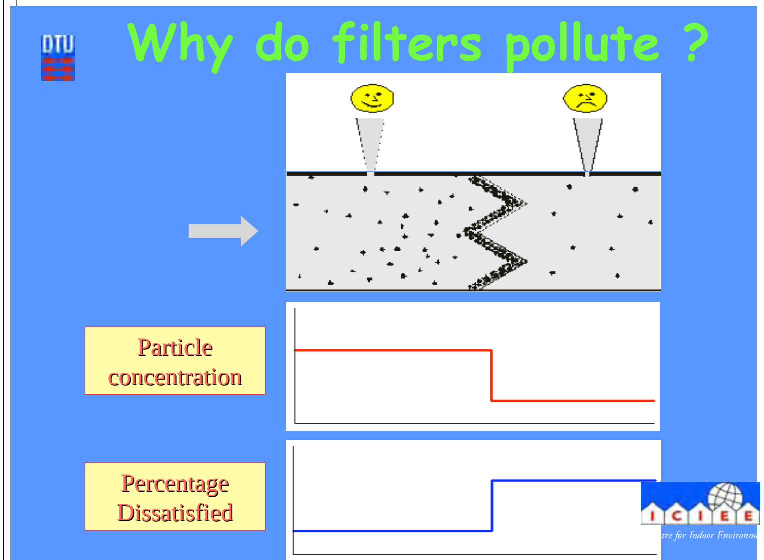

PCs are pr
s
The estimate
is more than
PCs are an indispensable tool in a
modern office

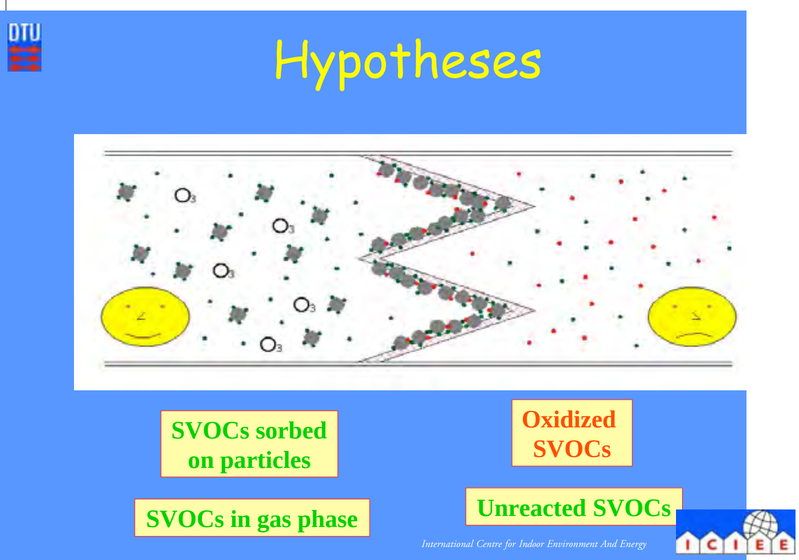

Methods
PCs present
10 L/s/person
Polluting PCs
(~500h operation)
Low-polluting
(>3 years operation)
Bako - Brio 2002

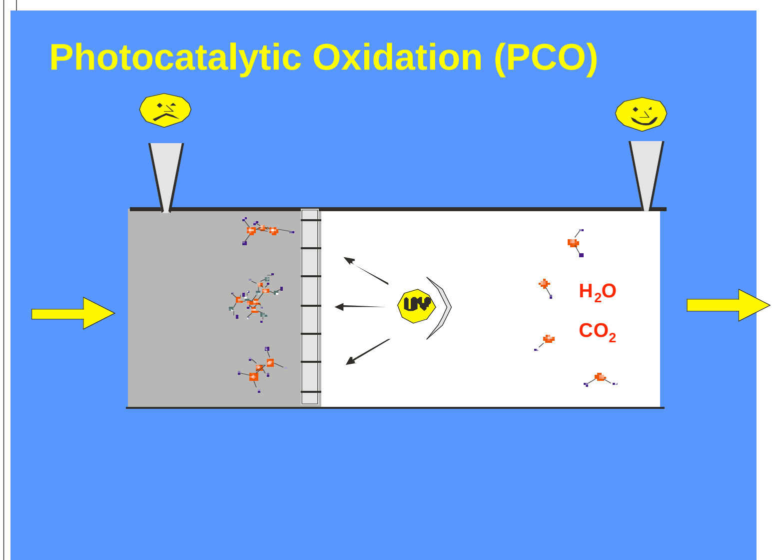

%
(P<0.01)
Dissatisfied
50
40
30
20
10
0
PCs
present
PCs
absent

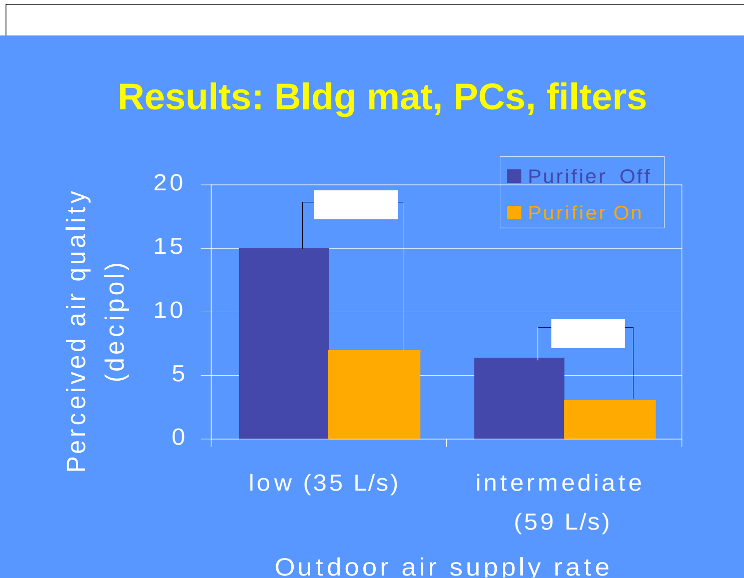

Decay of sensory pollution load of PC's
olf / unit
4
3
2
1
0
1 year average
0
400
550
half life
800
1200
1600
Time
[h]
1 year
office use

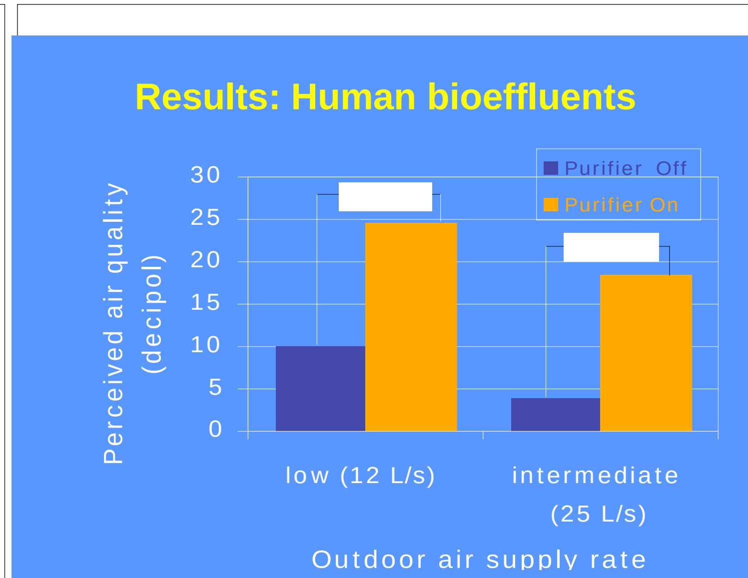

CRT
TFT
Wargocki 2003

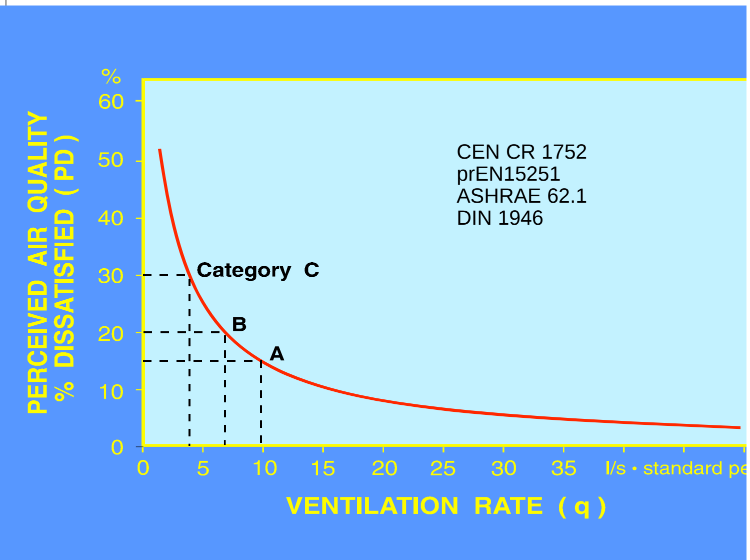

Why do filters pollute ?
Particle concentration
Percentage Dissatisfied


Hypotheses
SVOCs sorbed on particles
Oxidized SVOCs
SVOCs in gas phase
Unreacted SVOCs
International Centre for Indoor Environment And Energy

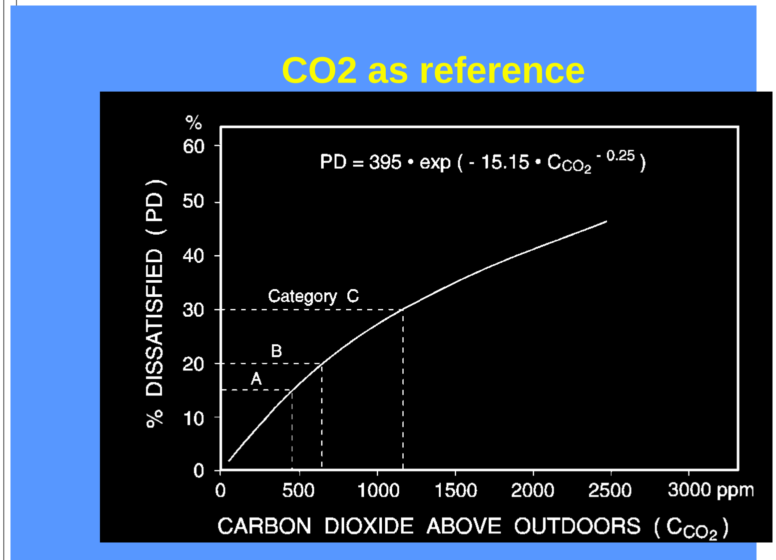

Photocatalytic Oxidation (PCO)
UV
H_2O
CO_2


Results: Bldg mat, PCs, filters
Purifier Off
Purifier On
Perceived air quality (decipol)
20
15
10
5
0
low (35 L/s)
intermediate (59 L/s)
Outdoor air supply rate

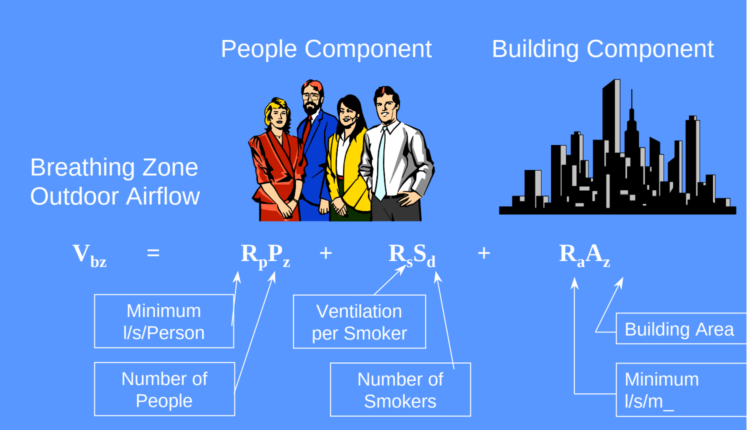

Results: Human bioeffluents
Purifier Off
Purifier On
Perceived air quality (decipol)
30
25
20
15
10
5
0
low (12 L/s)
intermediate (25 L/s)
Outdoor air supply rate



CO2 as reference



Concept for calculation of design ventilation rate



Recommended ventilation rates for non-residential buildings with default occupant density for three categories of pollution from the building itself.
If smoking is allowed the last column gives the additional required ventilation rate

Type of building or space	Category	Floor area m²/person	q_p	q_B	q_{tot}	q_B	q_{tot}	q_B	q_{tot}	smoking
			l/s, m² for occupancy	l/s,m² for very low polluted building		l/s,m² for low polluted building		l/s,m² for non-low polluted building		l/s,m²
Single office	A	10	1,0	0,5	1,5	1,0	2,0	2,0	3,0	0,7
	B	10	0,7	0,3	1,0	0,7	1,4	1,4	2,1	0,5
	C	10	0,4	0,2	0,6	0,4	0,8	0,8	1,2	0,3
Landscaped office	A	15	0,7	0,5	1,5	1,0	1,7	2,0	2,7	0,7
	B	15	0,5	0,3	1,0	0,7	1,2	1,4	1,9	0,5
	C	15	0,3	0,2	0,6	0,4	0,7	0,8	1,1	0,3
Conference room	A	2	5,0	0,5	1,5	1,0	6,0	2,0	7,0	5,0
	B	2	3,5	0,3	1,0	0,7	4,2	1,4	4,9	3,6
	C	2	2,0	0,2	0,6	0,4	2,4	0,8	2,8	2,0

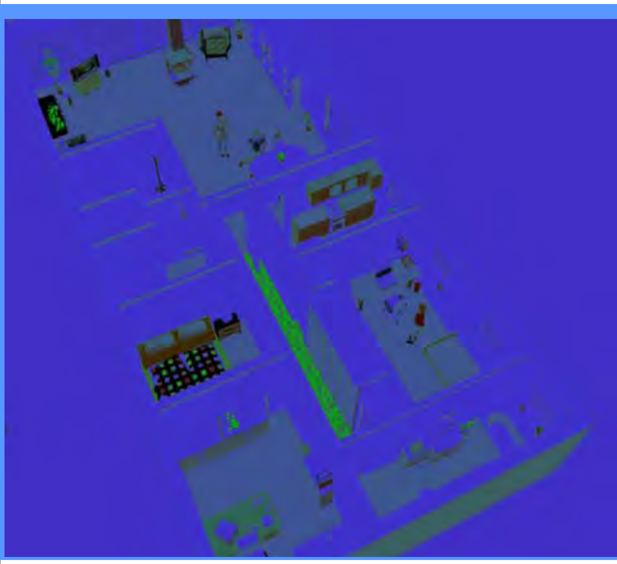
Type building/ space	Occupancy person/m²	Category CEN	Occupants only l/s person		Additional ventilation for building (add only one) l/s m²			Total l/s m²
			ASHRAE Rp	CEN	CEN low-polluting building	CEN *Non*-low-polluting building	ASHRAE Ra	CEN Low Pol.
Single office (cellular office)	0,1	A	2,5	10	1,0	2,0	0,3	2
		B		7	0,7	1,4		1,4
		C		4	0,4	0,8		0,8
Landscaped office	0,07	A	2,5	10	1,0	2,0	0,3	1,7
		B		7	0,7	1,4		1,2
		C		4	0,4	0,8		0,7
Conference room	0,5	A	2,5	10	1,0	2,0	0,3	6
		B		7	0,7	1,4		4,2
		C		4	0,4	0,8		2

1 l/s m² = 0.2 cfm/ft²

International Centre for Indoor Environment And Energy

Residential buildings

Category	Air change rate [1]		Living room and bedrooms, mainly outdoor air flow		Exhaust air flow, l/s		
	l/s,m² (1)	ach	l/s, pers[2] (2)	l/s/m² (3)	Kitchen (4a)	Bathrooms (4b)	To (4
I	0,49	0,7	10	1,4	28	20	14
II	0,42	0,6	7	1,0	20	15	10
III	0,35	0,5	4	0,6	14	10	7



Concentration of carbon dioxide measured in 12 locations within the house shown in Figure

Requirements for Residential Ventilation

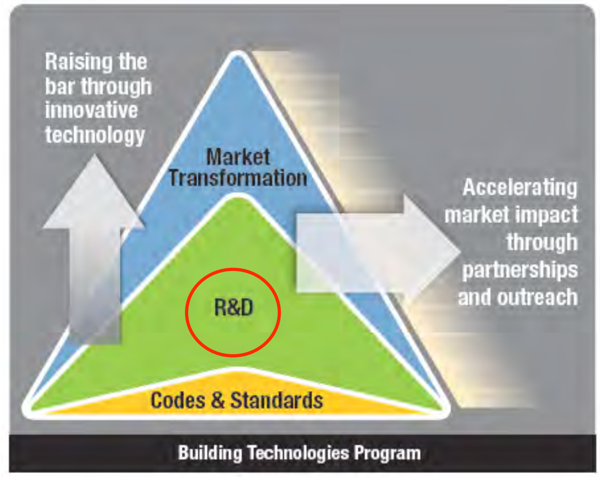
Dr. Ren Anderson, NREL

ASHRAE Winter Meeting
Ventilation Expert Meeting
January 26, 2007, Dallas, CA

Building America U.S. Department of Energy

NREL Research Funded in Part by USDOE

NREL is operated by Midwest Research Institute • Battelle



Cost Shared R&D Approach

Industry Teams and Partnerships

DOE Building America System Research

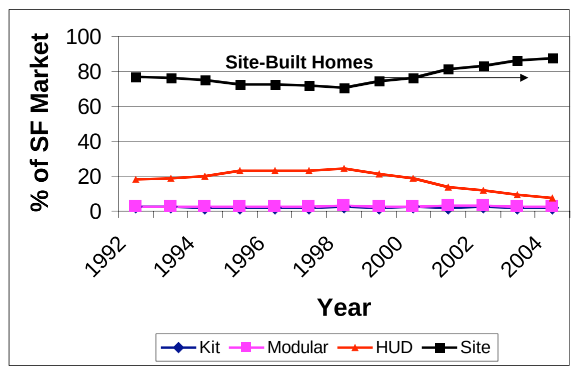
Team Members Include:

- Builders
- Material Suppliers
- Designers
- Developers
- Utilities
- Manufacturers

National Labs: Research Support

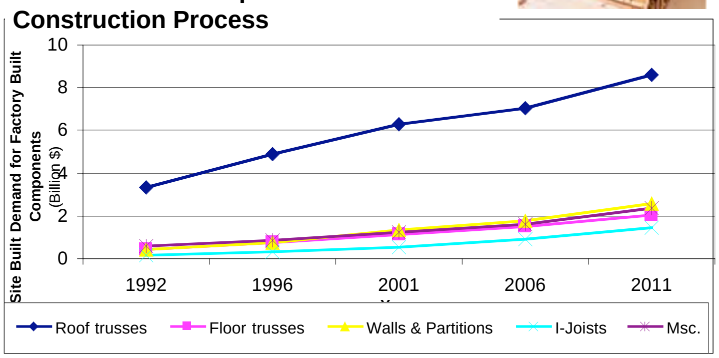
EEBA, Energy Star, Engineered for Life, ComfortWise, CEC, CEE Lighting for Tomorrow, SMUD, RESNET, NAHB and Others are Deployment Partners

Market Context:
Site Builders Currently Account for Nearly 90% of All New Homes Built in the US Each Year



U. S. Census Bureau, Residential Construction Characteristics

Market Context: Production Builders are Rapidly Shifting to the Use of Standardized, Pre-Manufactured Components to Reduce Onsite Labor and Speed the Construction Process



"The Factory Built Components Industry Is Almost as Large as the Softwood Lumber Industry", Al Schuler, **STRUCTURAL BUILDING COMPONENTS MAGAZINE, April 2003.**

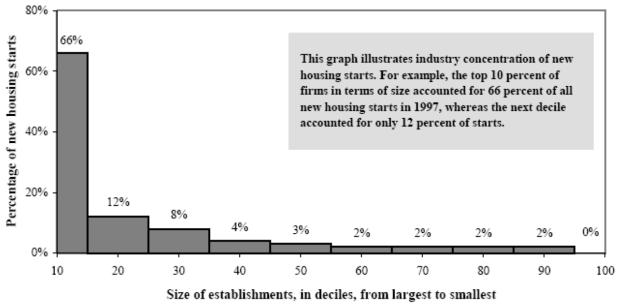
Residential construction is a highly automated process:

-A multi-step construction process that is managed across multiple homes, and

-"Just in Time" delivery of the systems, skills, and materials required for each step of the construction process

Production Building Techniques Have Standardized Construction Practices and Enabled Consolidation of the Homebuilding Industry:

The top 20% of Homebuilders Account for Over 78% of all of the Homes Built in the US Each Year



Source: Calculated from U.S. Census Bureau, 1997 Economic Census--Construction Sector Special Study, Housing Start Statistics (January 2000).

Review of Residential Ventilation Design Options

Packaged System ?

Custom Design ?

The Winner is:
"Packaged" System.
Simplest Approach.
No Site Assembly or Extra Construction Steps Required

Simplifications Provided by This Approach:
-System Will Work Independently of Individual House Geometry
-System Does Not Require Case by Case Engineering Design

Packaged System

No Source Control?

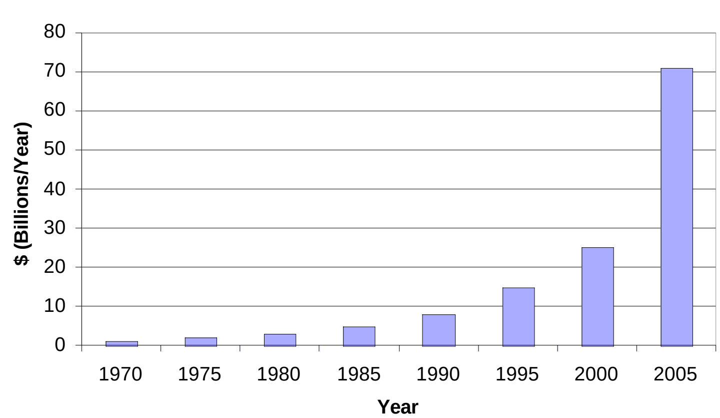
Source Control?

Builders and Contractors Tend to Embrace Changes That:

- Reduce risks,
- Reduce costs,
- Reduce complaints,
- Reduce training requirements
- Increase the reliability of suppliers, materials and equipment, and
- Reduce planning steps or approvals

Risk Minimization is a Residential Design Requirement

US Catastrophic Insurance Losses



Packaged System With Source Control

↓

<u>Best Practice Recommendations</u>:
-Local bath and kitchen exhaust
-Install radon mitigation in high risk areas
-Use closed combustion appliances
-Use low emission materials and furnishings
-Remove materials with known risks from consumer products used in homes
-Support research on risks of <u>total</u> exposures to air contaminants

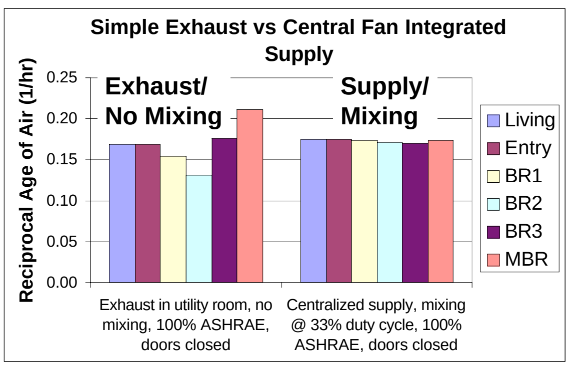
<u>Benefits of This Approach:</u>
-Overall risks are minimized; reliability is increased; simple, low cost, standard practice solutions are possible
-IAQ control decoupled from ventilation
-Ventilation rate determined primarily by odor and comfort control
-Easily controlled and understood by occupants
-IAQ sensors not required
-Air treatment not required

Packaged System With Source Control

↓

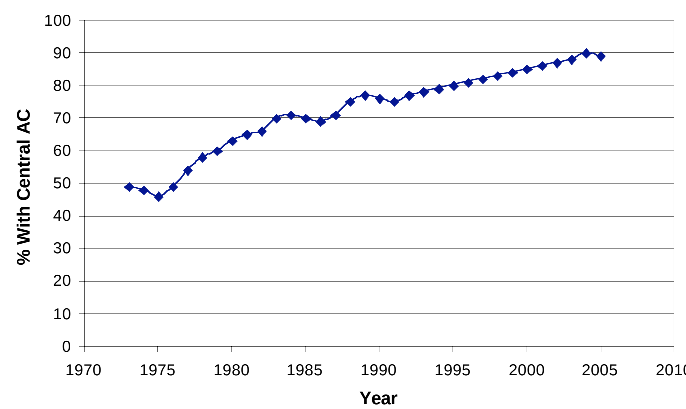
Mixed System? | **Unmixed System?**

Evaluation of Distribution Performance



Evaluation of Uniformity of Distribution of Outside Air, NREL Test Method

US Homebuyers Have Already Made This Decision!



Packaged System With Source Control And Mixing

↓

<u>Best Practice Recommendations</u>:
-Use low resistance duct designs, efficient air handlers, high EER AC, efficient furnaces
-Operate air handler on 20-30% duty cycle during periods with low sensible loads

<u>Benefits of This Approach:</u>
-Directly applicable to 90% of US market
-Solution meets requirements for use by production builders
-Provides uniform comfort and uniform ventilation air distribution

Final Reality Check: Compatible with Residential Requirements?

Level 1- <u>**Meets Minimum Residential Performance Requirements**</u>:
Technology meets minimum availability, reliability, O&M and durability requirements and provides high potential value to builders, contractors, and homeowners.

Reality Check: Compatible with Residential Requirements?

Level 1- <u>Meets Minimum Residential Performance Requirements</u>:
Technology meets minimum availability, reliability, O&M and durability requirements and provides high potential value to builders, contractors, and homeowners.

Level 2- <u>Can Be Integrated with the Residential Construction Process</u>:
Best practice design details and construction sequencing are known and accepted by builders, contractors, and local code officials. Costs and benefits have been validated based on construction of one or more pilot homes.

Level 1- <u>Meets Minimum Residential Performance Requirements</u>:
Technology meets minimum availability, reliability, O&M and durability requirements and provides high potential value to builders, contractors, and homeowners.

Level 2- <u>Can Be Integrated with the Residential Construction Process</u>:
Best practice design details and construction sequencing are known and accepted by builders, contractors, and local code officials. Costs and benefits have been validated based on construction of one or more pilot homes.

Level 3- <u>Can Be Built on a Production Basis</u>:
Quality assurance requirements, quality control requirements, and training requirements are understood and individual responsibilities are accepted by suppliers, builders and subcontractors.

Conclusions:

Homes are not high end commercial, industrial, or laboratory buildings

- **Limited custom engineering**
- **Limited custom design**
- **Limited commissioning**
- **No sophisticated controls or sensors**
- **No operating engineers**
- **Limited maintenance**

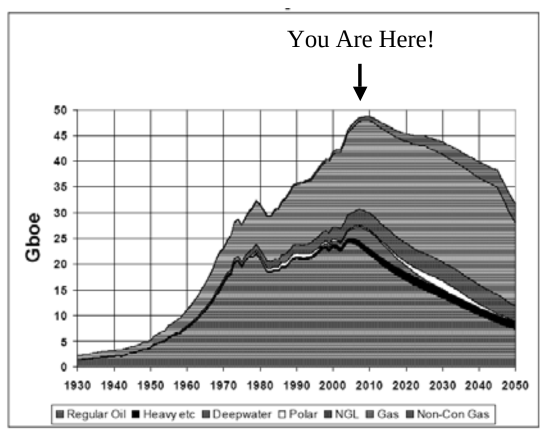
Therefore, while there are certainly lots of possible ventilation approaches that could work,

There is only one approach that is compatible with broad US market needs and also provides predictable, uniform performance that is independent of individual home geometry:

Central exhaust or supply with mixing and best practice source control.**

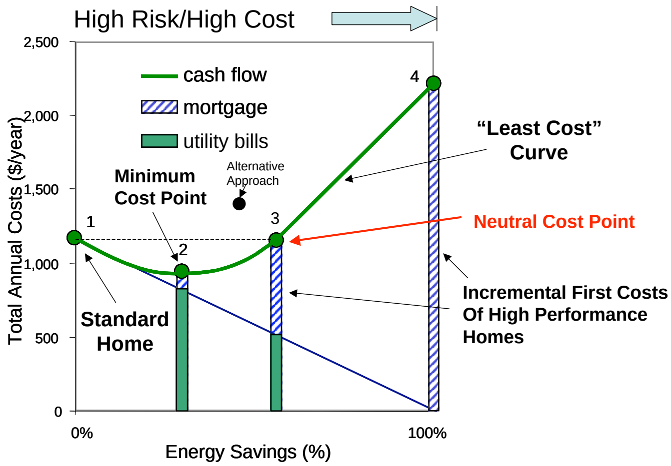
****Note. This problem can also be solved using more complicated approaches.**

Global Context: Resources are Constrained Efficient Resource Use is a Design Requirement



The Association for the Study of Peak Oil and Gas, October 2005 Newsletter, www.peakoil.ie

Overall Homeowner Costs vs. Benefits



Please see our website at:
www.buildingamerica.gov

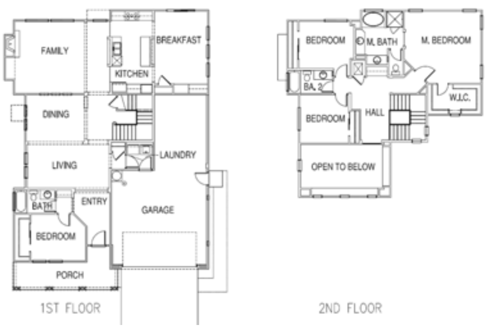
Ren_Anderson@nrel.gov
NREL
1617 Cole Blvd
Golden, Colorado 80401

Field Measurements and Simulations

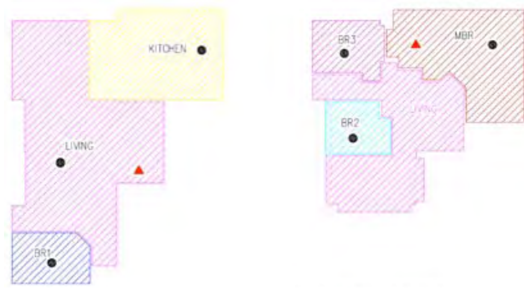
Ventilation Experts Meeting
Aaron Townsend
January 26, 2007

- Tracer gas test of production Building America house in Sacramento
- 2-story, 4 bedrooms, ~2500 square feet
- ELA = 2.5 square inches per 100 square feet
- January 2006

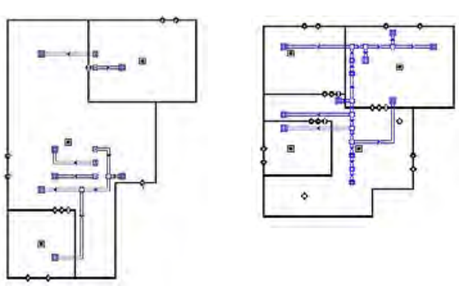
Floor Plan



Zones

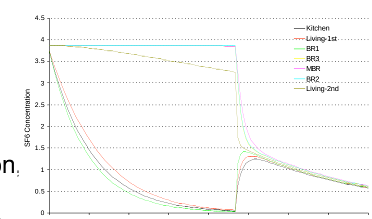


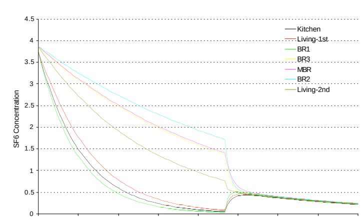
CONTAM Model



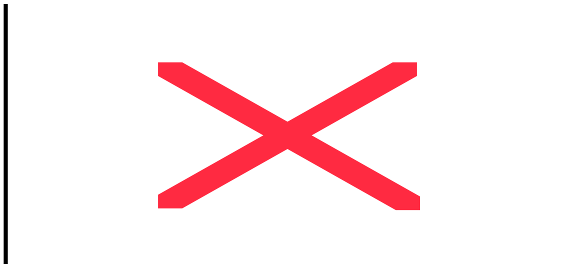
Results of the model very sensitive to certain inputs:

- Number, location, and size of leakage paths in each room
- Vertical elevation of leakage paths critical
- Indoor and outdoor temperatures

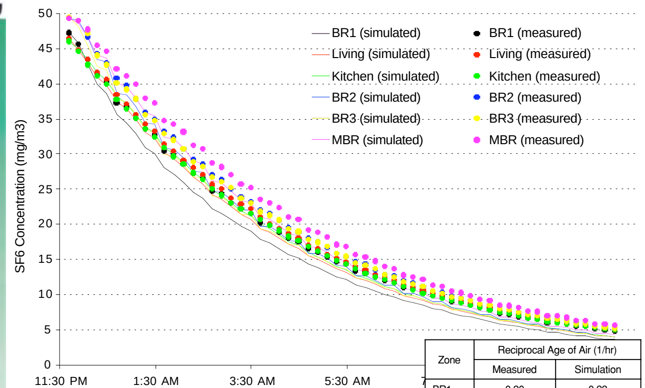




- Wind was neglected
  - Relatively low speed (0-4 mph)
  - Direction was not recorded
  - Uncertainty in wind pressure coefficient values and shielding by neighboring houses
- Results show good agreement with measured data

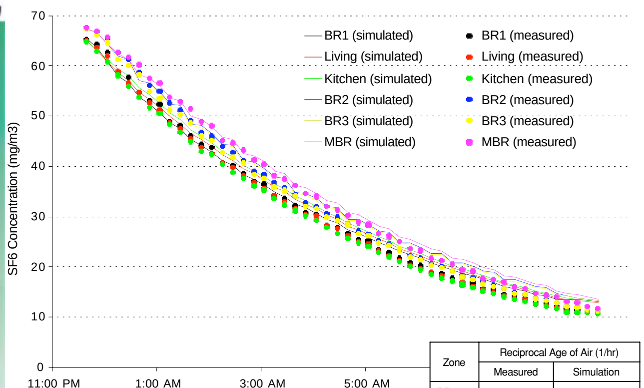


CFI, 100% of 62.2 Rate, Doors Closed, Transfer Grills Open



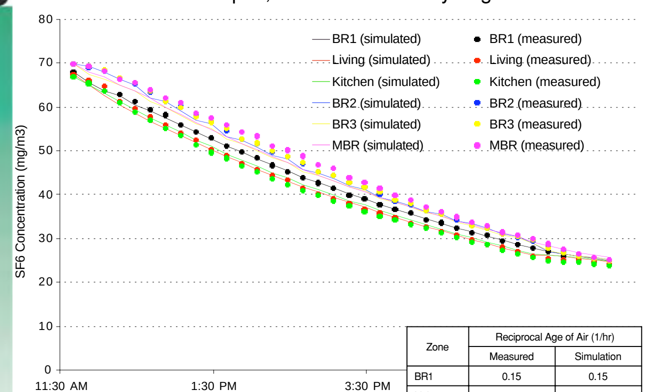
Zone	Reciprocal Age of Air (1/hr)	
	Measured	Simulation
BR1	0.20	0.23
Living	0.19	0.22
Kitchen	0.20	0.21
BR2	0.20	0.22
BR3	0.20	0.22
MBR	0.19	0.21

CFI, 60% of 62.2 Rate, Doors Closed, Transfer Grills Closed



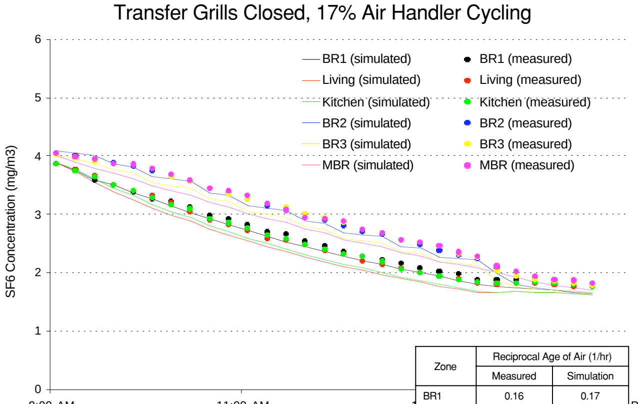
Zone	Reciprocal Age of Air (1/hr)	
	Measured	Simulation
BR1	0.19	0.17
Living	0.19	0.17
Kitchen	0.19	0.17
BR2	0.19	0.17
BR3	0.19	0.17
MBR	0.18	0.16

Laundry Exhaust, 100% of 62.2 Rate, Doors Closed, Transfer Grills Open, 33% Air Handler Cycling



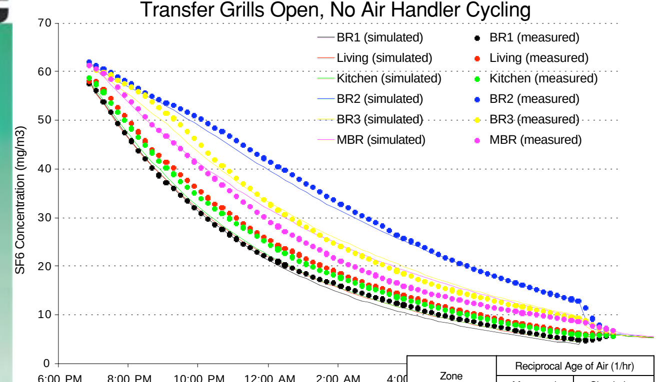
Zone	Reciprocal Age of Air (1/hr)	
	Measured	Simulation
BR1	0.15	0.15
Living	0.16	0.15
Kitchen	0.16	0.15
BR2	0.15	0.15
BR3	0.15	0.15
MBR	0.14	0.15

Laundry Exhaust, 100% of 62.2 Rate, Doors Closed, Transfer Grills Closed, 17% Air Handler Cycling



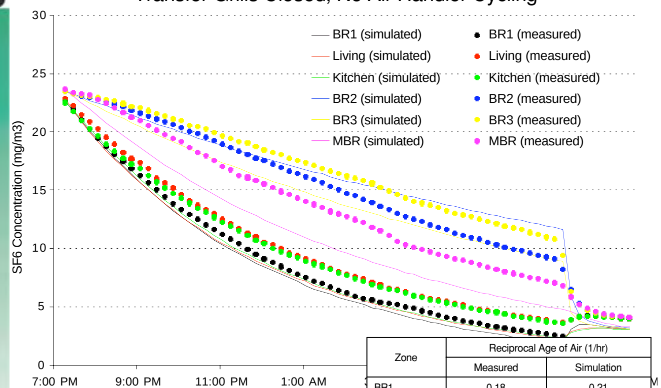
Zone	Reciprocal Age of Air (1/hr)	
	Measured	Simulation
BR1	0.16	0.17
Living	0.17	0.19
Kitchen	0.17	0.19
BR2	0.13	0.14
BR3	0.13	0.14
MBR	0.13	0.15

Laundry Exhaust, 100% of 62.2 Rate, Doors Closed, Transfer Grills Open, No Air Handler Cycling



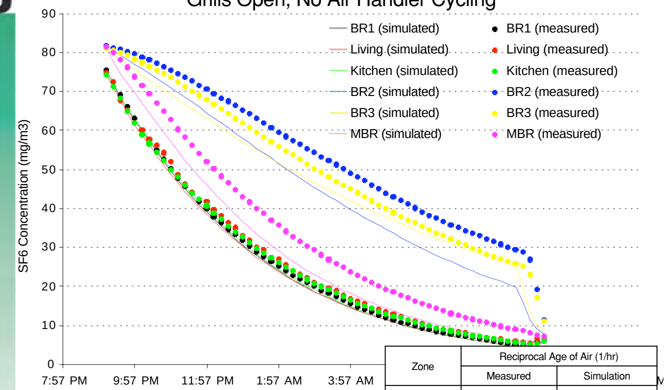
Zone	Reciprocal Age of Air (1/hr)	
	Measured	Simulation
BR1	0.18	0.19
Living	0.16	0.18
Kitchen	0.16	0.18
BR2	0.11	0.11
BR3	0.13	0.13
MBR	0.14	0.13

Laundry Exhaust, 100% of 62.2 Rate, Doors Closed, Transfer Grills Closed, No Air Handler Cycling



Zone	Reciprocal Age of Air (1/hr)	
	Measured	Simulation
BR1	0.18	0.21
Living	0.15	0.19
Kitchen	0.15	0.19
BR2	0.08	0.06
BR3	0.07	0.08
MBR	0.10	0.13

Master Bath Exhaust, 100% of 62.2 Rate, Doors Closed, Transfer Grills Open, No Air Handler Cycling



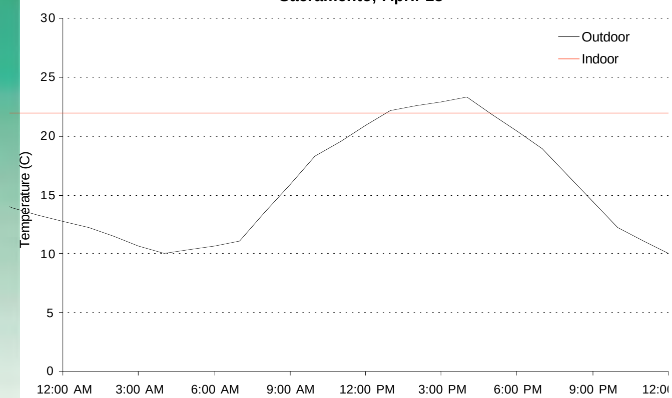
Zone	Reciprocal Age of Air (1/hr)	
	Measured	Simulation
BR1	0.24	0.25
Living	0.22	0.25
Kitchen	0.23	0.24
BR2	0.09	0.12
BR3	0.10	0.10
MBR	0.19	0.23

Extension to Other Systems

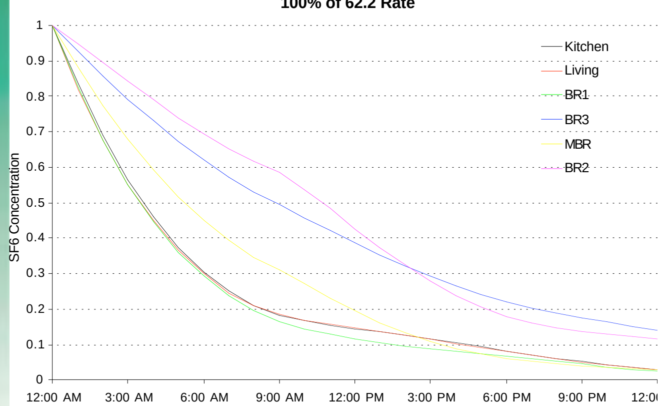
Six Systems Evaluated & Compared:

1. Exhaust ventilation, without central duct system
2. Supply ventilation, without central duct system
3. Exhaust ventilation, with central ducts, AHU controlled by standard thermostat
4. Exhaust ventilation, with central ducts, AHU controlled by thermostat with timer
5. Supply ventilation, with central ducts, AHU controlled by thermostat with timer
6. Fully ducted balanced ventilation system, without central duct system

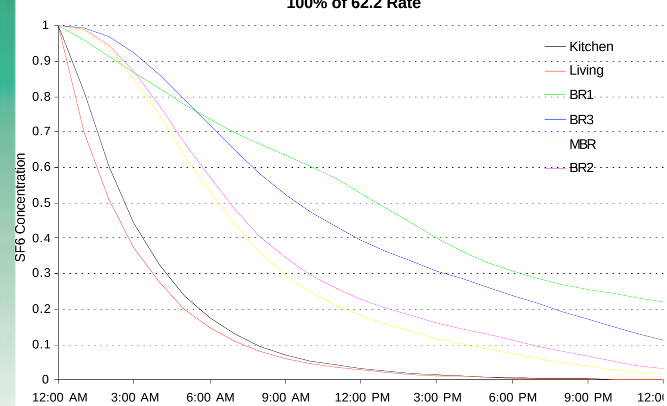
Indoor and Outdoor Temperature
Sacramento, April 13

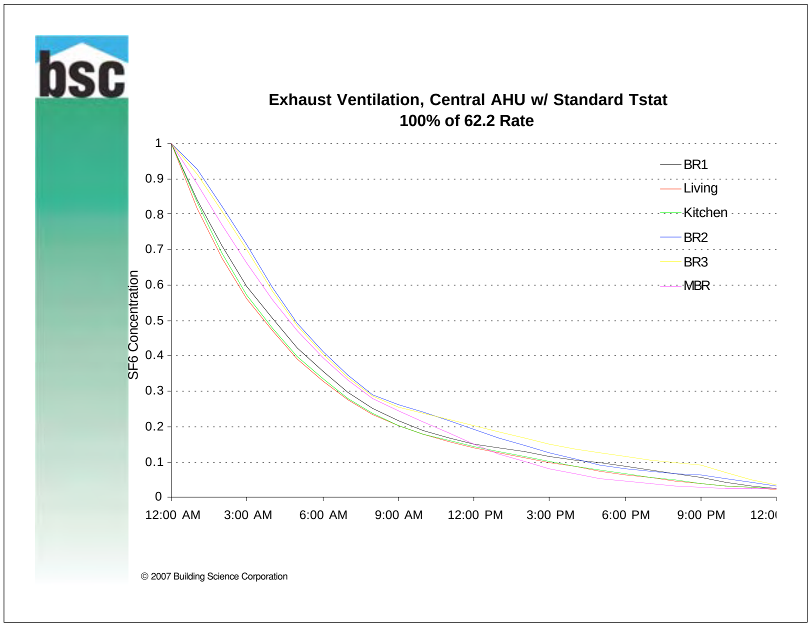


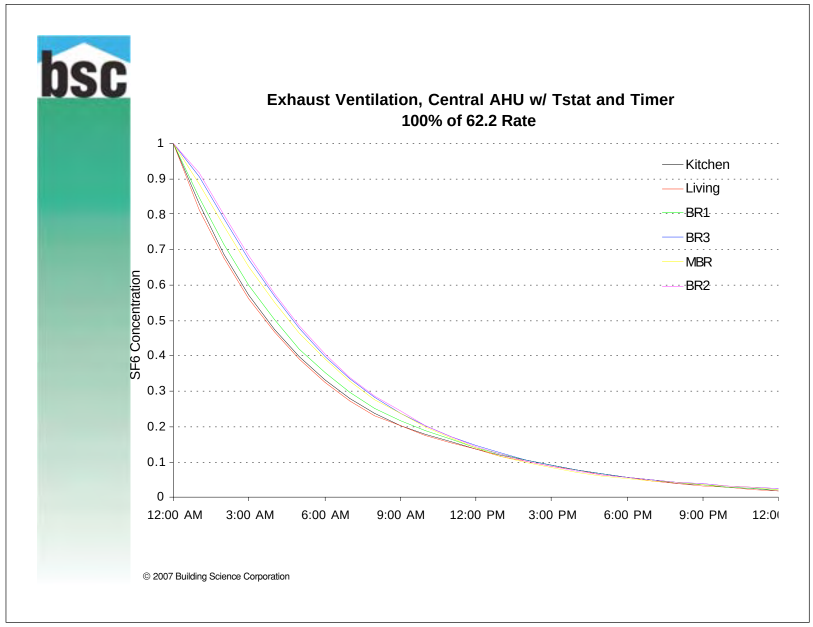
Exhaust Ventilation, No Central System
100% of 62.2 Rate

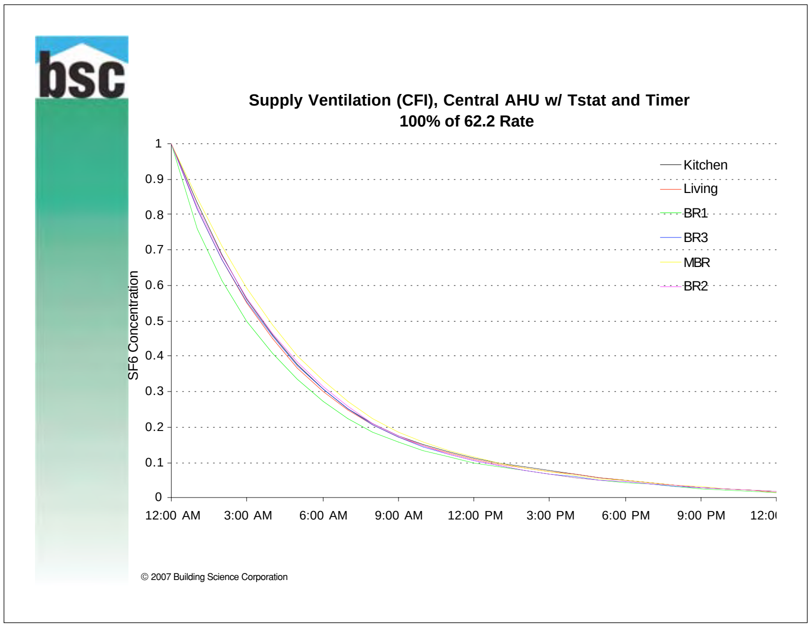


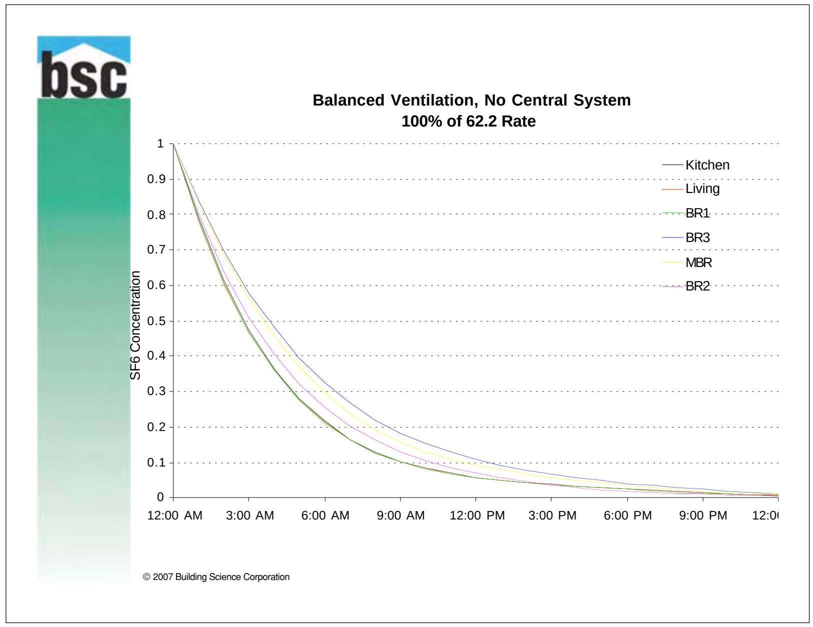
Supply Ventilation, No Central System
100% of 62.2 Rate




Exhaust Ventilation, Central AHU w/ Standard Tstat
100% of 62.2 Rate
SF6 Concentration
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
12:00 AM
3:00 AM
6:00 AM
9:00 AM
12:00 PM
3:00 PM
6:00 PM
9:00 PM
BR1
Living
Kitchen
BR2
BR3
MBR
© 2007 Building Science Corporation


Exhaust Ventilation, Central AHU w/ Tstat and Timer
100% of 62.2 Rate
SF6 Concentration
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
12:00 AM
3:00 AM
6:00 AM
9:00 AM
12:00 PM
3:00 PM
6:00 PM
9:00 PM
Kitchen
Living
BR1
BR3
MBR
BR2
© 2007 Building Science Corporation


Supply Ventilation (CFI), Central AHU w/ Tstat and Timer
100% of 62.2 Rate
SF6 Concentration
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
12:00 AM
3:00 AM
6:00 AM
9:00 AM
12:00 PM
3:00 PM
6:00 PM
9:00 PM
Kitchen
Living
BR1
BR3
MBR
BR2
© 2007 Building Science Corporation


Balanced Ventilation, No Central System
100% of 62.2 Rate
SF6 Concentration
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
12:00 AM
3:00 AM
6:00 AM
9:00 AM
12:00 PM
3:00 PM
6:00 PM
9:00 PM
Kitchen
Living
BR1
BR3
MBR
BR2
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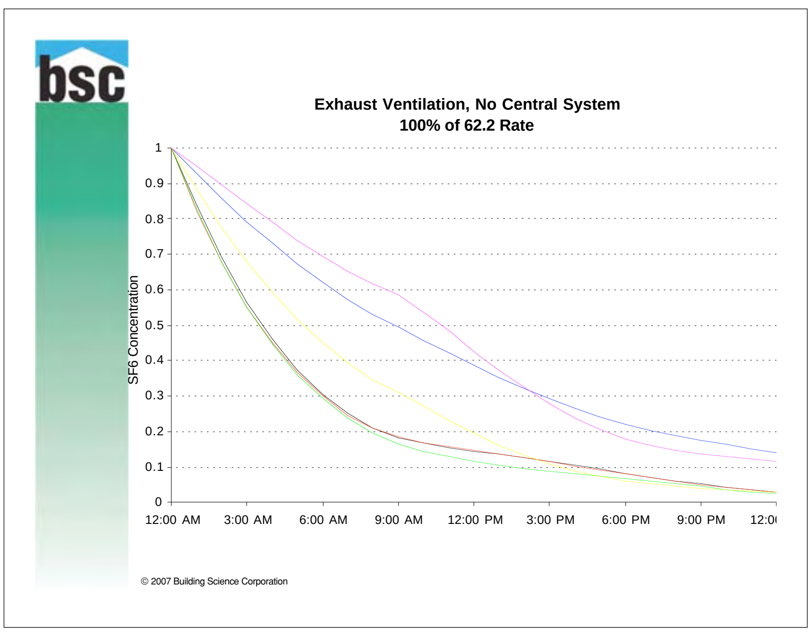
Exhaust Ventilation, No Central System
100% of 62.2 Rate
SF6 Concentration
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
12:00 AM
3:00 AM
6:00 AM
9:00 AM
12:00 PM
3:00 PM
6:00 PM
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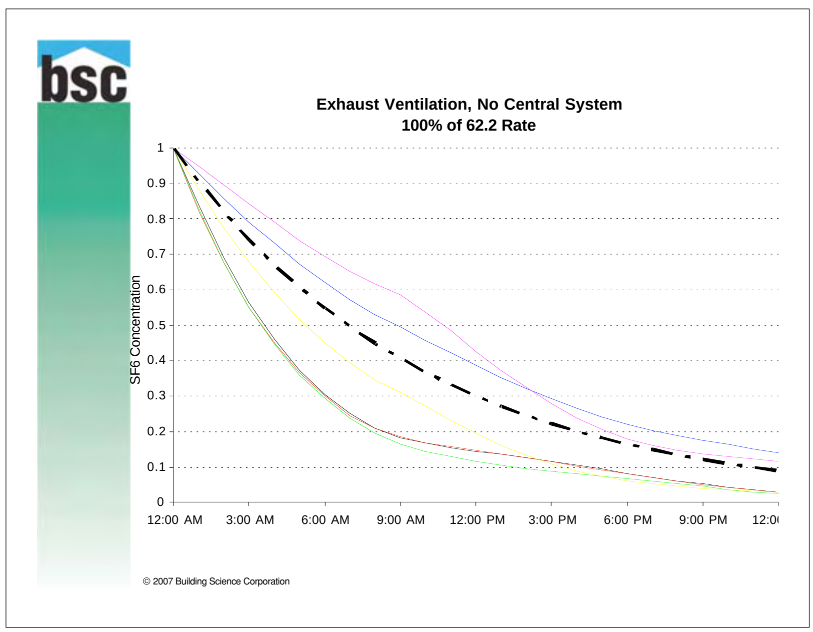
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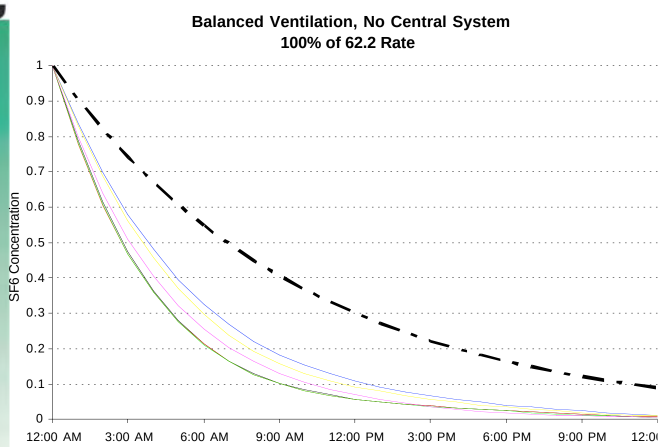

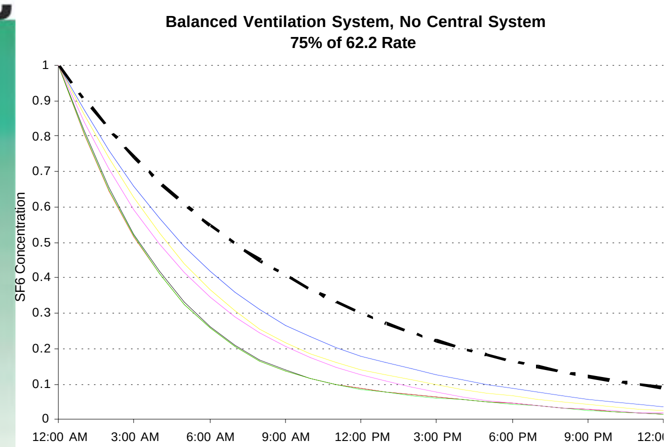

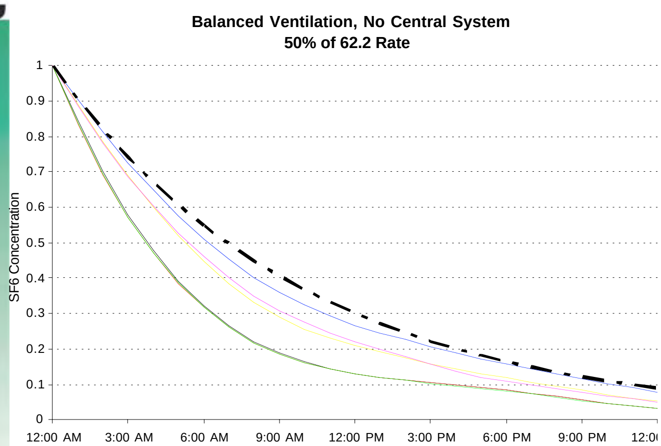

Coefficient of Distribution (C_D)

1. Exhaust ventilation, without central duct system C_D=1.25
2. Supply ventilation, without central duct system C_D=1.25
3. Exhaust ventilation, with central ducts, AHU controlled by standard thermostat C_D=1
4. Exhaust ventilation, with central ducts, AHU controlled by thermostat with timer C_D=0.75
5. Supply ventilation, with central ducts, AHU controlled by thermostat with timer C_D=0.75
6. Fully ducted balanced ventilation system, without central duct system C_D=0.5

2.18.3. June 2007 Expert Meeting Summary Report

SYSTEMS ENGINEERING APPROACH TO DEVELOPMENT OF ADVANCED RESIDENTIAL BUILDINGS

13.B.3 Final Expert Meeting Summary: Ventilation Effectiveness In Residential Systems

RE: TASK ORDER NO. **KAAX-3-32443-13**
UNDER
TASK ORDERING AGREEMENT NO. **KAAX-3-32443-10**

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U. S. GREENFIBER, LLC
TAMLYN
RESEARCH PRODUCTS CORPORATION/APRILAIRE

August 4, 2007

INTRODUCTION

The Building Science Consortium held two Expert Meetings on Ventilation Air Distribution Effectiveness in Residential Systems on 26 January 2007 at the Adam's Mark Hotel in Dallas, Texas, and on 21 June at the Renaissance Hotel in Long Beach, California. Both expert meetings were held immediately before the ASHRAE SSPC 62.2 meetings in advance of the ASHRAE technical program in order to make it easier for experts who had already traveled there to participate. There were 32 in attendance. Invited speakers gave presentations in their particular area of expertise. The presentations were followed by discussion with the expert audience.

The final agendas for these meetings are listed in Appendix A1 and A2.. A list of attendees for the first meeting is given in Appendix B.

A summary of the individual presentations and major discussion points is provided in the sections below.

26 January 2007
PRESENTATIONS

Speaker 1: Max Sherman, Lawrence Berkeley National Laboratory

Presenter bio: Max Sherman, Ph.D, is Group Leader of the Energy Performance of Buildings Group at LBNL. He is an ASHRAE Fellow and a long-time recognized expert in the field of indoor air.

Presentation Title: *Development of Metrics for Ventilation Distribution*

Presentation Summary:

In order to add ventilation air distribution to ASHRAE Standard 62.2 we need an appropriate metric to evaluate and compare different systems on the basis of acceptable air quality and health. The metric must be both useful and measurable. Evaluation and comparison could be by simulation or measurement or both. The metric should limit damage caused by contaminants of concern to which people are exposed over some time period. The damage may be a negative effect on comfort or health. Effects on comfort may include unpleasant odors and irritation which are covered by 62.2, and acoustics and thermal which are not covered by 62.2. Effects on health may include reduced physiological functioning, tissue damage, and increased susceptibility to disease.

To put this in perspective, whole-house ventilation does not address acute mortality or morbidity. For example, Standard 62.2 ventilation will not control for a release of phosgene gas. Standard 62.2 does intend to control for a reduction in life-expectancy, e.g. carcinogenesis, mutagenesis, and toxic loads. Standard 62.2 also intends to control for reduction in quality of life, e.g. hours of discomfort and minor disease.

An IAQ metric can focus on the peak concentration of a contaminant or the average concentration. For peak concentration the focus is on short-term dose and it is good for evaluating high exposure levels/acute effects and threshold-dominated contaminants. For average concentration the focus is on long-term dose and is good for cumulative exposures and steady exposures above thresholds. For the purposes of whole-house ventilation in the context of 62.2, the metric should be long-term average concentration, or dose. The contaminants of concern that we expect to control with whole-house ventilation must be above thresholds to be "of concern". Highly variable emission rates are not well controlled by whole-house ventilation and need source control by local exhaust.

Air distribution is only relevant when we are NOT working with a single well-mixed zone. A matrix formulation of the continuity equation allows for multiple zones where we can assume that each zone is individually well mixed. A local zonal matrix equation was described for a matrix of air flows, independent contaminant sources, and zonal concentrations. For psuedo-steady state conditions, the matrix inverse represents averages.

With dose as the IAQ metric, an activity variable is defined acknowledging that a person can only be in one zone at a time, a source fraction for each zone is defined since source strength may vary zonally, and since distribution impacts of different ventilation systems are relative, a relative dose versus perfect mixing is defined. The metric can be used to adjust the total ventilation rate by a ratio to increase or decrease it depending on the ventilation system.

The best and worst cases of the metric will be when the contaminant of concern is emitted in a single zone. The worst case, represented by the highest value in the matrix, represents the case where contaminants are generated in a single zone and someone stays in that same zone. The best case, represented by the lowest value in the matrix, represents the case where someone stays in the zone most isolated from the zone where contaminants are generated.

The range of metric options is as follows, with example ratios that would increase the ventilation flow rate to show equivalent performance to perfect mixing:

1. Evenly distributed sources and activities (ratio=1.06). In this case, the effect of ventilation air distribution would be minimal because there is no concentrated contaminant generation and people keep moving around all the time, so their exposure is smoothed or averaged. This would not represent sleeping in the same room overnight, for example.
2. Evenly distributed sources, but someone stays in the worst zone (1.26), such as sleeping in the least ventilated zone overnight.
3. If we have no clue on activity patterns or source distributions, we can measure the "distance" from perfect mixing using RMS deviation (1.80).
4. The worst ventilated zone is also where the highest source generation is and someone stays there (2.63). While this is certainly possible, this may be too extreme to be appropriate for a minimum standard.

Unless you can measure the metric it will be worthless. Direct field measurement can give the response in actual constructed configurations. This can only be done with tracer gas. Simulations are more practical and allow parametrics, but they must be verified by direct measurement to be believable.

A simplified or complete characterization tracer gas measurement method can be used. The simplified method requires that a reference source pattern and a reference activity pattern be established for a metric of choice (for example 1 through 4 above). The complete characterization method measures all flows to and from each zone. That can be used to compare different metrics, verify simulations, and derive a simplified approach.

Three measurement approaches are as follows:

1. Time Series, Single-tracer, Non-steady State: A single tracer gas is injected and uniformly mixed throughout all zones, then the time series tracer gas decay data are fit over the changing conditions to solve the differential equation.
2. Series, Single-tracer, Steady-state Tests: Multiple steady-state (constant injection) tests are done with a single tracer gas, in multiple zones, but only in one zone at a time. A single tracer is injected in a single zone and the response is measured in all zones.
3. Parallel, Multi-tracer, Steady-state Tests: Simultaneous steady-state tests are conducted with multiple tracer gases. A different tracer is injected into each zone simultaneously and the responses of all tracers are measured in all zones.

The Multi-Tracer Monitoring System developed at LBNL uses the third approach. Measurement of possible metrics in real buildings for various real systems are being planned for this year. This will be a collaboration between LBNL and Building Science Corp, under Building America.

Post-presentation discussion:

What defines a zone? There is no definition. It could be based on area, door closure, air handler service, or other factors. General consensus was to start by defining a zone to be any room that can be closed off with a door (except bathrooms and laundry) and the common area of each floor level.

Are the coefficients (ratios) independent of building/room geometry and duct layout? Unknown.

Standard 62.2 assumed continuous ventilation fan operation with uniformly distributed sources and occupants in a single well-mixed zone. Door closure, intermittent ventilation fan operation, and intermittent mixing via central air handler operation will give different answers than are currently built into 62.2.

Will temperature difference between rooms and floors make a difference? Thermal buoyancy will matter, but building enclosure leakiness will matter more.

Speaker 2: Bjarne Olesen, International Center for Indoor Environment and Energy, Technical University of Denmark

Presenter bio: Bjarne Olesen, Ph.D., is Professor at the International Centre for Indoor Environment and Energy. He has more than 30 years experience from University and Industry in research on the impact of the indoor environment on people, energy performance of buildings, and HVAC-systems. He has obtain several ASHRAE awards including the Ralph Nevins Award (1982), Distinguished Service Award (1997), Fellow Award (2001), and Exceptional Service Award. He is active in several ASHRAE-CEN-ISO-DIN standard committees regarding indoor environment and energy performance of HVAC systems. He has published more than 250 papers including more than 40 in peer reviewed journals.

Presentation Title: *Exposure and Risk*

Presentation Summary:

The highest human exposure to air contaminants is in the indoor environment. People spend about 90% of the time indoors including work, transportation, and at home. Over 50% of their relative exposure to air in a normal lifetime is in the dwelling.

In developing regions 5,000 persons die per day due to poor indoor air quality (WHO). In several industrial countries 50% of school children are suffering from Asthma or Allergy. This number has doubled within the last 20 years. Trends for the prevalence of allergic rhinitis, asthma and eczema among male conscripts (17-20 years age) in Sweden have continually increased from 1952 to 1981 (Bråbäck et al., 2004).

A large study looked at the relationship between asthma and indoor air quality. There were 11,000 children studied from 200 single-family houses with children suffering from asthma and from 200 single-family houses with healthy children. Detailed chemical, physical, biological and medical measurements were made. It was found that the likelihood (odds ratio) of having at least two out of three symptoms (wheezing, rhinitis, eczema) went continually down as ventilation rate increased from 0.17 air changes per hour (ach) to 0.62 ach (Bornehag et al., 2003). Houses that had a detectible bad odor had the highest prevalence of asthma, indicating that a person's sense of smell can be a good detector of some indoor air conditions that are bad for them. It was previously thought that the prevalence of asthma was higher in western Europe than in eastern Europe, but it was found that the prevalence was about the same in both.

Water condensation on windows is often a sign of poor ventilation in dwellings. Observation of condensation on bedroom window panes increased the prevalence and odds ratio for rhinitis among children (DBH-study group). The prevalence of rhinitis increases with the presence of PVC materials and with floor dampness in dwellings. The prevalence of asthma, rhinitis, and eczema goes up with increased mold odor smelled at wall baseboards (Hägerhed-Engman et al., 2005). Good ventilation should at least eliminate condensation on windows and bad odors.

Allergies are increasing also. Up to 50% of children have or have had symptoms of allergic disease. In Sweden, this is more so in the north. In Europe, this is more so in the west. In the USA, this is more so among the poor. This is more so in countries that speak English (UK, New Zeeland, Australia). There is also a high prevalence in Peru. The role of indoor air in this is mostly unknown. There are essentially no studies in residential buildings that establish the background of pollutants without people activities.

Indoor chemistry can influence the kind and concentration of organic chemicals in indoor air. Ozone reacts readily with other chemicals and creates fine particles in the air. Reactions between ozone and limonene are especially important. Fortunately that reaction has a higher odor effect, making it easier to detect by smell. Primary ozone sources are: outdoor to indoor transport; photocopiers; laser printers; and ozone generators. Indoor levels of ozone are normally lower than outdoor, but there are large outdoor variations with time of day, day of week, and season.

Indoor chemistry is most likely to happen when:

- indoor ozone levels are elevated (oxidation)
- humidity is elevated (hydrolysis)
- temperatures are elevated
- ventilation rates are low (gas phase)
- terpene levels are high
- surfaces are "dirty"

A new desktop computer emits enough pollutant to equal three people. That diminishes over the first year. The flame retardant used on CRT monitors is the most offending. Flat panel monitors are much better. The presence of computers can have a large negative impact on the perception of indoor air quality in offices.

A study of the effect of air filtration on perceived air quality (based on smell) was conducted. Fiber or cloth media type filters were observed to lower a person's perception of air quality. As the particle concentration in the airstream went down after the filter, the percentage dissatisfied went up. In other words, the air smelled better before it went through the filter. The reason was determined to be that unreacted SVOC's sorbed on particles on the filter react with ozone and become oxidized SVOC's with higher odor detection. Air treated by photocatalytic (UV) air cleaners was perceived to be better if the chemical loading was low, but worse if the chemical loading was high.

When designing for ventilation flow rate, you need to decide whether you are designing for adapted occupants in a space or for unadapted visitors to the space. There can be a three times factor difference between the answers. There should be a people component and a building component to the ventilation rate. The building component is still being worked on for commercial buildings where there is more measured data and more consensus than there is for residential buildings. Classes of buildings were proposed as: very low polluted, low polluted, and non-polluted. The typical ventilation rate in dwellings in Denmark is 0.5 air changes per hour. It is important to get ventilation air to the sleeping rooms since they have the highest pollutant levels all night.

Speaker 3: Ren Anderson, National Renewable Energy Laboratory

Presenter bio: Ren Anderson, Ph.D, is Residential Section Leader at NREL. At NREL since 1983, he has been involved the development of advanced window coatings, building energy design tools, advanced desiccant cooling and heat recovery systems, BCHP (Building Cooling, Heating, and Power) systems, and residential ventilation systems. Ren is currently working on the development of least cost approaches to the design of zero energy homes and is providing training on sustainable construction techniques for reconstruction of homes in disaster areas.

Presentation Title: *Performance Requirements for Residential Ventilation Systems*

Presentation Summary:

The Building America approach is one of raising the bar through innovative technology. Market transformation is supported by research and development which leads codes and standards. The market impact is accelerated by industry partnerships and educational outreach.

Site builders currently account for nearly 90% of all new homes built in the U.S. 80% of the homes are built by 20% of the builders. Production builders are rapidly shifting to the use of standardized, pre-manufactured components to reduce onsite labor and speed the construction process.

When it comes to ventilation, packaged systems will win over custom designs. Packaged systems are the simplest approach, with no site assembly or extra construction steps required. The successful packaged system should work Independently of individual house geometry and not require case-by-case engineering design. Source control in combination with the packaged ventilation system is the best way to minimize risk, which is a residential design requirement. Builders and contractors tend to embrace changes that:

- Reduce risks,
- Reduce costs,
- Reduce complaints,
- Reduce training requirements
- Increase the reliability of suppliers, materials and equipment, and
- Reduce planning steps or approvals

Best Practice recommendations for the source control side are:

- Local bath and kitchen exhaust
- Install radon mitigation in high risk areas
- Use closed combustion appliances
- Use low emission materials and furnishings
- Remove materials with known risks from consumer products used in homes
- Support research on risks of total exposures to air contaminants

A primary benefit of this approach is that IAQ control decoupled from ventilation. Source control takes care of the IAQ health concerns and ventilation with mixing takes care of odor and comfort control. The whole-house ventilation rate can then be determined primarily by odor and comfort. With this approach, overall risks are minimized, reliability is increased, simple low-cost standard-practice solutions are possible, the system is easily controlled and understood by occupants, and IAQ sensors and air treatment are not required.

Using a previously presented tracer gas measurement and analysis approach to evaluate the uniformity of outside air distribution performance, the clear benefit of ventilation with central system mixing versus simple exhaust has been shown. It appears that the U.S. market has already figured that out – 90% of new U.S. homes have central heating and cooling systems.

Best Practice recommendations for the packaged ventilation system side are:

- Use low resistance duct designs, efficient air handlers, high EER AC, efficient furnaces
- Operate air handler on 20-30% duty cycle during periods with low loads

Primary benefits of this approach are that it is directly applicable to 90% of the U.S. market, it is a solution that meets requirements for wide use by production builders, and it provides uniform comfort at the same time that it provides uniform ventilation air distribution.

Post presentation discussion:

Why do people buy central air conditioning? Is it for the uniformity of air distribution or do the builders make that choice for them? Builders provide what people expect.

Higher Building America savings goals may lead toward getting away from central forced air systems.

What about running the fan on low speed all the time? That has a dramatic negative effect on moisture control in humid climates as the wet cooling coil is constantly dried off again after cooling cycles.

How do you size the outside air duct if the central air handler operates at different speeds? If necessary, that can be handled as it is in commercial buildings with a modulating damper and outside air duct pressure control.

Speaker 4: Aaron Townsend, Building Science Corporation

Presenter bio: Aaron Townsend is an Associate with Building Science Consulting. He holds a bachelor's degree in mechanical engineering from the University of Texas and a master's degree in mechanical engineering from Stanford University. His work focuses on all aspects of energy efficiency, building durability, and indoor air quality.

Presentation Title: *Field Measurements and Simulations*

Presentation Summary:

A CONTAM[1] airflow network model was developed and compared to measurements from testing a production Building America house in Sacramento in January 2006. The testing results had been presented in detail at the previous meeting in June 2006.

[1] CONTAM is a multizone indoor air quality and ventilation analysis program, developed by NIST, designed to help you determine: airflows and pressures – infiltration, exfiltration, and room-to-room airflows and pressure differences in building systems driven by mechanical means, wind pressures acting on the exterior of the building, and buoyancy effects induced by temperature differences between the building and the outside; contaminant concentrations – the dispersal of airborne contaminants transported by these airflows and transformed by a variety of processes including chemical and radio-chemical transformation, adsorption and desorption to building materials, filtration, and deposition to building surfaces; and/or personal exposure – the prediction of exposure of building occupants to airborne contaminants for eventual risk assessment. CONTAM can be useful in a variety of applications. Its ability to calculate building airflows and relative pressures between zones of the building is useful for assessing the adequacy of ventilation rates in a building, for determining the variation in ventilation rates over time, for determining the distribution of ventilation air within a building, and for estimating the impact of envelope airtightening efforts on infiltration rates. (source: NISTIR 7251, CONTAM 2.4 User Guide and Program Documentation)

Results from the model were very sensitive to certain inputs, including: the number, location, and size of leakage paths in each room; the vertical elevation of leakage paths; and indoor and outdoor temperatures. Wind was neglected for this work, at this time, because wind speed was relatively low (0-4 mph) during the testing, the wind direction was not recorded, and there was considerable uncertainty in establishing wind pressure coefficient values and accounting for the impact of shielding by neighboring houses. Despite neglecting wind effects, the modeled results showed good agreement with measured data.

After establishing that the model could adequately represent the measured condition, the model was extended to evaluate other systems. Six systems were evaluated and compared:

1. Exhaust ventilation, without a central duct system
2. Supply ventilation, without a central duct system
3. Exhaust ventilation, with central duct system, AHU controlled by standard thermostat
4. Exhaust ventilation, with central duct system, AHU controlled by thermostat with minimum runtime timer
5. Supply ventilation, with central duct system, AHU controlled by thermostat with minimum runtime timer
6. Fully ducted balanced ventilation system, without central duct system

The systems without a central duct system showed wide variation in ventilation air distribution between zones (each bedroom and the common area on each floor was defined as a zone). Adding a central duct system with the air handler controlled by a standard thermostat reduced the variation significantly. Adding a minimum runtime timer to make sure that the air handler operated one-third of each hour reduced the variation between zones to almost nothing.

Taking the first system (exhaust with no central duct system) as the reference system, and taking the average of the decays curves for the bedroom zones as the reference curve, all of the other systems were modeled parametrically to find the ventilation airflow rate that would give equivalent results compared to the reference curve. In this way, the relative ventilation air distribution performance of each system could be compared via a ratio of the subject ventilation system's ventilation rate at the point where it matched the reference curve to the ventilation flow rate of the reference system.

The distribution coefficients in Table 1 show the resulting relative performance of each system, with the third system (exhaust with a central duct system and standard thermostat) arbitrarily given a coefficient of 1.0.

Table 1. Coefficient of Distribution (C_{dist})

Exhaust ventilation, without central duct system	C_{dist}=1.25
Supply ventilation, without central duct system	C_{dist}=1.25
Exhaust ventilation, with central ducts, AHU controlled by standard thermostat	C_{dist}=1.0
Exhaust ventilation, with central ducts, AHU controlled by thermostat with timer	C_{dist}=0.75
Supply ventilation, with central ducts, AHU controlled by thermostat with timer	C_{dist}=0.75
Fully ducted balanced ventilation system, without central duct system	C_{dist}=0.50

GENERAL DISCUSSION

The general open discussion period was moderated by Joseph Lstiburek, Principal of Building Science Corporation:

A wider range of boundaries needs to be considered. Generate a list, including:

- Provision for multiple fans, and multiple speeds
- Ducts not just in conditioned space, but not leaky ducts.
- Reconsider not neglecting wind (two people for and one against).
- Model people moving around the house for contaminant exposure.
- Basements should also be a zone

NIST can make tools available to run CONTAM in batch mode to make it easier to look at more options. NIST also has a suite of prepared CONTAM models that were designed to represent a range of the housing market.

Europeans ask questions about people first. North Americans consider the building first. Lowering the ventilation is increasing risk. However, with relatively few houses currently going in with any whole-house ventilation system at all, just getting them in at any level will by default raise ventilation rates.

It is too complex to estimate residential contaminant sources and occupant exposure. Look at systems that get more ventilation where people spend their time. One-half air change per hour is recommended but that is not needed in each space all the time, put it where needed.

Standard 62.2 is a ventilation standard, not an energy standard, so lowering ventilation rates to save energy is not a concern of 62.2. Yet, in practice, they are both combined. No ventilation systems go in without concern for the energy impact.

The metric should be average exposure over a year. It can't be annual average exposure. Who would accept living in a smelly house in Spring knowing that it would get better in Winter? The exposure metric is for health not odor. More ventilation can be worse for odor if there is high outdoor ozone – reactions with indoor chemicals.

If exposure is to be the metric, and we know that there is a large difference in exposure between interior doors closed and open, how do you decide which doors are open or closed, and when and for how long? Prescriptive compliance is what most people will want to use, but exposure as a metric requires a complex performance approach. Simply requiring distribution by mixing eliminates the unnecessary complexity.

What happens when the central system ducts become part of the contaminant source? Would mixing be a benefit in that case? Duct and coil maintenance is part of source control which should be a prerequisite to an effective ventilation strategy.

The impacts of infiltration and duct leakage should be broken apart from distribution effects. Need to do simulations to see whether we need to merge or separate ventilation and infiltration. Lumping them into common systems is where we are right now.

A task force on distribution efficiency should be convened to assemble a matrix of all the take backs and give backs. The outcome of that would likely require a revision of 62.2.

The Indoor Environment Research Program at NRC may be interested in following the LBNL testing protocol which could provide additional data (contact Morad Atif).

We need to consider giving credit for systems that tell people when the ventilation system is working or not. That is more important than distribution. Moving toxics around can be worse than leaving them alone.

A straw vote was taken on how to break up zones within a house. The vote was almost unanimous to consider each bedroom with the door closed as a zone, and at least one zone for the common area on each floor level, and a basement if applicable.

A straw vote was taken on whether to use annual average exposure or uniform distribution of outside air as the primary metric. The vote was split down the middle. Consensus was to do both since the exposure method would also provide the uniformity of air distribution information. The attendees were all invited to continue their valued participation by emailing any further comments and ideas to us. They were also asked to plan to attend another expert meeting on this topic on Friday morning before the ASHRAE 62.2 meetings in Long Beach in June 2007.

21 June 2007
PRESENTATIONS

Building America Program introduction by Terry Logee, U.S. Department of Energy

Speaker 1: Max Sherman and Iain Walker, Lawrence Berkeley National Laboratory

Presenter bio: Max Sherman, Ph.D, is Group Leader of the Energy Performance of Buildings Group at LBNL. He is an ASHRAE Fellow and a long-time recognized expert in the field of indoor air.

Iain Walker, Ph.D, is Scientist in the Energy Performance of Buildings Group at LBNL. His focus as a researcher is related to energy use, moisture issues, comfort, and health in buildings. He serves on a number of ASHRAE and ASTM committees.

Presentation Title: *Measurements of Multizone Air Distribution: What's Distribution got to do with it?*

Presentation Summary:

A review of perceived consensus from previous meetings is that we want to give air distribution systems appropriate "credit" towards ventilation rates, and that "Credit" is couched in terms of impact on longer-term exposure to contaminants (on the order of days at least).

A key question is, "What is the impact of different air distribution strategies on dose received by occupants?" The answer is not simple because we don't know many important parameters, such as: where the sources are in home; where the occupants are in the home; how internal doors are operated (which effectively breaks houses up into multiple zones); and, how much infiltration air leakage there is (higher infiltration diminishes the impact of mechanical air distribution).

A defined goal, and a defined strategy to meet it, is needed. Are we striving to achieve something in addition to minimizing exposure for health reasons? For example, you may want perfect mixing so that exposure to contaminants would be uniform, and lower on average, for all occupants. Or you may accept that some occupants will have higher exposure to contaminants so that other occupants can be perfectly isolated from those sources.

Distribution of sources can be: 1) spread equally in each zone, or equivalently, completely unknown; 2) weighted by zone volume, such as is the case when using "Age of Air" source distribution; 3) concentrated and depending on occupant location; and 4) concentrated and independent of occupant location.

In a similar way, distribution of occupants can be: 1) spread equally in each zone, or equivalently, completely unknown; 2) weighted by zone volume; 3) concentrated and independent of sources; and 4) concentrated and correlated to sources.

"Age-of-air" is a special case metric. Age-of-air can be measured more easily than what is involved with the LBNL Multi-Tracer Monitoring System (MTMS), but it has some limitations. While it provides a good estimate of how long air has been in the zone, it assumes sources are distributed by volume weighting, and is only applicable to metrics that are based on volume distribution of indoor sources. In other words, it assumes that each unit of air has the same contaminant source as every other unit of air. Age-of-air also rolls together ventilation rate and air distribution information such that it is not possible to know the independent impact of each.

LBNL research is taking two approaches. The first approach is as follows:

a) Develop potential norms that may represent typical contaminant sources and occupant activities;
b) Develop a Relative Exposure metric that evaluates how good or bad a particular system is, using a home that is a single well-mixed zone as the reference (assumption built into 62.2); and
c) Develop a Distribution Matrix that contains all the relevant information about air flows for finding the Relative Exposure.

The second approach is as follows:

a) Measure multi-zone air flows in real houses with systems that span a range of proposed distribution technologies, in both tight and leaky houses, with both open and closed interior doors;
b) Measure flows to and from all zones in real time; and
c) Use a distribution matrix to evaluate the measurements for a range of metrics (best to worst cases) using the theoretically perfectly mixed case as a reference.

Using the LBNL Multi-Tracer Monitoring System (MTMS) two houses were tested so far this year. One house had a very leaky building enclosure, and leaky ducts, and was tested in winter conditions near Lake Tahoe. The other house was had a tight building enclosure, and tight ducts, and was tested in mild spring conditions near Sacramento. All interzonal air flows were measured for an exhaust ventilation system and an intermittent central-fan-integrated supply ventilation system in each house. The ventilation systems were sized to meet 62.2 flow requirements. Multiple tests were run with a range of open and closed interior doors and mechanical air mixing strategies. Each test was run for 4 hours.

Three systems were analyzed using MTMS system. These systems were intended to bracket the range of ventilation air distribution impacts on long-term relative exposure, from most to least:

1. Simple single-point exhaust with no central system air handler operation. This involved a continuously operating exhaust fan in a single zone with no mechanical distribution at all, such as might be the case in a house with baseboard heating and no central cooling.
2. Central-fan-integrated supply (CFI) with a central system air handler that runs at a minimum programmed rate.
3. Single-point exhaust with continuous central air handler operation.

Based on the MTMS measurements, seven metric cases were analyzed using the distribution matrix approach. These cases were intended to bracket the range of possibility for ventilation air distribution impacts on long-term relative exposure. The exposures were calculated as typical for the whole year based on the flows measured in the 4 hour tests. The relative exposure ratios are ratios of the concentration in a zone to the concentration if it were all a single perfectly mixed zone. A relative exposure ratio of 1.0 signifies that you would have the same exposure as if it were a single, perfectly mixed zone. Ratios below 1.0 mean that it is better than single zone perfect mixing because of plug-flow displacement ventilation from a first to second floor. The metric cases analyzed, and their respective results for the tight house, were as follows:

1. Equal source in each zone and occupant spends equal time in each zone.
    a. Nicknamed “Everything and Everybody Everywhere”. Assumes equal contaminant generation in every zone the occupant moves around equally between zones. This case could also be said to assume random occupant movement that is uncorrelated to changes in source strengths in various zones.
    b. **Results:** If all interior doors are open, then the simple exhaust ventilation flow rate should be about 40% greater to match the long-term occupant exposure of the other systems. If all interior doors are closed, then the simple exhaust ventilation flow rate should be over 2 times greater to match the long-term occupant exposure of the other systems.
2. Volume weighted sources and occupant spends equal time in each zone.
    a. Because the source strengths are weighted by zone volume, this case can be used for comparison to age-of-air results. This is equivalent to volume weighted

average age-of-air for a given total ventilation rate when occupants spend equal time in every zone.

   b. **Results:** If all interior doors are left open, then all systems perform about the same. If interior doors are closed, then the simple exhaust ventilation flow rate should be about 20% greater to match the long-term occupant exposure of the other systems.

3. Volume weighted sources and occupant stays in the least ventilated zone.
   a. Because of the volume weighted sources, this case meets the age-of-air assumptions. Assumes that an occupant spends all their time in the zone with the lowest age-of-air.
   b. **Results:** If all interior doors are open, then the simple exhaust ventilation flow rate should be about 10% greater to match the long-term occupant exposure of the other systems. If all interior doors are closed, then the simple exhaust ventilation flow rate should be almost 2 times greater to match the long-term occupant exposure of the other systems.
4. Sources concentrated in the least ventilated zone and the occupant stays in that zone all the time (Worst Case)
   a. Nicknamed “I Stink”. Assumes occupant is the direct or indirect generator of the contaminant and assumes occupant stays in the worst zone. This case may useful for evaluating a special limiting cases, such as home offices or in-law quarters, and can be useful for comparison to non-worst case metrics, but is probably too limiting for a minimum standard.
   b. **Results:** If all interior doors are open, then the simple exhaust ventilation flow rate should be over 2 times greater to match the long-term occupant exposure of the other systems. If all interior doors are closed, then the simple exhaust ventilation flow rate should be almost 9 times greater to match the long-term occupant exposure of the other systems.
5. Sources are concentrated in a zone that is remote from the zone where the occupant stays, and the zone where the occupant stays is the least ventilated zone.
   a. Nicknamed “You Stink”. Assumes that the contaminant of concern is concentrated in a different zone than the occupant is localized in. This would be applicable where the contaminant of concern is localized in a zone not frequented often by occupants.
   b. **Results:** Regardless of whether all interior doors are open or closed, the simple exhaust ventilation flow rate should be over 2 times greater to match the long-term occupant exposure of the other systems.

The metric of Cases 6 and 7 is not directly relative exposure, instead, it measures deviation (root-mean square) from a desired outcome. The deviation will always be greater than 1. Case 6 measures deviation from perfect mixing, while Case 7 measures deviation from perfect isolation.

6. “Perfection” Metric, where the contaminants are perfectly averaged.
   a. **Results:** If all interior doors are open, then the simple exhaust ventilation flow rate should be about 50% greater to match the deviation from perfect mixing of the other systems. If all interior doors are closed, then the simple exhaust ventilation flow rate should be 4 times greater to match the deviation from perfect mixing of the other systems.
7. “Isolation” Metric, where ventilation air is supplied to each zone and the zones don’t communicate with each other.
   a. **Results:** If all interior doors are open, then the simple exhaust ventilation flow rate should be about 20% greater to match the deviation from perfect isolation of the other systems. If all interior doors are closed, then the deviation from perfect isolation is about the same for all systems.

While opening interior doors significantly reduces variation in relative exposure, it was found that, with interior doors closed, there is not much air flow through door undercuts and room-to-hall jump ducts or transfer grilles unless the central air handler operates. That result is consistent with age-of-air results previously presented by NREL and BSC.

Mechanical ventilation air distribution impacts are small in houses with high building enclosure leakage, because infiltration acts like additional ventilation, further diluting contaminant concentrations and reducing relative exposure.

Low variations in relative exposure occur when sources and occupants are uniformly distributed and when age-of-air is averaged. Large variations in relative exposure occur when sources and occupants are not uniformly distributed but are correlated. In other words, if people keep moving around the house, and contaminant sources are not concentrated, then mechanical ventilation air distribution makes only small improvements in relative exposure. However, if people spend significant amounts of time in a single place or if contaminant sources are concentrated, then mechanical ventilation distribution can have a large impact on relative exposure.

Speaker 2: Bob Hendron, National Renewable Energy Laboratory

Presenter bio: Bob Hendron, Senior Engineer, has been at the National Renewable Energy Laboratory since 1999, and currently supports the technical efforts for the U.S. Department of Energy's Building America program. Building America works in partnership with the residential building industry to develop and implement innovative building processes and technologies that save homeowners millions of dollars in energy costs. NREL serves as Field Manager for the program, oversees the work of five Building America teams, provides R&D and field test support, and plays a national leadership role in bioclimatic design for residential buildings. Bob's efforts have been focused on performance analysis and field testing of advanced energy systems in new and existing homes.

Presentation Title: *Procedure for Evaluating Outside Air Distribution Using a Single-Tracer Gas, and Results from Three New Test Sites*

Presentation Summary:

The NREL team acknowledges the participation of several Building America teams in this work: BSC, CARB, IBACOS, and BAIHP.

Objectives of this work are to develop a practical field test procedure to quantitatively compare the uniformity of outside air distribution for alternate mechanical ventilation schemes, and to add the procedure to NREL's standard package of short-term field tests for Building America houses. The test would be repeated in several homes in various climates to evaluate its applicability to relevant ASHRAE Standards (129 and 62.2)

Building America/NREL is trying to work out a test procedure to apply to tight houses that is as simple as possible but accurate enough to show the meaningful differences between ventilation air distribution of different spaces. We want to evaluate the house itself because that is all a builder can control. We are not trying to determine contaminant exposure because that is unknowable (i.e. where the contaminants will be generated at what level and where the people will be at any given time).

Local mean age of air, which is equal to the average length of time air molecules at a specific location have resided within a test space, is the primary result. The performance metric is an Effective Ventilation Rate (EVR). The EVR was defined by the NREL team as the reciprocal of the local mean age-of-air in a well-mixed zone, which is equal to the ACH for the limiting case when the whole house is a single, well-mixed zone. It quantifies the average rate at which outside air reaches each zone during the test period, regardless of the path taken, including both ventilation and infiltration. What the EVR does not tell us is the amount of air provided to each zone by ventilation compared to infiltration, the inter-zonal airflow rates, the length of time air molecules have been in each zone, and occupant contaminant exposure.

The EVR test procedure includes the following steps:

1. Thoroughly mix air and SF_6 tracer gas throughout the test space
2. Turn off whole-house mixing fans but continue mixing within each individual zone
3. Establish ventilation system operating conditions of interest
4. Monitor decay rate in each zone
5. Run test until slowest decay reaches <20% of initial concentration (~1.5 air changes)
6. Re-mix entire test space
7. Calculate average ACH for whole house
8. Examine decay curves to determine if conditions sufficiently reached steady state
9. Calculate local age-of-air and EVR for each zone

Some cautions for applying the EVR test method are that: weather conditions must be stable and/or the infiltration rate must be very small, the whole-house must be initially very well-mixed, the test must be run until all zones are in the exponential decay regime (if the zone decay curves are observed to rise and fall, or flatten out, or cross over each other, then exponential decay is not reached).

The RDI house was tested with two exhaust fans as the whole-house ventilation system, and was tested with and without a 4 in^2 window opening in each of the two secondary bedrooms. Natural infiltration was also measured and was found to be very low (<0.05 ach) and relatively even between zones. With the exhaust fans on, and interior doors closed, there was a wide variation in EVR (over 100%) between the two secondary bedrooms and the living room and master bedroom zones. Very little variation existed if interior doors were kept open. The secondary bedrooms had the lowest EVR without any window opening, but had the highest EVR with a 4 in^2 window opening (a 32 inch wide window opened 1/8th inch).

The 2-story Fort Wayne house was tested with exhaust, single-point supply, and central-fan-integrated supply ventilation. The kitchen and dining zones always had the highest EVR. The inter-zonal variation in EVR was not large for any of the systems tested, except for the reduced flow rate exhaust test.

The Burlingame 2-story test house (attached on one side to an adjoining dwelling unit) was tested with a Heat Recovery Ventilator (HRV) and a bathroom exhaust fan. The HRV supplied ventilation air to the bedrooms and exhausted from one bathroom. The exhaust fan was located in the second bathroom. EVR varied widely in all tests with bedroom doors closed, and varied significantly even with bedroom doors open. The master bedroom had the highest ERV except in the Bath 2 exhaust test.

The following conclusions were drawn from all of the EVR testing thus far:

- Opening doors tends to provide good mixing regardless of ventilation type
- Central fan operation at duty cycles as low as 17% provides good mixing regardless of ventilation type even with doors closed
- Central fan integrated supply ventilation results in much better mixing of outside air than single-point exhaust ventilation
- Small window openings (4 in^2) greatly increase the outside air provided to bedrooms for point exhaust ventilation
- By design, an HRV supplying ventilation air to bedrooms does not necessarily result in uniform mixing, but ensures that key areas of the house (bedrooms) are not under-ventilated

EVR measurement is one method to quantify uniformity of air distribution for alternative ventilation systems and operating conditions in a field test setting. EVR results may be useful for developing air distribution correction factors for ASHRAE 62.2.

Speaker 3: Aaron Townsend, Building Science Corporation

Presenter bio: Aaron Townsend is an Associate with Building Science Consulting. He holds a bachelor's degree in mechanical engineering from the University of Texas and a master's degree in mechanical engineering from Stanford University. His work focuses on all aspects of energy efficiency, building durability, and indoor air quality.

Presentation Title: *Results of multi-zone, multi-city CONTAM modeling*

Presentation Summary:

CONTAM modeling was conducted to determine annual average contaminant exposure for different ventilation rates, ventilation systems, and air handler unit (AHU) operation schedules. The ventilation systems modeled were:

- single-point exhaust with and without AHU operation
- single-point supply with and without AHU operation
- central-fan-integrated supply with AHU operation
- balanced ventilation with and without AHU operation

In review, previous testing in two Sacramento, CA houses showed the following conclusions:

- Mixing is very important to whole-house and individual zone pollutant decay rate
- Supply ventilation is slightly more effective than exhaust ventilation, even with mixing
- The location of a single-point ventilation system affects the performance but the effect is not predictable
- Central-fan-integrated supply ventilation with 33% air handler operation and one-third the ASHRAE Standard 62.2 ventilation rate, gave a uniform Effective Ventilation Rate (EVR) throughout the house that exceeded the EVR of the least ventilated rooms using single-point exhaust providing 100% of the 62.2 ventilation rate.

Computer modeling was used to replicate field testing (tune the model) and to predict performance of systems not tested in the field. The tuned model was then applied to other systems not tested. Conclusions were as follows:

1. Ventilation systems do not perform equally just because they have equal nominal airflow
2. Airflow requirements could be adjusted based on performance of each system
3. Further simulations are needed to predict year-round performance to help distribution coefficients that would modify the required 62.2 airflow

The current modeling effort is focused on expand the previous modeling from 1 day in 1 house in 1 climate to a full-year with various house characteristics (leakage, mechanical systems, etc) and different climates. The methodology of simulations changed from decay to contaminant exposure. Uniform generation of pollutant within house was modeled. An assumed occupancy schedule was created that assumed people were home on weekends and at night, and were at work or school during weekdays. Average exposures were calculated on a 3-hr, 8-hr, and annual basis.

A description of the modeling assumptions is as follows:

1. Weather

a. Temperature: outdoor temperature from hourly TMY2 data, indoor temperature constant at 22 C
b. Wind: speed and direction from hourly TMY2 data, wind shielding model and modifiers as described in ASHRAE Fundamentals 2005 Chapters 16 and 27 for typical suburban surroundings

2. HVAC equipment
    a. Heating and cooling system sizing per Manual J for each climate
    b. Duty cycle each hour based on the outdoor temperature and the design temperature for the climate, maximum 80% runtime at design conditions, heating balance point = 65 F, cooling balance point = 75 F, two cycles per hour, cycle time rounded to nearest 5 minute increment to match the simulation time step of 5 minutes
3. Building enclosure air leakage
    a. Distribution: leakage distribution per ASHRAE Fundamentals Chapter 27 with:
        i. Walls, windows, doors = 62%
        ii. Ceilings and non-operating exhaust vents = 23%
        iii. Ducts = 15%
        iv. Total leakage varied as follows:
            1. 1.5 ACH50 (R-2000)
            2. 3.5 ACH50 (Building America)
            3. 7 ACH50 (standard construction)
4. Pollutant generation
    a. Uniform generation of unique pollutant in each room
    b. Generation rate proportional to room square footage (1 mg/hr/sf)
    c. Pollutants unique, but assumed identical in analysis presented later
5. Occupant schedules (same schedule for each occupant)
    a. 10 PM to 7 AM in bedroom with door closed
    b. 7 AM to 9 AM in kitchen
    c. 9 AM to 12 PM in living room
    d. 12 PM to 1 PM in kitchen
    e. 1 PM to 6 PM in living room
    f. 6 PM to 10 PM in other bedrooms
    g. Bedroom doors open except during sleeping period 10 PM to 7 AM
6. Varied paramenters
    a. Climate: Minneapolis, Seattle, Phoenix
    b. Central air handler unit: not present, in conditioned space, outside of conditioned space
    c. AHU Schedule: standard thermostat, minimum runtime per hour (10 on/20 off)
    d. Duct Leakage: 6% of air handler flow, 12% of air handler flow
    e. Ventilation systems: single-point exhaust, single-point supply, dual-point balanced, fully-ducted balanced
    f. Ventilation Rate: percentage of current 62.2 rate 0%, 50%, 100%, 150%

Taking the fully ducted, balanced ventilation system as a performance reference to compare other systems to, what ratio of airflows do other systems need to provide equal yearly average exposure? Table 2 shows the resulting ventilation rate ratios as a range and approximate median.

Table 2. Ventilation rate ratios to show equivalent annual contaminant exposure with the fully ducted balance ventilation system taken as the reference

System Type	Range	Approximate Median
Fully ducted balanced ventilation system, with or without central duct system	1.0	1.0
Non-fully ducted balanced ventilation, with central duct system, and central air handler unit controlled to a minimum runtime of at least 10 minutes per hour	0.9 to 1.1	1.0
Supply ventilation, with central duct system, and central air handler unit controlled to a minimum runtime of at least 10 minutes per hour	1.1 to 1.7	1.25
Exhaust ventilation, with central duct system, and central air handler unit controlled to a minimum runtime of at least 10 minutes per hour	1.1 to 1.9	1.25
Exhaust ventilation, with central duct system, and central air handler unit not controlled to a minimum runtime of at least 10 minutes per hour	1.0 to 1.8	1.5
Supply ventilation, without central duct system	1.4 to 1.9	1.75
Exhaust ventilation, without central duct system	1.3 to 2.6	2.0

Post-presentation discussion:

Was there a programmed temperature difference between zones? There is concern about the model sensitivity when doors are open if there is no temperature difference between rooms (as there would be in reality). Yes, it was found that a 0.1 C temperature difference between bedrooms and the common area drove a significant amount of air mixing through the open door.

Over-sizing of furnace units should be considered by simulating more than Manual J sizing cases. RESNET standards, Energy Star standards, and a number of progressive building codes refer to correct sizing using Manual J. How many instances of bad design can we allow for and still get anything useful done?

The ASHRAE Standard 136 method of combining ventilation and air infiltration should be used. We need to separate out the effects of building leakage and duct leakage from ventilation. The current modeling may not be specific enough to those details, but it is hard to tell since they are combined. This modeling may be tailored to tight houses with tight ducts, which 62.2 does not force. While ventilation air distribution matters less in houses with leaky enclosures or leaky ducts, we should acknowledge that the future of construction is tight enclosures and tight ducts. Really leaky buildings don't need mechanical ventilation. The results of this testing and modeling provide us with enough information to get within at least 75% of the right answer on the ventilation air distribution issue. Over the next several years it may evolve somewhat, but in the meantime, we will be much farther ahead to acknowledge that not all ventilation systems perform the same and apply distribution coefficients to 62.2.

Building America Expert Meeting

VENTILATION AIR DISTRIBUTION EFFECTS IN HOMES

Meeting Manager: Joseph Lstiburek, Building Science Corporation
Date/Time: **Friday, 26 January 2007, 8 am to 12 pm**
Breakfast refreshments begin at 7:30 am
Location: Dallas, TX, **Adam's Mark, Houston Ballroom A**
(ASHRAE Winter Meeting hotel)
Featured Speakers:

- Max Sherman, Lawrence Berkeley National Laboratory
- Bjarne Olesen, International Center for Indoor Environment and Energy, Denmark
- Ren Anderson, National Renewable Energy Laboratory
- Aaron Townsend, Building Science Corporation

Invitees:
Participants will be key people working in the indoor air quality field. Participants are invited from the following groups: Building America teams, ASHRAE Standard 62.2 committee members and participants, residential HVAC and construction industry, national and state government laboratories and agencies, university researchers, energy efficiency organizations, and building consultants.

Meeting Agenda:

- 7:30 am to 8:00 am, Breakfast refreshments
- 8:00 am to 8:15 am, Welcome and Meeting Introduction – Joseph Lstiburek

- Presentations

    - 8:15 to 8:45, (30 min) Max Sherman, "Development of Metrics for Ventilation Distribution"
    - 8:45 to 8:55, (10 min) Questions and discussion

    - 8:55 to 9:25, (30 min) Bjarne Olesen, "Exposure and Risk"
    - 9:25 to 9:35, (10 min) Questions and discussion

- 9:35 to 9:45 (10 min) Break/refreshments

- 9:45 to 10:15, (30 min) Ren Anderson, "Performance Requirements for Residential Ventilation Systems"

- 10:15 to 10:25, (10 min) Questions and discussion

- 10:25 to 10:55, (30 min) Aaron Townsend, "Field Measurements and Simulations"
- 10:55 to 11:05, (10 min) Questions and discussion

- General discussion, 11:05 to 11:55 (50 min), Joseph Lstiburek- discussion moderator
    - Whole-house ventilation air distribution is important to achieve reliable ventilation performance.
    - What are the metrics that can be used to quantify the effective differences between systems?
    - How can those metrics be applied to ASHRAE Standard 62.2?

- Wrap up, action items, and follow-up plan, 11:55 to 12:00

Key questions regarding this meeting:

Mechanical ventilation is becoming an increasingly larger portion of the total space conditioning load in high-performance buildings. Where contaminant sources are managed (for example, closed combustion) and ventilation air distribution is assured, reduced ventilation requirements may be acceptable and advantageous. Hot-humid climates may benefit the most.

1. What does the latest research tell us about ventilation effectiveness due to spatial air distribution?

2. Should not ventilation systems with better spatial distribution be credited for having more reliable whole-house performance relative to indoor air quality?

3. What are the best metrics to account for ventilation air distribution in determining appropriate minimum residential ventilation rates?

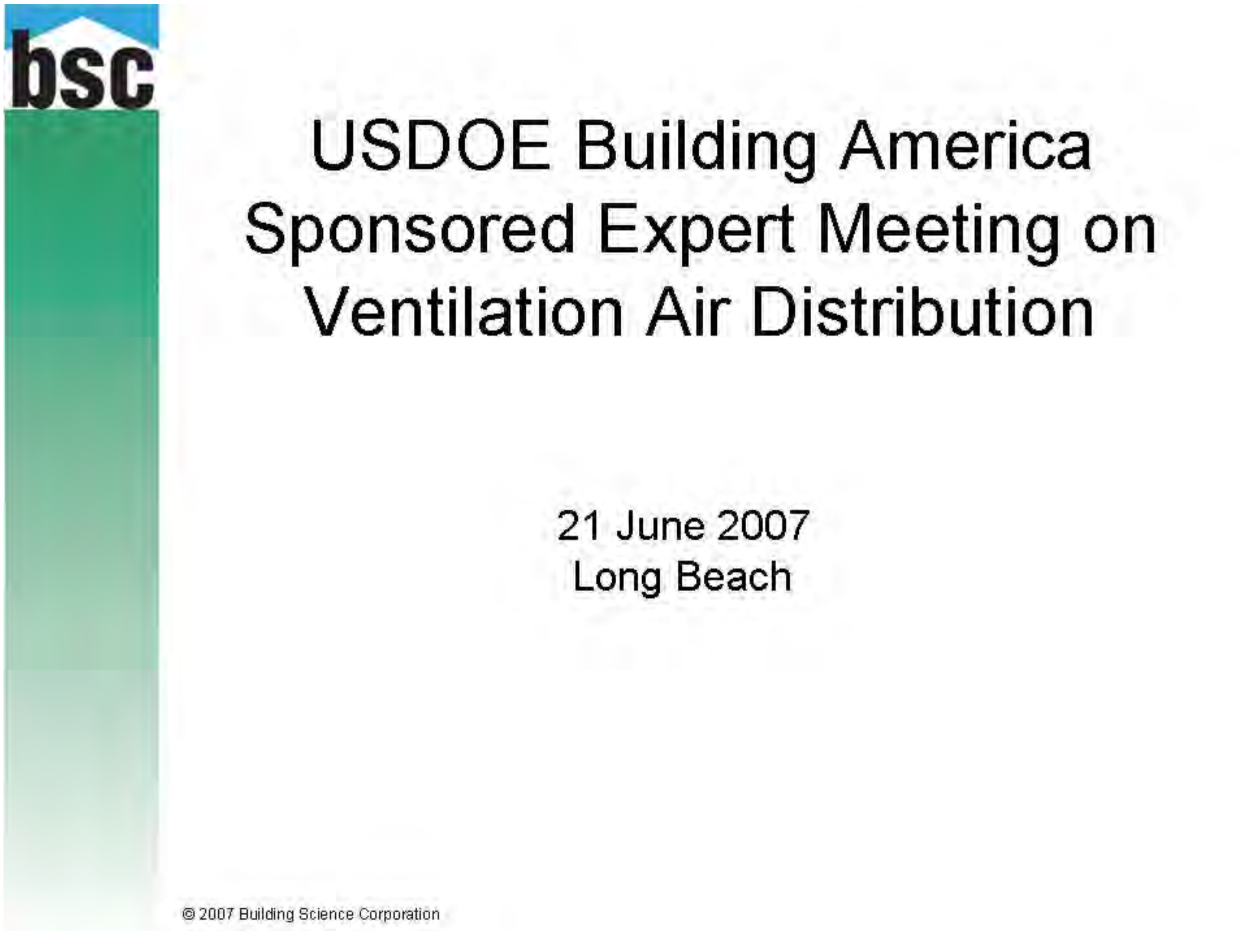
References/Supporting Documents

Hendron, R, Rudd, A., Anderson, R., Barley, D., Hancock, E., Townsend, A., 2006. "Field test of room-to-room uniformity of ventilation air distribution in two new houses." Submitted for publication to IAQ 2007, ASHRAE, December.

Lstiburek, J., Townsend, A., Rudd, A., 2006. "Engineering based guidelines for effective ventilation in new homes." Final report submitted to USDOE, December.

Lstiburek, J. Townsend, A., Rudd, A., 2006. “Evaluation of unique systems issues and research needs for multifamily housing.” Final report submitted to USDOE, December.

Rudd, A., Lstiburek, J., 2000. “Measurement of ventilation and interzonal distribution in single-family homes.” ASHRAE Transactions 2000, MN-00-10-3, V. 106, Pt.2.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USDOE Building America Sponsored Expert Meeting on Ventilation Air Distribution
21 June 2007
Long Beach
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Agenda

- BA program introduction by Terry Logee
- "Measurements of Multizone Air Distribution" by Dr. Max Sherman of Lawrence Berkeley National Laboratory
- "Procedure for Evaluating Outside Air Distribution Using a Single-Tracer Gas, and Results from Three New Test Sites" by Bob Hendron of the National Renewable Energy Laboratory
- "Results of multi-zone, multi-city CONTAM modeling" by Aaron Townsend of Building Science Consulting
- Dr. Joseph Lstiburek will lead discussions concerning the presentations and on the application of ventilation air distribution coefficients for use in the ASHRAE Standard 62.2.

Appendix B: 26 January 2007 Expert Meeting Attendee List (based on sign-in sheet)

#	Last name	First name	Company	Email
1	Anderson	Ren	NREL	ren_anderson@nrel.gov
2	Baxter	Van	ORNL	baxtervd@ornl.gov
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4	Brennan	Terry	Camroden Associates	terry@camroden.com
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6	Crawford	Roy	Trane	roy.crawford@trane.com
7	Drumheller	Craig	NAHB Research Center	cdrumheller@nahbrc.org
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10	Ferris	Rob	Fantech	rofe@fantech.net
11	Forest	Daniel	Venmar Ventilation	forestd@venmar.ca
12	Francisco	Paul	University of Illinois-UC	pwf@uiuc.edu
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What's *Distribution* got to do with it?

Max Sherman
Iain Walker
LBL

June 22, 2007

Overview

- Objectives for today
- Background & Review
- Issues needing to be addressed
- LBL Approach
- Experiment and MTMS Data
- Analysis of Experimental Data

Objectives

- Approaches to understanding air distribution impacts
- Framing of key issues
- Review of case study of two houses
- Discussion of possible metrics
- Some consensus
- Maybe recommendations for SSPC 62.2

DON'T MAKE ME DO IT

- Why long-term exposure should be the norm for ventilation standards
- The types and range of contaminants of concern
- Matrix definitions of air flows and the continuity equation
- Derivation of multizone age of air

Review of Consensus

- Want to give air distribution systems appropriate "credit" towards ventilation rates.
- "Credit" is couched in terms of impact on longer-term exposure to contaminants
  - Days/weeks/months not minutes/hours
- Many contaminants of concern
  - Not always known, but of known classes

Measurement Review

- Need system of providing credit that does not require complex measurements
  - No tracer gas techniques for user
- Need accurate R&D to determine appropriate values for standard
  - Tracer gas techniques for researchers
- Simplified techniques may work
  - If they measure the right thing

KEY QUESTION

What is impact of different air distribution strategies on dose received by occupants?

- Not that simple because we don't know…
  - Where sources are in home
  - Where occupants are in home
  - How internal doors are operated
  - How much leakage there is

CONTINUITY EQUATION

- Zonal Description
  - Matrix of flows
  - Independent sources
  - Zonal concentrations

$$\underline{\underline{V}} \cdot \dot{\underline{C}} + \underline{\underline{Q}} \cdot \underline{C} = \underline{S}$$

- Psuedo-Steady State
  - Matrix inverse
  - Represents averages

$$\underline{C} = \underline{\underline{Q}}^{-1} \cdot \underline{S}$$

DISTRIBUTION MATRIX

- For N zones: N rows & N columns
- Sum of all entries gives single zone value
- Distribution Matrix contains normalized information

$$Q_o \equiv \sum_{i,j} Q_{ij}$$

$$\underline{\underline{D}} = Q_o \underline{\underline{Q}}^{-1}$$

Need to Define Strategy

- Are we striving to achieve something in addition to minimizing exposure:
  - Perfect mixing or perfect isolation?
  - Air delivery or pollutant removal?
  - Accuracy or robustness?
- Base Case: Where are we starting from?
  - i.e. for 62.2: What do we currently assume

LBL Research Approach 1

- Develop potential norms and metrics
  - Reviewed last time and will do more later
- Relative Exposure metric evaluates how good or bad a particular system is
  - Reference is single zone home
- Distribution Matrix contains all relevant information about air flows for finding RE

LBL Research Approach 2

- Measure multizone air flows in real houses
  - Span range of proposed distribution technologies
  - Both tight and leaky houses
  - Open & closed internal doors
  - Flows to/from all zones in real time
- Use measurements with metrics to find out what it all means

Measurements

IAIN WALKER

Field Measurements

- Tested two houses: one leaky, one tight
- Leaky house had leaky ducts (40%), tight house had tight ducts (<6%)
- Leaky in winter, tight in spring (no ΔT)
- Multi-Tracer Multi-Sample (MTMS) system for interzonal air flows
- Exhaust and intermittent Central Fan Integrated Supply sized to meet 62.2

Test Summary – Tahoe Leaky

CFIS operates 10 minutes out of every 30

- Furnace Fan Auto
  - Natural Infiltration, open doors
  - Natural Infiltration, closed doors
  - Exhaust, open doors
  - Exhaust, closed doors
  - CFIS, open doors
  - CFIS, closed doors
  - Ex + CFIS, open doors
  - Ex + CFIS, closed doors
- Co-Heat
  - Natural Infiltration, open doors
  - Natural Infiltration, closed doors
  - *Exhaust, open doors*
  - *Exhaust, closed doors*
  - *Exhaust + continuous furnace fan, open doors*
  - *Exhaust + continuous furnace fan, closed doors*
  - *CFIS, open doors*
  - *CFIS, closed doors*
  - Alternate Exhaust, open doors
  - Alternate Exhaust, closed doors

Test Summary – Sparks Tight

No heating or cooling central fan operation
No Co-heating
CFIS operates 15 minutes out of every 30

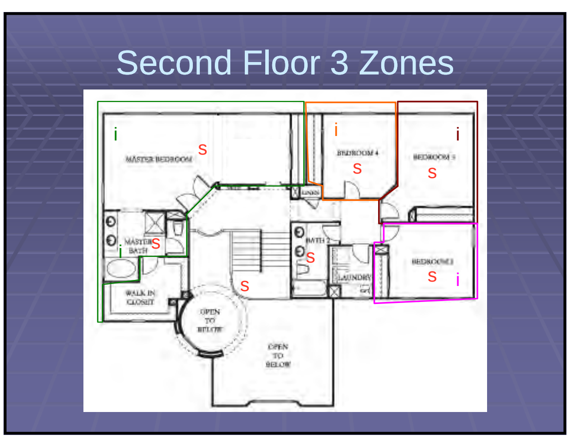
- Natural Infiltration, doors open
- Natural Infiltration, doors closed
- *Exhaust, doors open*
- *Exhaust, doors closed*
- *CFIS, doors closed*
- *CFIS, doors open*
- *Exhaust + continuous furnace fan, doors open*
- *Exhaust + continuous furnace fan, doors closed*
- CFIS + continuous furnace fan, doors open
- CFIS + continuous furnace fan, doors closed
- Exhaust + CFIS, doors closed

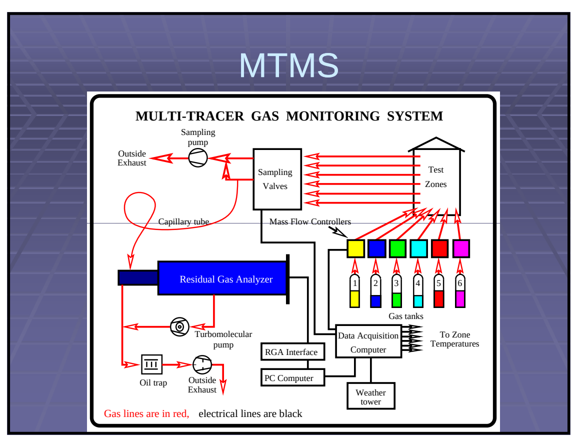

Ceiling fan used
to aid mixing
Leaky ceiling
Trees
Oscillating fan
Used for injection


Central Fan Integrated Supply at three times 62.2,
on 1/3 of the time - need big fixed flow


0.1 ACH w/o mech. vent.
0.2 ACH with mech. Vent
0.15 ACH added for 62.2
Q50 =1350 cfm


Ground floor all one zone
KITCHEN
NOOK
FAMILY ROOM
DINING ROOM
ENTRY
PORCH
LIVING ROOM
THREE CAR TANDEM GARAGE


Second Floor 3 Zones
MASTER BEDROOM
BEDROOM 4
BEDROOM 3
BEDROOM 2
MASTER BATH
BATH 2
LAUNDRY
WALK IN CLOSET
OPEN TO BELOW
OPEN TO BELOW


MTMS
MULTI-TRACER GAS MONITORING SYSTEM
Sampling pump
Outside Exhaust
Sampling Valves
Test Zones
Capillary tube
Mass Flow Controllers
Residual Gas Analyzer
Gas tanks
Turbomolecular pump
Data Acquisition Computer
To Zone Temperatures
RGA Interface
PC Computer
Oil trap
Outside Exhaust
Weather tower
Gas lines are in red, electrical lines are black

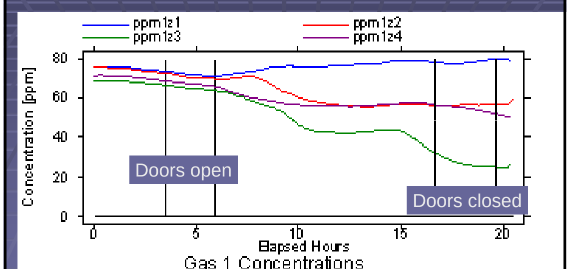
MTMS

- Inject different tracer in each zone at fixed rate
- Sample from several locations in each zone
- Each zone well mixed with fans

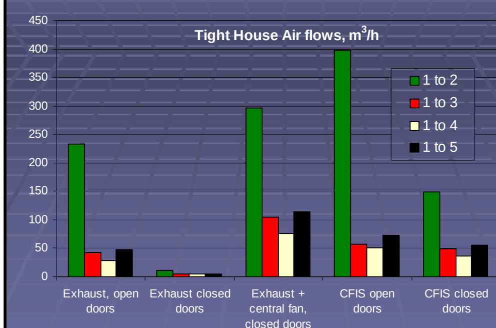
MTMS

- Residual Gas Analyzer
- Each zone sampled every 4 minutes
- Each experiment lasts several hours – to allow steady-state analysis

Exhaust only



Zone to zone air flows



Questions on Measurements?

Otherwise Max comes back

MEASUREMENTS TO METRICS AND NORMS

How do we use these measurements to evaluate air distribution systems

Distribution of Sources

- Spread Equally in Each Zone
  - Or, equivalently completely unknown
- Weighted by Zone Volume
  - "Age of Air" source distribution
- Concentrated
  - Dependent on occupant location
  - Independent of occupant location

Distribution of Occupants

- Spread Equally in Each Zone
  - Or, equivalently completely unknown
- Weighted by Zone Volume
- Concentrated
  - Independent of sources
  - Correlated (Anti-correlated) to source

Age of Air Metric

- Using "Age of Air" is a special case
  - Good estimate of how long air has been "inside"
- Assumes sources distributed by volume
  - Applicable to norms/metrics that are based on volume distribution of indoor sources
- Convolves rate and distribution information
  - Can be measured more easily than MTMS

Systems Analyzed

- Simple Exhaust: No blower operation
  - Continuously operating exhaust fan in a single zone; no mechanical distribution at all
- CFI: Normal operation
  - Blower runs always at programmed rate
- Exhaust with continuous blower operation
  - Upper limit of distribution impact

CASES ANALYZED

1. Fully distributed sources and activities
2. Volume weighted sources (Average)
3. Worst case "age of air" (NREL/BSC)
4. Worst case (worst case)
5. Remote contaminants (worst case)
6. "Perfection" Metric
7. "Isolation" Metric

Case 1: Everybody Everywhere

- Assume equal source in every zone
- Assume equal time by occupant in every zone
- Or assume random movement uncorrelated to changes in source strengths in various zones

Everybody Everywhere Relative Exposures

Simple Exhaust		CFI		Exhaust w/mixing	
open	closed	open	closed	open	closed
1.06	1.64	1.16	1.36	1.13	1.18
1.37	2.43	1.01	1.10	1.03	1.05

Case 2: Volume Weighted

- Similar to Case 1
- Source strengths are weighted by volume
  - Therefore meets Age of Air assumptions
- Equal time in every zone
- Equivalent to volume weighted average age of air given total ventilation rate

Volume Weighted Relative Exposures

Simple Exhaust		CFI		Exhaust w/mixing	
open	closed	open	closed	open	closed
0.95	1.14	1.01	1.04	1.00	0.99
1.05	1.20	1.00	1.00	1.00	0.99

Case 3: Worst Age of Air

- Assumes volume weighted sources
  - Meets Age of Air assumptions
- Assumes person spends all their time in the zone with the lowest age of air
- Cf. results presented by BSC last time

NREL/BSC Age of Air Relative Exposures

Simple Exhaust		CFI		Exhaust w/mixing	
open	closed	open	closed	open	closed
1.05	1.59	1.06	1.18	1.06	1.05
1.09	1.83	1.01	1.03	1.01	1.02

Case 4: “I Stink”

- Assumes occupant is the direct or indirect generator of the contaminant
- Assumes occupant stays in worst zone
- Worst case, but may be useful for comparison
- Applicable e.g. home office, in-law, etc.

"I Stink" Relative Exposures

Simple Exhaust		CFI		Exhaust w/mixing	
open	closed	open	closed	open	closed
3.25	10.85	2.96	7.22	3.14	5.19
4.25	24.80	1.94	2.83	1.88	2.21

Case 5: "You Stink"

- Assumes that the contaminant of concern is concentrated in a different zone than the occupant is localized in.
- Worst case choice of zones
- Applicable if contaminate is localized in zone not frequented often by occupants.

"You Stink" Relative Exposures

Simple Exhaust		CFI		Exhaust w/mixing	
open	closed	open	closed	open	closed
1.88	1.04	2.04	0.90	1.28	0.94
2.95	2.53	1.20	1.16	1.14	1.13

Cases 6 & 7: Not RE

- Metrics, but not directly relative exposure
- Measure (root-mean square) deviation from a desired outcome. Can not be better (i.e. metric never less than 1)
- Case 6: Measures deviation from perfect mixing.
- Case 7: Measures deviation from perfect isolation: (aka Greta Garbo case)

Deviation from Perfect Mixing Performance Metric

Simple Exhaust		CFI		Exhaust w/mixing	
open	closed	open	closed	open	closed
1.89	4.20	1.80	3.29	1.69	2.45
1.96	6.32	1.28	1.57	1.28	1.40

Greta Garbo Performance Metric

Simple Exhaust		CFI		Exhaust w/mixing	
open	closed	open	closed	open	closed
1.77	1.43	1.83	1.40	1.74	1.51
2.25	1.84	1.84	1.81	1.85	1.82

Simple Results: Sources

- Low variations when sources and occupants are distributed.
  - Averaging Age of Air gets rid of differences
- Big variations when source and occupants are correlated
- Cases 5 & 7 behave opposite to others
  - Mixing is "bad" for these approaches

Simple Results: Tightness

Infiltration acts like air distribution

- Leaky houses perform better when there is no mechanical air distribution
  - More so for cases 5 & 7
- Air leakage makes mechanical air distribution perform worse
  - Except cases 5 & 7

Best Systems: Tightness

	LEAKY	TIGHT
1	Exhaust (open)	Any mixing
2	Any open doors	Any mixing
3	Any mixing or open	Any mixing
4	Any open doors	Any mixing
5	Closed doors	Mixing
6	Open doors	Open doors & mixing
7	Closed doors	Closed doors or mixing

Air Distribution Results

- For leaky house with open interior doors, air handler operation does little
  - Benefit for closed door
    - Penalty for close doors for cases 5 & 7
- For tight houses air handler operation can improve mixing significantly
  - Whether that is good or bad depends on which case you care about

Simple Results: Open Doors

- Opening doors improves mixing
  - Good except in cases 5 & 7
- Impact big when sources are localized
- Impact big when no air distribution
  - No significant impact when air handler on
- Transfer grilles/jump ducts not the same as open doors.

Conclusions

- Mixing helps most cases
- Open doors are mixing aid
  - Especially in leaky house
- Relative performance of systems depends in detail on metric chosen
  - Range: 2% to 300%
  - But some generalizations are possible

What to do?

- **Option 1:** Ignore mixing credit/debit issues. Too complicated for a standard.
- **Option 2:** Agree on fixed metric and base case assumptions. Derive (and validate) credit/debits. Include in standard.
- **Option 3:** Use broad approach to eliminate "bad actors" through minimum requirements. No quantitative credit/debit.

DISCUSSION

Max's Metric Mantra:

Metrics must be meaningful and measurable

What is Acceptable IAQ?

- Won't discuss this quantitatively, but operationally is it
  - Limiting **damage**
  - Caused by **contaminants** of concern
  - To which people are exposed over some **time** period

Types of DAMAGE

- Comfort
  - Unpleasant Odors, Irritation *(covered by 62.2)*
  - Acoustics, lighting, thermal, etc. *(not covered)*
- Health
  - Reduced physiological functioning
  - Tissue damage
  - Increased susceptibility to disease

Contaminants of Concern

- Compounds and specifics: ***Various***
- Whole-house ventilation looks at what?
  - Acute Mortality/Morbidity: No
    - E.g. we don't control phosgene with 62.2
  - Reduction in life-expectancy: Yes
    - E.g. carcinogenesis, mutagenesis, toxic loads
  - Reduction in quality of life: Yes
    - E.g. hours of discomfort, minor disease etc.

Timed Exposure

- Delay in absorption of contaminant
  - Important for short-term exposure
- Body can repair/adapt sometimes; e.g.
  - 10 ppm CO for 400 hours: small impact
  - 400 ppm CO for 10 hours: death
- But not others; e.g.
  - Irreparable tissue damage
  - Risk increases during exposure

Damage Equation: $D \cdot (C/C_c)^n$

$D \cdot (C/C_c)^n$

- Linear (n=1) for many cumulative risks
  - Most cancer, metals, stable (e.g. DDT)
- n=3 for Chlorine
  - Typical of oxidants, poisons
- n>>1 represents a threshold
  - Time above threshold is important
- Linear approximation good if little variation

IAQ METRICS

- Peak concentration of contaminant
  - Good for high exposure levels/acute effects
  - Good for threshold-dominated contaminants
  - Focus on short-term dose
- Average concentration (e.g. linearized)
  - Good for cumulative exposures
  - Good for steady exposures above thresholds
  - Focus on long-term dose

Average Concentration It is

- Highly variable emission rates
  - Not well controlled by continuous ventilation
  - Need source control (e.g. exhaust ventilation)
- Contaminants of concern
  - Must be above thresholds to be "of concern"
  - Are the ones we expect to control with whole-house ventilation
- Metric is then long-term average concentration

How Do We Get Concentration

- Depends on
  - Sources & sinks
  - Volumes
  - Ventilation & air transport
- Linked by Continuity Equation
- Need to proceed generically
  - No pollutant specifics (i.e. a tracer gas)
  - Ignore species-specific interactions

CONTINUITY EQUATION

- Locally Covariant Derivation
  - Good everywhere
  - Even near black holes

$$J_\mu \partial G = \Lambda$$

- Steady state, single zone expression:
  - S=emission rate (e.g. cfm)
  - Q= ventilation (e.g. cfm)

$$C_o = S/Q$$

Getting Back to Distribution

- Air distribution is only relevant when it is not a single well-mixed zone.
  - Can't get too crazy (e.g. CFD)
  - Need to relate it to the simple result
- We use a multizone continuity equation
  - But we can assume the zones are well mixed
  - Need matrix formulation of continuity equation

MATRIX EQUATION

- Zonal Description
  - Matrix of flows
  - Independent sources
  - Zonal concentrations

$$\underline{\underline{V}} \cdot \dot{\underline{C}} + \underline{\underline{Q}}\,\underline{C} = \underline{S}$$

- Psuedo-Steady State
  - Matrix inverse
  - Represents averages

$$\underline{C} = \underline{\underline{Q}}^{-1} \cdot \underline{S}$$

MATRIX NOTATION

- For N zones: N rows & N columns
- Sum of all entries gives single zone value
- Diagonal is total for zone
- Off-diagonal elements of Q matrix are (negative of) flow between zones

$$Q_o \equiv \sum_{i,j} Q_{ij}$$

Exposure not Concentration

- A person can only be in one zone at a time
  - So, we define an <u>a</u>ctivity variable.
- Source strength may vary zonally.
  - So, we define a <u>s</u>ource fraction for each zone
- Distribution impacts are relative
  - So, we define a relative dose v. perfect mixing

How Should We Use Metric

1. Evaluate Metric for distribution system of interest
2. Evaluate Metric for distribution in reference case (e.g. 62.2 default)
3. Adjust total rate by ratio to increase or decrease depending on system
   - Could be tabulated like in 62.1

RELATIVE DOSE METRIC

$$d = 1 + \frac{1}{N}\sqrt{\sum_{i,j} D_{ij}^2}$$

- *d* is relative dose
- <u>s</u> is fractional source strength
- <u>a</u> is fractional time spent in each zone
- **D** is Distribution Matrix

$$\underline{\underline{D}} = Q_o \underline{\underline{Q}}^{-1}$$

DISTRIBUTION MATRIX

- Couples emission in one zone to exposure in all other zones; e.g.
  - All entries the same (1) for fully mixed
  - Matrix diagonal for isolated zones
- ***Independent*** of sources, activities, etc
- So, we could base final metric on it
  - If we define activity/source distribution

3-Zone Example (PFT data)

- Q Matrix=>
  - m^3/hr
  - Q_o=726 m^3/hr

653	-291	0
-130	448	-206
-17	-23	292

- D Matrix =>
  - Dimensionless
  - D_o=9.54

1.30	0.88	0.62
0.43	1.97	1.39
0.11	0.21	2.63

Metric Choices

- Need to determine how to use the Distribution Matrix in a way that does not depend on knowing activity/sources.
- What is appropriate for a standard?
  - Best case?
  - Worst case?
  - Typical case?
    - What is that??

Extreme Metrics

- The best and worst cases of the metric will be when the contaminant of concern is emitted in a single zone
- Worst case: Highest value in matrix; e.g. someone generates contaminants and lives in same zone: 2.63 in example
- Best case: lowest value: e.g. live in most isolated room: 0.11 in example

Distributed Distribution

- Assume sources are fully dispersed and activity is spread between all zones

$$d = D_o/N^2$$

- d=1.06 in example
- Tends toward perfect mixing result because of source distribution and activity patterns

Inactivity Patterns

- Suppose sources were distributed but someone spent all their time in the worst zone
- Relative dose would then be from the row of Distribution Matrix with highest sum.
- From example
  - 0.93, 1.26, 0.98
  - RMS mean=1.07

Deviation from Perfection

- Suppose we have no clue on activity patterns or source distributions
- We can measure the "distance" from perfect mixing using RMS deviation

$$d = 1 + \frac{1}{N}\sqrt{\sum_{i,j}(D_{ij} - 1)^2}$$

- Not actually Relative Exposure

Deviation from Isolation

- Suppose we have no clue on activity patterns or source distributions
- We can measure the "distance" from non-mixing using RMS deviation

$$d = 1 + \frac{1}{N}\sqrt{\sum_{i \neq j} D_{ij}^2}$$

- Not actually Relative Exposure

HOW TO MAKE THE MEAUSURMENTS

The diagnostics necessary to measured air distribution effects

TWO TRACER APPROACHES

- Simplified for the Metric of Choice; e.g.
  - Inject tracer in reference source pattern
  - Sample in reference activity pattern
- Complete Characterization
  - Measure all flows to/from zones
  - Can be used to compare metrics
    - And derive simplified approach
  - Can be used to verify simulations

TRACER CONTINUITY

- Same Continuity equation, but
  - this time we know concentrations
  - and are looking to determine the flows
- Unfortunately, no direct solution
  - N^2 unknowns, but only N equations
  - Need to run under N different conditions

THREE APPROACHES

- Time Series in Non-steady State
  - Fit time series data over changing conditions (e.g. decay) to solve differential equation
- Simultaneous Multi-Tracer Tests
  - Use N tracer gases to run simultaneous tests (e.g. inject one in each zone)
- Series (Single-Tracer) Tests
  - N tests are done one at a time

TIME SERIES

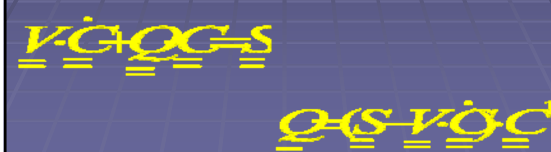
- Fit data to=>
- To find eigenvalues
- "A"s are relevant air change rates
  - N of the them; C_{ij} are their eigenvectors
  - Slowest is whole-building air change rate
  - Quickest determines uncertainty
- This approach never works in real buildings
  - Mixing issues obscure vital information
  - DON'T DO THIS AT HOME

MIXING KILLS

- In all real experiments mixing will obscure short-term information with noise
- Don't differentiate---INTEGRATE
- Even in single-zone situations, fitting decay data is inferior to integrating under the curve
- In multizone situations it is much worse
  - Alternative approaches are needed

MULTIPLE EXPERIMENTS

- Do N different experiments & integrate/average
  - inject in N independent ways
    - E.g. in 1 zone different zone each experiment
- Add to Matrix equation
  - Can be inverted now

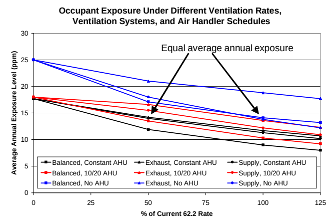


SERIES OR PARALLEL

- Series Option
  - Can be done with one tracer gas
  - Very sensitive to changes in air flows
- Parallel (MultiTracer) Option
  - Can accurately find average flow
  - Takes less time
  - LBL's MTMS uses this approach

DISCUSSION

Results of Multi-, Multi-, Multi-CONTAM Modeling



Aaron Townsend

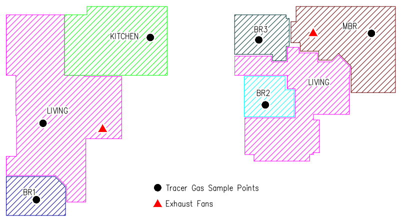
June 22, 2007

Sacramento Tracer Gas Testing January 2006

- Tracer gas test of production Building America house in Sacramento
- 2-story, 4 bedrooms, ~2500 square feet
- Supply and exhaust ventilation tested, with and without mixing via central air handler
- Each test 4-14 hours long
- Weather conditions slightly different during each test

Floor Plan - 2 Story House

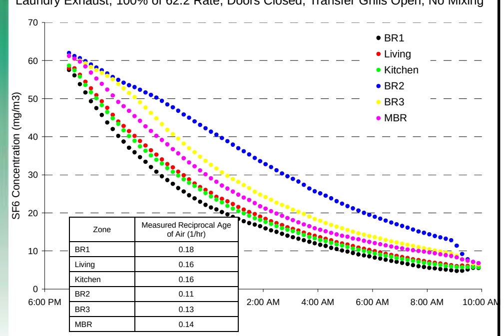
Zones – 2 Story House



- These were tracer gas decay tests—establish uniform concentration of tracer gas and then activate ventilation system to remove it.
- Reciprocal age-of-air can be calculated from decay curves (if weather conditions are sufficiently constant)

Example Results of Sacramento Tracer Gas Testing

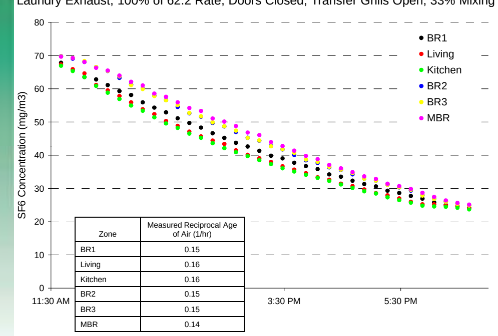
Laundry Exhaust, 100% of 62.2 Rate, Doors Closed, Transfer Grills Open, No Mixing



Zone	Measured Reciprocal Age of Air (1/hr)
BR1	0.18
Living	0.16
Kitchen	0.16
BR2	0.11
BR3	0.13
MBR	0.14

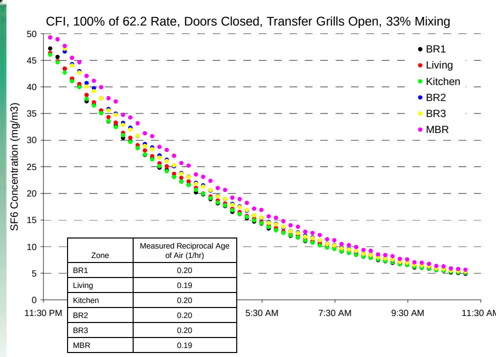
Example Results of Sacramento Tracer Gas Testing

Laundry Exhaust, 100% of 62.2 Rate, Doors Closed, Transfer Grills Open, 33% Mixing



Zone	Measured Reciprocal Age of Air (1/hr)
BR1	0.15
Living	0.16
Kitchen	0.16
BR2	0.15
BR3	0.15
MBR	0.14

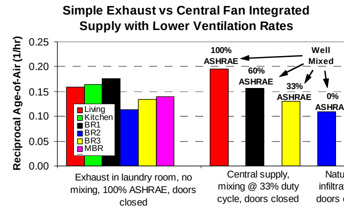
Example Results of Sacramento Tracer Gas Testing



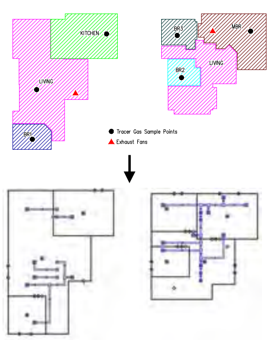
Zone	Measured Reciprocal Age of Air (1/hr)
BR1	0.20
Living	0.19
Kitchen	0.20
BR2	0.20
BR3	0.20
MBR	0.19

Conclusions From Sacramento Tracer Gas Testing

- Mixing is very important to whole-house and individual zone pollutant decay rate
- Supply ventilation is slightly more effective than exhaust ventilation, even with mixing
- The location of a single-point ventilation system affects the performance but the effect is not predictable

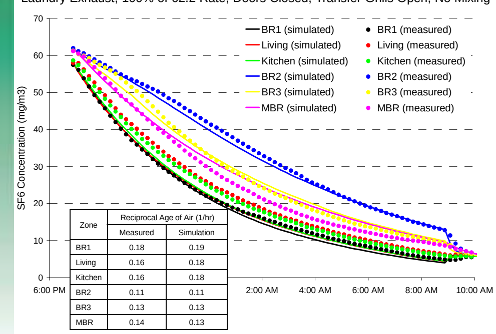


CONTAM Modeling, Nov. 2006-Jan. 2007



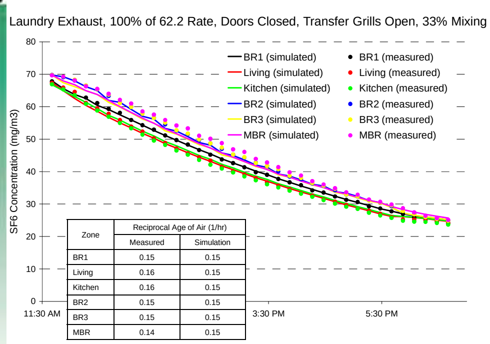
Computer modeling used to replicate field testing (tune the model) and predict performance of systems not tested in the field

Example Results of Tuned CONTAM Model



Zone	Reciprocal Age of Air (1/hr) Measured	Simulation
BR1	0.18	0.19
Living	0.16	0.18
Kitchen	0.16	0.18
BR2	0.11	0.11
BR3	0.13	0.13
MBR	0.14	0.13

Example Results of Tuned CONTAM Model



Zone	Reciprocal Age of Air (1/hr) Measured	Simulation
BR1	0.15	0.15
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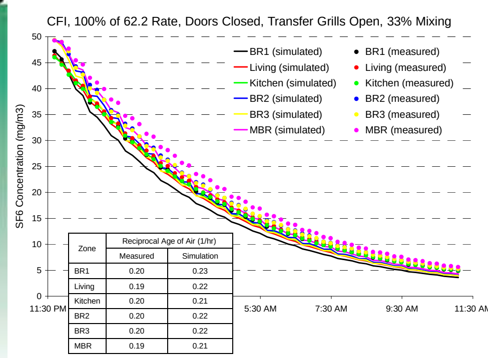
BR2	0.15	0.15
BR3	0.15	0.15
MBR	0.14	0.15

Example Results of Tuned CONTAM Model

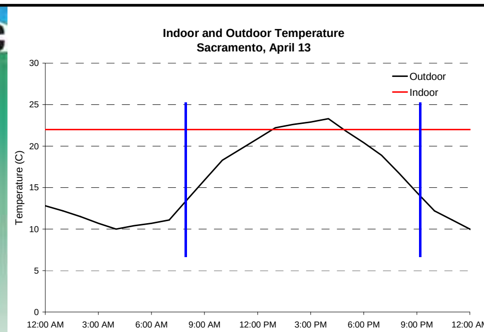


Zone	Reciprocal Age of Air (1/hr) Measured	Simulation
BR1	0.20	0.23
Living	0.19	0.22
Kitchen	0.20	0.21
BR2	0.20	0.22
BR3	0.20	0.22
MBR	0.19	0.21

Tuned CONTAM Model Applied to Other Systems

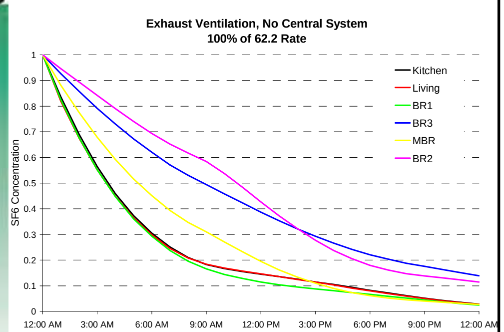
Six Systems Evaluated & Compared:

1. Exhaust ventilation, without central duct system
2. Supply ventilation, without central duct system
3. Exhaust ventilation, with central ducts, AHU controlled by standard thermostat
4. Exhaust ventilation, with central ducts, AHU controlled by thermostat with timer
5. Supply ventilation, with central ducts, AHU controlled by thermostat with timer
6. Fully ducted balanced ventilation system, without central duct system

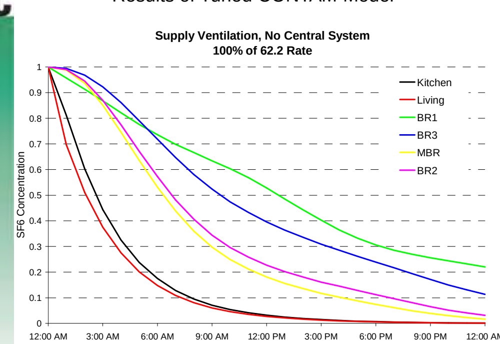


Simulation allows identical weather conditions for each system (generally not possible in field tests).

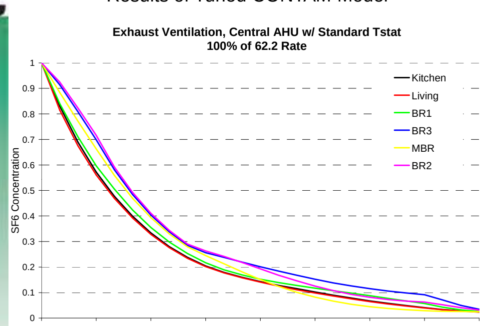
Results of Tuned CONTAM Model



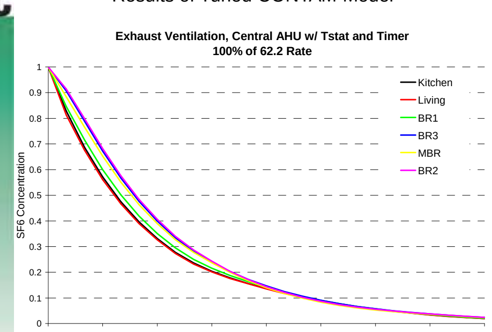
Results of Tuned CONTAM Model



Results of Tuned CONTAM Model

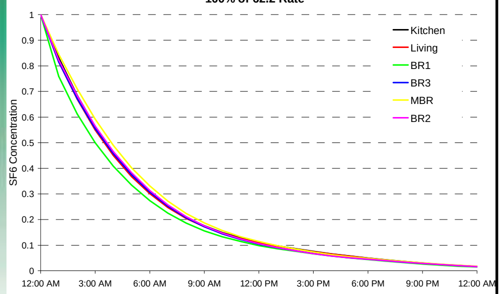


Results of Tuned CONTAM Model



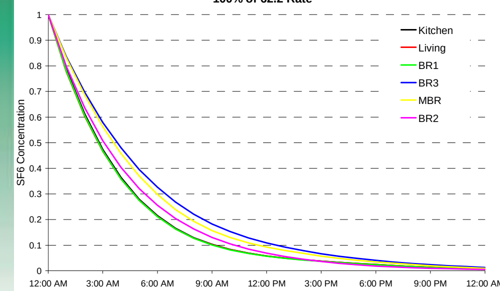
Results of Tuned CONTAM Model

Supply Ventilation (CFI), Central AHU w/ Tstat and Timer
100% of 62.2 Rate



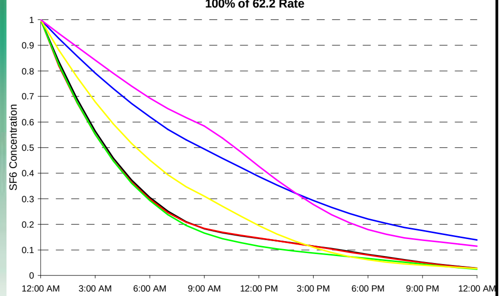
Results of Tuned CONTAM Model

Balanced Ventilation, No Central System
100% of 62.2 Rate



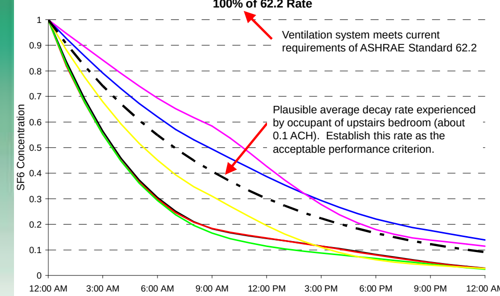
Adjusting Ventilation Rate to Achieve Equivalent Performance

Exhaust Ventilation, No Central System
100% of 62.2 Rate



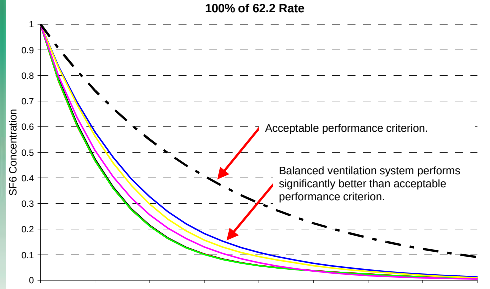
Adjusting Ventilation Rate to Achieve Equivalent Performance

Exhaust Ventilation, No Central System
100% of 62.2 Rate



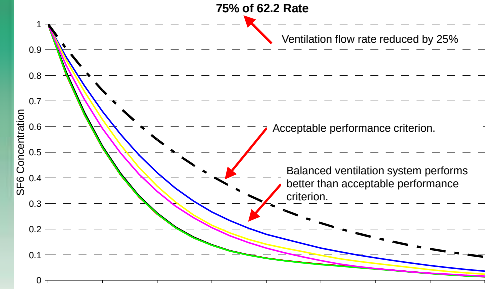
Adjusting Ventilation Rate to Achieve Equivalent Performance

Balanced Ventilation, No Central System
100% of 62.2 Rate

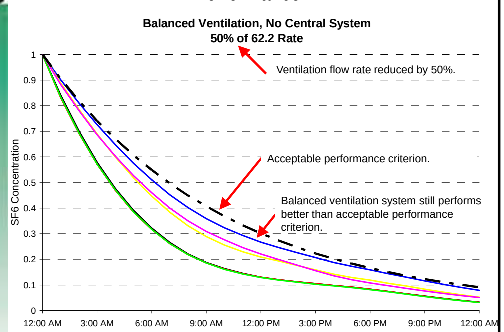


Adjusting Ventilation Rate to Achieve Equivalent Performance

Balanced Ventilation System, No Central System
75% of 62.2 Rate



Adjusting Ventilation Rate to Achieve Equivalent Performance



Conclusions from Tuned CONTAM Model

1. Ventilation systems do not perform equally just because they have equal nominal airflow
2. Airflow requirements can be adjusted based on performance of each system
3. Further simulations were needed to predict year-round performance for general guidance
4. Can we create a “distribution coefficient” to modify the required airflow?

Current Work

1. Comparison of 1 day in 1 house in 1 climate is useful but needs to be expanded before establishing general guidelines.
2. Expand modeling from 1 day in 1 house in 1 climate to full-year with various house characteristics (leakage, mechanical systems, etc) and different climates.
3. Methodology of simulations changed from decay to exposure
   1. Uniform generation of pollutant within house
   2. Assumed occupancy schedule
   3. Calculated 3-hr, 8-hr, and yearly average exposures

Model Characteristics

1. Specific model became more general
2. Vary certain parameters to cover reasonable subset of current construction
3. Include effects of:
   1. Wind
   2. Stack effect
   3. Ventilation systems
   4. Occupant schedule
   5. Pollutant generation

Modeling Assumptions: Weather

1. Temperature
   1. Outdoor temperature from TMY2 data
   2. Indoor temperature constant at 22 C
2. Wind
   1. Wind speed and direction from TMY2 data
   2. Wind shielding model and modifiers as described in ASHRAE Fundamentals 2005 Chapters 16 and 27 for typical suburban surroundings

Model Assumptions: Air Handler

1. Sizing per Manual J for each climate
2. Duty cycle each hour based on temperature and design temperature for the climate
   1. Maximum 80% runtime at design conditions
   2. Heating balance point = 65 F
   3. Cooling balance point = 75 F
3. Two cycles per hour
   1. Cycles rounded to nearest 5 minute increment (simulation time step = 5 minutes)

Model Assumptions: Envelope Leakage

1. Distribution
   1. Leakage distribution per ASHRAE Fundamentals Chapter 27
      1. Walls, windows, doors: 62%
      2. Ceilings & nonoperating exhaust vents: 23%
      3. Ducts: 15%
2. Total leakage varied as described later

Model Assumptions: Pollutant Generation

1. Uniform generation of unique pollutant in each room
   1. Generation rate proportional to room square footage (1 mg/hr/sf)
   2. Pollutants unique, but assumed identical in analysis presented later

Model Assumptions: Occupant Schedules

1. Assume similar schedule for each occupant:
   1. 10 PM to 7 AM: in bedroom with door closed
   2. 7 AM to 9 AM: in kitchen
   3. 9 AM to 12 PM: in living room
   4. 12 PM to 1 PM: in kitchen
   5. 1 PM to 6 PM: in living room
   6. 6 PM to 10 PM: in other bedrooms
2. Bedroom doors open except during sleeping period 10 PM to 7 AM

Varied Parameters

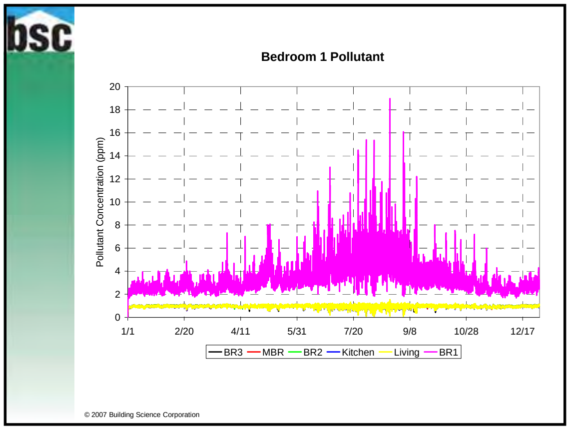
1. Climate
   1. Minneapolis
   2. Seattle
   3. Phoenix
2. Envelope leakage
   1. 1.5 ACH50 (R-2000)
   2. 3.5 ACH50 (Building America)
   3. 7 ACH50 (standard construction)

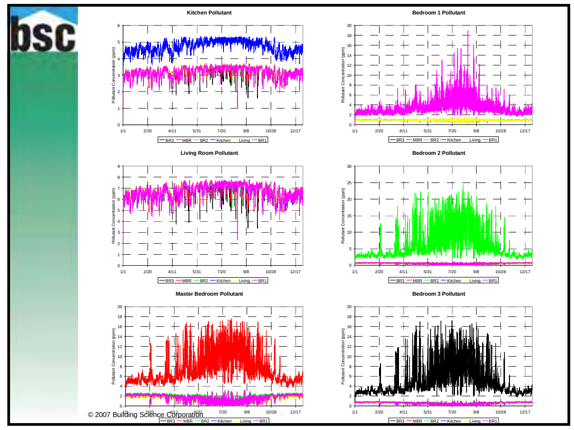
Varied Parameters

3. Central AHU System
   1. Not present
   2. In conditioned space
   3. Outside of conditioned space
4. AHU Schedule
   1. Standard thermostat
   2. Minimum runtime per hour (10 on/20 off)
5. Duct Leakage
   1. 6% of air handler flow
   2. 12% of air handler flow

Varied Parameters

6. Ventilation System
   1. Single-point exhaust
   2. Single-point supply
   3. Dual-point balanced
   4. Fully-ducted balanced
7. Ventilation Rate
   1. 0, 50, 100, 150% of current 62.2 rate


bsc
Bedroom 1 Pollutant
Pollutant Concentration (ppm)
0
2
4
6
8
10
12
14
16
18
20
1/1
2/20
4/11
5/31
7/20
9/8
10/28
12/17
BR3 MBR BR2 Kitchen Living BR1
© 2007 Building Science Corporation


bsc
Kitchen Pollutant
Bedroom 1 Pollutant
Living Room Pollutant
Bedroom 2 Pollutant
Master Bedroom Pollutant
Bedroom 3 Pollutant
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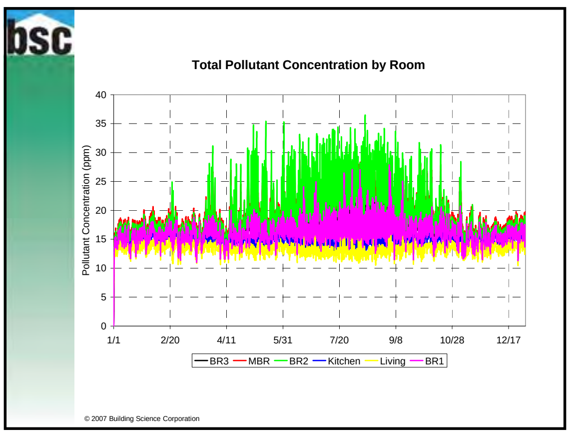
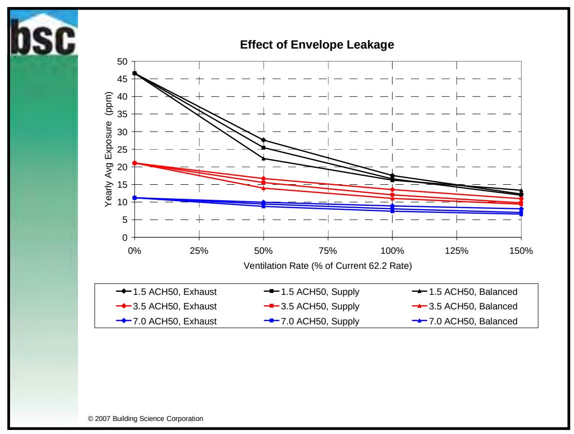

bsc
Total Pollutant Concentration by Room
Pollutant Concentration (ppm)
0
5
10
15
20
25
30
35
40
1/1
2/20
4/11
5/31
7/20
9/8
10/28
12/17
BR3 MBR BR2 Kitchen Living BR1
© 2007 Building Science Corporation


bsc
Effect of Envelope Leakage
Yearly Avg Exposure (ppm)
0
5
10
15
20
25
30
35
40
45
50
0%
25%
50%
75%
100%
125%
150%
Ventilation Rate (% of Current 62.2 Rate)
1.5 ACH50, Exhaust
1.5 ACH50, Supply
1.5 ACH50, Balanced
3.5 ACH50, Exhaust
3.5 ACH50, Supply
3.5 ACH50, Balanced
7.0 ACH50, Exhaust
7.0 ACH50, Supply
7.0 ACH50, Balanced
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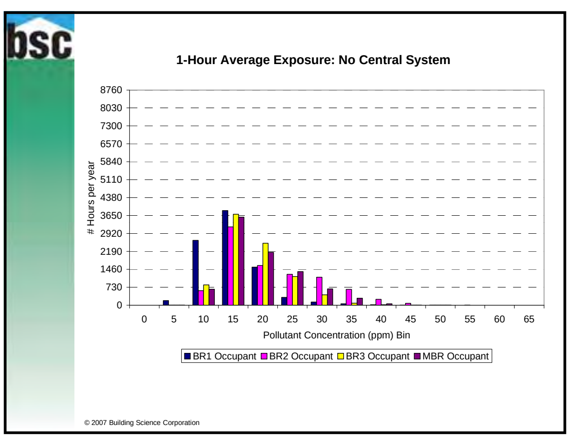
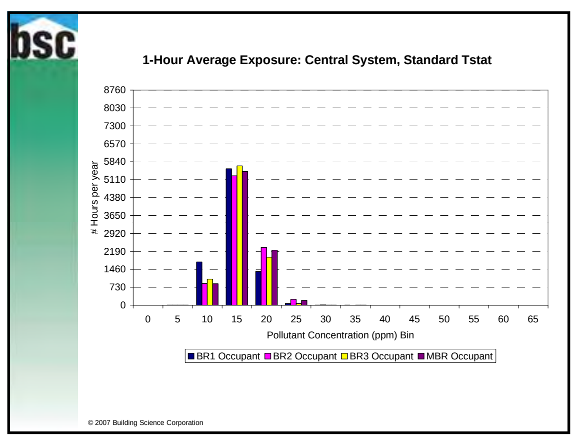
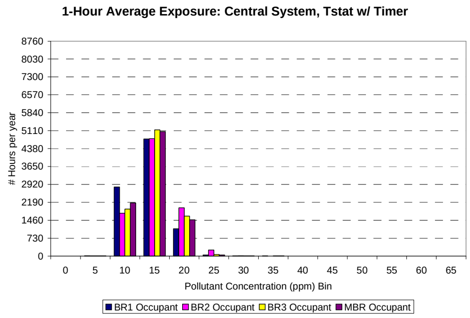
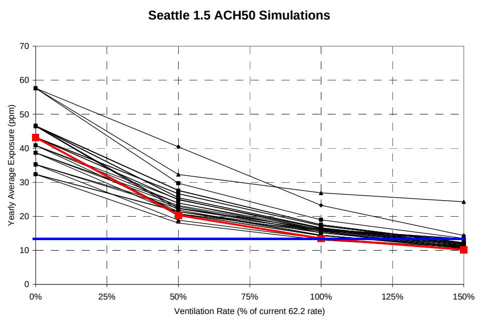

bsc
1-Hour Average Exposure: No Central System
Hours per year
0
730
1460
2190
2920
3650
4380
5110
5840
6570
7300
8030
8760
0
5
10
15
20
25
30
35
40
45
50
55
60
65
Pollutant Concentration (ppm) Bin
BR1 Occupant BR2 Occupant BR3 Occupant MBR Occupant
© 2007 Building Science Corporation

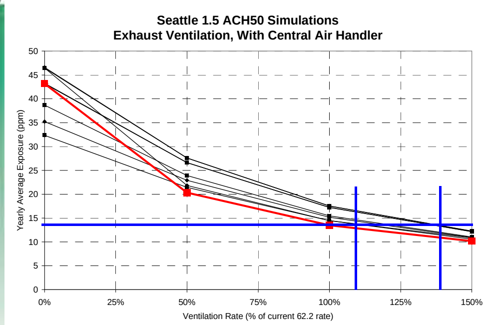

bsc
1-Hour Average Exposure: Central System, Standard Tstat
Hours per year
0
730
1460
2190
2920
3650
4380
5110
5840
6570
7300
8030
8760
0
5
10
15
20
25
30
35
40
45
50
55
60
65
Pollutant Concentration (ppm) Bin
BR1 Occupant BR2 Occupant BR3 Occupant MBR Occupant
© 2007 Building Science Corporation



Reference System

- Best available system: fully ducted, balanced ventilation system
- Compare other systems to this system: what ratio of airflows do other systems need to provide equal yearly average exposure?





Airflow Ratios—All Simulations

System Type	Range	Approximate Median
Fully ducted balanced ventilation system, with or without central duct system	1.0	1.0
Non-fully ducted balanced ventilation, with central duct system, and central air handler unit controlled to a minimum runtime of at least 10 minutes per hour	0.9 to 1.1	1.0
Supply ventilation, with central duct system, and central air handler unit controlled to a minimum runtime of at least 10 minutes per hour	1.1 to 1.7	1.25
Exhaust ventilation, with central duct system, and central air handler unit controlled to a minimum runtime of at least 10 minutes per hour	1.1 to 1.9	1.25
Exhaust ventilation, with central duct system, and central air handler unit not controlled to a minimum runtime of at least 10 minutes per hour	1.0 to 1.8	1.5
Supply ventilation, without central duct system	1.4 to 1.9	1.75
Exhaust ventilation, without central duct system	1.3 to 2.6	2.0

2.18.4. January 2008 Expert Meeting Summary Report

Final Report on the Expert Meeting for Ventilation Effectiveness in Residential Systems

Building Science Corporation Industry Team

March 3, 2008

Work Performed Under Funding Opportunity Number:
DE-FC26-08NT00601

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EXECUTIVE SUMMARY

1. Title: Final Report on the Expert Meeting for Ventilation Effectiveness in Residential Systems (Gate 1B)

2. Overview: The Building Science Consortium held an Expert Meeting on Ventilation Air Distribution Effectiveness in Residential Systems on 18 January 2008 at the Hilton Hotel in New York City, New York. The expert meeting was held immediately before the ASHRAE SSPC 62.2 meetings in advance of the ASHRAE technical program. Invited speakers gave presentations in their particular area of expertise. Speakers included Armin Rudd of Building Science Corporation, who presented for Bud Offerman of Indoor Environmental Engineering as he was not able to attend, Bill Rittelmann of IBACOS, Keith Gawlik of NREL, and Aaron Townsend of Building Science Corporation.

3. Key Results: Key results from this meeting were a greater buy-in from the ASHRAE 62.2 community that BSC's approach to ventilation effectiveness is producing meaningful results and with appropriate modifications can reach results that can be adopted by the 62.2 committee.

4. Gate Status: This project meets the "must meet" and "should meet" criteria for Gate 1B. The project provides source energy and whole building performance benefits by incentivizing efficient ventilation systems and tight enclosures, thereby reducing the source energy needed to condition the house. The project also meets the performance-based safety, health, and building code requirements for use in new homes, as it directly attempts to improve the ventilation code, which will likely be adopted by building codes at some point in the future. For the same reason, this project meets the prescriptive-based code requirements. The project will be cost-neutral for new homes, as builders will still be free to choose from a variety of ventilation systems. The project will increase reliability by increasing the likelihood of uniform indoor air quality. Finally, the project does not require any new products to be manufactured, and suppliers, manufactures, and builders will continue responding to market forces as they always do.

5. Conclusions: The key gaps that remain are objections by the weatherization industry as to how the proposed revisions would affect their industry, and drafting, approval, and execution of a final simulation plan. Next steps involve continuing a dialogue with the weatherization community to further identify and address their concerns, and drafting, submitting for approval, and executing a final set of simulations. After these steps are complete, the ASHRAE 62.2 committee will be given the opportunity to adopt the suggested revisions into the next version of the 62.2 standard. Expected benefits include energy savings (due to credit given to ducted ventilation systems), reliability (due to improved indoor air quality), durability (due to guaranteed ventilation and therefore lower chances of moisture damage), and expected value to builders, contractors, and homeowners (due to improved homeowner satisfaction with their homes, which also benefits builders and contractors).

INTRODUCTION

The Building Science Consortium held an Expert Meetings on Ventilation Air Distribution Effectiveness in Residential Systems on 18 January 2008 at the Hilton Hotel in New York City, New York. The expert meeting was held immediately before the ASHRAE SSPC 62.2 meetings in advance of the ASHRAE technical program in order to make it easier for experts who had already traveled there to participate. There were 37 in attendance. Invited speakers gave presentations in their particular area of expertise. The presentations were followed by discussion with the expert audience.

A summary of the individual presentations and major discussion points is provided in the sections below.

The final agenda for the meeting is listed in Appendix A. A list of attendees for the first meeting is given in Appendix B. The presentations are included in Appendices C through G. A plan for further work in ventilation simulations is included in Appendix H.

PRESENTATIONS

Speaker 1: Armin Rudd, Building Science Corporation, for Francis (Bud) Offerman, PE, CIH, Indoor Environmental Engineering, San Francisco

Presenter bio: Armin Rudd is a Principal of Building Science Corporation. He presented for Francis (Bud) Offerman, PE, CIH. Mr. Offerman has 28 years experience as an IAQ researcher, sick building investigator, mitigation planner, healthy building design consultant, and expert witness. He is president of Indoor Environmental Engineering, a San Francisco based IAQ consulting firm.

Presentation Title: *Window Usage, Ventilation, and Formaldehyde Concentrations in New California Homes: Summer Field Sessions*

Presentation Summary:

Note that Armin Rudd of Building Science Corporation presented in place of Bud Offerman of Indoor Environmental Engineering, as Bud was not able to attend the meeting for personal reasons.

In 2006-2007, Indoor Environmental Engineering performed a study of ventilation and indoor air contaminants in 108 occupied new California homes. Key findings presented were the following:

- The majority of the houses in the study had similar envelope leakage characteristics, as measured by a blower door, at 4-5 ACH50.
- The data set included 42 houses without mechanical ventilation, 8 houses with supply ventilation, and 3 houses with HRV ventilation.
- Those houses with a central-fan-integrated (CFI) supply system did not have a minimum runtimer on the air handler and the median continuous outside air flow rate was 7 cfm.
- Perhaps because of this, the houses with CFI systems had about the same natural air change rate as the houses without any mechanical ventilation system.

- The houses in this study with HRV ventilation systems had a median outside air flow rate of 153 cfm, about 20 times that of the CFI systems and 3 times the recommended ASHRAE 62.2 rate for this size home.
- Occupants in houses with CFI supply systems opened their windows about the same amount as occupants in houses without any mechanical ventilation system.
- Occupants in houses with HRV ventilation systems opened their windows about twice as often as occupants in houses with supply or no mechanical ventilation.
- PFT tests were performed on a subset of the homes in the study. The median natural air change rate of homes with CFI systems was 0.36; in homes without ventilation systems it was 0.33 and in homes with HRVs it was 1.43.
- 50% of the homes in the study had natural air change rates of less than 0.35 ACH.
- A subset of the homes in the study was monitored for formaldehyde concentration. 62% of the homes monitored exceeded the California Air Resources Board guideline exposure concentration of 33 $\mu g/m^3$.

Post-presentation discussion:

The audience had several questions about the study; however due to the fact none of the authors of the report were present there were not answers forthcoming. The questions and comments were as follows:

- This data was from part of the study done in the summer. Bruce Wilcox said that the winter results (not yet published) include some different results that he cannot yet divulge.
- Joe Lstiburek and Philip Fairey felt that the number of houses in the sample presented was too small to have statistical significance, especially the HRV group (3 houses)
- The audience wanted to know more about the attributes of the homes that had high formaldehyde levels.

Speaker 2: Bill Rittelmann, PE, IBACOS, Inc., Pittsburgh, PA

Presenter bio: Bill Rittelmann is a Research Project Manager at IBACOS. He is a registered Professional Engineer, a Certified Energy Manager, and Certified in Plumbing Engineering. At IBACOS he is responsible for managing the domestic hot water and HVAC research projects. He graduated with a Bachelor’s of Science in Architectural Engineering from Pennsylvania State University.

Presentation Title: *Room Air Temperature Uniformity of a Forced-Air System Relative to Runtime*

Presentation Summary:

Bill presented results from a project IBACOS had performed on the effects of air conditioner and furnace runtime on temperature distributions within a house. In this project, an HVAC system (along with a duct system) was installed within a finished 2-story house in Ft. Wayne, Indiana. One system consisted of high sidewall registers, and a second consisted of floor registers. Floor-to-floor and head-to-toe temperature stratification was measured over four months in winter, with and without minimum air handler runtimes. Results showed that the higher airflow of the high sidewall registers resulted in higher temperature air from the register. The floor registers had lower total airflow and the duct system was located between floors; therefore the delivered air temperature was lower. With high sidewall registers, floor-to-floor stratification was 0-4 degrees F and head-to-toe stratification (within the same room) was 0-3 degrees F. Lower outdoor temperatures and higher supply air temperatures increased the level of stratification. Additionally, lower supply air velocity increased the level of stratification as the supply air did not entrain room air. With floor registers, floor-to-floor stratification was 2-3 degrees F and decreased with decreasing outdoor temperature. Higher supply air temperatures increased the level of stratification. Finally, head-to-toe stratification was 0-3 degrees F and increased with decreasing outdoor temperature. Overall, lower supply air temperatures resulted in lower stratification due to higher velocities and longer runtimes.

IBACOS also performed tracer gas decay tests in the same house. The main conclusions from these tests were that single-point exhaust or supply ventilation was only marginally effective, and that continuous low-level supply to a central fan operating on low speed was effective.

Post-presentation discussion:

The audience agreed that the project's findings confirmed what they would have assumed about the systems presented.

Speaker 3: Keith Gawlik, National Renewable Energy Laboratory

Presenter bio: Keith Gawlik is a Senior Engineer at NREL. Since he joined NREL in 1992, his work has included experimental and numerical analysis of the fluid flow and heat transfer performance of transpired solar air heaters, geothermal binary cycle power plants, enhanced heat transfer surfaces, corrosion barrier polymer coatings, heat sinks for electronics modules, photocatalytic oxidizers, polymer heat exchangers, natural convection cooling towers, solar domestic hot water systems, building HVAC systems, and hydrogen venting systems. He has received R&D 100 and Federal Laboratory Consortium for Technology Transfer awards related to his work on polymer coatings. He is co-inventor on one patent related to the transpired collector, one on an enhanced heat transfer surface, and two on chemical application systems, the latter two from his experience as a mechanical engineer at a company designing and manufacturing water analysis equipment. He graduated from the Massachusetts Institute of Technology with S.B. and S.M. degrees in mechanical engineering, and earned his Ph.D. at the University of Colorado at Boulder.

Presentation Title: *CFD Evaluation of Air Distribution Systems for Residential Forced Air Systems in Cold Climates*

Presentation Summary:

Keith described a joint modeling and experimental approach at NREL to categorize the effect of throw from high sidewall registers. Fluent 6.2 was used for computational fluid dynamics (CFD) modeling, and a full-size experimental chamber was built to perform physical experiments as well. His results show that high supply air temperature causes more stratification, as does low supply air speed, and the effects combine. For example, high temperature, low speed supply air results in the highest level of stratification.

Post presentation discussion:

Low temperature, high speed supply air would be the best case from a stratification perspective. However there are limits to this case: high speed supply air causes noise and whistling at the supply register, and both high speed and low temperature supply air can cause uncomfortable conditions for the occupants in the space.

Speaker 4: Aaron Townsend, Building Science Corporation

Presenter bio: Aaron Townsend is an Associate with Building Science Corporation. He has worked for Building Science for over four years, where he focuses on all aspects of energy efficiency, building durability, and indoor air quality. Aaron holds a bachelor's degree in mechanical engineering from the University of Texas and a master's degree in mechanical engineering from Stanford University.

Presentation Title: *Update on Results of Field Measurements and CONTAM Simulations*

Presentation Summary:

A CONTAM[1] airflow network model was developed and compared to measurements from field tests of a production Building America house in Sacramento in January 2006. The field testing results had been presented in detail at a previous meeting (January 2006), and the CONTAM model had been presented in January and June 2007. Based on the simulation work, the previous presentations asked the question, "Can we quantify the difference in performance between different ventilation systems?"

In this current presentation (January 2008), questions raised at previous meetings were addressed. Specifically, Aaron addressed the question of what the relative exposures were under a wider set of assumptions about sources and occupancy behaviors (based on the cases presented in June 2007 by Max Sherman and Iain Walker of LBL), what the effect of the sizing assumption was (i.e. what happens if the space conditioning system was not sized according to Manual J), and what the effect was of various parameters that were varied (i.e. climate, central system type, duct leakage, minimum system runtime, and envelope tightness).

The contaminant source and occupant behavior included the following cases:

1. "Everybody Everywhere." Each zone has a contaminant with the same source strength, and the occupant is exposed to the air in each zone equally.
2. Volume Weighted Sources. Each zone has a contaminant with source strength proportional to its volume, and the occupant is exposed to the air in each zone equally. This source strength assumption meets the criteria for age of air analysis.

[1] CONTAM is a multizone indoor air quality and ventilation analysis program, developed by NIST, designed to help you determine: airflows and pressures – infiltration, exfiltration, and room-to-room airflows and pressure differences in building systems driven by mechanical means, wind pressures acting on the exterior of the building, and buoyancy effects induced by temperature differences between the building and the outside; contaminant concentrations – the dispersal of airborne contaminants transported by these airflows and transformed by a variety of processes including chemical and radio-chemical transformation, adsorption and desorption to building materials, filtration, and deposition to building surfaces; and/or personal exposure – the prediction of exposure of building occupants to airborne contaminants for eventual risk assessment. CONTAM can be useful in a variety of applications. Its ability to calculate building airflows and relative pressures between zones of the building is useful for assessing the adequacy of ventilation rates in a building, for determining the variation in ventilation rates over time, for determining the distribution of ventilation air within a building, and for estimating the impact of envelope airtightening efforts on infiltration rates. (source: NISTIR 7251, CONTAM 2.4 User Guide and Program Documentation)

3. “Worst Case” Age of Air. Each zone has a contaminant source with strength proportional to its volume. The occupancy is one of three cases: (a) moves each hour to the most contaminated zone, (b) stays in the zone with the highest average contaminate level for the entire year, and (c) moves about according to a normal schedule, but sleeps in the most contaminated bedroom.
4. “I Stink.” There is a single contaminant source, in the same room as the occupant. The occupant stays in the room that maximizes exposure over the course of the year.
5. “You Stink.” There is a single contaminant source, in some other room than the occupant. The occupant stays in the room that maximizes exposure over the course of the year.

Even though there are substantial differences in the methodologies between the LBL (Max Sherman and Iain Walker) and BSC approaches, the relative exposure for each case examined came out similar. There is significantly more variation from case to case than there is from the LBL approach to the BSC approach.

The effect of system sizing is very small. If a system is oversized, it simply delivers the same amount of air in a shorter time period. Since even an undersized space conditioning system delivers significantly more air than a ventilation system or infiltration, the house stays mixed at about the same level independent of space conditioning system size. Aaron showed an example of a system sized by Manual J and a system sized at two times Manual J, and the pollutant concentration over the course of a day is nearly indistinguishable.

Variations in model inputs had the following effects:

- Climate has an effect, but less so at high ventilation rates or with tight houses. All other things being equal, climates with fewer infiltration degree days will have higher contaminant concentrations.
- The central system type does have an effect. With a reasonable amount of ventilation (at least 50% of the current 62.2 value), a house with no means to distribute ventilation air (i.e. no central system and a single-point ventilation system) will have the highest contaminant concentration. A ventilation system with a supply duct to each room and a central forced-air space conditioning system will have the lowest contaminant concentration. Single-point ventilation systems with a central forced-air space conditioning system fall in between the two.
- Duct leakage has an effect if the ducts are outside of conditioned space. If ducts are outside of conditioned space, increased duct leakage causes increased air change within the house, and therefore lowers the contaminant level. If ducts are within the conditioned space, duct leakage has a negligible effect on the contaminant level.
- Having a forced-air system minimum runtime lowers contaminant concentration levels. The effect is more pronounced if the ducts are located outside of conditioned space, as the additional runtime results in additional duct leakage and therefore more air change.
- Envelope leakage has a large effect—perhaps the largest of all the parameters studied. Houses with leaky envelopes have lower contaminant concentrations than houses with tighter concentrations.

<u>Post presentation discussion:</u>

Jamie Lyons and Terry Brennen asked if multiport exhaust systems had been examined with the model. They had not. Jamie asked for an educated guess at what the coefficient would be.

Aaron responded that he would guess 1.5 but would have to run the simulations. Terry and Phillip Fairey indicated that they would also guess 1.5 would be close. Paul Francisco stated that exhaust fans should be located in the zones where pollutants are generated, but other pointed out that we cannot predict where that will be, other than the kitchen and bathrooms (which we already do).

Max Sherman asked if airflow ratios could be calculated based on Case 1 exposure and occupant behavior. They could be but have not yet been.

Dennis Deitz pointed out that if we increase the required flowrate for exhaust-only systems, we exacerbate negative air pressure problems. Paul Francisco pointed out a need to differentiate where the ducts are located, that bad air from leaky ducts in a crawlspace should not be credited. He suggested that if a house has leaky ducts in a crawlspace it should not be able to claim a low coefficient.

GENERAL DISCUSSION

The general open discussion period was moderated by Joseph Lstiburek, Principal of Building Science Corporation.

- Bruce Wilcox wanted to see the coefficients with duct leakage taken out of consideration.
- Max Sherman pointed out the need to make sure that if the central system is used more that it won't increase contaminant levels.
- Someone asked if it makes a difference for a balanced system, if the system exhausts from each zone or if a single location is sufficient.
- Max Sherman agreed that the results from the LBL MTMS data are consistent with the BSC modeling results.
- Philip Fairey pointed out that the previous starting point for 62.2 assumed that the building had a certain amount of envelope leakage (i.e. the building was leaky).
- Paul Francisco suggested that the 62.2 standard be split for existing versus new buildings. He is okay with distribution credits for new buildings but does not want to see them required for existing buildings because he does not want to get rid of the infiltration credit.
- Max suggested that 62.2 could require the higher coefficient (2.0) for all systems and then allow lower coefficients if the house proves it has tight ducts, mixing, etc. Joe disagreed because he does not want to credit leakage, so 62.2 should start at 1.0 and go up if the building has an inferior ventilation system.

FOLLOW-UP WORK

As a result of the expert meeting, there was general consensus that the distribution coefficient concept was sound and could be implemented. Some members of the committee wanted additional systems or scenarios simulated. In order to accommodate this, BSC collaborated with Bruce Wilcox and Steve Emmerich to develop a simulation plan that, when executed, would provide the information necessary for the 62.2 committee to adopt the distribution coefficients at the next 62.2 committee meeting in June 2008.

A copy of the final simulation plan is attached as Appendix H.

Appendix A: Expert Meeting Agenda

INVITATION and AGENDA

Building America Expert Meeting

VENTILATION SYSTEM INTERACTIONS IN HOMES

Meeting Manager: Armin Rudd, Building Science Corp.
Date/Time: **Friday, 18 January 2008, 8:00 am to 12 pm**
Location: New York City, ASHRAE Winter Meeting hotel
Hilton New York, Beekman room

Featured Speakers:

- Bud Offermann, Indoor Environmental Engineering
- Bill Rittelmann, IBACOS
- Keith Gawlik, NREL
- Aaron Townsend, Building Science Corp.

Key questions regarding this meeting:

Mechanical ventilation is becoming an increasingly larger portion of the total space conditioning load in energy efficient homes. When contaminant source control is a first priority, and whole-house ventilation air distribution is assured, reduced ventilation requirements may be acceptable and advantageous. Hot and humid climates may benefit the most.

1. What does the latest research tell us about indoor air contaminants in homes?

2. How do thermal comfort requirements in energy efficient homes relate to whole-house ventilation air distribution; what are the systems interactions?

3. Should ventilation systems with better spatial distribution be credited for having more reliable whole-house performance relative to indoor air quality?

4. Can we use the information we currently have to account for ventilation air distribution for comfort and air quality to determine appropriate minimum residential ventilation requirements?

Invitees:

Participants will be key people working in the indoor air quality, comfort, and space conditioning fields. Participants are invited from the following groups: Building America teams, ASHRAE Standard 62.2 committee members and participants, residential HVAC and construction industry, national and state government laboratories and agencies, university researchers, energy efficiency organizations, and building consultants.

Meeting Agenda:

- 8:00 am to 8:05 am, Welcome and Meeting Introduction
- 8:05-8:15 Building America Zero Energy Home Overview (DOE/NREL)
- Presentations
    - 8:15 to 8:45, (30 min) Bud Offermann, *Window Usage, Ventilation, and IAQ in 108 New California Homes*
    - 8:45 to 8:55, (10 min) Questions and discussion
    - 8:55 to 9:25, (30 min) Bill Rittelmann, *Air distribution for thermal comfort in high-performance homes and its interaction with ventilation*
    - 9:25 to 9:35, (10 min) Questions and discussion
    - 9:35 to 10:05 (30 min) Keith Gawlik, *CFD evaluation of air distribution systems for residential forced air systems in cold climates*
    - 10:05-10:15 (10 Min) Questions and Discussion
    - 10:15 to 10:45, (30 min) Aaron Townsend, *CONTAM simulations to evaluate uniformity of ventilation air distribution and occupant exposure to indoor contaminants*
    - 10:45 to 10:55, (10 min) Questions and discussion
- General discussion, 10:55 to 11:45 (50 min), Joseph Lstiburek-discussion moderator
- Wrap up, action items, and follow-up plan, 11:45 to 12:00

Appendix B: Expert Meeting Attendee List (based on sign-in sheet)

Last name	First name	Company	Email
Baxter	Van	ORNL	baxtervd@ornl.gov
Bloemer	John	Research Products Corp.	jb@aprilaire.com
Brennan	Terry	Camroden Associates	terry@camroden.com
Crawford	Roy	Trane	roy.crawford@trane.com
Dietz	Dennis	American Aldes Ventilation	eng@aldes-us.com
Drumheller	Craig	NAHB Research Center	cdrumheller@nahbrc.org
Emmerich	Steve	NIST	steven.emmerich@nist.gov
Fairey	Philip	FSEC	pfairey@fsec.ucf.edu
Forest	Daniel	Venmar Ventilation	forestd@venmar.ca
Francisco	Paul	University of Illinois-UC	pwf@uiuc.edu
Gawlik	Keith	NREL	keith_gawlik@nrel.gov
George	Marquam	Blu Spruce Construction	marquam.george@uas.alaska.edu
Grimsrud	David		grimsrud@earthlink.net
Henderson	Hugh	CDH Energy	hugh@cdhenergy.com
Karg	Rick	R.J.Karg Associates	rjkarg@karg.com
Langan	Glen	Gulf Power-Southern Co.	gplangan@southernco.com
Lstiburek	Joseph	Building Science Corp.	joe@buildingscience.com
Lyons	Jamie	Newport Partners, LLC	jameslyons@newportpartnersllc.com
Moore	Mike	Newport Partners, LLC	mmoore@newportpartnersllc.com
Nelson	Gary	Energy Conservatory	gnelson@energyconservatory.com
Olson	Collin	Energy Conservatory	colson@energyconservatory.com
Poirier	Bertrand	Fantech	bepo@fantech.ca
Prahl	Duncan	IBACOS	dprahl@ibacos.com
Puttagunta	Srikanth	Steven Winter Associates	sri@swinter.com
Raymer	Paul		paul.raymer@heysol.com
Rittelmann	Bill	IBACOS	brittelmann@ibacos.com
Rudd	Armin	Building Science Corp.	arudd@buildingscience.com
Sherman	Max	LBNL	mhsherman@lbl.gov
Stevens	Don	Panasonic	stevensd@us.panasonic.com
Stroud	Thomas	Health Patio & Barbeque Assoc	stroud@hpba.org
Talbot	John		jmtalbott@comcast.net
Taylor	Sam	DOE	samuel.taylor@ee.doe.gov
Townsend	Aaron	Building Science Corp.	aaron@buildingscience.com
Walker	Iain	LBNL	iswalker@lbl.gov
Werling	Eric	USEPA	werling.eric@epa.gov
Wettergren	Ola	Fantech	olwe@fantech.net
Wilcox	Bruce		bwilcox@lmi.net

Appendix C: Introductory Presentation

U.S. Department of Energy
Energy Efficiency and Renewable Energy
Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable
Building Technologies Program

Building America
U.S. Department of Energy
Research Leading to Zero Energy Homes

Building America Expert Meeting

Ventilation System Interactions In Homes

Hilton New York
18 January 2008
8 am to noon

Building Science Consortium

Meeting Agenda:

Welcome and Meeting Introduction
Building America Zero Energy Home Overview (DOE/NREL)

1. Francis (Bud) Offerman, *Window Usage, Ventilation, and IAQ in New California Homes*

2. Bill Rittelmann, *Air distribution for thermal comfort in high-performance homes and its interaction with ventilation*

3. Keith Gawlik, *CFD evaluation of air distribution systems for residential forced air systems in cold climates*

4. Aaron Townsend, *CONTAM simulations to evaluate uniformity of ventilation air distribution and occupant exposure to indoor contaminants*

General discussion, Joseph Lstiburek-discussion moderator

Wrap up, action items, and follow-up plan

Building Science Consortium

Appendix D: Presentation 1: Summary of the paper “Window Usage, Ventilation, and IAQ in New California Homes” by Francis (Bud) Offerman, presented by Armin Rudd

Window Usage, Ventilation, and Formaldehyde Concentrations in New California Homes: Summer Field Sessions

Francis Offermann PE CIH, Principal Investigator
Jonathan Robertson CIH and Teresa Woo EIT
Indoor Environmental Engineering, San Francisco, CA www.iee-sf.com
Steve Brennan PE and Dave Springer
Davis Energy Group, Davis, CA

Window usage

- People opened their windows about the same amount in houses with no mechanical ventilation system as they did in houses with supply ventilation (outdoor air ducted to the central return).
- People in houses with HRV ventilation systems opened their windows about twice as much as people in houses with either no mechanical ventilation or supply ventilation.

Table 2. Window and door opening expressed as the average opening in square feet over the 24-hour air quality sampling period and the average of the previous seven 24-hour periods in new single-family detached homes in California; with and without mechanical outdoor air ventilation.

	No Mechanical Outdoor Air [a] Homes (n=42)		DOA Mechanical Outdoor Air [b] Homes (n=8)		HRV Mechanical Outdoor Air [c] Homes (n=3)	
	Test Day 24 hr Average (ft^2)	Week 24 hr Average (ft^2)	Test Day 24 hr Average (ft^2)	Week 24 hr Average (ft^2)	Test Day 24 hr Average (ft^2)	Week 24 hr Average (ft^2)
Minimum	0.0	0.0	0.0	0.2	12.1	14.2
25% Quartile	1.7	1.9	3.3	5.0	16.4	16.5
50% Median	7.9	8.5	10.4	7.8	20.7	18.8
75% Quartile	17.5	19.2	19.2	23.9	33.6	28.7
Maximum	102.0	52.5	52.8	43.7	46.4	38.6

a.) 42 homes with no mechanical outdoor air systems and no nighttime ventilation cooling systems.
b.) 8 homes with operational mechanical ducted outdoor air (DOA) ventilation systems and no nighttime ventilation cooling systems.
c.) 3 homes with operational mechanical heat recovery ventilator (HRV) outdoor air ventilation systems and no nighttime ventilation cooling systems.

Building enclosure leakage

- All of the house groups had about the same range of building air tightness as tested by blower door, about 4 to 5 ach50, or 2 to 3 SLA.

Table 4. Building envelope air leakage area as calculated from building envelope depressurization tests and as expressed as ACH_{50} and SLA in new single-family detached homes in California with and without mechanical outdoor air ventilation.

	No Mechanical Outdoor Air [a] Homes (n=42)		DOA Mechanical Outdoor Air [b] Homes (n=7)		HRV Mechanical Outdoor Air [c] Homes (n=3)	
	ACH_{50} (ach)	SLA	ACH_{50} (ach)	SLA	ACH_{50} (ach)	SLA
Minimum	3.5	1.7	3.2	1.4	4.3	2.1
25% Quartile	4.0	2.4	4.0	2.5	4.4	2.2
50% Median	4.7	2.7	4.3	2.8	4.6	2.4
75% Quartile	5.3	3.0	5.0	3.0	4.8	2.6
Maximum	8.4	5.5	6.1	3.7	4.9	2.8

a.) 42 homes with no mechanical outdoor air systems and no nighttime ventilation cooling systems.
b.) 7 homes with operational mechanical ducted outdoor air (DOA) ventilation systems and no nighttime ventilation cooling systems (one home without blower door measurements excluded)
c.) 3 homes with operational mechanical heat recovery ventilator (HRV) outdoor air ventilation systems and no nighttime ventilation cooling systems.

Ventilation flow rates

- Houses with supply ventilation had about the same estimated outside air exchange rate as houses with no mechanical ventilation.
- Only one of the eight supply ventilation houses had a fan cycling control to assure a minimum fan duty cycle (11 minutes every 30). That house was lumped with all the others for reporting the air exchange results so there was no way to differentiate performance due to a programmed minimum fan duty cycle.
- The median estimated outside air flow rate for the supply systems was 40 cfm, and the median fan runtime was 18%. That was the equivalent of 7 cfm continuous.

Ventilation flow rates (cont.)

- The median outside air flow rate for the HRV houses was 153 cfm and 100% runtime. Therefore, the median HRV system delivered about 20 times more outside air than the median supply ventilation system over the test period.
- The median house size was 2,260 ft2, assuming 3 bedrooms, the median HRV ventilation rate was 3 times the 62.2 rate.

Table 3. Exhaust and outdoor air fan ventilation as expressed as expressed as the average air changes per hour (ach) over the 24-hour air quality sampling period as well as the average of the previous seven 24-hour periods in new single-family detached homes in California with and without mechanical outdoor air ventilation.

	No Mechanical Outdoor Air [a] Homes (n=42)	DOA Mechanical Outdoor Air [b] Homes (n=8)		HRV Mechanical Outdoor Air [c] Homes (n=3)	
	Exhaust Fan 24 hr Average (ach)	Exhaust Fan 24 hr Average (ach)	Mechanical Outdoor Air 24 hr Average (ach) / (%ON) / (cfm)	Exhaust Fan 24 hr Average (ach)	Mechanical Outdoor Air 24 hr Average (ach) / (%ON) / (cfm)
Minimum	0.00	0.00	0.00 / 0 / 27	0.11	0.12 / 32 / 149
25% Quartile	0.00	0.00	0.01 / 0 / 30	0.23	0.38 / 66 / 151
50% Median	0.01	0.00	0.02 / 18 / 40	0.35	0.44 / 100 / 153
75% Quartile	0.01	0.02	0.04 / 25 / 48	0.43	0.46 / 100 / 156
Maximum	0.10	0.03	0.07 / 40 / 71	0.51	0.47 / 100 / 159

a.) 42 homes with no mechanical outdoor air systems and no nighttime ventilation cooling systems.
b.) 8 homes with operational mechanical ducted outdoor air (DOA) ventilation systems and no nighttime ventilation cooling systems.
c.) 3 homes with operational mechanical heat recovery ventilator (HRV) outdoor air ventilation systems and no nighttime ventilation cooling systems.

PFT measured air change rate

- As measured by PFT, houses with the supply ventilation system had a slightly higher 24 hour average air exchange rate compared to houses with no mechanical outdoor air, 0.36 ach compared to 0.33 ach.
- Houses with HRV systems had four times that amount, 1.43 ach.
- In all, 50% of the 62 homes with PFT measurements had outdoor air exchanges rates below 0.35 ach.

Table 5. Average 24-hour outdoor air exchange rates as calculated from passive PFT tracer gas measurements in new single-family detached homes in California with and without mechanical outdoor air ventilation.

	No Mechanical Outdoor Air [a] Homes (n=41)	DOA Mechanical Outdoor Air [b] Homes (n=8)	HRV Mechanical Outdoor Air [c] Homes (n=3)
	Outdoor Air Exchange Rate (ach)	Outdoor Air Exchange Rate (ach)	Outdoor Air Exchange Rate (ach)
Minimum	0.13	0.10	0.33
25% Quartile	0.20	0.20	0.88
50% Median	0.33	0.36	1.43
75% Quartile	0.66	0.46	2.86
Maximum	6.47	0.58	4.28

a.) 41 homes with no mechanical outdoor air systems and no nighttime ventilation cooling systems (one home without a PFT measurement excluded).
b.) 8 homes with operational mechanical ducted outdoor air (DOA) ventilation systems and no nighttime ventilation cooling systems.
c.) 3 homes with operational mechanical heat recovery ventilator (HRV) outdoor air ventilation systems and no nighttime ventilation cooling systems.

Formaldehyde concentrations

- The median 24 hour average formaldehyde concentration was 38 µg/m^3 for the 42 houses with no mechanical ventilation. It was about 50% higher for the 7 houses with supply ventilation (59 µg/m^3), and about four times less for the 3 HRV houses (10 µg/m^3).
- In all, 62% of the 61 homes with formaldehyde measurements had indoor concentrations that exceeded the California Air Resources Board exposure guideline of 33 µg/m^3.

Table 6. Average 24-hour indoor formaldehyde concentrations in new single-family detached homes in California with and without mechanical outdoor air ventilation.

	No Mechanical Outdoor Air [a] Homes (n=42)	DOA Mechanical Outdoor Air [c] Homes (n=7)	HRV Mechanical Outdoor Air [c] Homes (n=3)	Outdoor All [d] Homes (n=23)
	Indoor Formaldehyde Concentrations (µg/m^3)	Indoor Formaldehyde Concentrations (µg/m^3)	Indoor Formaldehyde Concentrations (µg/m^3)	Outdoor Formaldehyde Concentrations (µg/m^3)
Minimum	4.7	34.6	7.8	0.7
25% Quartile	22.2	42.2	8.9	1.5
50% Median	38.3	58.5	10.0	2.2
75% Quartile	73.8	87.0	23.4	3.1
Maximum	143.6	135.5	36.7	8.0

a.) 42 homes with no mechanical outdoor air systems and no nighttime ventilation cooling systems.
b.) 7 homes with operational mechanical ducted outdoor air (DOA) ventilation systems and no nighttime ventilation cooling systems (one home with a formaldehyde sample failure excluded)
c.) 3 homes with operational mechanical heat recovery ventilator (HRV) outdoor air ventilation systems and no nighttime ventilation cooling systems.

Discussion?

Building Science Consortium

Appendix E: Presentation 2: Room Air Temperature Uniformity of a Forced-Air System Relative to Runtime, presented by Bill Rittelmann

Room Air Temperature Uniformity of a Forced-Air System Relative to Runtime

BA Ventilation Experts Meeting
January 18, 2008
IBACOS, Inc.
Bill Rittelmann

Overview

- Project Description
- Runtime vs. Temperature Uniformity
- Ventilation Tracer Gas
- Conclusions

Project Overview

- Project Partners – Carrier Corporation and Cardinal Glass
- Features – Redundant forced-air systems in high-performance house – Perimeter floor and high sidewall
- Focus – Thermal comfort performance of high sidewall diffusers using low-temperature supply air in the heating mode
- Target Climates – All climates requiring heat
- Location – Fort Wayne, IN

Floor Diffuser System

- 2-stage gas-fired furnaces were installed that are capable of delivering supply air temperatures as low as 95ºF (25ºF rise @ 70ºF).
- Fancoil is setup to supply air at 84ºF, 99ºF, & 113ºF at a constant volume of 1100 cfm, which is equal to cooling.

Space Conditioning in High Performance Homes IBACOS

High Sidewall SAO System

Ductwork inside envelope

Adjustable Vane Diffusers

Space Conditioning in High Performance Homes IBACOS

High Sidewall SAO System

- Diffusers were mounted near interior walls and sized using current ASHRAE guidelines for cooling
- $T_{50} / L = 1.5$
- To achieve required throw velocity, only one diffuser per room was used

Space Conditioning in High Performance Homes IBACOS

High Sidewall SAO System

Room airflows were calculated as an average of the peak heating and cooling room airflows.

Each diffuser was balanced to achieve the desired flow

$$CFM_{bal} = \frac{CFM_{Hpeak} + CFM_{Cpeak}}{2}$$

Space Conditioning in High Performance Homes

IBACOS

Standards & Guidelines

ACCA – Manual D, Residential Duct Systems

This reference can't be found in Manual B.

Manual B (Principles of Air Conditioning) is no longer published by ACCA.

It was last published in 1970.

…there should not be more than a 2ºF temperature difference between any two rooms. However, as explained below, it is difficult, if not impossible, to satisfy this requirement with a single zone air distribution system for some homes. (As per ***Manual B****, 2ºF is ideal, but the maximum allowable difference is equal to 4ºF).*

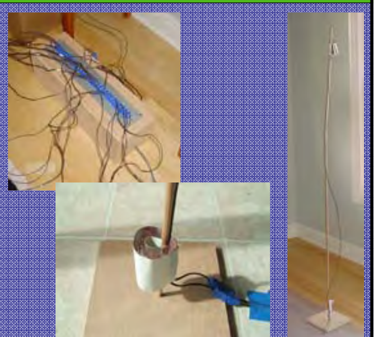
Space Conditioning in High Performance Homes

IBACOS

Temperature Measurements

Test measures a volumetric grid of air temperatures to determine temperature distribution in a room relative to system operation and load

Apparatus is designed for quick assembly and compliance with ASHRAE measurement protocols



Space Conditioning in High Performance Homes

IBACOS

Current Research

Heating Season Cases

- Fancoil/High Sidewall Diffusers
  - Stage 1, 1,222 CFM, 5 kW
  - Stage 2, 1,222 CFM, 10 kW
  - Stage 3, 1,222 CFM, 15 kW
- Furnace/Floor Diffusers
  - Stage 1, 474 CFM
  - Stage 2, 680 CFM

Space Conditioning in High Performance Homes

IBACOS

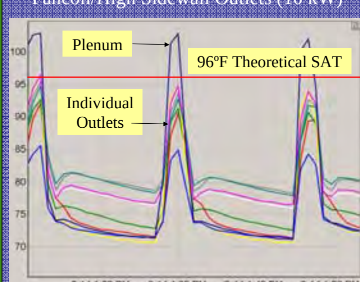
High Sidewall SAO System

Outlet temperatures approach steady-state by end of cycle and are relatively equal

Plenum temperature is high due to location of sensor relative to heating coils

1,222 cfm

Heating Supply Air Temperatures
Fancoil/High Sidewall Outlets (10 kW)



Space Conditioning in High Performance Homes

IBACOS

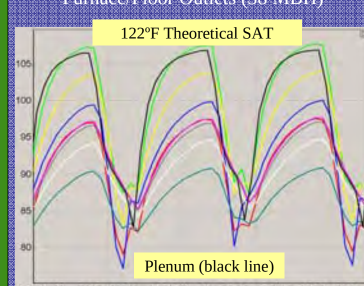
Floor Diffuser System

Outlet temperatures are nowhere near steady-state by end of cycle and the are relatively diverse

Duct mass, thermal losses, and low outlet velocity leads to longer cycles

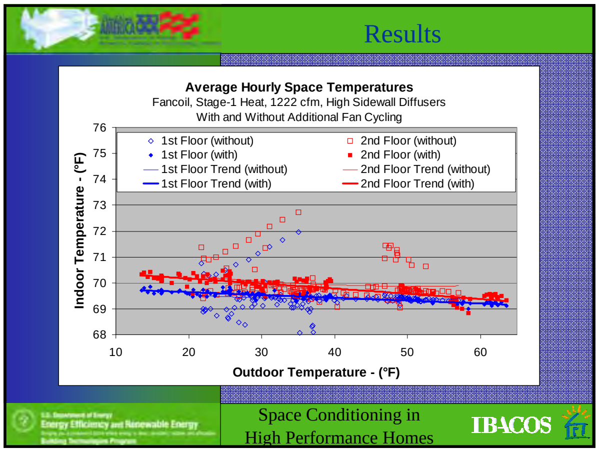
680 cfm

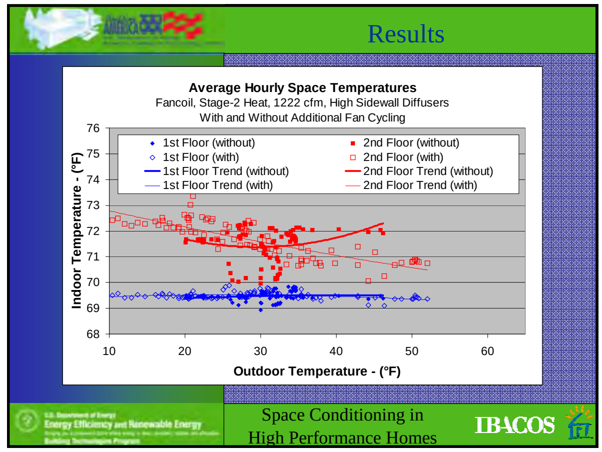
Heating Supply Air Temperatures
Furnace/Floor Outlets (38 MBH)

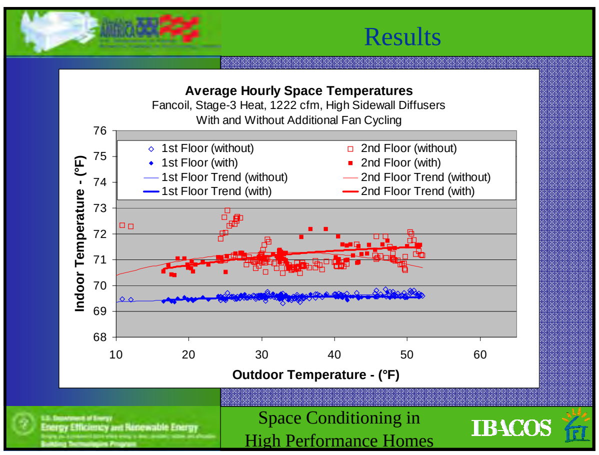


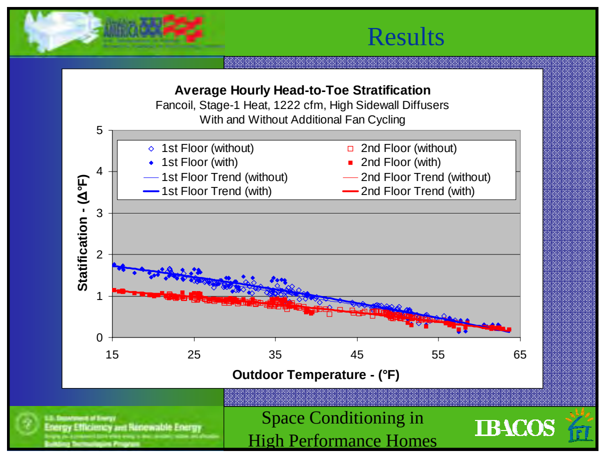
Space Conditioning in High Performance Homes

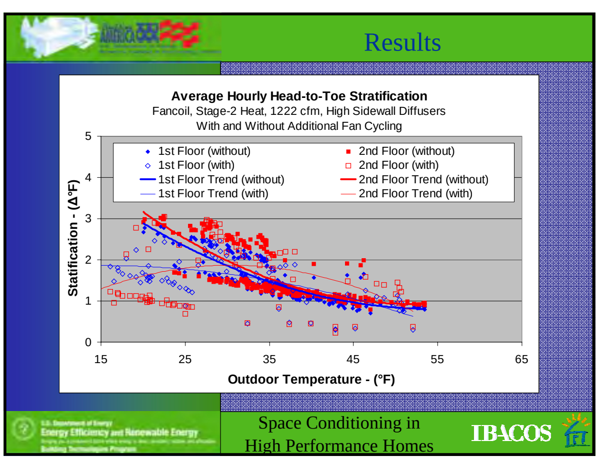
IBACOS


Results
Average Hourly Space Temperatures
Fancoil, Stage-1 Heat, 1222 cfm, High Sidewall Diffusers
With and Without Additional Fan Cycling
1st Floor (without)
1st Floor (with)
1st Floor Trend (without)
1st Floor Trend (with)
2nd Floor (without)
2nd Floor (with)
2nd Floor Trend (without)
2nd Floor Trend (with)
Indoor Temperature - (°F)
Outdoor Temperature - (°F)
Space Conditioning in
High Performance Homes
IBACOS


Results
Average Hourly Space Temperatures
Fancoil, Stage-2 Heat, 1222 cfm, High Sidewall Diffusers
With and Without Additional Fan Cycling
1st Floor (without)
1st Floor (with)
1st Floor Trend (without)
1st Floor Trend (with)
2nd Floor (without)
2nd Floor (with)
2nd Floor Trend (without)
2nd Floor Trend (with)
Indoor Temperature - (°F)
Outdoor Temperature - (°F)
Space Conditioning in
High Performance Homes
IBACOS


Results
Average Hourly Space Temperatures
Fancoil, Stage-3 Heat, 1222 cfm, High Sidewall Diffusers
With and Without Additional Fan Cycling
1st Floor (without)
1st Floor (with)
1st Floor Trend (without)
1st Floor Trend (with)
2nd Floor (without)
2nd Floor (with)
2nd Floor Trend (without)
2nd Floor Trend (with)
Indoor Temperature - (°F)
Outdoor Temperature - (°F)
Space Conditioning in
High Performance Homes
IBACOS


Results
Average Hourly Head-to-Toe Stratification
Fancoil, Stage-1 Heat, 1222 cfm, High Sidewall Diffusers
With and Without Additional Fan Cycling
1st Floor (without)
1st Floor (with)
1st Floor Trend (without)
1st Floor Trend (with)
2nd Floor (without)
2nd Floor (with)
2nd Floor Trend (without)
2nd Floor Trend (with)
Statification - (Δ°F)
Outdoor Temperature - (°F)
Space Conditioning in
High Performance Homes
IBACOS


Results
Average Hourly Head-to-Toe Stratification
Fancoil, Stage-2 Heat, 1222 cfm, High Sidewall Diffusers
With and Without Additional Fan Cycling
1st Floor (without)
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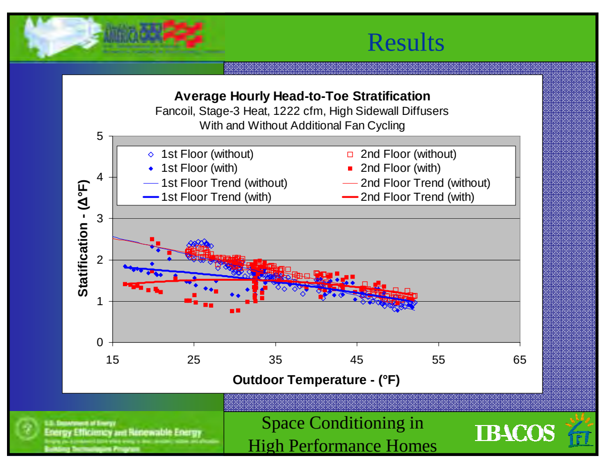
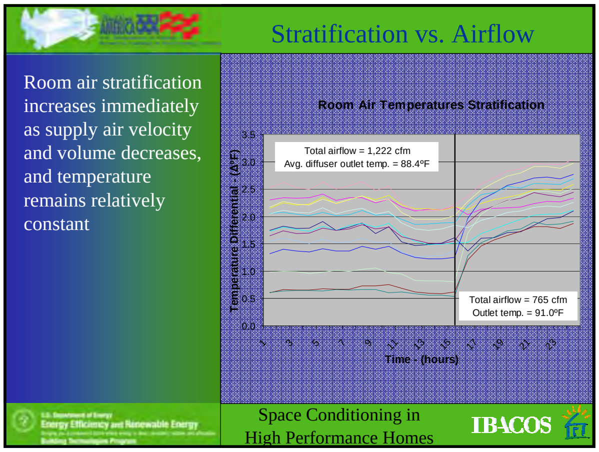
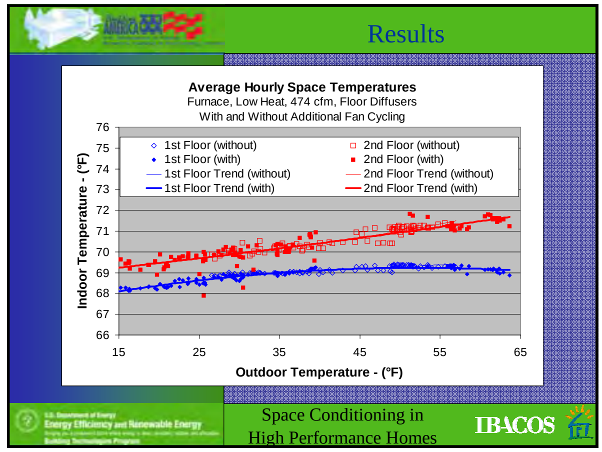
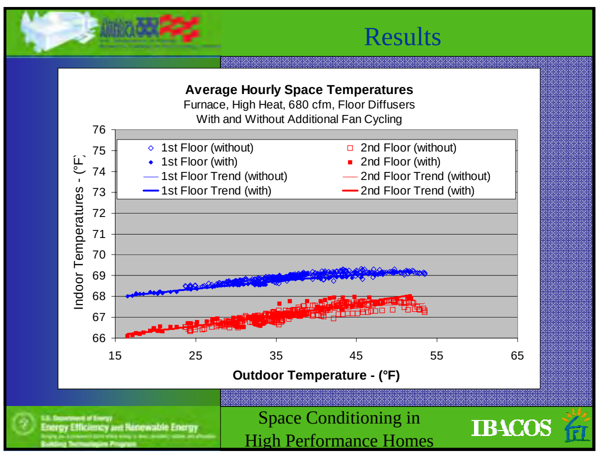
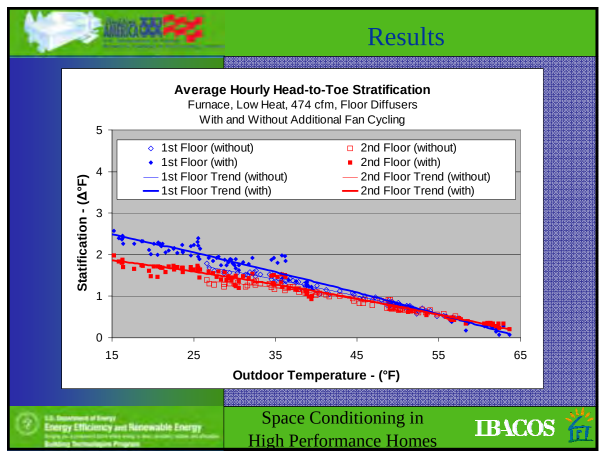
1st Floor Trend (with)
2nd Floor (without)
2nd Floor (with)
2nd Floor Trend (without)
2nd Floor Trend (with)
Statification - (Δ°F)
Outdoor Temperature - (°F)
Space Conditioning in
High Performance Homes
IBACOS

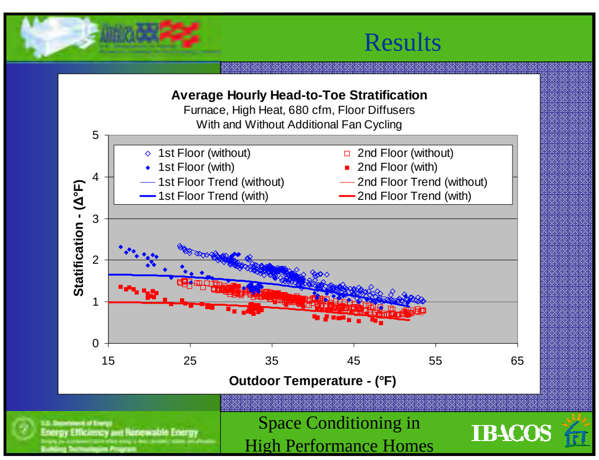

Results
Average Hourly Head-to-Toe Stratification
Fancoil, Stage-3 Heat, 1222 cfm, High Sidewall Diffusers
With and Without Additional Fan Cycling
1st Floor (without)
1st Floor (with)
1st Floor Trend (without)
1st Floor Trend (with)
2nd Floor (without)
2nd Floor (with)
2nd Floor Trend (without)
2nd Floor Trend (with)
Statification - (Δ°F)
Outdoor Temperature - (°F)
Space Conditioning in
High Performance Homes
IBACOS

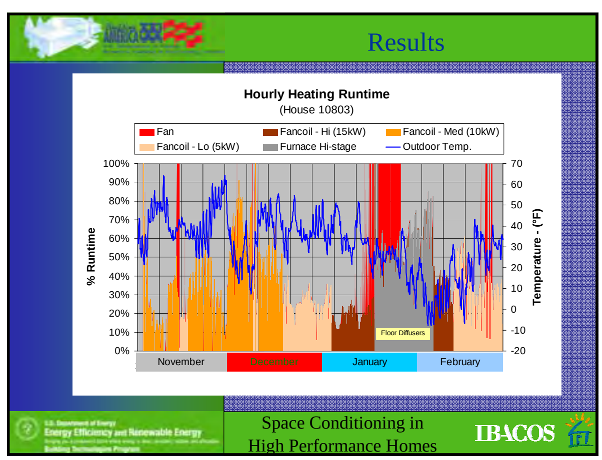

Stratification vs. Airflow
Room air stratification increases immediately as supply air velocity and volume decreases, and temperature remains relatively constant
Room Air Temperatures Stratification
Total airflow = 1,222 cfm
Avg. diffuser outlet temp. = 88.4°F
Total airflow = 765 cfm
Outlet temp. = 91.0°F
Temperature Differential - (Δ°F)
Time - (hours)
Space Conditioning in
High Performance Homes
IBACOS


Results
Average Hourly Space Temperatures
Furnace, Low Heat, 474 cfm, Floor Diffusers
With and Without Additional Fan Cycling
1st Floor (without)
2nd Floor (without)
1st Floor (with)
2nd Floor (with)
1st Floor Trend (without)
2nd Floor Trend (without)
1st Floor Trend (with)
2nd Floor Trend (with)
Indoor Temperature - (°F)
Outdoor Temperature - (°F)
Space Conditioning in
High Performance Homes
IBACOS

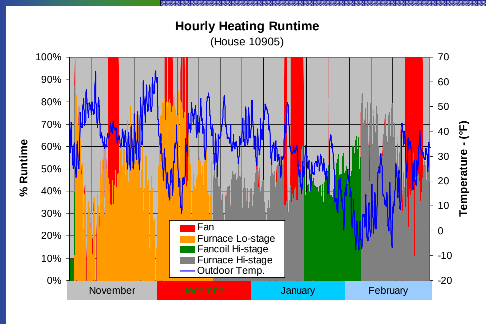

Results
Average Hourly Space Temperatures
Furnace, High Heat, 680 cfm, Floor Diffusers
With and Without Additional Fan Cycling
1st Floor (without)
2nd Floor (without)
1st Floor (with)
2nd Floor (with)
1st Floor Trend (without)
2nd Floor Trend (without)
1st Floor Trend (with)
2nd Floor Trend (with)
Indoor Temperatures - (°F)
Outdoor Temperature - (°F)
Space Conditioning in
High Performance Homes
IBACOS


Results
Average Hourly Head-to-Toe Stratification
Furnace, Low Heat, 474 cfm, Floor Diffusers
With and Without Additional Fan Cycling
1st Floor (without)
2nd Floor (without)
1st Floor (with)
2nd Floor (with)
1st Floor Trend (without)
2nd Floor Trend (without)
1st Floor Trend (with)
2nd Floor Trend (with)
Stratification - (Δ°F)
Outdoor Temperature - (°F)
Space Conditioning in
High Performance Homes
IBACOS


Results
Average Hourly Head-to-Toe Stratification
Furnace, High Heat, 680 cfm, Floor Diffusers
With and Without Additional Fan Cycling
1st Floor (without)
2nd Floor (without)
1st Floor (with)
2nd Floor (with)
1st Floor Trend (without)
2nd Floor Trend (without)
1st Floor Trend (with)
2nd Floor Trend (with)
Statification - (Δ°F)
Outdoor Temperature - (°F)
Space Conditioning in
High Performance Homes
IBACOS


Results
Hourly Heating Runtime
(House 10803)
Fan
Fancoil - Hi (15kW)
Fancoil - Med (10kW)
Fancoil - Lo (5kW)
Furnace Hi-stage
Outdoor Temp.
% Runtime
Temperature - (°F)
Floor Diffusers
November
December
January
February
Space Conditioning in
High Performance Homes
IBACOS

Results



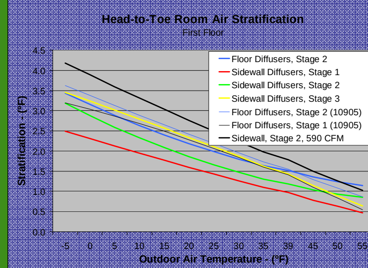
Space Conditioning in High Performance Homes

IBACOS

Summary

All conditions were well within ASHRAE criteria of 3ºC (5.4ºF)

First and second stage of the high sidewall system outperformed the floor outlet system due to lower outlet temperatures



Space Conditioning in High Performance Homes

IBACOS

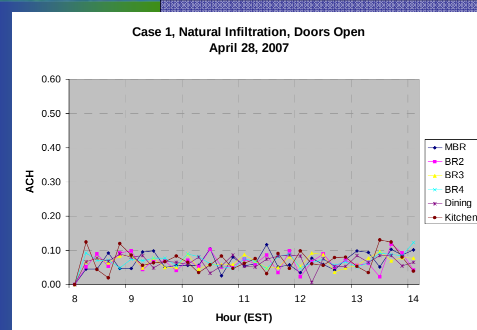
Tracer Gas Results

Case	Central Air (cfm)	Ventilation		Interior Doors
		Supply (cfm)	Exhaust (cfm)	
1	**0**	**0**	**0**	**Open**
2	**0**	**0**	**0**	**Closed**
3	350	70	0	Open
4	**350**	**70**	**0**	**Closed**
5	350	70	Up Bath	Open
6	350	70	Up Bath	Closed
7	350	70	Down Bath	Open
8	**350**	**70**	**Down Bath**	**Closed**
9	**350**	**0**	**70**	**Closed**
10	**350**	**0**	**0**	**Closed**
11	**350**	***70***	**0**	**Closed**
12	**0**	**0**	**55**	**Closed**

Space Conditioning in High Performance Homes

IBACOS

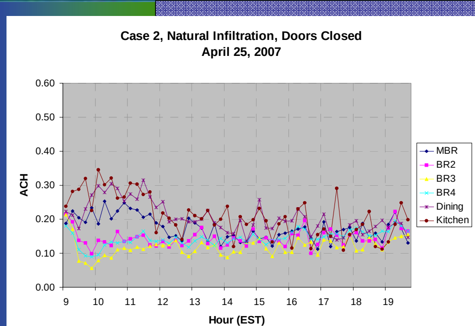
Tracer Gas Results



Space Conditioning in High Performance Homes

IBACOS

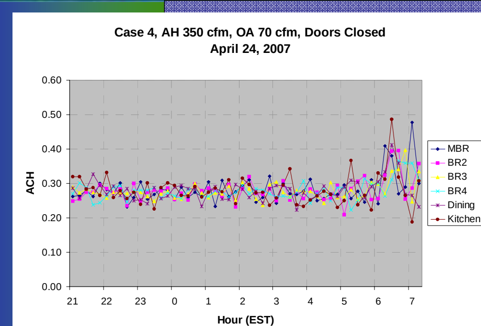
Tracer Gas Results



Space Conditioning in High Performance Homes

IBACOS

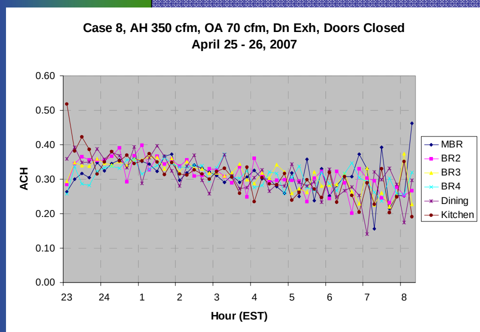
Tracer Gas Results



Space Conditioning in High Performance Homes

IBACOS

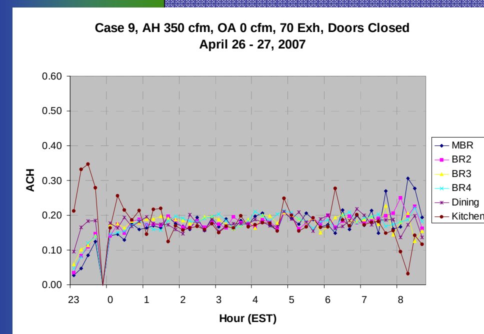
Tracer Gas Results



Space Conditioning in High Performance Homes

IBACOS

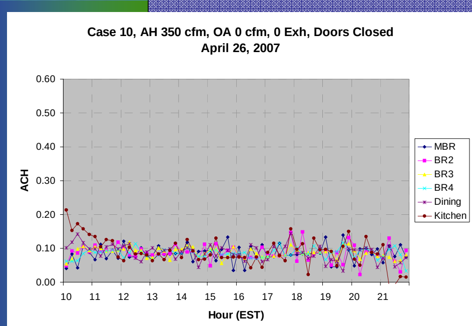
Tracer Gas Results



Space Conditioning in High Performance Homes

IBACOS

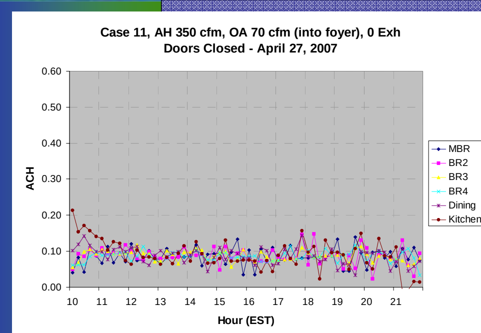
Tracer Gas Results



Space Conditioning in High Performance Homes

IBACOS

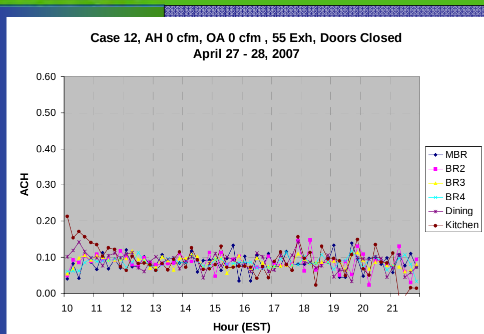
Tracer Gas Results



Space Conditioning in High Performance Homes

IBACOS

Tracer Gas Results



Space Conditioning in High Performance Homes

IBACOS

Conclusions

Additional fan operation appears to:

Reduce extreme space temperature excursions under most operating conditions, but general trends are not noticeably affected

Reduce head-to-toe temperature stratification under almost all operating conditions – more noticeable at higher supply air temperatures and lower outdoor air temperatures.

Space Conditioning in High Performance Homes

IBACOS

Conclusions

Additional fan operation appears to:

Be less effective in “ironing out” temperature differences using floor diffusers.

Space Conditioning in High Performance Homes

IBACOS

Conclusions

Tracer Gas

Continuous low-volume central air provides adequate and uniform distribution of ventilation air when OA is injected into return air stream

Single-point unbalanced ventilation systems appear to be only marginally effective whether they are supply or exhaust

Space Conditioning in High Performance Homes

IBACOS

Appendix F: Presentation 3: CFD Evaluation of Air Distribution Systems for Residential Forced Air Systems in Cold Climates, presented by Keith Gawlik

CFD Evaluation of Air Distribution Systems for Residential Forced Air Systems in Cold Climates

Keith Gawlik
NREL

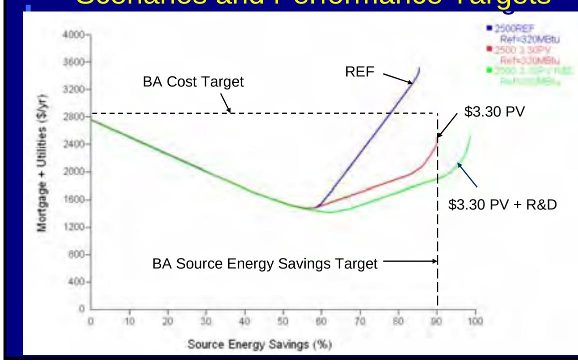
Outline

- Context of this project in ZEH research
- Review of past simulation work
- Results and correlation development
- Comparisons between test and simulation

Background

- Neutral cost of ZEH by 2020
- Improved shell (R30-R60-R5) + best available equipment = 50% by 2015
- ZEH shell + PV + ZEH systems by 2020

Scenarios and Performance Targets



How to maintain comfort?

- ZEH shells:
  - 50% less HVAC capacity
  - 50% smaller duct cross sections and registers
  - 50% less CFM
- Need integrated comfort conditioning for thermal, odor, humidity control

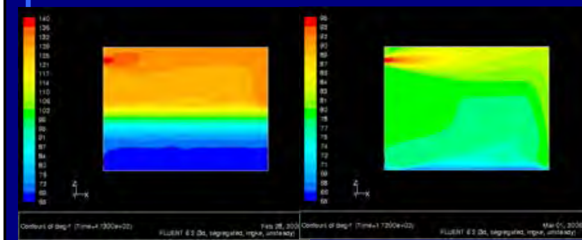
A least cost option

- Use A/C system for integrated comfort conditioning
- 80% market penetration of A/C, so systems available
- Uniform distribution of ventilation air

Major barriers

- Heating airflows less than cooling airflows
- Good supply air mixing not assured in heating mode unless carefully designed
- Stratification possible

Good air mixing required



Stratified Well mixed

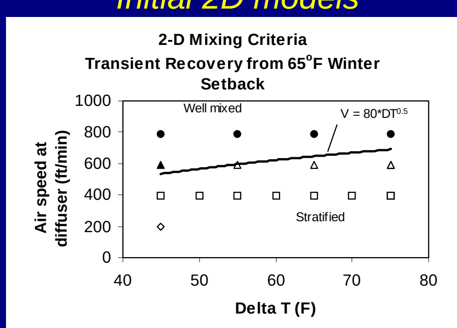
Objective

Develop demonstrated numerical models in collaboration with IBACOS to provide initial design guidance on mixing performance and direct experimental plans

Past work

- Recovery from 65ºF setback
- Variety of room sizes, diffuser sizes, air flowrates, supply temperatures
- 2D and 3D models
- Performance parameters defined
- Correlation developed

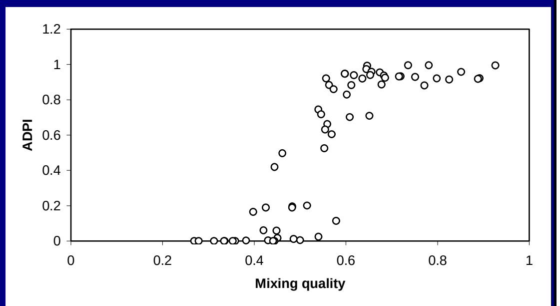
Initial 2D models



Performance criteria

- Displacement efficiency, η_d
- Mixing quality $Q = (1 - \eta_d)/(0.368)$
- Air diffuser performance index (ADPI)
  - Draft temperature between -1.5º and 1ºC
    $$\theta = T - T_{avg} - 8(V - 0.15)$$
  - Air speed less than 0.35 m/s

3D model results

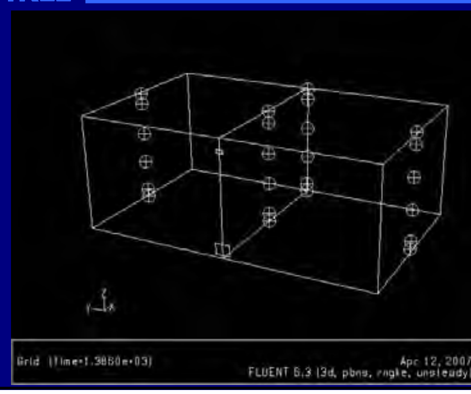


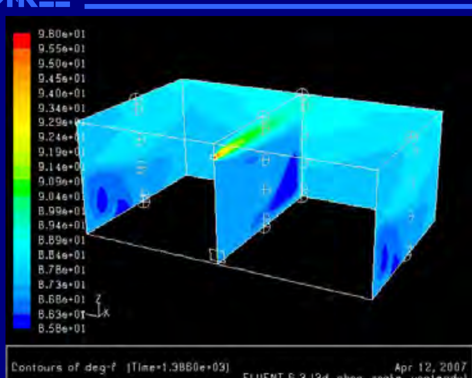
Comparison between test and simulation

- Experimental data from Ventilation Test Facility
- Field test data from IBACOS and Cardinal Glass house in Ft. Wayne

NREL Ventilation Test Room

- Two cases chosen for modeling
- Low flow, high temp. (L3)
  - 87 cfm, 102ºF SAT
- Medium flow, low temp. (M2)
  - 122 cfm, 96ºF SAT

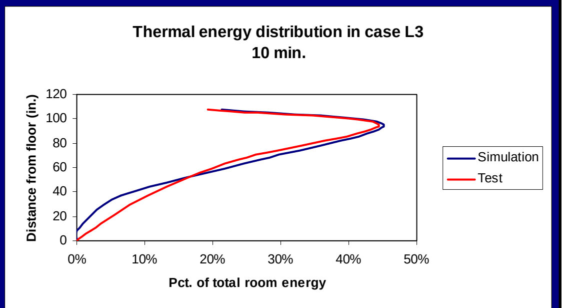




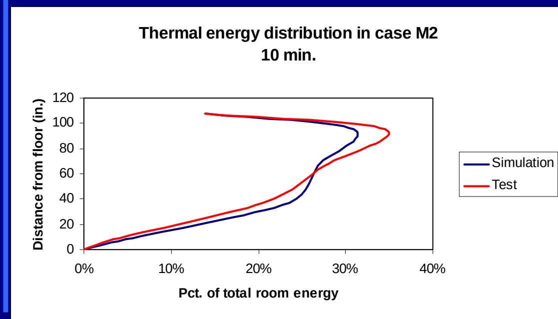
NREL Ventilation Test Room

- Stratification effects explored via relative energy content in room

NREL Ventilation Test Room



NREL Ventilation Test Room



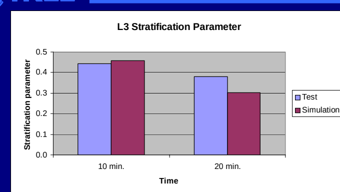
NREL Ventilation Test Room

- Stratification parameter:

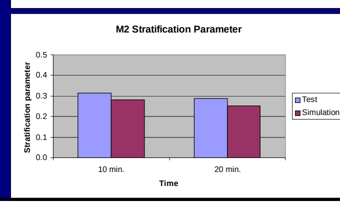
$(T_{ceiling}-T_{floor})/T_{weighted\ average}$

0: perfectly mixed

>1: extremely stratified



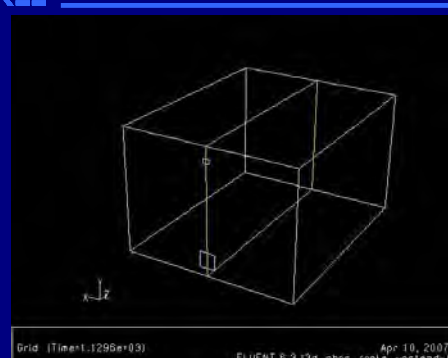
L3: 3 % diff. at 10 min.

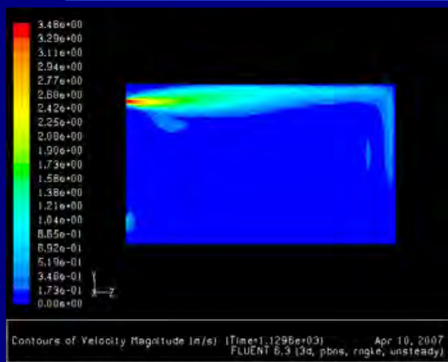


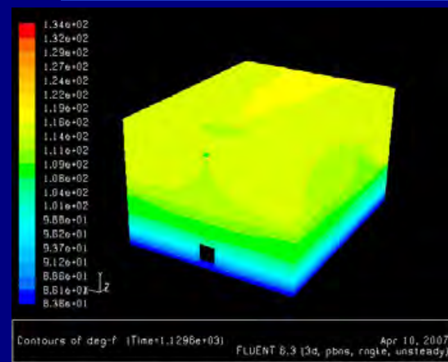
M2: -11 % diff. at 10 min.

Ft. Wayne Test Room

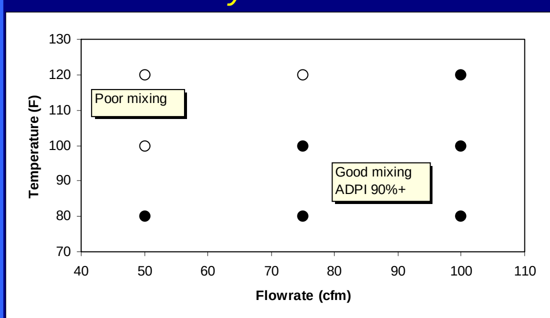
- Bedroom supplied by single 6" by 4" high sidewall diffuser
- Range of flowrates modeled (design 71 cfm)
- Supply temperatures fixed and functions of return temperature







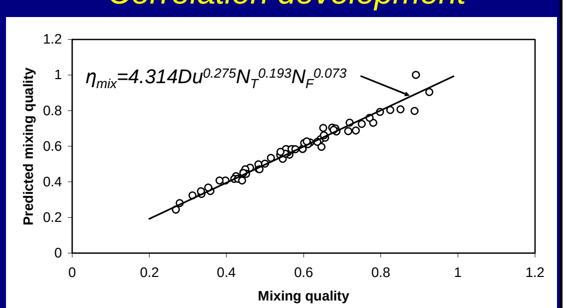
Ft. Wayne Test Room



Correlation development

- Geometry
  - Duct fineness ratio, N_F = *(height/width)*
  - Isothermal throw ratio, N_T = *(X/L),*
- Air kinetic energy / thermal energy, $Du=V^2/\{c_p(T-T_o)\}$

Correlation development



Summary

- 2D and 3D models developed and used to predict mixing performance
- Good agreement between simple model and ventilation test room data

Future work

- Compare model to Ft. Wayne data
- Determine thermostatic control effects for select cases
- Develop design guidelines

Appendix G: Presentation 4: Update on Results of Field Measurements and CONTAM Simulations, presented by Aaron Townsend

Update on Results of Field Measurements and CONTAM Simulations

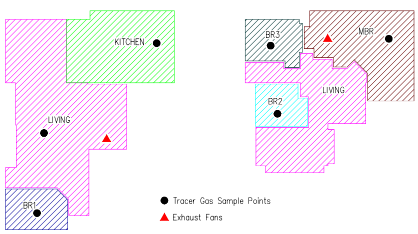
Aaron Townsend

January 18, 2008

Tracer Gas Testing Sacramento January 2006

- Tracer gas test of production Building America house in Sacramento
- 2-story, 4 bedrooms, ~2500 square feet
- Supply and exhaust ventilation tested, with and without mixing via central air handler
- Each test 4-14 hours long

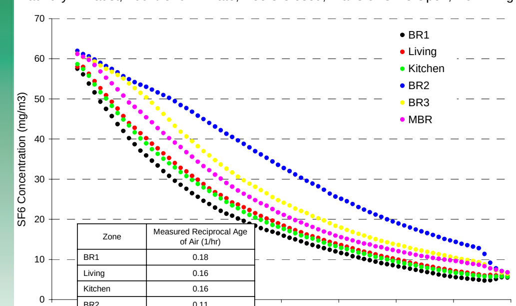
Zones – 2 Story House



- These were tracer gas decay tests—establish uniform concentration of tracer gas and then activate ventilation system to remove it.
- Reciprocal age-of-air can be calculated from decay curves (if weather conditions are sufficiently constant)

Example Results of Sacramento Tracer Gas Testing

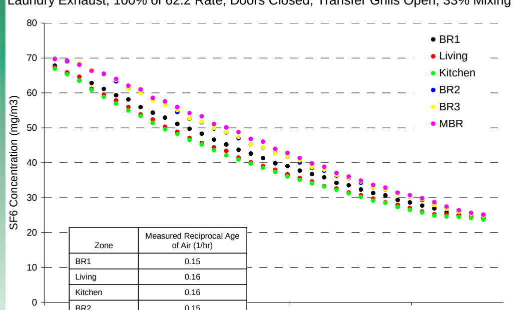
Laundry Exhaust, 100% of 62.2 Rate, Doors Closed, Transfer Grills Open, No Mixing



Zone	Measured Reciprocal Age of Air (1/hr)
BR1	0.18
Living	0.16
Kitchen	0.16
BR2	0.11
BR3	0.13
MBR	0.14

Example Results of Sacramento Tracer Gas Testing

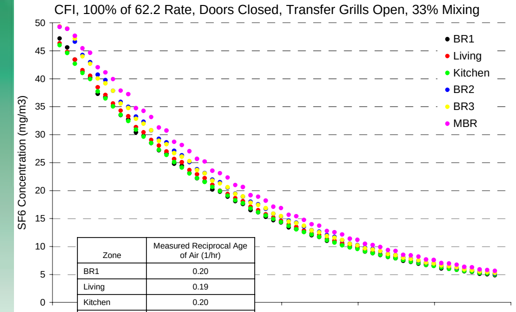
Laundry Exhaust, 100% of 62.2 Rate, Doors Closed, Transfer Grills Open, 33% Mixing



Zone	Measured Reciprocal Age of Air (1/hr)
BR1	0.15
Living	0.16
Kitchen	0.16
BR2	0.15
BR3	0.15
MBR	0.14

Example Results of Sacramento Tracer Gas Testing

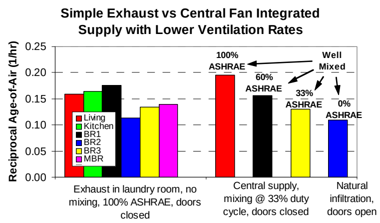
CFI, 100% of 62.2 Rate, Doors Closed, Transfer Grills Open, 33% Mixing



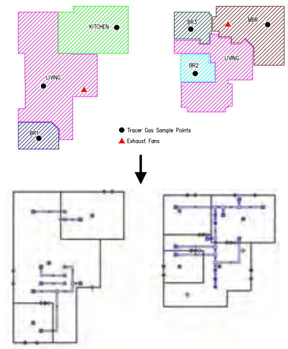
Zone	Measured Reciprocal Age of Air (1/hr)
BR1	0.20
Living	0.19
Kitchen	0.20
BR2	0.20
BR3	0.20
MBR	0.19

Conclusions From Sacramento Tracer Gas Testing

- Mixing is very important to whole-house and individual zone pollutant decay rate
- Supply ventilation is slightly more effective than exhaust ventilation, even with mixing
- The location of a single-point ventilation system affects the performance but the effect is not predictable



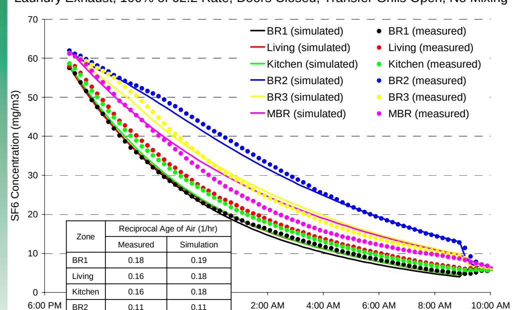
CONTAM Modeling, Nov. 2006-Jan. 2007



Computer modeling used to replicate field testing (tune the model) and predict performance of systems not tested in the field

Example Results of Tuned CONTAM Model

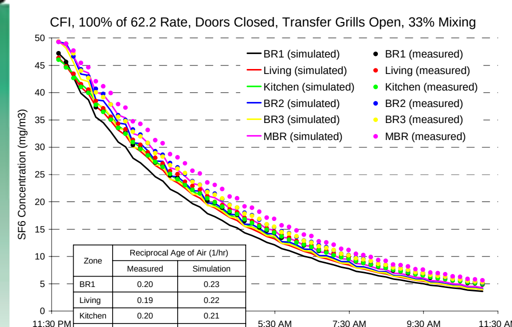
Laundry Exhaust, 100% of 62.2 Rate, Doors Closed, Transfer Grills Open, No Mixing



Zone	Reciprocal Age of Air (1/hr)	
	Measured	Simulation
BR1	0.18	0.19
Living	0.16	0.18
Kitchen	0.16	0.18
BR2	0.11	0.11
BR3	0.13	0.13
MBR	0.14	0.13

Example Results of Tuned CONTAM Model

CFI, 100% of 62.2 Rate, Doors Closed, Transfer Grills Open, 33% Mixing

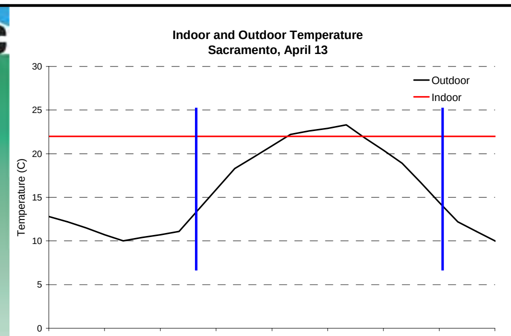


Zone	Reciprocal Age of Air (1/hr)	
	Measured	Simulation
BR1	0.20	0.23
Living	0.19	0.22
Kitchen	0.20	0.21
BR2	0.20	0.22
BR3	0.20	0.22
MBR	0.19	0.21

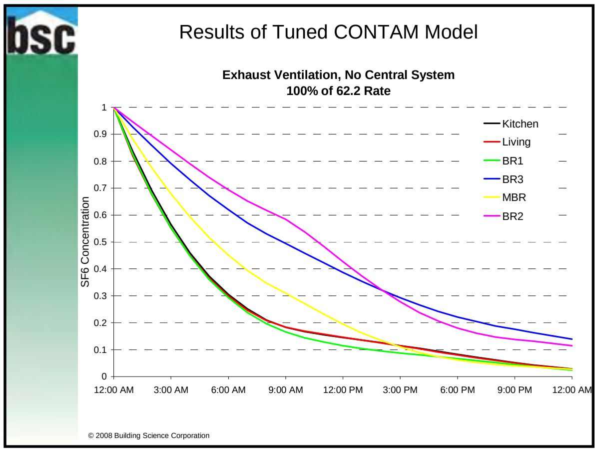
Tuned CONTAM Model Applied to Other Systems

Six Systems Evaluated & Compared:

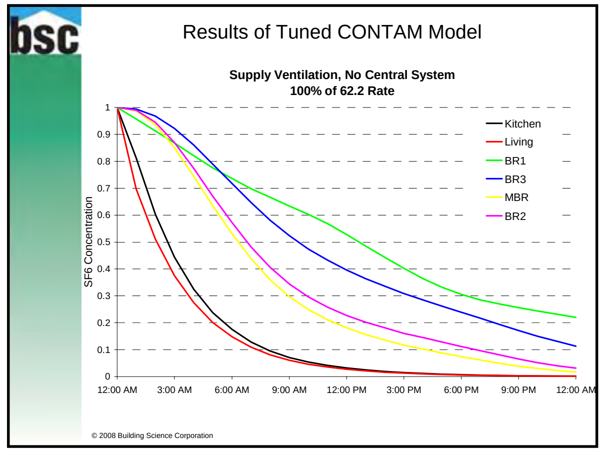
1. Exhaust ventilation, without central duct system
2. Supply ventilation, without central duct system
3. Exhaust ventilation, with central ducts, AHU controlled by standard thermostat
4. Exhaust ventilation, with central ducts, AHU controlled by thermostat with timer
5. Supply ventilation, with central ducts, AHU controlled by thermostat with timer
6. Fully ducted balanced ventilation system, without central duct system



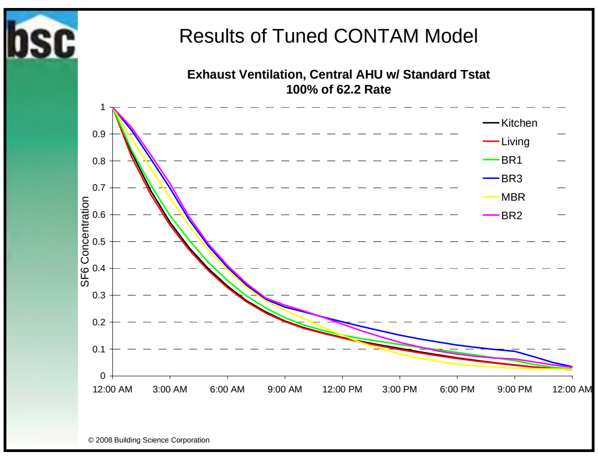
Simulation allows identical weather conditions for each system (generally not possible in field tests).



bsc
Results of Tuned CONTAM Model
Exhaust Ventilation, No Central System
100% of 62.2 Rate
SF6 Concentration
Kitchen
Living
BR1
BR3
MBR
BR2
12:00 AM 3:00 AM 6:00 AM 9:00 AM 12:00 PM 3:00 PM 6:00 PM 9:00 PM 12:00 AM
© 2008 Building Science Corporation



bsc
Results of Tuned CONTAM Model
Supply Ventilation, No Central System
100% of 62.2 Rate
SF6 Concentration
Kitchen
Living
BR1
BR3
MBR
BR2
12:00 AM 3:00 AM 6:00 AM 9:00 AM 12:00 PM 3:00 PM 6:00 PM 9:00 PM 12:00 AM
© 2008 Building Science Corporation



bsc
Results of Tuned CONTAM Model
Exhaust Ventilation, Central AHU w/ Standard Tstat
100% of 62.2 Rate
SF6 Concentration
Kitchen
Living
BR1
BR3
MBR
BR2
12:00 AM 3:00 AM 6:00 AM 9:00 AM 12:00 PM 3:00 PM 6:00 PM 9:00 PM 12:00 AM
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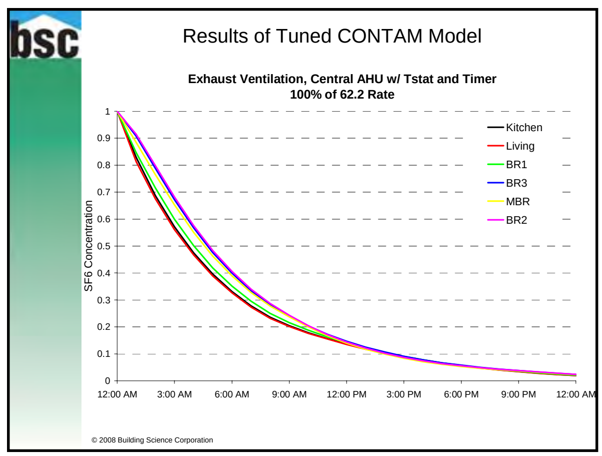

bsc
Results of Tuned CONTAM Model
Exhaust Ventilation, Central AHU w/ Tstat and Timer
100% of 62.2 Rate
SF6 Concentration
Kitchen
Living
BR1
BR3
MBR
BR2
12:00 AM 3:00 AM 6:00 AM 9:00 AM 12:00 PM 3:00 PM 6:00 PM 9:00 PM 12:00 AM
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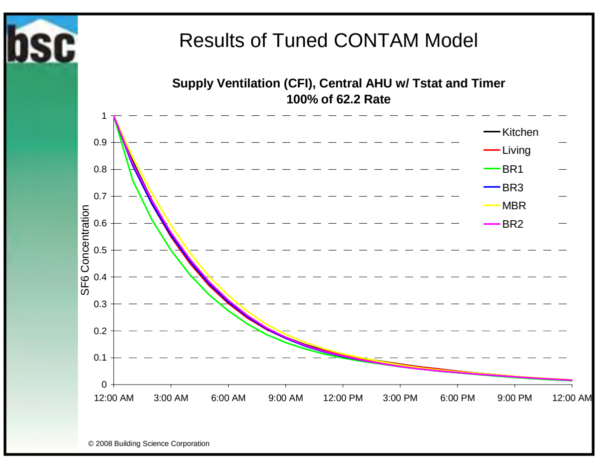

bsc
Results of Tuned CONTAM Model
Supply Ventilation (CFI), Central AHU w/ Tstat and Timer
100% of 62.2 Rate
SF6 Concentration
Kitchen
Living
BR1
BR3
MBR
BR2
12:00 AM 3:00 AM 6:00 AM 9:00 AM 12:00 PM 3:00 PM 6:00 PM 9:00 PM 12:00 AM
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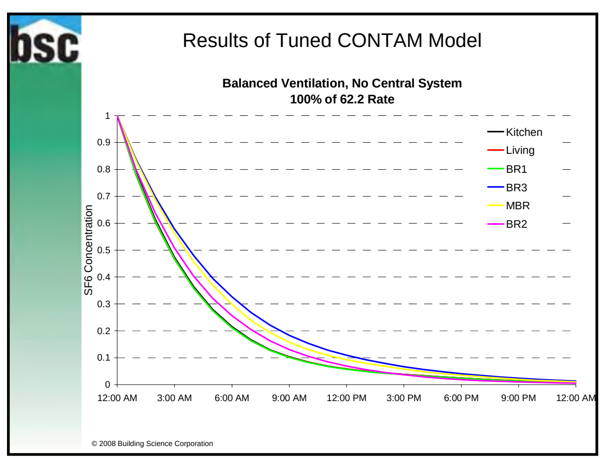

bsc
Results of Tuned CONTAM Model
Balanced Ventilation, No Central System
100% of 62.2 Rate
SF6 Concentration
Kitchen
Living
BR1
BR3
MBR
BR2
12:00 AM 3:00 AM 6:00 AM 9:00 AM 12:00 PM 3:00 PM 6:00 PM 9:00 PM 12:00 AM
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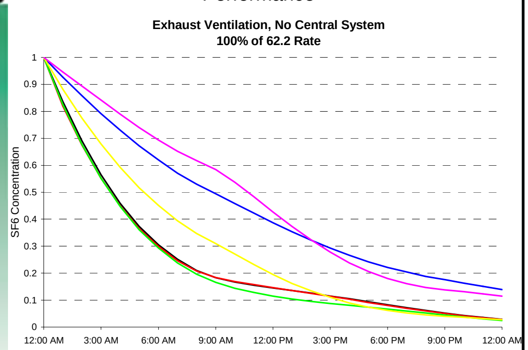
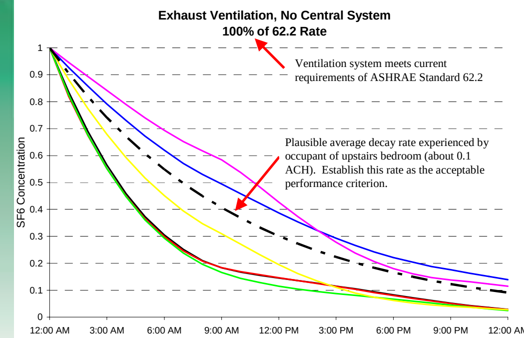
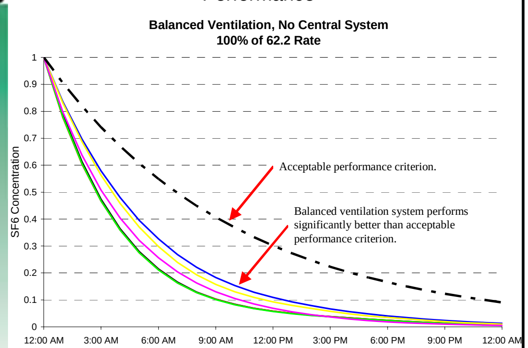
Adjusting Ventilation Rate to Achieve Equivalent Performance



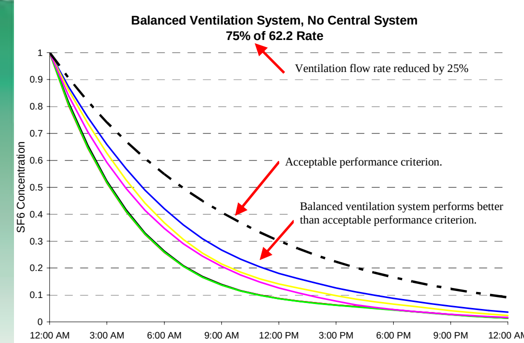
Adjusting Ventilation Rate to Achieve Equivalent Performance



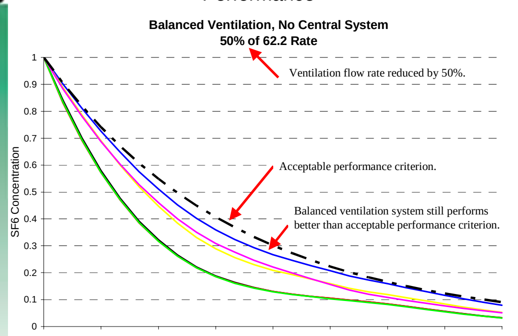
Adjusting Ventilation Rate to Achieve Equivalent Performance



Adjusting Ventilation Rate to Achieve Equivalent Performance



Adjusting Ventilation Rate to Achieve Equivalent Performance



Conclusions from Tuned CONTAM Model

1. Ventilation systems do not perform equally just because they have equal nominal airflow
2. Airflow requirements can be adjusted based on performance of each system
3. Further simulations were needed to predict year-round performance for general guidance
4. Can we create a “distribution coefficient” to modify the required airflow?

Next Steps

1. Comparison of 1 day in 1 house in 1 climate is useful but needs to be expanded before establishing general guidelines.
2. Expand modeling from 1 day in 1 house in 1 climate to full-year with various house characteristics (leakage, mechanical systems, etc) and different climates.
3. Methodology of simulations changed from decay to exposure
   1. Uniform generation of pollutant within house
   2. Assumed occupancy schedule
   3. Calculated 3-hr, 8-hr, and yearly average exposures

Model Characteristics

1. Specific model became more general
2. Vary certain parameters to cover reasonable subset of current construction
3. Include effects of:
   1. Wind
   2. Stack effect
   3. Ventilation systems
   4. Occupant schedule
   5. Pollutant generation

Modeling Assumptions: Weather

1. Temperature
   1. Outdoor temperature from TMY2 data
   2. Indoor temperature constant at 22 C
2. Wind
   1. Wind speed and direction from TMY2 data
   2. Wind shielding model and modifiers as described in ASHRAE Fundamentals 2005 Chapters 16 and 27 for typical suburban surroundings

Model Assumptions: Air Handler

1. Sizing per Manual J for each climate
2. Duty cycle each hour based on temperature and design temperature for the climate
   1. Maximum 80% runtime at design conditions
   2. Heating balance point = 65 F
   3. Cooling balance point = 75 F
3. Two cycles per hour
   1. Cycles rounded to nearest 5 minute increment (simulation time step = 5 minutes)

Model Assumptions: Envelope Leakage

1. Distribution
   1. Leakage distribution per ASHRAE Fundamentals Chapter 27
      1. Walls, windows, doors: 62%
      2. Ceilings & nonoperating exhaust vents: 23%
      3. Ducts: 15%
2. Total leakage varied as described later

Model Assumptions: Pollutant Generation

1. Uniform generation of unique pollutant in each room
   1. Generation rate proportional to room square footage (1 mg/hr/sf)
   2. Pollutants unique, but assumed identical in analysis presented later

Model Assumptions: Occupant Schedules

1. Assume similar schedule for each occupant:
   1. 10 PM to 7 AM: in bedroom with door closed
   2. 7 AM to 9 AM: in kitchen
   3. 9 AM to 12 PM: in living room
   4. 12 PM to 1 PM: in kitchen
   5. 1 PM to 6 PM: in living room
   6. 6 PM to 10 PM: in other bedrooms
2. Bedroom doors open except during sleeping period 10 PM to 7 AM

Varied Parameters

1. Climate
   1. Orlando (Daytona Beach)
   2. Minneapolis
   3. Seattle
   4. Phoenix
   5. Raleigh
2. Envelope leakage
   1. 1.5 ACH50 (R-2000)
   2. 3.5 ACH50 (Building America)
   3. 7 ACH50 (standard construction)

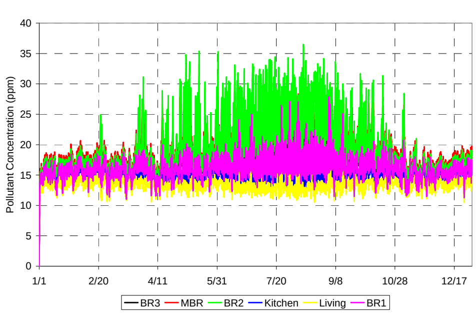
Varied Parameters

3. Central AHU System
   1. Not present
   2. In conditioned space
   3. Outside of conditioned space
4. AHU Schedule
   1. Standard thermostat
   2. Minimum runtime per hour (10 on/20 off)
5. Duct Leakage
   1. 6% of air handler flow
   2. 12% of air handler flow

Varied Parameters

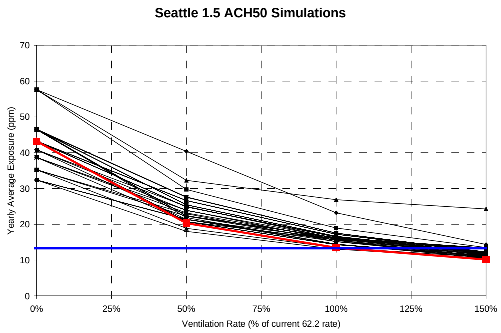
6. Ventilation System
   1. Single-point exhaust
   2. Single-point supply
   3. Dual-point balanced
   4. Fully-ducted balanced
7. Ventilation Rate
   1. 0, 50, 100, 150, 200% of current 62.2 rate

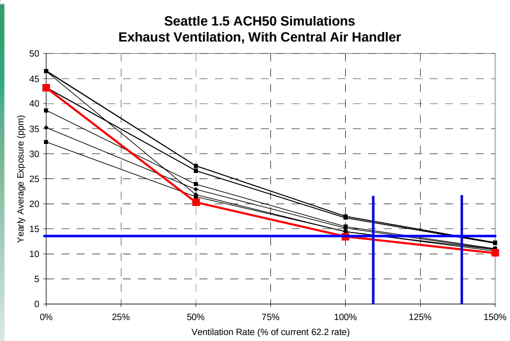
Total Pollutant Concentration by Room



Reference System

- Best available system: fully ducted, balanced ventilation system
- Compare other systems to this system: what ratio of airflows do other systems need to provide equal yearly average exposure?





Airflow Ratios—All Simulations

System Type	Range	Approximate Median
Fully ducted balanced ventilation system, with or without central duct system	1.0	1.0
Non-fully ducted balanced ventilation, with central duct system, and central air handler unit controlled to a minimum runtime of at least 10 minutes per hour	0.9 to 1.1	1.0
Supply ventilation, with central duct system, and central air handler unit controlled to a minimum runtime of at least 10 minutes per hour	1.1 to 1.7	1.25
Exhaust ventilation, with central duct system, and central air handler unit controlled to a minimum runtime of at least 10 minutes per hour	1.1 to 1.9	1.25
Exhaust ventilation, with central duct system, and central air handler unit not controlled to a minimum runtime of at least 10 minutes per hour	1.0 to 1.8	1.5
Supply ventilation, without central duct system	1.4 to 1.9	1.75
Exhaust ventilation, without central duct system	1.3 to 2.6	2.0

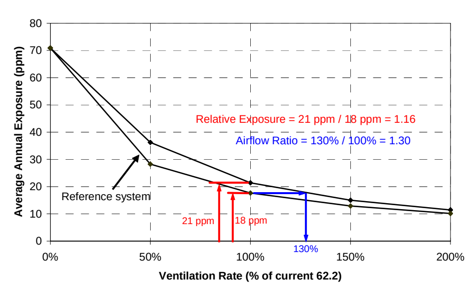
Questions From Long Beach

- How do these cases compare to the LBL cases (Iain & Max's cases)?
- What about oversized space conditioning systems?
- What is the effect of _____?

Comparison to LBL Metrics

- Relative Exposure vs Airflow Ratio
- Both are ratios used to help quantify effectiveness of different ventilation systems
- Relative Exposure: Ratio of exposures at the same nominal airflow (usually 100% of 62.2)
- Airflow Ratio: Ratio of airflows at the same exposure level (usually at the exposure at 100% of 62.2 of the reference system)

Relative Exposure vs Airflow Ratio



LBL Cases for Source & Occupant Distribution

1. Fully distributed sources & activities
2. Volume weighted sources, distributed activities
3. Worst case age-of-air (3 options)
4. Worst case
5. Remote contaminants

Ventilation Systems Compared

- Simple Exhaust
  - Single-point exhaust, no central mechanical system
- Central Fan Integrated
  - Central mechanical system with 10 minutes per 30 minute runtime, outside air duct to return plenum
- Exhaust With Constant Mixing
  - Single-point exhaust, with central system that runs 100% of the time

Apples and Oranges

LBL	BSC
Field measurements & calculation	Simulation from tuned model
Individual field tests (~4-12 hour duration each)	Year-long simulation
"Steady-state" for-real weather	TMY2 data
Leaky house in Tahoe	Leaky house in 5 climates
Tight house in Reno	Tight house in 5 climates
Different house plans	Same plan all climates
Separate tests with doors open and closed	Doors open and close on a daily schedule

Case 1: "Everybody Everywhere"

- Equal source in each zone (source strengths independent of zone sizes)
- Occupants spend equal time in each zone
- Exposure each hour is average of all zones

Case 1: "Everybody Everywhere"

Relative Exposure versus an identical house with perfect mixing

Simple Exhaust

	BSC	LBL
Leaky House	1.22 to 1.27	1.06 to 1.64
Tight House	1.22 to 1.44	1.37 to 2.43

CFI

	BSC	LBL
Leaky House	1.16 to 1.20	1.16 to 1.36
Tight House	0.96 to 1.06	1.01 to 1.10

Exhaust with Mixing

	BSC	LBL
Leaky House	1.12 to 1.16	1.13 to 1.18
Tight House	1.00 to 1.07	1.03 to 1.05

Case 2: Volume Weighted Sources

- Source strengths proportional to volume of each zone (meets age of air assumptions)
- Occupants spend equal time in each zone
- Exposure each hour is average of all zones

Case 2: Volume Weighted

Relative Exposure versus an identical house with perfect mixing

Simple Exhaust

	BSC	LBL
Leaky House	0.91 to 1.01	0.95 to 1.14
Tight House	0.90 to 1.10	1.05 to 1.20

CFI

	BSC	LBL
Leaky House	0.98 to 1.00	1.01 to 1.04
Tight House	0.92 to 1.02	1.00 to 1.00

Exhaust with Mixing

	BSC	LBL
Leaky House	0.99 to 1.00	0.99 to 1.00
Tight House	0.99 to 1.06	0.99 to 1.00

Case 3: Worst Age of Air

- Source strengths proportional to volume of each zone (meets age of air assumptions)
- Varying degrees of worst case:
  - Case A: Occupant in worst zone each hour
  - Case B: Occupant always in zone with worst yearly average
  - Case C: Occupant has worst exposure of all occupants in the house, assuming a daily schedule

Case 3: Worst Age of Air

Simple Exhaust

	BSC			LBL
	Case A	Case B	Case C	
Leaky House	1.30 to 1.44	0.98 to 1.33	1.01 to 1.17	1.05 to 1.59
Tight House	1.22 to 1.50	1.00 to 1.42	0.98 to 1.23	1.09 to 1.83

CFI

	BSC			LBL
	Case A	Case B	Case C	
Leaky House	1.14 to 1.22	1.02 to 1.18	1.07 to 1.09	1.06 to 1.18
Tight House	1.05 to 1.12	1.05 to 1.11	0.93 to 1.03	1.01 to 1.03

Exhaust with Mixing

	BSC			LBL
	Case A	Case B	Case C	
Leaky House	1.10 to 1.13	1.02 to 1.10	1.05 to 1.06	1.05 to 1.06
Tight House	1.05 to 1.11	1.05 to 1.09	1.00 to 1.07	1.01 to 1.02

Case 4: “I Stink”

- Single source in same zone as occupant
- Occupant stays in worst zone

Case 4: “I Stink”

Simple Exhaust

	BSC	LBL
Leaky House	9.09 to 10.05	3.25 to 10.85
Tight House	8.47 to 10.44	4.25 to 24.80

CFI

	BSC	LBL
Leaky House	6.14 to 7.68	2.96 to 7.22
Tight House	3.21 to 3.70	1.94 to 2.83

Exhaust with Mixing

	BSC	LBL
Leaky House	4.62 to 5.94	3.14 to 5.19
Tight House	2.17 to 2.45	1.88 to 2.21

Case 5: “You Stink”

- Single source different zone than occupant
- Worst combination of source zone and occupied zone

Case 5: “You Stink”

Simple Exhaust

	BSC	LBL
Leaky House	1.44 to 2.05	1.04 to 1.88
Tight House	1.72 to 2.43	2.53 to 2.95

CFI

	BSC	LBL
Leaky House	1.13 to 1.22	0.90 to 2.04
Tight House	1.02 to 1.13	1.16 to 1.20

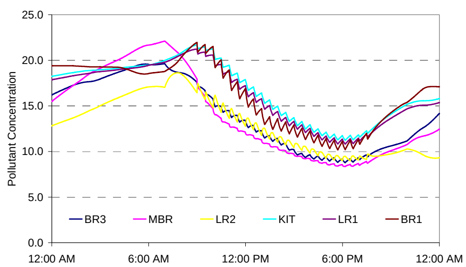
Exhaust with Mixing

	BSC	LBL
Leaky House	1.1 to 1.19	0.94 to 1.28
Tight House	1.02 to 1.09	1.13 to 1.14

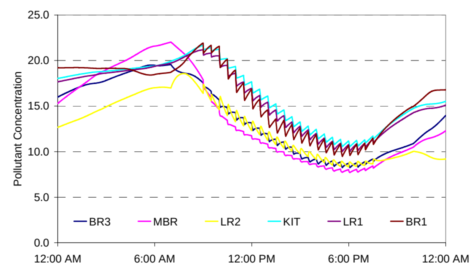
Effect of Oversized Systems

- Sizing generally doesn’t matter (for mixing)
- Volume of air delivered to zone depends on:
  - Space conditioning load
  - Temperature of supply air
- Unless there is a minimum runtime, in which case the zone gets more mixing
  - But most zones are already well mixed by right-sized systems

Manual J Sizing

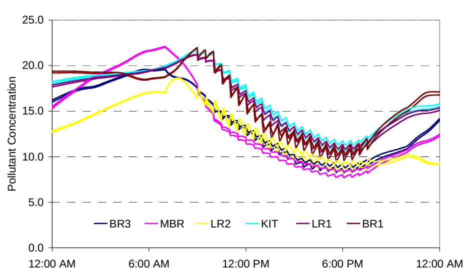


2x Manual J Sizing



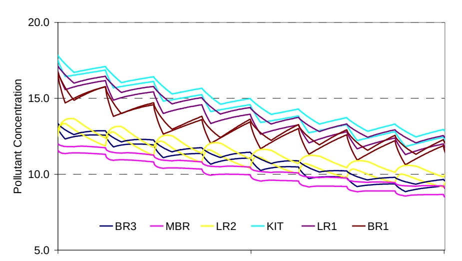
Notice any difference?

1x and 2x Manual J



Still need help?

Look Closely

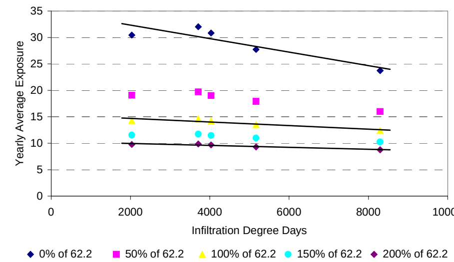


Oversizing means mixing happens faster but stops sooner—giving nearly identical results

What is the effect of ____?

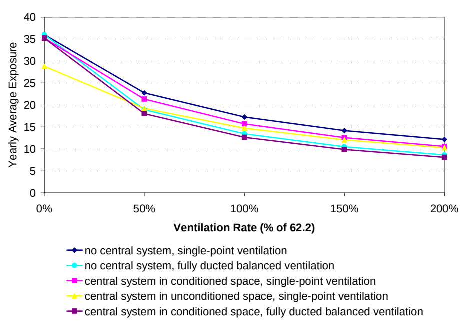
- Climate
- Central System
- Duct Leakage
- Minimum central system runtime
- Envelope tightness

Climate

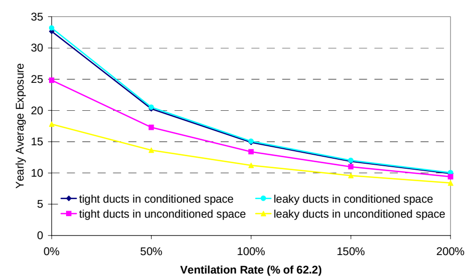


- Climate matters, but less so at high ventilation rates or with tight houses

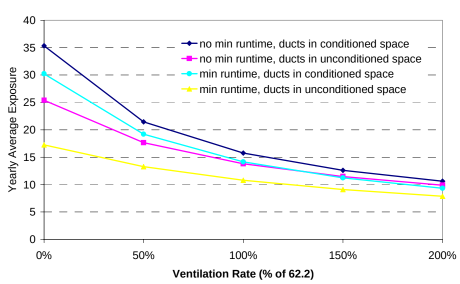
Central System



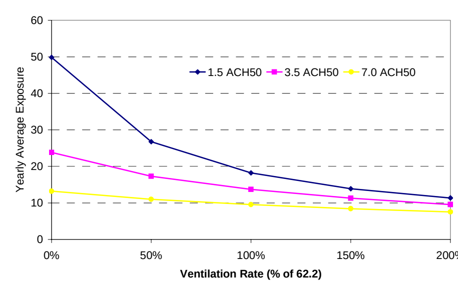
Duct Leakage



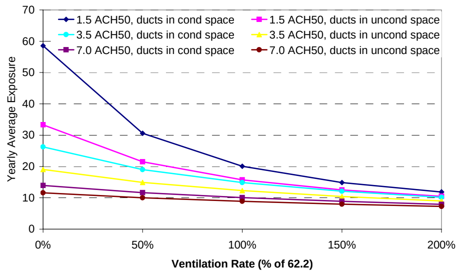
Minimum Runtime



Envelope Leakage



Envelope Leakage & Duct Leakage



- Similar results with minimum runtime (more difference with tight envelope)

Appendix H: Final Simulation Plan

Revised Simulation Plan and Assumptions for CONTAM Modeling

revision date 2/25/08

Model category	**Existing model assumptions**	**Revised model assumptions**
Simulation time step	5 min	No change
Climates	CZ 2A: Daytona Beach CZ 2B: Phoenix CZ 4C: Seattle CZ 4A (close to 3A): Raleigh CZ 6: Minneapolis	Same but add 2 more locations in California (Bruce to pick from TMY2 locations: Arcata, Bakersfield, Dagget, Fresno, Long Beach, Los Angeles, Sacramento, San Diego, San Francisco, Santa Maria)
Temperature	Outdoor temperature from TMY2 data Indoor temperature constant at 22 C (71.6)	No change
Wind	Wind speed and direction from TMY2 data; Wind shielding model and modifiers as described in ASHRAE Fundamentals 2005 Chapters 16 and 27 for typical suburban surroundings	No change
Minimum AHU runtime criteria	When central system is present and a minimum runtimer is used, central fan runs at least 10 minutes out of every 30 minutes.	When central system is present and a minimum runtimer is used, central fan runs at least long enough to provide 1 air change per hour.
Central heating and cooling equipment sizing and fan flow	Sizing per Manual J for each climate for cooling: cooling airflow 400 cfm/ton heating airflow 85% of cooling airflow	No change. Due to change in minimum runtime criteria, size will be self-correcting for minimum runtime just as it is for space conditioning. For example, a system oversized by 25% will reach 1 air turnover 25% faster than a system that is properly sized, and therefore provide the same amount of mixing.
Activation of heating and cooling	Linearly interpolate from 80% runtime to 0% runtime between outdoor design condition and balance point temperature. Heating balance point = 65 F Cooling balance point = 75 F Two cycles per hour, cycles rounded to nearest 5 minute increment.	No change
Duct leakage	6% of air handler flow, and 12% of air handler flow	Eliminate duct leakage. Redistribute effective leakage area to walls and ceiling in proportion to their relative leakage.
Central system duct location	1) No central duct system 2) In conditioned space 3) Outside of conditioned space	1) No central duct system 2) Outside of conditioned space (but no leakage)
Building enclosure leakage rate	R-2000 house: 1.5 ach50 Building America house: 3.5 ach50 Standard house: 7 ach50	No change
Building enclosure leakage distribution	Leakage distribution per ASHRAE Fundamentals, Chapter 27. Walls (range 18 to 50%; middle of range 35%) Windows & doors (range 6 to 22%; 15%) Ceiling details (range 3 to 30%; 18%) Fireplaces (range 0 to 30%; 12%) Nonoperating exhaust vents (range 2 to 12%; 5%) Air handler & ductwork (range 3 to 28%; 18%) Model combines in the following manner: Walls, windows, doors, fireplaces (all modeled as wall leakage, uniformly distributed by wall area): 62% Ceilings & nonoperating exhaust vents (all modeled as ceiling leakage, uniformly distributed by ceiling area): 23% Air handler & ductwork (modeled as duct leakage): 15%	Leakage distribution per ASHRAE Fundamentals, Chapter 27. Walls (range 18 to 50%; middle of range 35%) Windows & doors (6 to 22%; 15%) Ceiling details (3 to 30%; 18%) Fireplaces (0 to 30%; 12%) Nonoperating exhaust vents (2 to 12%; 5%) Air handler & ductwork (3 to 28%; 18%) Model combines in the following manner: Walls, windows, doors, fireplaces, plus proportionate share (2/3) of air handler & ductwork (all modeled as wall leakage, uniformly distributed by wall area): 68% Ceilings, nonoperating exhaust vents, plus proportionate share (1/3) of air handler & ductwork (all modeled as ceiling leakage, uniformly distributed by ceiling area): 32%
Zones	<u>1st Floor:</u> Living Room 1 Kitchen Bedroom 1 <u>2nd Floor:</u> Living Room 2 Bedroom 2 Bedroom 3 Master Bedroom	Add the following zones <u>1st Floor:</u> Laundry Room Bathroom 1 <u>2nd Floor:</u> Bathroom 2 Master Bathroom
Airflow between zones[2] when interior doors are open	Modeled by forcing small (0.1 C) temperature difference between neighboring zones	No change
Pollutant generation	Uniform generation of unique pollutant in each zone. Generation rate proportional to room area (1 mg/hr/ft^2).	No change, but additional post-processing as described below.
Interior door scheduling	Bedroom doors open except during sleeping period 10 PM to 7 AM	No change

Ventilation system types	1) Single-point exhaust from common area 2) Single-point exhaust from common area with minimum central fan runtime (10 min per hour) 3) Central-fan-integrated supply without minimum runtime 4) Central-fan-integrated supply with minimum runtime (10 min per hour) 5) Two-point balanced (supply into common area, exhaust from the same well-mixed common area) 6) Fully-ducted balanced (independent ventilation duct system, supply into the common area and each bedroom, exhaust from the common area)	1) Single-point exhaust from common area 2) Single-point exhaust from master bathroom 3) Single-point exhaust from common area with minimum central fan runtime[1] 4) Single-point exhaust from master bathroom with minimum central fan runtime[1] 5) Single-point supply to common area 6) Single-point supply to common area with minimum central fan runtime[1] 7) Central-fan-integrated supply without minimum runtime 8) Central-fan-integrated supply with minimum runtime[1] 9) Three-point exhaust, 1/3 from each bathroom continuously 10) Three-point exhaust, 1/3 runtime from each of the laundry, family bath, and master bath 11) Two-point balanced (supply into common area, exhaust from family bathroom) 12) Fully-distributed balanced (independent ventilation duct system, supply into the common area and each bedroom, single exhaust from the common area)
Ventilation rates	Percent of 62.2 rate 7.5(Nbr+1)+0.01(CFA): 0, 50, 100, 150, 200	No change
Occupant scheduling	Same schedule for each occupant: 10 PM to 7 AM: in bedroom with door closed 7 AM to 9 AM: in kitchen 9 AM to 12 PM: in living room 12 PM to 1 PM: in kitchen 1 PM to 6 PM: in living room 6 PM to 10 PM: in other bedrooms	Change to: Same schedule for each occupant: 10 PM to 7 AM: in bedroom with door closed 7 AM to 7:30 AM: in the bathroom nearest to occupant's bedroom 7:30 AM to 9 AM: in kitchen 9 AM to 12 PM: in living room 12 PM to 1 PM: in kitchen 1 PM to 5 PM: in living room 5 PM to 7 PM: in kitchen 7 PM to 9:30 PM: in other bedrooms 9:30 PM to 10:00 PM: in the bathroom nearest to occupant's bedroom
Post-processing	Calculate annual exposure for each occupant in the house according to the occupant schedule, for each ventilation rate, and calculate distribution coefficient based on the occupant with the highest annual average exposure in each simulation	Calculate exposure and distribution coefficients for each ventilation system under the following scenarios: 1) As done previously, with new occupant schedule described above 2) As done previously, except assuming occupants spend equal time in each zone each hour ("Everybody Everywhere" scenario) 3) 1/3 of pollutants generated in master bathroom and 2/3 in kitchen (no pollutants generated anywhere else), with new occupant schedule described above Create table of distribution coefficients for each of the three enclosure leakage levels, for each of: 1) annual average exposure 2) monthly average exposure 3) weekly average exposure 4) sleeping hours (10 PM to 7 AM) annual average exposure

Footnotes:

[1] The central fan operates for heating and cooling plus any amount needed to accomplish a minimum of one house air volume turnover per hour

[2] CONTAM does not handle gas diffusion between zones. All movement of contaminants from zone to zone are by air flow.

Revised Simulation Plan Output Table

		Distribution coefficients Based on: Sources uniformly distributed (volume weighted) Occupant schedule Occupant with highest exposure				Distribution coefficients Based on: Sources uniformly distributed (volume weighted) Occupants uniformly distributed ("Everybody Everywhere" scenario)				Distribution coefficients Based on: Sources: 1/3 master bathroom, 2/3 kitchen Occupant schedule Occupant with highest exposure			
Vent Sys #	Description	annual avg exposure	highest monthly avg exposure	highest weekly avg exposure	sleeping hrs annual avg exposure	annual avg exposure	highest monthly avg exposure	highest weekly avg exposure	sleeping hrs annual avg exposure	annual avg exposure	highest monthly avg exposure	highest weekly avg exposure	sleeping hrs annual avg exposure
1	Single-point exhaust from common area												
2	Single-point exhaust from master bathroom												
3	Single-point exhaust from common area with minimum central fan runtime												
4	Single-point exhaust from master bathroom with minimum central fan runtime												
5	Single-point supply to common area												
6	Single-point supply to common area with minimum central fan runtime												
7	Central-fan-integrated supply without minimum runtime												
8	Central-fan-integrated supply with minimum runtime												
9	Three-point exhaust, 1/3 from each bathroom continuously												
10	Three-point exhaust, 1/3 runtime from each of the laundry, family bath, and master bath												
11	Two-point balanced (supply into common area, exhaust from family bathroom)												
12	Fully-distributed balanced (independent ventilation duct system, supply into the common area and each bedroom, single exhaust from the common area)												

2.18.5. January 2009 Expert Meeting Summary Report

Final Report on the Expert Meeting for Ventilation Effectiveness in Residential Systems

Building Science Corporation Industry Team

February 20, 2009

Work Performed Under Funding Opportunity Number:
DE-FC26-08NT00601

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EXECUTIVE SUMMARY

1. Title: Final Report on the Expert Meeting for Ventilation Effectiveness in Residential Systems (Gate 1B)

2. Overview: The Building Science Consortium held an Expert Meeting on Ventilation Air Distribution Effectiveness in Residential Systems on 23 January 2009 at the Hilton Hotel in Chicago, Illinois. The expert meeting was held immediately before the ASHRAE SSPC 62.2 meetings in advance of the ASHRAE technical program. Invited speakers gave presentations in their particular area of expertise. Speakers included Dr. Jeffrey Siegel and Dr. Atila Novoselac of the University of Texas at Austin and Aaron Townsend of Building Science Corporation.

3. Key Results: Key results from this meeting were a greater buy-in from the ASHRAE 62.2 community that BSC's approach to ventilation effectiveness is producing meaningful results and with appropriate modifications can reach results that can be adopted by the 62.2 committee.

4. Gate Status: This project meets the "must meet" and "should meet" criteria for Gate 1B. The project provides source energy and whole building performance benefits by incentivizing efficient ventilation systems and tight enclosures, thereby reducing the source energy needed to condition the house. The project also meets the performance-based safety, health, and building code requirements for use in new homes, as it directly attempts to improve the ventilation code, which will likely be adopted by building codes at some point in the future. For the same reason, this project meets the prescriptive-based code requirements. The project will be cost-neutral for new homes, as builders will still be free to choose from a variety of ventilation systems. The project will increase reliability by increasing the likelihood of uniform indoor air quality. Finally, the project does not require any new products to be manufactured, and suppliers, manufactures, and builders will continue responding to market forces as they always do.

5. Conclusions: The key gaps that remain are concerns by certain members of the 62.2 committee to certain aspects of the proposed changes, particularly assumptions about the contaminant sources and decisions regarding the appropriate magnitude of the system coefficients, and drafting and approval of a change to the ASHRAE Standard 62.2. The next steps involve continuing the dialogue with the committee members to further identify and address their concerns, and drafting and submission of a change proposal to the 62.2 committee. After these steps are complete, the ASHRAE 62.2 committee will be given the opportunity to adopt the suggested revisions into the 62.2 standard. Expected benefits include energy savings (due to credit given to ducted ventilation systems), reliability (due to improved indoor air quality), durability (due to guaranteed ventilation and therefore lower chances of moisture damage), and expected value to builders, contractors, and homeowners (due to improved homeowner satisfaction with their homes, which also benefits builders and contractors).

INTRODUCTION

The Building Science Consortium held an Expert Meetings on Ventilation Air Distribution Effectiveness in Residential Systems on 23 January 2009 at the Hilton Hotel in Chicago, Illinois. The expert meeting was held immediately before the ASHRAE SSPC 62.2 meetings in advance of the ASHRAE technical program in order to make it easier for experts who had already traveled there to participate. There were 31 in attendance. Invited speakers gave presentations in their particular area of expertise. The presentations were followed by discussion with the expert audience.

A summary of the individual presentations and major discussion points is provided in the sections below.

The final agenda for the meeting is listed in Appendix A. A list of attendees for the meeting is given in Appendix B. The presentations are included in Appendices C through F.

PRESENTATIONS

Speaker 1: Dr. Jeffrey Siegel, Department of Civil, Architectural, and Environmental Engineering, the University of Texas at Austin

Presenter bio: Dr. Jeffrey A. Siegel is an associate professor in the Department of Civil, Architectural, and Environmental Engineering at The University of Texas at Austin. He received his B.S. in Engineering from Swarthmore College in 1995 and his Ph.D. from U.C. Berkeley in Mechanical Engineering in 2002. Dr. Siegel and his research team have ongoing research on HVAC filtration, portable and passive air cleaners, particle resuspension, human exposure, and particle transport and deposition in HVAC systems. He is the recipient of the Early Career Award from the International Society for Exposure Assessment /American Chemistry Council, the 3M Non-Tenured Faculty Grant, and the ASHRAE New Investigator Award. He is the co-director of the National Science Foundation funded Integrative Graduate Education and Research Traineeship (IGERT) graduate program in Indoor Environmental Science and Engineering at The University of Texas. He is a voting member of TC 2.4, TC 6.3, SSPC 52.2, research subcommittee chair of TC2.4, and PI of RP1299 (Energy Implications of Filters in Residential and Light Commercial Buildings).

Presentation Title: *Pollutant Sources and Occupant Activities*

Presentation Summary:

Dr. Siegel presented the results of a literature review of indoor air contaminant sources. He gave examples of different categories of contaminant sources, such as area sources, point sources, and occupant-associated sources.

Dr. Siegel made the following key points during his presentation:

- Sources can roughly be divided into three categories: area sources, point sources, and occupant-associated sources; however these areas are roughly defined and some sources could be grouped in more than one category depending on the specific criteria used.
- The effect of an exposure to a contaminant depends on the contaminant and for many contaminants on the individual exposed as well. Because of this it is difficult to compare the impact of different contaminants.
- Area sources can be the dominant source of certain contaminants. These types of sources often decline in strength over time.
- Depending on the specific contaminant, point sources may decline over time or may remain constant.
- Occupant sources are very activity and contaminant dependent. The source strength of contaminants associated with an occupant's activities varies widely. The sources due to one occupant appear to be a point source from other occupants' perspectives.
- The National Human Activity Survey (NHAPS) is a significant resource for analyzing effects of human sources.
- The occupants are disproportionately exposed to occupant-generated sources due to their proximity and non-uniform mixing in the zone.
- There is little in the literature to suggest that fugitive emissions from items stored in kitchens and bathrooms (cleaning products, for example) are a significant source. Many of the emissions that occur in kitchens and bathrooms are a result of the occupant's activities while in those rooms. Cleaning products, etc, generally need ozone to react with to form harmful byproducts, and there is generally little ozone in the cabinets where they are stored.
- There is evidence that increasing ventilation rates causes higher emission rates from formaldehyde sources, such that the formaldehyde concentration does not change substantially.
- Dr. Siegel concludes that occupant-associated sources are often the dominant cause of exposure in homes.
- Dr. Siegel would like to see actual pollutants modeled instead of a single tracer-gas contaminant.
- Dr. Siegel would currently assume occupant activities account for 50-75% of total exposure.

<u>Questions and discussion during and after the presentation:</u>

The audience had several questions and comments during and after the discussion, which Dr. Siegel answered or discussed. The questions and comments were as follows:

- Q: How did the work presented define pollutant? A: Chemicals that are known to be harmful to humans.
- Q: How does one differentiate between emissions from humans themselves and emissions from their activities? A: It is mostly the activities, very little we personally emit is harmful.
- Q: How aggressive or conservative is this analysis? A: 50% would be the absolute lowest percentage exposure Dr. Siegel would expect to be due to occupant-generated sources.
- Q: What size particles did the analysis consider? A: PM10, PM2.5, ultrafine (1 nm)
- Q: Which contaminant species are the current dominant long-term health risks in residential settings? A: Formaldehyde and paradichlorobenzene.

- Q: Is there disproportionate exposure to either of these chemicals? A: Studies indicate no disproportionate exposure to formaldehyde but the Hispanic population is disproportionately exposed to paradichlorobenze, presumably due to higher tendencies to use the types of products that contain the chemical
- Q: How much difference is there between the occupant-generated emissions based on the actual activity level? Are the emissions while sleeping and moving around substantially different? A: The emissions rates are substantially higher while moving around but it is difficult to quantify how much. The NHAPS might be a good resource to try to determine occupant activities and typical locations.
- Q: Is the higher exposure of the Hispanic population due to increased use of moth crystals? A: Only one study looked at this question and it suggested that increased use of toilet bowl deodorizers was the most likely reason.

Speaker 2: Dr. Atila Novoselac, Department of Civil, Architectural, and Environmental Engineering, the University of Texas at Austin

Presenter bio: Dr. Atila Novoselac is an assistant professor in the Department of Civil, Architectural, and Environmental Engineering at The University of Texas at Austin. His research encompasses analysis of pollutant transport in indoor environments, human exposure studies, and development and experimental validation of models for air and particle dynamics. He has developed several indoor air quality indicators for evaluation of various air mixing and stratified ventilation systems. His current work includes studies related to the effects that the human microenvironment and ventilation type have on human exposure to gaseous and particulate contaminants. Dr. Novoselac is very active in ASHRAE indoor environmental modeling and room air distribution technical committees (voting member in TCs 5.3 and 4.10). He is also a corresponding member of TCs 4.3 and 4.7, and PI on the RP1416 project sponsored by ASHRAE (Development of Internal Surface Convection Correlations for Energy and Load Calculation Methods).

Presentation Title: *Contaminant Generation and Spatial Ventilation Effectiveness: How do Sources Relate to Human Exposure?*

Presentation Summary:

Dr. Novoselac presented data on the impact of the thermal plume that exists around a person sitting in a still air environment. This thermal plume draws contaminants into the person's breathing zone that would otherwise remain outside the breathing zone.

Dr. Novoselac made the following key points during his presentation:

- Personal exposure depends on the local concentration of the pollutants in a person's breathing zone.
- The local concentration of pollutants in a person's breathing zone can be different than the average concentration in the room, due to the thermal plume caused by the person's body heat.
- The thermal plume is important when the air is still, but is not when there is a fan or other mechanism for actively moving air within the space.

- His research includes both computer modeling (CFD) and physical testing.
- The location of a source in relation to the person and thermal plume has an important impact on the person's exposure to the contaminant.
- In a test house, their work determined that buoyancy-driven flow (i.e. the thermal plume) was the dominant flow mechanism when the central air handler was not operating.
- An assumption of well-mixed zones may be a bad assumption in a house without an operating air handler. Non-uniform mixing will generally increase the exposure to the occupant.

Questions and discussion during and after the presentation:

Dr. Novoselac answered the following questions and comments after his presentation:

- Q: What is a typical air velocity in the thermal plume? A: Approximately 0.5 feet per second.

Speaker 3: Aaron Townsend, Building Science Corporation

Presenter bio: Aaron Townsend is an Associate with Building Science Corporation. He has worked for Building Science for five years, where he focuses on energy efficiency, building durability, and indoor air quality. Aaron holds a bachelor's degree in mechanical engineering from the University of Texas and a master's degree in mechanical engineering from Stanford University.

Presentation Title: *System Coefficients: Where Have We Been and Where Are We Going?*

Presentation Summary:

Townsend reviewed the work to date towards establishing a system coefficient for the 62.2 standard. This history includes:

- Development of a CONTAM airflow network model and comparison to measurements from field tests of a production Building America house in Sacramento in January 2006
- Presentation of these results at the ventilation expert meeting in January 2006
- Modification and presentation of results for and after expert meetings in January and June 2007 as well as in January and June 2008
- Conference calls in between meetings to consult with participating 62.2 committee members and present results of additional work

Townsend also presented the results of one additional ventilation system that was modeled since the previous meeting. This system was a two-point exhaust system with an exhaust point on each of the two floors in the house. Townsend then presented a sensitivity analysis on effect of the source scenario on the ventilation system coefficients. Townsend made the following points during this part of the presentation:

- The sensitivity analysis examined the effect of mixing the three initial (or "pure") source assumptions in different ratios.
- The first pure scenario (volume-weighted sources) has about 25% of the emissions in the kitchens and bathrooms.
- The third pure scenario (occupant-generated sources) has about 15% of the emissions in the kitchens and bathrooms.

- Seven blends of the pure scenarios were presented. The blends chosen ranged from heavily dominated by volume-weighted and occupant-generated contaminants (50-50 split) to evenly divided between the volume-weighted, kitchens and bathrooms, and occupant-generated sources (1/3 each).
- The resulting coefficient tables for each of the pure and blended scenarios were presented and discussed. Increasing the ratio of occupant-generated contaminants resulted in lower system coefficients for ventilation systems with minimum turnover requirements and higher system coefficients for ventilation systems without a central air handling system.

<u>Questions and discussion during and after the presentation:</u>

Townsend answered the following questions and comments after his presentation:

- Q: Have there been more houses compared to this model? A: Yes, the results presented by Max Sherman and Iain Walker of LBNL were compared to results from this model, with good agreement given the differences in approach.
- Q: The sources in the model do not vary with time? A: Correct, the sources in the current model do not vary with time. It is within the model's capabilities but was not done in order to keep the results independent of a particular contaminant species.

GENERAL DISCUSSION

The general open discussion period was moderated by Joseph Lstiburek, Principal of Building Science Corporation.

- A proposal was made to assign system coefficient values simply: all systems with minimum turnover or balanced ventilation get values of 1.0 and all others get values of 1.5. The general response to this proposal was that it was too general and ignored some of the differences between systems, such as the effect of ducting.
- A proposal was made to use the blended scenario with 1/3 of each of the pure scenarios, but to scale the coefficients down such that all the values of 1.33 became 1.25 and all the values of 1.65 became 1.5. The general response to this proposal was positive, in that the audience was receptive to the idea of reducing the penalty of the poorer-performing systems.
- Another proposal was made to have 3 categories: a balanced ventilation system with a minimum turnover has a coefficient of 1.0; a system that is either balanced or has a minimum turnover (but not both) has a coefficient of 1.25; and a system with neither balanced nor minimum turnover has a coefficient of 1.5. The general response to this proposal was mixed, as it ignores some differences seen in the presented results.

FOLLOW-UP WORK

Further discussion and work occurred after the SSPC 62.2 meeting. The concept of scaling back the magnitude of the coefficients to the range of 1.0 to 1.5 is being pursued. BSC is collaborating with Bruce Wilcox and Steve Emmerich to present the data in different ways (as requested by the committee) and to advance the proposed change to the 62.2 standard.

Appendix A: Expert Meeting Agenda

INVITATION and AGENDA

Building America Expert Meeting

CONTAMINANT GENERATION AND SPATIAL VENTILATION EFFECTIVENESS

Meeting Manager: Armin Rudd, Building Science Corp.
Date/Time: **Friday, 23 January 2009, 8:00 am to 12 pm**
(light breakfast refreshments after 7:30 am)
Location: Chicago, ASHRAE Winter Meeting
Hilton Hotel, **Grant Park** meeting room

Featured Speakers:

- Jeffrey Siegel and Atila Novoselac, Department of Civil, Architectural, and Environmental Engineering, The University of Texas at Austin
- Aaron Townsend, Building Science Corp.

The objective of this session is to present and discuss recent experimental and modeling research on indoor air quality, with a particular focus on occupant activity, sources associated with occupants, and exposure to pollutants in residential indoor environments. The goal is to describe the state-of-the-art research in this field so that the Building America and Standard 62.2 communities can make informed decisions in assessing ventilation systems and distribution of ventilation air.

Key questions regarding this meeting:

1. What are the main pollutant sources and how do they relate to occupant activities? (Siegel)
The goal of this part of the presentation is to summarize recent literature on important sources of pollutants in homes. Many of the sources are either emitted directly by occupants or caused by their activities. This has important ramifications for assessing human exposure and the impact of ventilation. Pollutant sources will be associated with data from the National Human Activity Pattern Survey (NHAPS) which characterizes the duration and nature of occupant activities in their homes.

2. How do sources relate to human exposure? (Novoselac)
Given that many important sources are caused by the occupants themselves, this part of the presentation will show recent and ongoing research that demonstrates that for many of the pollutants associated with human activities, occupants have higher exposures than are usually assumed. Factors that increase exposure include air flows driven by thermal plumes, non-uniform mixing, and source-occupant proximity. The connection

between exposure, source position, ventilation flow rates and air distribution will also be explored.

3. How should source generation scenarios be treated for use in determining spatial ventilation effectiveness factors in ASHRAE Standard 62.2? (Townsend)
The ASHRAE SSPC 62.2 Committee has evaluated a number of iterations of CONTAM modeling results on this topic. Analysis and discussion continues to inform the process.

Invitees:

Participants will be key people working in the indoor air quality, comfort, and space conditioning fields. Participants are invited from the following groups: Building America teams, ASHRAE Standard 62.2 committee members and participants, residential HVAC and construction industry, national and state government laboratories and agencies, university researchers, energy efficiency organizations, and building consultants.

Meeting Agenda:

- 8:00 am to 8:05 am, Welcome and Meeting Introduction

- Presentations

    - 8:05 to 8:35, (30 min) Jeffrey Siegel, *Indoor pollutant sources and their relation to occupant activities*.
    - 8:35 to 8:45, (10 min) Questions and discussion

    - 8:45 to 9:15, (30 min) Atila Novoselac, *Indoor pollutant sources and their relation to human exposure*.
    - 9:15 to 9:25, (10 min) Questions and discussion

    - 9:25 to 9:40, (15 min) Break

    - 9:40 to 10:10 (30 min) Aaron Townsend, *CONTAM simulations to evaluate the effect of ventilation system interactions on occupant exposure to indoor contaminants*
    - 10:10 to 10:20 (10 Min) Questions and Discussion

- Group discussion, 10:20 to 11:45

- Wrap up, action items, and follow-up plan, 11:45 to 12:00

Bios

Dr. Jeffrey A. Siegel is an associate professor in the Department of Civil, Architectural, and Environmental Engineering at The University of Texas at Austin. He received his B.S. in Engineering from Swarthmore College in 1995 and his Ph.D. from U.C. Berkeley in Mechanical Engineering in 2002. Dr. Siegel and his research team have ongoing research on HVAC filtration, portable and passive air cleaners, particle resuspension, human exposure, and particle transport and deposition in HVAC systems. He is the recipient of the Early Career Award from the International Society for Exposure Assessment /American Chemistry Council, the 3M Non-Tenured Faculty Grant, and the ASHRAE New Investigator Award. He is the co-director of the National Science Foundation funded Integrative Graduate Education and Research Traineeship (IGERT) graduate program in Indoor Environmental Science and Engineering at The University of Texas. He is a voting member of TC 2.4, TC 6.3, SSPC 52.2, research subcommittee chair of TC2.4, and PI of RP1299 (Energy Implications of Filters in Residential and Light Commercial Buildings).

Website: http://www.ce.utexas.edu/prof/siegel/
IGERT Website: http://www.caee.utexas.edu/igert/

Dr. Atila Novoselac is an assistant professor in the Department of Civil, Architectural, and Environmental Engineering at The University of Texas at Austin. His research encompasses analysis of pollutant transport in indoor environments, human exposure studies, and development and experimental validation of models for air and particle dynamics. He has developed several indoor air quality indicators for evaluation of various air mixing and stratified ventilation systems. His current work includes studies related to the effects that the human microenvironment and ventilation type have on human exposure to gaseous and particulate contaminants. Dr. Novoselac is very active in ASHRAE indoor environmental modeling and room air distribution technical committees (voting member in TCs 5.3 and 4.10). He is also a corresponding member of TCs 4.3 and 4.7, and PI on the RP1416 project sponsored by ASHRAE (Development of Internal Surface Convection Correlations for Energy and Load Calculation Methods).

Website: http://www.ce.utexas.edu/prof/novoselac/

Appendix B: Expert Meeting Attendee List (based on sign-in sheet)

Building America Ventilation Expert Meeting
Invitee/Attendee List
Building Science Corporation
January 23, 2009

Last name	First name	Company	Present 1/23/2009
Anderson	Ren	NREL	
Atif	Morad	NRC	
Baxter	Van	ORNL	x
Bloemer	John	Research Products Corp.	
Brandt	Donald	Brandt Training	
Brennan	Terry	Camroden Associates	
Cardenal	Bernardo	Rocamar Engineering	
Carlson	Steve	CDH Energy	
Chandra	Subrato	Florida Solar Energy Center	
Christensen	Dane	NREL	x
Christensen	Dane	NREL	x
Crawford	Roy	Trane	x
Delaquila	David	GAMA	
DeLaura	Lance	Southern California Gas Co.	
Dietz	Dennis	American Aldes Ventilation	x
Dobbs	Gregory	United Technologies Research Center	x
Drumheller	Craig	NAHB Research Center	
Emmerich	Steve	NIST	x
Fairey	Philip	FSEC	x
Ferris	Rob	Fantech	
Flynn	Victor	Panasonic	
Forest	Daniel	Venmar Ventilation	x
Francisco	Paul	University of Illinois-UC	x
Fugler	Don	Canada Mortgage and Housing Corp.	
Gawlik	Keith	NREL	
George	Marquam	Blu Spruce Construction	
Glenn	Langan	Southern Company	
Goel	Rakesh	Lennox	
Griffiths	Dianne	Steven Winter Associates	
Grimsrud	David		
Hammon	Rob	Consol	
Harrell	John	American Aldes Ventilation	
Hedrick	Roger	Gard Analytics	
Heidel	Tom	Broan-Nutone	x
Henderson	Hugh	CDH Energy	
Hendron	Robert	NREL	x
Hoeschele	Marc	Davis Energy	x
Hoeschele	Marc	Davis Energy Group	x
Holton	John		
Jackson	Mark	Lennox	x
James	George	USDOE	
Karg	Rick	R.J.Karg Associates	
Keller	Fred	Carrier	
Kenney	Tom	NAHB Research Center	
Kosar	Douglas	University of Illinois-Chicago	x
LaLiberte	Mark	Building Knowledge	
Langan	Glenn	Gulf Power-Southern Co.	x

Logee	Terry	USDOE	
Lstiburek	Joseph	Building Science Corp.	x
Lubliner	Mike	Washington State University	
Lyons	Jamie	Newport Partners	
Malone	Jane	Alliance for Healthy Homes	
Moore	Mike	Newport Partners	x
Neilsen	Patrick	Broan-Nutone	
Nelson	Gary	Energy Conservatory	x
Novoselac	Atila	UT-Austin	
Oberg	Brad	IBACOS	
Offermann	Bud	Indoor Environmental Engineering	
Olesen	Bjarne	Denmark Technical University	
Olson	Collin	Energy Conservatory	
Patenuaude	Raymond	The Holmes Agency	
Persily	Andrew	NIST	
Pettit	Betsy	Building Science Corp.	
Phillips	Bert	Unies Ltd.	
Poirier	Bertrand	Fantech	x
Pollock	Ed	USDOE	
Prahl	Duncan	IBACOS	
Price	David	USEPA	
Proctor	John	Proctor Engineering	
Puttagunta	Srikanth	Steven Winter Associates	x
Ranfone	James	AGA	
Rashkin	Sam	USEPA	
Raymer	Paul	Heyoka Solutions	x
Reardon	James	National Research Council Canada	
Rittelmann	Bill	IBACOS	
Rudd	Armin	Building Science Corp.	
Ryan	William	Univ of Illinois	
Sachs	Harvey	ACEEE	
Sagan	Kenneth	NAHB	
Schumacher	Chris	Building Sceince Consulting	
Shah	Raj	Carrier	
Sherman	Max	LBNL	x
Siegel	Jeffrey	UT-Austin	
Springer	David	Davis Energy Group	
Stamatopoulos	Anthony	IBACOS	
Stevens	Don	Panasonic	x
Straube	John	Building Science Corp.	
Stroud	Thomas	Health Patio & Barbeque Assoc	
Talbot	John		
Taylor	Sam	USDOE	x
Thompson	Rob	USEPA	
Townsend	Aaron	Building Science Corp.	x
Uselton	Dutch	Lennox	
Walker	Iain	LBNL	x
Weber	Mark	ASHRAE	
Werling	Eric	USEPA	x
Wettergren	Ola	Fantech	
Wilcox	Bruce		x
Williams	Ted	AGA	x
Wojcieson	Ray	Lennox	

Appendix C: Introductory Presentation

Building America Expert Meeting

CONTAMINANT GENERATION AND SPATIAL VENTILATION EFFECTIVENESS

Friday, 23 January 2009
8:00 am to 12 pm
in conjunction with the ASHRAE Winter Meeting
Chicago, Hilton Hotel, Grant Park meeting room

Featured Speakers

- Jeffrey Siegel and Atila Novoselac

  Department of Civil, Architectural, and Environmental Engineering, The University of Texas at Austin
- Aaron Townsend

  Building Science Corp.

Key questions

- *What are the main pollutant sources and how do they relate to occupant activities?*
- *How do sources relate to human exposure?*
- *How should source generation scenarios be treated for use in determining spatial ventilation effectiveness factors in ASHRAE Standard 62.2?*

Development of BA Dehumidification Performance Standard

- Field testing ongoing 2008
- Lab testing to begin at NREL
- Working Group meetings June and October 2008
  - Longer term goal of industry based test procedure
    - need to establish industry partnerships to move this forward
  - Focus on development and consensus for:
    - Workable strategy for standards development/improvement
      - ANSI-ARI 210/240 (Performance Rating Of Unitary Airconditioning And Airsource Heat Pump Equipment)
      - ASHRAE 37 (Methods of Testing for Rating Electrically Driven Unitary Air-Conditioning and Heat Pump Equipment)
    - Indoor humidity control criteria
    - Field test design
    - Lab test design
- Expert Meeting: 2009 ASHRAE Summer Annual Meeting
- BA Quarterly Meeting October 2009
  - Draft Industry-based Test Procedure
- Industry Test Procedure by October 2010

Appendix D: Presentation 1

Pollutant Sources and Occupant Activities

Jeffrey Siegel
Department of Civil, Architectural, and Environmental Engineering
The University of Texas at Austin

IGERT: Indoor Environmental Science & Engineering
The University of Texas

Motivation

- How much residential indoor pollution is associate with occupant activities?
- Framework for exploring this question
- Literature and research that informs answer
  - National Human Activity Pattern Survey (NHAPS)
  - Indoor sources of interest
- Specific comments for Standard 62.2 about sources

My Confession

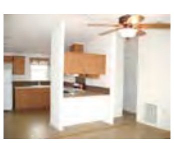
I ♥ dirty filters

An Anecdote

- Collecting used filters to explore their role as "passive" samplers
  - Subject filter cake to a variety of chemical and biological tests

  Noris et al. (2008) *Indoor Air 2008 Proc.*, Noris et al. (2009) *ASHRAE Trans.*
- Conducted tests in eight residences
- Conducted follow-up measurements in unoccupied test house
  - Test house is near two major highways
  - Minimal activity (occasional visits by students)

UTest House



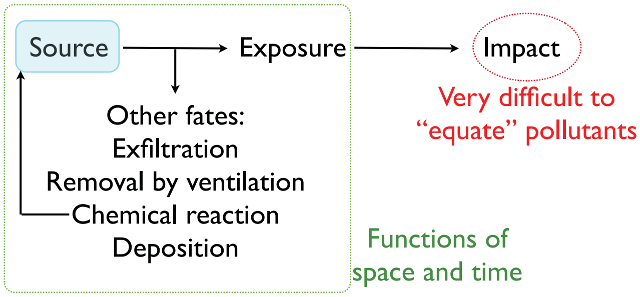
- Two systems
  - 910±60 CFM each system
  - Fans ran continuously
  - High-efficiency (MERV 11) filters
  - Filter ΔP (Pa) after 30 days

	Clean	Dirty
Upflow	76±1.1	79±1.1
Downflow	83±1.2	85±1.2

Hypothesis

- Occupants are responsible for most indoor air pollution
  - Details of exact split are building, occupant, and pollutant specific

Framework



Different Types of Sources

- Area sources
  - Examples: new carpet, paint (Brown, 2002, *Indoor Air*)
- Point sources
  - Examples: cleaning products, plug-in air freshener (Nazaroff and Weschler, 2004, *Atmos. Environ.*; Singer et al., 2006, *Indoor Air*)
- Occupant sources
  - Examples: vacuuming, walking, cooking, showering (Corsi et al., 2008, *JOEH*; Thatcher and Layton, 1995, *Atmos. Environ.*; Qian and Ferro, 2008, *AS&T*; Wallace et al., 2008, *ES&T*; Moya et al., 1999, *ES&T*)
- Acknowledgment: Lots of grey areas

Area Sources

1. **Can** be dominant source of a pollutant
2. Tend to decline with age (Brown, 2002, *Indoor Air*)
   - Texanol from paint (Lin and Corsi, 2007, *Atmos. Environ.*)
   - VOCs from carpet (Brown, 2002, *Indoor Air*)
   - Not exclusively true (Hodgson et al., 2000, *Indoor Air*)

Point Sources

1. Some decline with age
   - VOCs (many) from computers (Destaillats, 2008, *Atmos. Environ.*)
   - Formaldehyde emissions from furniture
2. Others stay approximately constant
   - Ozone emissions from air cleaners (Waring et al, 2008, *Atmos. Environ.*)
   - Plug-in air fresheners (Singer et al., 2006, *Indoor Air*)
   - Particles from scented candles (Lee et al., 2006, *Atmos. Environ.*)

Occupant Sources

1. Very activity and pollutant dependent
   - Cooking as a source of ultrafine particles and NO_x (Wallace et al., 2008, *ES&T*; Baxter et al., 2007, *JESEE*)
   - Walking (resuspension) as a source of allergens (Thatcher and Layton, 1995, *Atmos. Environ.*; Qian and Ferro, 2008, *AS&T*)
   - Ozone reactions with personal care products and skin oils (Corsi et al., 2007, *Atmos Environ*; Wisthaler et al., 2005 *ES&T*)
2. Looks like a point source to other occupants

What do we know about human activities?

- Activities → Occupant sources
- National Human Activity Pattern Survey
  - 9,386 subjects (diverse regionally and demographically)
  - Two types of questions: detailed diaries and survey questions
  - Huge dataset - lots of tools for analyzing
  - Good summary: Klepeis et al. (1999) *Environ. Health Persp.*
  - Canadians have successfully infiltrated: Leech (2002) *JEAEE*
  - Detailed data: Tsang and Klepeis (1996) *EPA/600/R-96/148*

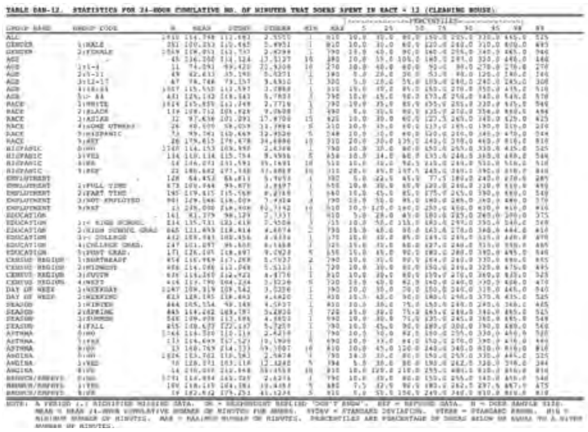


TABLE DAN-12. STATISTICS FOR 24-HOUR CUMULATIVE NO. OF MINUTES THAT DOERS SPENT IN NACT = 12 (CLEANING HOUSE)

Analysis

$$avg.\ time\ spend\ doing\ activity = \frac{\#\ of\ \ doers}{sample\ size} \times avg.\ time$$

- Extremely conservative assessment: 100 min/day
- Does not account for
  - Others exposed to source (e.g., eating in kitchen)
  - Activities that aren't characterized enough or at all in NHAPS (e.g., housework)
  - Sources that are hard to assess (ozone reactions)

Why focus on occupant sources?

1. Area sources often decline with age
   - Diminishes their importance
2. Occupants spend time near point sources
   - If you are ventilating for occupants, you will get these sources
3. Many/most of our activities generate pollution
4. We are disproportionally exposed to occupant sources

What is the split?

- It depends ...
- If you consider potency and proximity and activity
  - 50 - 75% of all exposure is directly related to us "dirty beasts"

Standard 62.2 Comments

- Why focus on kitchens and bathrooms, rather than on occupants?
- Kitchens
  - Occupant sources: cooking, dishwashing, cleaning, dishwashers
  - Point sources: Cleaning product storage - closed containers, limited ozone reactions
- Bathrooms
  - Occupant sources: showering, personal care, cleaning
  - Point sources: Personal care product storage

Why focus on single pollutant approach?

- Pollutants deposit/sorb/react - transport properties are very different
- Pollutant health effects are dramatically different and generally not well studied
  - Not even sure of a suitable comparison metric

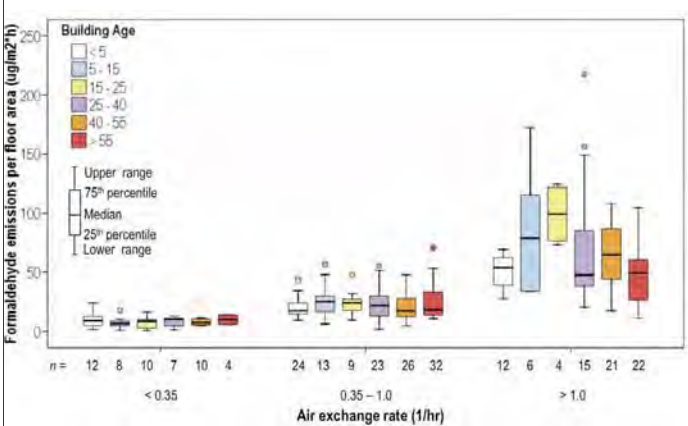
Transport

Pollutant	Example/Source	Typ. Loss Rate
1 nm particle	Cooking	5/hr
0.1 µm particle	Candle	0.05/hr
10 µm particle	Vacuuming	4/hr
Reactive Gas	Ozone/outdoors	2.8 - 4/hr
Unreactive Gas	CO_2/occupants	~0

Transport influences exposure and ventilation

Health Effects

- Data from RIOPA study
  - ~300 homes in Houston, Elizabeth, Los Angeles
  - Indoor, outdoor, personal concentration measurements
- Dominant cancer risks (VOCs and aldehydes only)
  Hun et al. (2008) *Indoor Air Conf.*
  - Formaldehyde (personal conc. > indoor conc.)
  - *para*-dichlorobenzene
    - Snake repellent, moth crystals, toilet bowl deodorizers
    - Hispanic population is particularly exposed



Conclusions

- Occupant sources are important and are often dominant causes of exposure in homes
  - Ventilation strategies should reflect this fact
- A single-pollutant approach is not likely to yield correct answers in any model

Appendix E: Presentation 2

Contaminant Generation and Spatial Ventilation Effectiveness

How do Sources Relate to Human Exposure?

Presenter: Atila Novoselac
The University of Texas at Austin

Building America Expert Meeting
Chicago, January 23rd 2009

INTRODUCTION

Personal exposure depending on:

Indoor airflow
- Ventilation rate
- Airflow distribution

Pollutant characteristics
- Properties
  - Gases: reactive noncreative
  - Particles: different sizes
- Position

Occupant activity
- Movement
- Breathing

OBJECTIVES

Specific presentation objectives:

- Show the impact that thermal plume has on airflow and pollutant concentration in human vicinity
- Present the transport mechanisms from source location to the occupant breathing zone for different pollutants and airflows
- Point out the impact that ventilation effectiveness and pollutant source have on human exposure

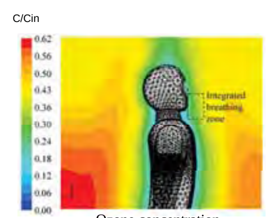
RESEARCH METHODOLOGY

We use advantage of both:

1) Experiments
- Realistic environment
- Reliable first-hand data

2) Numerical Simulations
- Detailed results
- Perfect repeatability


Particle exposure

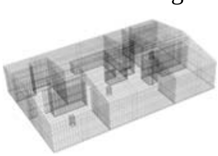


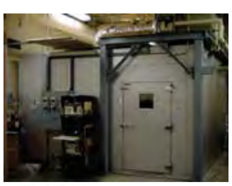
Ozone concentration

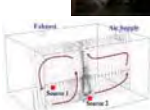
RESEARCH METHODOLOGY

Different scales:


Building






Room


Occupant vicinity

RESULTS

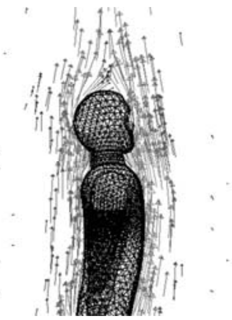
Examples from studies related to:

1) Transport of Particulate and Gaseous Pollutants in the Vicinity of a Human Body under Mixing and Buoyancy Driven Flow

2) Ventilation Effectiveness as an Indicator of Occupant Exposure to Indoor Pollutants

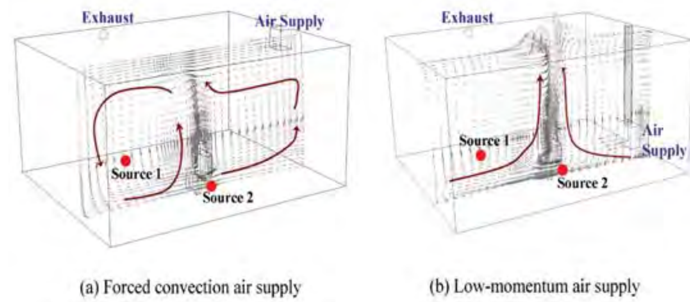
3) Pollutant Distribution in Multizone Residential Buildings with Portable Air Cleaning Devices

RESULTS: Effect of Thermal Plume



RESULTS: Effect of room airflow

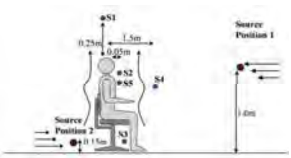
Example of airflow patterns in a space with dominant
a) forced and b) natural convection



HVAC on: mixed flow

Infiltration: stratified flow

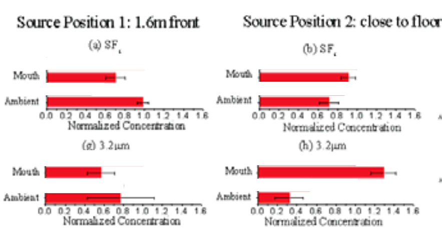
RESULTS: Effect of: Airflow & Source Position



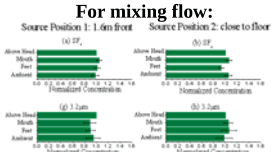
Constant Source Intensity

Ambient: Concentration in the vicinity of the thermal manikin but without the thermal plume

For stratified (buoyancy driven) flow:

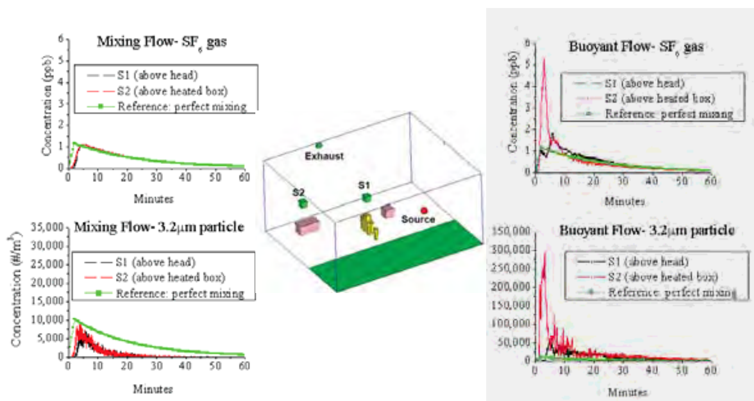


For mixing flow:



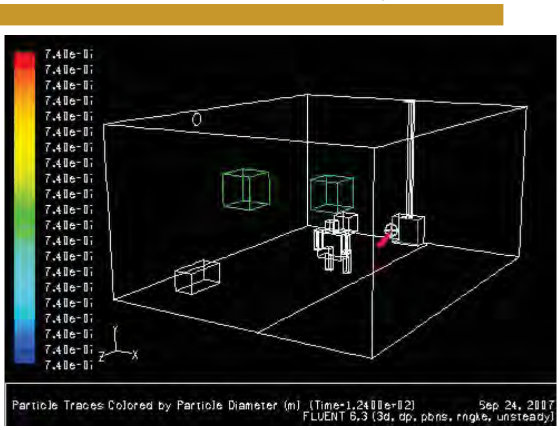
RESULTS: Effect of Source Dynamics

Short Source Emission 2 min



Same flow rate

RESULTS: Effect of Source Dynamics



Intermittent source and buoyancy driven flow result in higher exposure

RESULTS: Ventilation Effectiveness (VE)

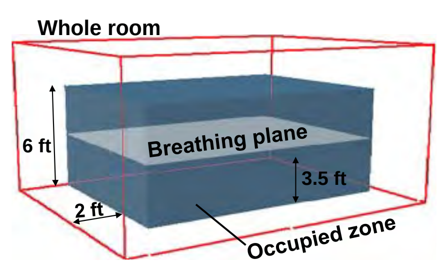
Air-change Effectiveness as exposure indicator ?

Air-change Effectiveness

$$\frac{\text{Average age of air in space}}{\text{Age of air at exhaust}}$$

For perfect mixing:
Air-change Effectiveness = 1

Exposure to most common:
1) Gaseous pollutants
2) Particles



Differences of Air-change Effectiveness defined for room occupied zone and breathing plane vary up to 25%

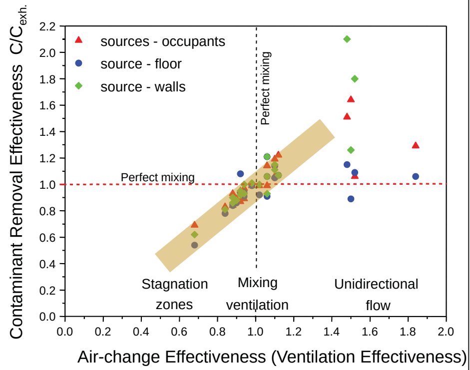
RESULTS: Ventilation Effectiveness (VE)

For Gases

Space types:
- personal office
- cubical office
- classroom
- residential room

Ventilation strategies:
- mixing
- stratified flow

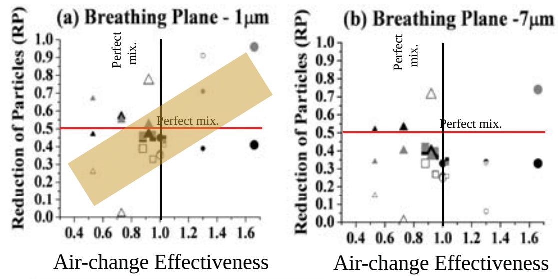
Different sources:
- occupants
- floor
- walls



RESULTS: Ventilation Effectiveness (VE)

For Particles

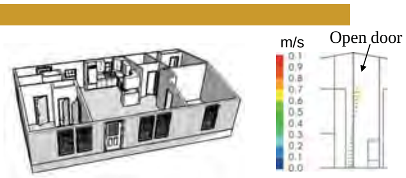
$$RP = \frac{1}{1+\int C/C_{perf.mix}}$$



Airflow pattern (Symbol shape)	Air exchange rate (Symbol size)	Source location (Symbol color)
● Floor Supply	• $1.9hr^{-1}$	● Floor Source
■ Ceiling Supply	● $3.9hr^{-1}$	● Occupant thermal plume
▲ All Air-heating	● $7.7hr^{-1}$	○ Momentum source

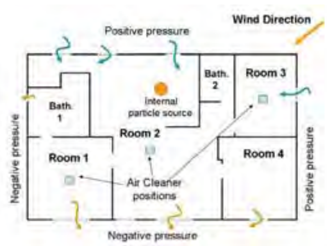
RESULTS: Pollutant Distribution in Homes

Air and particle mixing in a residence with and without portable air cleaning devices



House with open doors ~ heavily partitioned space

Analyzed :
- particle concentrations
- for cases with HVAC off

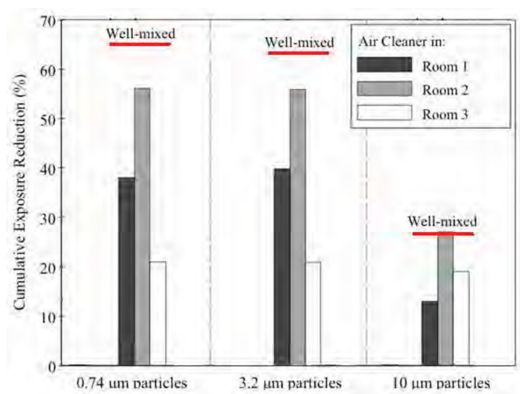


Cumulative exposure reduction

$$\int_{0}^{120\,min} \left(1 - \frac{C_{\text{with AC}}}{C_{\text{without AC}}}\right) dt$$

AC effectiveness

RESULTS: Pollutant Distribution in Homes



Buoyancy driven flow dominates in homes when HVAC is off

SUMMARY

Thermal plume has significant impact on the pollutant transport, positive or negative. Air mixing can decrease this effect of the thermal plume.

Exposure shows a strong dependency on source location. Sources in the vicinity of occupants almost always cause higher exposure.

Use of Air-change Effectiveness as a pollutant exposure indicator is valid to certain point for gases. However, it is not relevant for large particles.

Assumption of perfect mixing in human exposure studies should be used carefully. With HVAC fan off, pollutant concentration in homes can be very nonuniform.

Appendix F: Presentation 3

System Coefficients

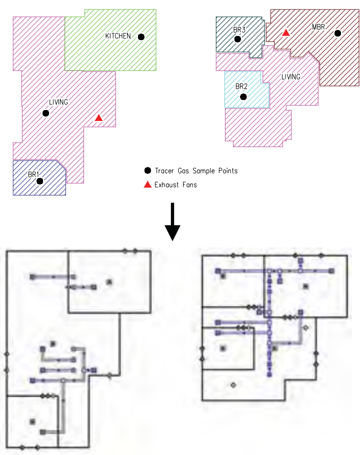
Where Have We Been
and Where Are We Going?

Aaron Townsend
January 23, 2009

Tracer Gas Testing Sacramento January 2006

- Tracer gas test of production Building America house in Sacramento
- 2-story, 4 bedrooms, ~2600 square feet
- Tested two ventilation systems, with and without mixing via central air handler
- Results published by NREL (Bob Hendron) at IAQ 2007

CONTAM Modeling, Nov. 2006-Jan. 2007



Computer modeling used to replicate field testing (tune the model) and predict performance of systems not tested in the field

Expert Meeting, Dallas, January 2007

1. Presented:
   1. Tracer gas testing and results
   2. Calibrated model and results
   3. Coefficients ranging from 0.5 to 1.25 based on a reference of an exhaust-only system with a central AHU controlled by a thermostat only
2. Results:
   1. Committee wanted to see annual simulations, and a wider number of climates and house characteristics (leakage rates, ventilation systems, etc).

Expert Meeting, Long Beach, June 2007

1. Presented:
   1. First parametric study
   2. 3 climates, 3 enclosure leakage levels, 3 options for AHU, 2 options for AHU control, 2 options for duct leakage, 4 ventilation systems, ventilation rate 0-150% of 62.2
   3. Volume-weighted sources only
   4. Coefficients ranging from 1.0 to 2.0 based on a reference of a fully-ducted balanced ventilation system
2. Results:
   1. Committee wanted to see more climates, and had questions about how the various parameters affected the results

Expert Meeting, New York, January 2008

1. Presented:
   1. Second parametric study
   2. 5 climates, 3 enclosure leakage levels, 3 options for AHU, 2 options for AHU control, 2 options for duct leakage, 4 ventilation systems, ventilation rate 0-200% of 62.2
   3. Volume-weighted sources only
   4. Coefficients ranging from 1.0 to 2.0 based on a reference of a fully-ducted balanced ventilation system
   5. Comparison of exposure ratios from BSC's simulations to LBL's field testing & calculations
   6. Effect of AHU size
   7. Effect of parameters: climate, enclosure leakage, etc.
2. Results:
   1. Committee wanted no duct leakage, very leaky results, effect of sources in kitchens & bathrooms, and many more ventilation systems

Conference Calls, April-June 2008

1. April 18, 2008
   1. Revised simulation plan for third parametric study
2. June 10, 2008
   1. Presented third parametric study
   2. 8 climates, 4 enclosure leakage levels, 2 options for AHU, 2 options for AHU control, ~10 ventilation systems, ventilation rate 0-200% of 62.2
   3. Volume-weighted sources or kitchens & bathrooms sources
   4. Coefficients ranging from 1.0 to 2.0 based on a reference of a fully-ducted balanced ventilation system

Meeting, Salt Lake City, June 2008

1. Presented:
   1. Third parametric study
   2. 8 climates, 4 enclosure leakage levels, 2 options for AHU, 2 options for AHU control, 36 ventilation systems, ventilation rate 0-200% of 62.2
   3. Volume-weighted sources or kitchens & bathrooms sources
   4. Coefficients ranging from 1.0 to 2.0 based on a reference of a fully-ducted balanced ventilation system
2. Results:
   1. Committee wanted another enclosure leakage level (5 ach50), occupant-generated sources, and a few more ventilation systems

Conference Call, October 30 2008

1. Presented:
   1. Fourth parametric study
   2. 8 climates, 5 enclosure leakage levels, 2 options for AHU, 2 options for AHU control, ~12 ventilation systems, ventilation rate 0-200% of 62.2
   3. Volume-weighted sources, kitchens & bathrooms sources, or occupant-generated sources; also a combination of volume-weighted and occupant-generated
   4. Coefficients ranging from 1.0 to 2.0 based on a reference of a fully-ducted balanced ventilation system
2. Results:
   1. Participants wanted to see a sensitivity analysis of the effect of source scenario

Conference Call, December 12 2008

1. Presented:
   1. Sensitivity analysis
   2. 8 climates, 5 enclosure leakage levels, 2 options for AHU, 2 options for AHU control, ~12 ventilation systems, ventilation rate 0-200% of 62.2
   3. Different combinations of volume-weighted sources, kitchens & bathrooms sources, and occupant-generated sources
   4. Coefficients ranging from 1.0 to 2.0 based on a reference of a fully-ducted balanced ventilation system
2. Results:
   1. Participants disagree or need more information regarding appropriate assumptions for pollutant sources
   2. One additional ventilation system was requested

New System

- New ventilation system:
  – Two-point exhaust system
  – Exhaust points in hall bathrooms upstairs and downstairs
  – Without AHU, with AHU, and with AHU and minimum turnover

New System

- Results: 3.5 ach50, average of climates

Scenario A

Description	no central system	with central system	with min turnover
Single-point continuous exhaust from first floor common area	2.17	1.79	1.40
Single-point continuous exhaust from second floor master bathroom	2.88	2.15	1.45
Two-point continuous exhaust from 1st and 2nd floor hall bathrooms	2.30	1.87	1.39
Three-point continuous exhaust, 1/3 from each bathroom	2.25	1.72	1.26
Four-point continuous exhaust 1/4 from kitchen and each bathroom	2.00	1.61	1.26

New System

- Results: 3.5 ach50, average of climates

Scenario C

Description	no central system	with central system	with min turnover
Single-point continuous exhaust from first floor common area	2.10	1.87	1.76
Single-point continuous exhaust from second floor master bathroom	2.56	2.34	2.26
Two-point continuous exhaust from 1st and 2nd floor hall bathrooms	2.16	1.83	1.55
Three-point continuous exhaust, 1/3 from each bathroom	1.65	1.49	1.37
Four-point continuous exhaust 1/4 from kitchen and each bathroom	1.43	1.38	1.34

New System

- Results: 3.5 ach50, average of climates

Scenario E

Description	no central system	with central system	with min turnover
Single-point continuous exhaust from first floor common area	2.36	1.79	1.04
Single-point continuous exhaust from second floor master bathroom	3.46	2.08	0.82
Two-point continuous exhaust from 1st and 2nd floor hall bathrooms	2.55	1.94	1.08
Three-point continuous exhaust, 1/3 from each bathroom	2.71	1.80	0.95
Four-point continuous exhaust 1/4 from kitchen and each bathroom	2.45	1.73	0.94

Sensitivity Analysis

- Effect of mixing 3 “pure” scenarios in different ratios
- Pure scenarios:
  - A: Volume-weighted sources
  - C: Sources in kitchens & baths only
  - E: Occupant-generated sources only

Scenario	A	C	E
% K&B zones	25%	100%	0%
% Other zones	75%	0%	0%
% Occupants	0%	0%	100%

Sensitivity Scenarios

- Sensitivity scenarios:
  - F, G1 through G6

Scenarios as a mix of “pure” scenarios

Scenario	F	G1	G2	G3	G4	G5	G6
% VW	50	40	30	50	50	33	20
% K&B	0	10	20	10	20	33	20
% Occ.	50	50	50	40	30	33	60

Sensitivity Scenarios

- Sensitivity scenarios:
  - K&B have volume—how much?
  - 25% in K&B, 75% elsewhere

Scenario emissions by zones & occupants

Scenario	F	G1	G2	G3	G4	G5	G6
% K&B	13	20	28	23	33	41	25
% Other	38	30	23	38	38	25	15
% Occ.	50	50	50	40	30	33	60

Sensitivity Scenarios

- Sensitivity scenarios:
  - Occupants move around—where are their emissions?
  - 15% in K&B, 85% elsewhere

Total emissions by emission location

Scenario	F	G1	G2	G3	G4	G5	G6
% in K&B	20	28	35	29	37	46	34
% in Other	80	73	65	72	63	53	66

Scenario A

(25% in K&B, 75% in other zones, 0% from occupants)

Ventilation type	Ventilation ducting	With AHU		Without AHU
		With Min Turnover	Without Min Turnover	
Supply	fully ducted	1.35	1.65	1.65
	not fully ducted	1.35	1.65	1.65
Exhaust	fully ducted	1.65	2	2
	not fully ducted	1.65	2	2
Balanced	fully ducted	1	1	1
	not fully ducted	1	1.35	1.35

Scenario C

(100% in K&B, 0% in other zones, 0% from occupants)

Ventilation type	Ventilation ducting	With AHU		Without AHU
		With Min Turnover	Without Min Turnover	
Supply	fully ducted	1.65	2	2
	not fully ducted	2	2	2
Exhaust	fully ducted	1.35	1.65	1.65
	not fully ducted	2	2	2
Balanced	fully ducted*	1.35	1.35	1.35
	not fully ducted	1.35	1.65	2

*Any fully-ducted balanced system with returns from all K&B has a coefficient of 1.0

Scenario E

(0% in K&B, 0% in other zones, 100% from occupants)

Ventilation type	Ventilation ducting	With AHU		Without AHU
		With Min Turnover	Without Min Turnover	
Supply	fully ducted	1	1	1
	not fully ducted	1	1.35	1.65
Exhaust	fully ducted	1	1.65	2
	not fully ducted	1	2	2
Balanced	fully ducted	1	1	1.35
	not fully ducted	1	2	2

Scenario F

(13% in K&B, 38% in other zones, 50% from occupants)

Ventilation type	Ventilation ducting	With AHU		Without AHU
		With Min Turnover	Without Min Turnover	
Supply	fully ducted	1	1.35	1.35
	not fully ducted	1	1.35	1.65
Exhaust	fully ducted	1.35	2	2
	not fully ducted	1.35	2	2
Balanced	fully ducted	1	1	1.35
	not fully ducted	1	1.65	2

Scenario G1

(20% in K&B, 30% in other zones, 50% from occupants)

Ventilation type	Ventilation ducting	With AHU		Without AHU
		With Min Turnover	Without Min Turnover	
Supply	fully ducted	1	1.35	1.35
	not fully ducted	1	1.35	1.65
Exhaust	fully ducted	1.35	1.65	2
	not fully ducted	1.35	2	2
Balanced	fully ducted	1	1	1.35
	not fully ducted	1	1.65	2

Scenario G2

(28% in K&B, 23% in other zones, 50% from occupants)

Ventilation type	Ventilation ducting	With AHU		Without AHU
		With Min Turnover	Without Min Turnover	
Supply	fully ducted	1	1.35	1.35
	not fully ducted	1	1.35	1.65
Exhaust	fully ducted	1	1.65	2
	not fully ducted	1.35	2	2
Balanced	fully ducted	1	1	1.35
	not fully ducted	1	1.65	2

Scenario F

(13% in K&B, 38% in other zones, 50% from occupants)

Ventilation type	Ventilation ducting	With AHU: With Min Turnover	With AHU: Without Min Turnover	Without AHU
Supply	fully ducted	1	1.35	1.35
	not fully ducted	1	1.35	1.65
Exhaust	fully ducted	1.35	2	2
	not fully ducted	1.35	2	2
Balanced	fully ducted	1	1	1.35
	not fully ducted	1	1.65	2

Scenario G3

(23% in K&B, 38% in other zones, 40% from occupants)

Ventilation type	Ventilation ducting	With AHU: With Min Turnover	With AHU: Without Min Turnover	Without AHU
Supply	fully ducted	1	1.35	1.35
	not fully ducted	1	1.35	1.65
Exhaust	fully ducted	1.35	1.65	2
	not fully ducted	1.35	2	2
Balanced	fully ducted	1	1	1.35
	not fully ducted	1	1.65	2

Scenario G4

(33% in K&B, 38% in other zones, 30% from occupants)

Ventilation type	Ventilation ducting	With AHU: With Min Turnover	With AHU: Without Min Turnover	Without AHU
Supply	fully ducted	1	1.35	1.35
	not fully ducted	1.35	1.65	1.65
Exhaust	fully ducted	1.35	1.65	2
	not fully ducted	1.35	2	2
Balanced	fully ducted	1	1	1
	not fully ducted	1	1.65	2

Scenario G5

(41% in K&B, 25% in other zones, 33% from occupants)

Ventilation type	Ventilation ducting	With AHU: With Min Turnover	With AHU: Without Min Turnover	Without AHU
Supply	fully ducted	1	1.35	1.35
	not fully ducted	1.35	1.65	1.65
Exhaust	fully ducted	1.35	1.65	2
	not fully ducted	1.35	2	2
Balanced	fully ducted	1	1	1
	not fully ducted	1	1.65	2

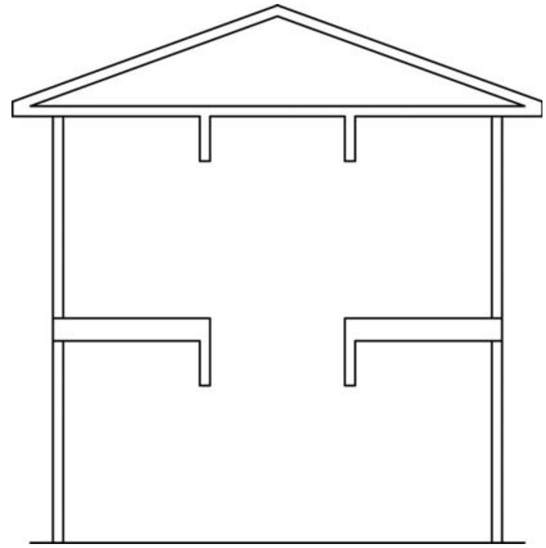
Scenario G6

(25% in K&B, 15% in other zones, 60% from occupants)

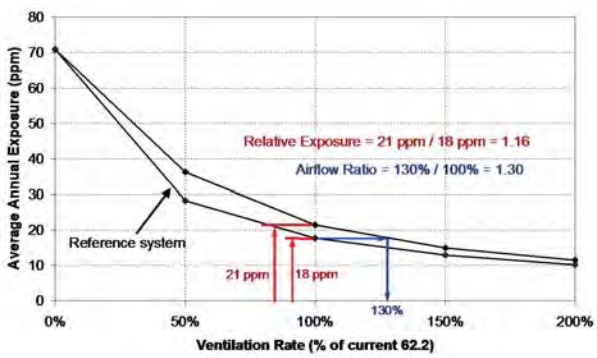
Ventilation type	Ventilation ducting	With AHU: With Min Turnover	With AHU: Without Min Turnover	Without AHU
Supply	fully ducted	1	1	1.35
	not fully ducted	1	1.35	1.65
Exhaust	fully ducted	1	2	2
	not fully ducted	1	2	2
Balanced	fully ducted	1	1	1.35
	not fully ducted	1	2	2

Scenarios G2, G5, G6

		Ventilation type	Ventilation ducting	With AHU: With Min Turnover	With AHU: Without Min Turnover	Without AHU
Scenario	**G2**	Supply	fully ducted	1	1.35	1.35
% K&B	28		not fully ducted	1	1.35	1.65
% Other	23	Exhaust	fully ducted	1	1.65	2
% Occ.	50		not fully ducted	1.35	2	2
		Balanced	fully ducted	1	1	1.35
			not fully ducted	1	1.65	2
Scenario	**G5**	Supply	fully ducted	1	1.35	1.35
% K&B	41		not fully ducted	1.35	1.65	1.65
% Other	25	Exhaust	fully ducted	1.35	1.65	2
% Occ.	33		not fully ducted	1.35	2	2
		Balanced	fully ducted	1	1	1
			not fully ducted	1	1.65	2
Scenario	**G6**	Supply	fully ducted	1	1	1.35
% K&B	25		not fully ducted	1	1.35	1.65
% Other	15	Exhaust	fully ducted	1	2	2
% Occ.	60		not fully ducted	1	2	2
		Balanced	fully ducted	1	1	1.35
			not fully ducted	1	2	2



Relative Exposure vs Airflow Ratio



Relevant Sections of 62.2

- Forward, paragraph 8 (62.2 does not address certain events such as cleaning or other high-polluting events)
- Section 2.2 "[Acceptable indoor air quality] will not necessarily be achieved even if all requirements [of 62.2] are met"
  - Diversity of sources and susceptibility
  - Other factors: temperature, RH, etc
  - Outdoor air quality
  - Poor operation or maintenance
  - During high-polluting events

2.18.6. 2009 ASHRAE Transactions 11, Paper #1 Presentation

A Calibrated Multi-Zone Airflow Model for Extension of Ventilation System Tracer Gas Testing

Aaron Townsend, P.E.
Armin Rudd
Joseph Lstiburek, Ph.D., P.Eng.
Building Science Corporation

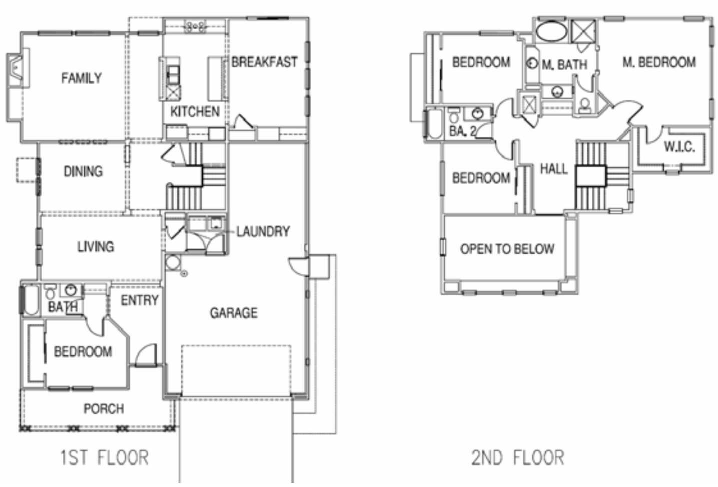
Introduction

- A software model was calibrated to reproduce field test results from tracer gas testing of ventilation systems

House Characteristics

- 2 story, 4 bedroom, 2600 ft^2 (240 m^2)

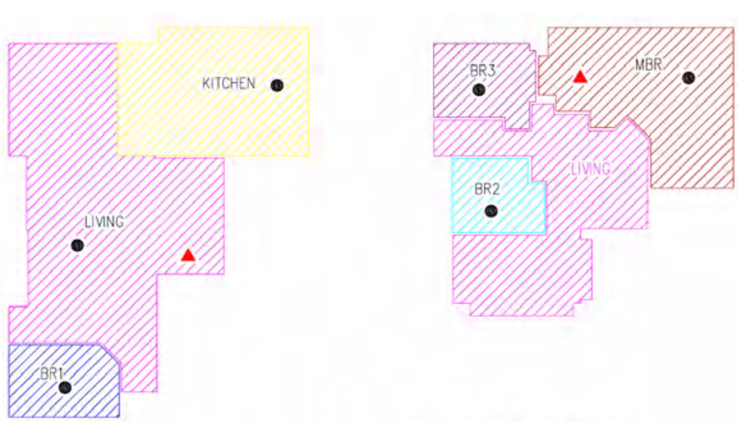
Floor Plan



Tracer Gas Testing

- 17 tests of ventilation systems under different conditions:
  - System (single-point exhaust or central-fan integrated supply)
  - Duty cycle of central fan (single-point exhaust only)
  - Ventilation rate (CFIS only)
  - Bedroom doors open or closed
  - Transfer grills open or closed

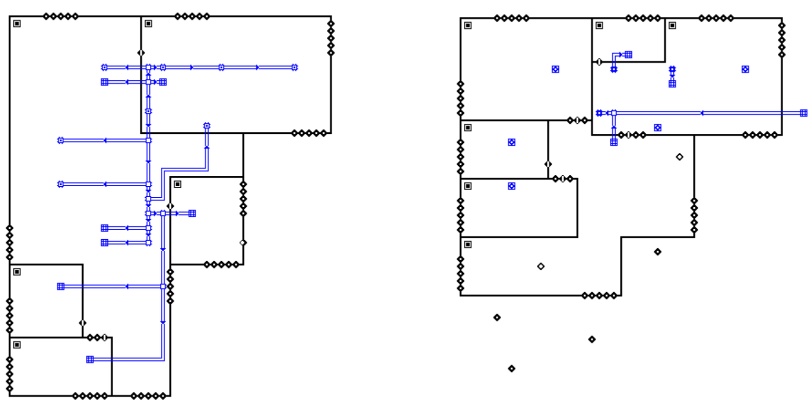
Zones



CONTAM Modeling Software

- Commonly-used multi-zone air flow network model software by NIST
- User specifies zones, air flow paths, contaminant sources and sinks, temperatures, weather, etc.
- Software determines flows and contaminant concentrations

CONTAM Screenshot



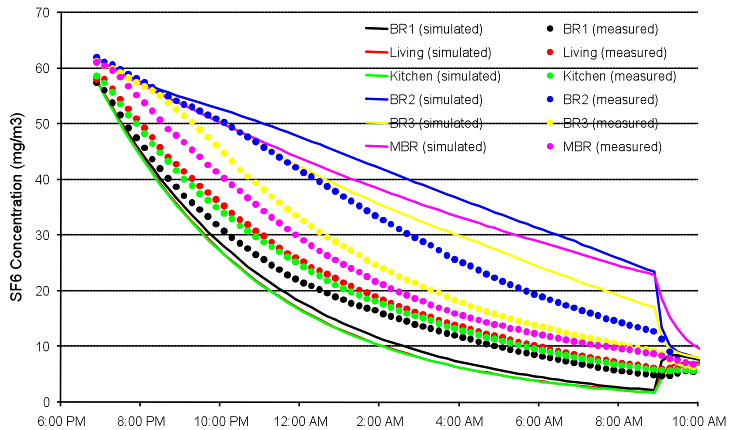
Modeling Procedure

- Initial guess values taken from testing of a similar house
- Simulation performed and educated guesses made to correct visual differences between tested results and simulated results
- No formal error function
- Not an optimized or unique solution

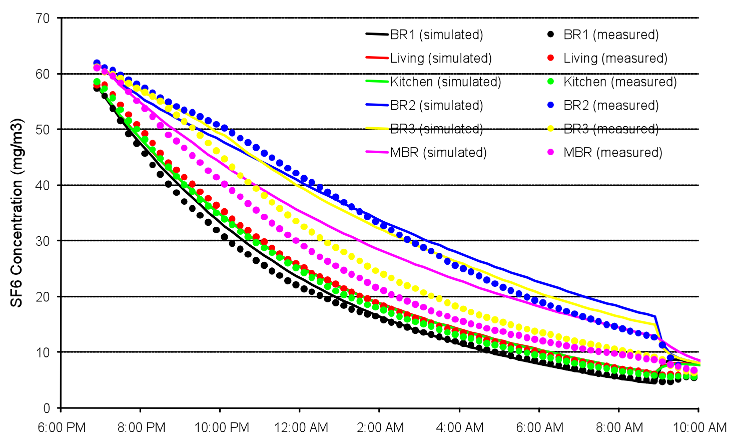
Modeling Procedure, II

- The most difficult tests to reproduce behavior were those with large differences between rooms
- One test used to calibrate model, remaining tests used to evaluate quality of calibration
- Calibration process stopped when visual behavior deemed sufficient (subjective)

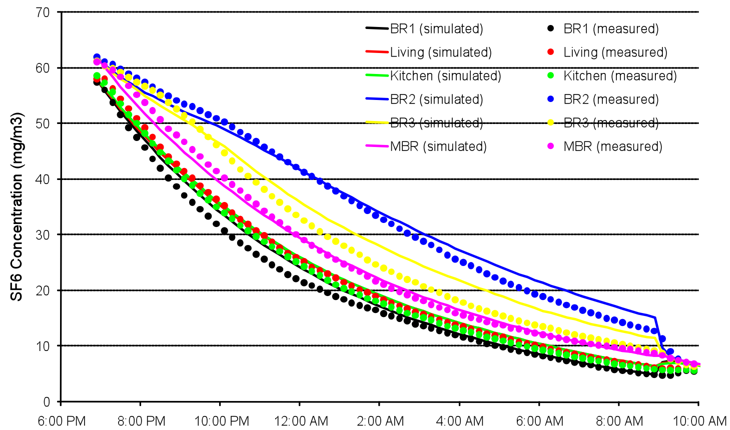
Results of Initial Guess



Mid-Calibration



Results of Final Calibration



Modeling Procedure, III

- Remaining tests simulated and compared to experimental results

Statistical Evaluation of Results

- ASTM D5157-97 Standard Guide for Statistical Evaluation of Indoor Air Quality Models used to evaluate quality of calibration.

ASTM D5157

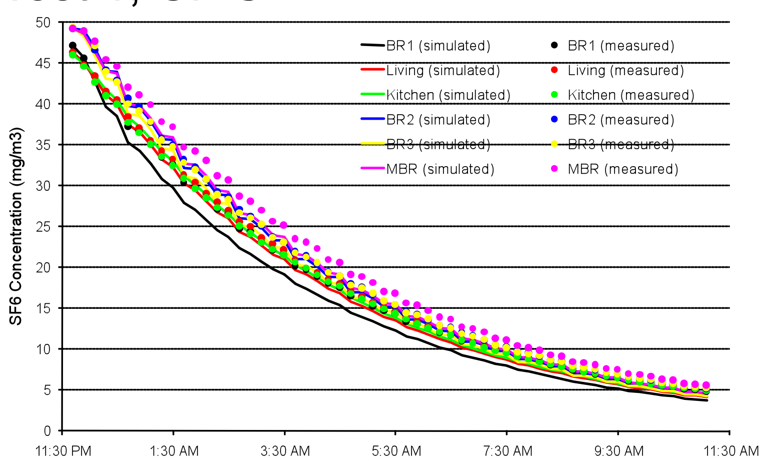
- Three criteria for evaluating models:
  - Data used for evaluation should be separate from data used for developing model
  - A set of quantitative parameters calculated from the modeled and observed data sets
  - Visual comparison of plotted data sets

ASTM D5157 Quantitative Parameters

- Correlation coefficient (should be >0.9)
- Best-fit line of regression components: m and b (0.75 < m < 1.25, $b/C_{o,avg}$ < 0.25)
- Normalized mean square error (NMSE < 0.25)
- Fractional bias (FB < 0.25)
- Index of variance bias (FS < 0.5)

Modeling Results

- Test 1, CFIS

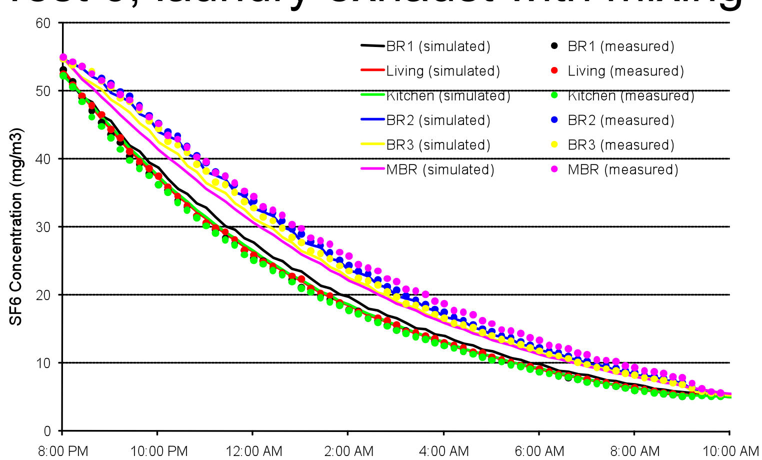


ASTM D5157 Parameters for Test 1

ASTM D5157 parameter	r	m	b/Co	NMSE	FB	FS
ASTM D5157 "adequate" range	>0.9	0.75 to 1.25	<0.25	<0.25	<0.25	<0.5
BR1	1.00	0.99	-0.09	0.01	-0.10	-0.01
Living	1.00	1.01	-0.07	0.00	-0.05	0.01
Kitchen	1.00	1.04	-0.05	0.00	-0.01	0.04
BR2	1.00	1.02	-0.05	0.00	-0.02	0.02
BR3	1.00	1.01	-0.06	0.00	-0.05	0.01
MBR	1.00	1.00	-0.06	0.00	-0.07	0.00

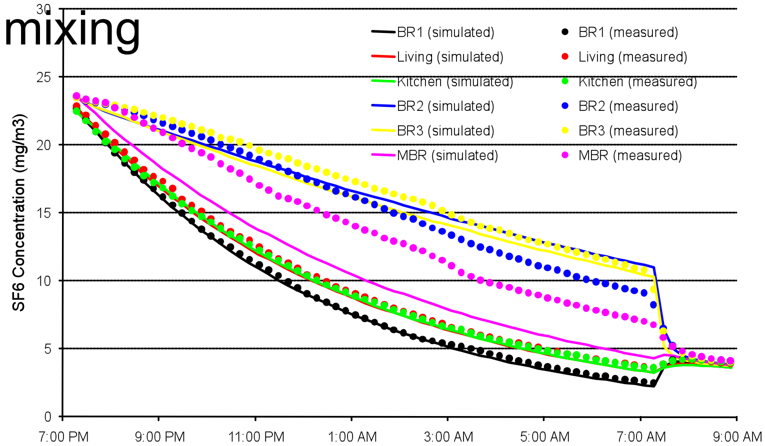
Modeling Results

- Test 6, laundry exhaust with mixing



Modeling Results

- Test 10, laundry exhaust without mixing



Modeling Results

- Good agreement between modeled and physical results
- Greatest agreement for cases with mixing due to central fan
- Least agreement for natural infiltration cases
- Most statistical parameters well within suggested limits

Discussion of Error

- Numerical and graphical comparisons of data sets indicate general agreement
- Some shapes in graphical comparison not replicated
- High number of assumptions about leakage distribution, effect of wind

Extension to Other Systems

- Calibrated model used to compare performance of systems not tested in physical testing
- Balanced, supply, and exhaust systems under identical environmental conditions
- Effective decay rate calculated as comparative metric

Extension Cases Studied

Case Number	Description
1	CFIS, AHU 20 min off/10 min on
2	Laundry exhaust, AHU 20 min off/10 min on
3	Laundry exhaust, AHU off
4	Balanced, AHU 20 min off/10 min on
5	Balanced, AHU off

- Cases 1, 2, & 4 mixed
- Cases 4 & 5 balanced

Extension Cases Results

- Effective decay rate of each system:

Case	BR1	Living	Kitchen	BR2	BR3	MBR
1	0.21	0.20	0.20	0.20	0.20	0.20
2	0.16	0.16	0.16	0.15	0.15	0.15
3	0.19	0.16	0.16	0.07	0.09	0.14
4	0.23	0.23	0.23	0.24	0.23	0.21
5	0.40	0.27	0.26	0.37	0.34	0.15

- Mixed cases have uniform rates
- Balanced cases have higher decay rates

Conclusions

- A calibrated model can be created that replicates results of tracer gas testing, given sufficient detail is known about the enclosure
- Visual agreement of the tracer gas decay curves can result in satisfactory results to statistical testing via ASTM D5157

Conclusions

- Agreement between modeled and measured data is high for well-mixed cases and lower for non-well-mixed cases.
- Agreement lowest at low or no ventilation flow rate.

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Questions?

2.18.7. 2009 ASHRAE Transactions 12, Paper #2 Presentation

A Method for Modifying Ventilation Airflow Rates to Achieve Equivalent Occupant Exposure

Aaron Townsend, P.E.
Armin Rudd
Joseph Lstiburek, Ph.D., P.Eng.
Building Science Corporation

Introduction

- ASHRAE Standard 62.2, Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings
  - Ventilation rate = 7.5 cfm/person + 0.01 cfm/ft^2 floor area
  - No differentiation between different types of systems known to have different performance

The Goal

- Can the standard account for the difference in performance between systems?
- A modification to the base ventilation rate based on what type of system is installed
- $Q_{fan} = C_S * Q_{vent}$

The Approach

- Establish a baseline system and determine the airflow ratio needed in order to achieve equivalent performance
- What is the baseline system?
- What is equivalent performance?

The Approach, II

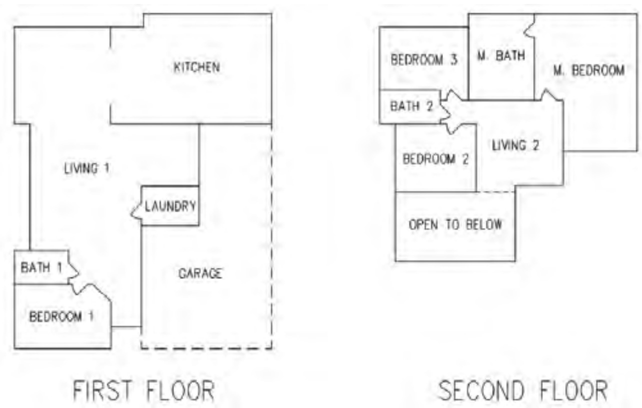
- Use computer model to compare different systems using occupant exposure as the comparison metric
- Work with the 62.2 committee to determine assumptions to make and systems to simulate

The Computer Model

- CONTAM was used as the modeling software
- Multi-zone airflow network modeling tool
- Exercised model over a range of parameters to cover a reasonable subset of new and existing houses

The House

- 2 story, 4 bedroom, 2600 ft^2 (240 m^2)



Assumptions

- 5 occupants on a daily occupancy schedule
- Bedroom doors closed at night
- Small interior temperature differences to drive airflow through open doorways

Contaminant Generation

- Unique contaminant generated in each zone and by each occupant
- Contaminant behaves as tracer gas: non-reacting, non-decaying, non-settling. Only removed by dilution with outdoor air.
- Outdoor air contaminant-free

Enclosure Leakage

- Total enclosure leakage varied to determine effect (1.5 to 20 ach @ 50 Pa)
- Leakage distribution over enclosure held constant
- Diffuse leakage approximated in walls and ceiling
- Attic and garage neglected as outdoors

Climates and Wind

- 9 climates modeled, from Florida to California to Minnesota
- Wind modeled from TMY2 data and standard shielding factors for suburban terrain

Central Air Handling System

- AHU size determined by design temperature of each climate using industry-standard procedures
- AHU runtime determined by linear interpolation of hourly outdoor temperature, design temperature, and balance point temperature

Minimum Runtime or Turnover

- Some ventilation systems included minimum runtime or turnover criteria for AHU
- Minimum runtime [min/hr]
- Minimum turnover of house (% of house volume of air passed through AHU each hour) [1/hr]

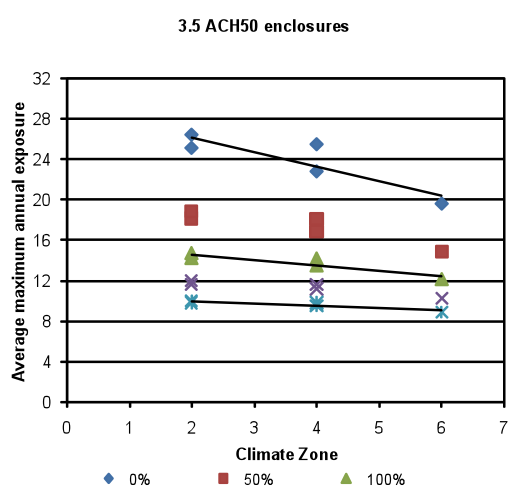
Post-Processing

- Occupants exposed to the contaminants in the zone according to their daily schedule
- Hourly exposures averaged over a time period to determine average exposure
- Generally focused on annual average exposure

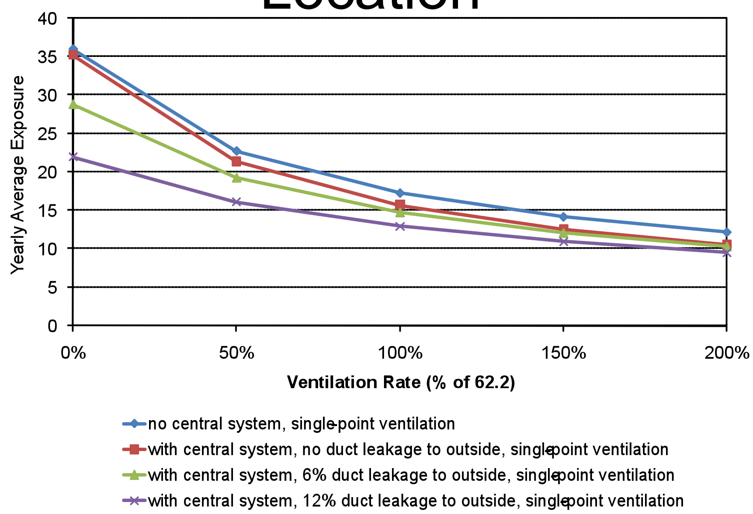
Initial Results

- Initial set of simulations performed to determine general effect of certain parameters

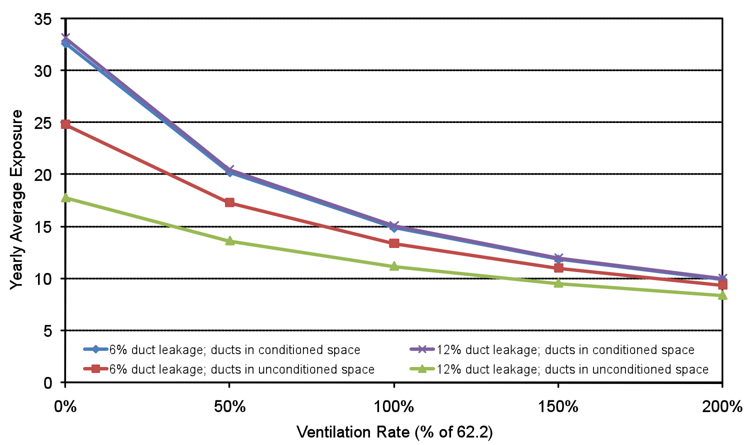
Effect of Climate



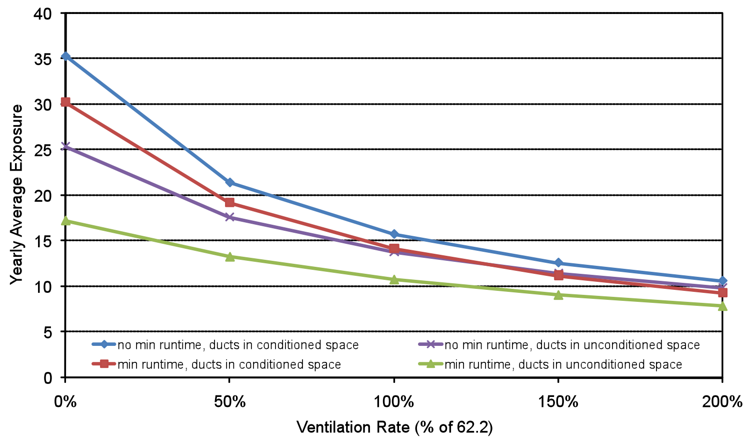
Effect of AHU Presence & Location



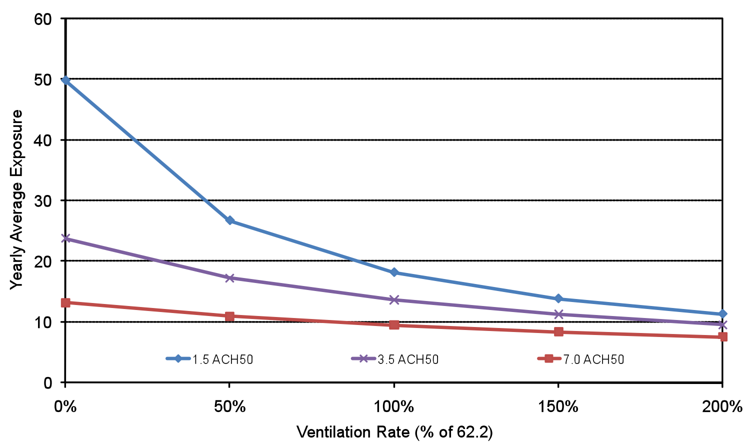
Effect of Duct Leakage and Location



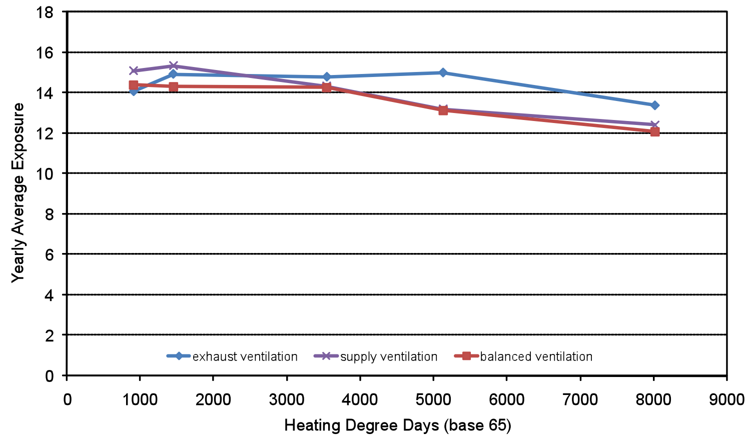
Effect of Duct Location and Minimum AHU Runtime



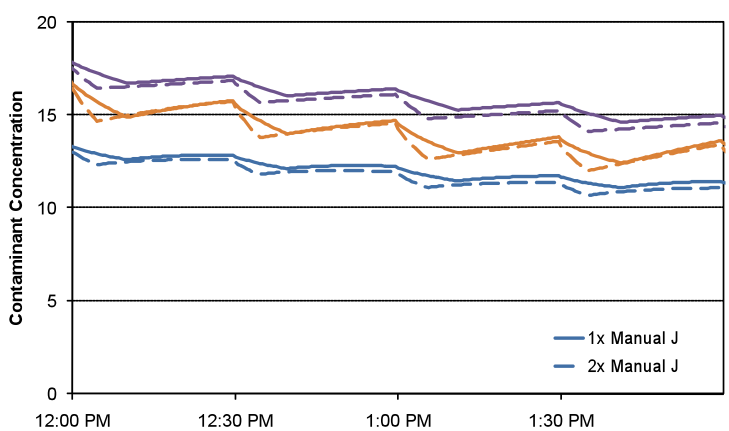
Effect of Enclosure Leakage



Effect of Ventilation Direction and Climate



Effect of AHU Sizing



Final Simulations

- Reference system chosen and reference exposure level established (occupant with highest exposure in each simulation)
- Other systems simulated and compared to reference exposure level
- Airflow ratio calculated to achieve equivalent exposure

Ventilation Systems

- 36 ventilation systems
  - Supply-only, exhaust-only, balanced
  - Single-point, ducted, central-fan integrated
  - With or without minimum turnover requirements

Exposure Scenarios

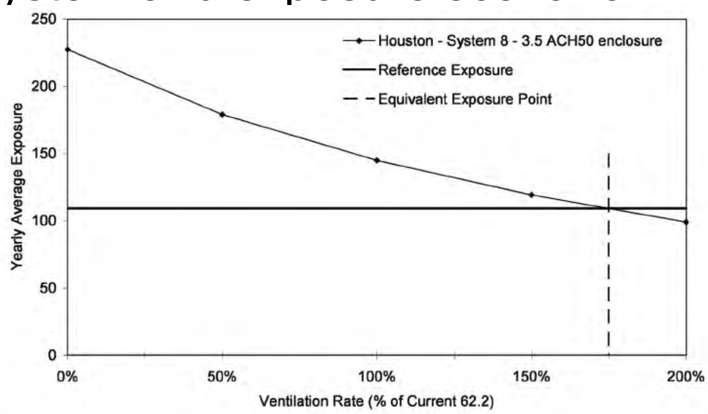
- Volume-weighted contaminant sources
- Contaminants from kitchens and bathrooms
- Occupant-generated contaminants

Reference Exposures

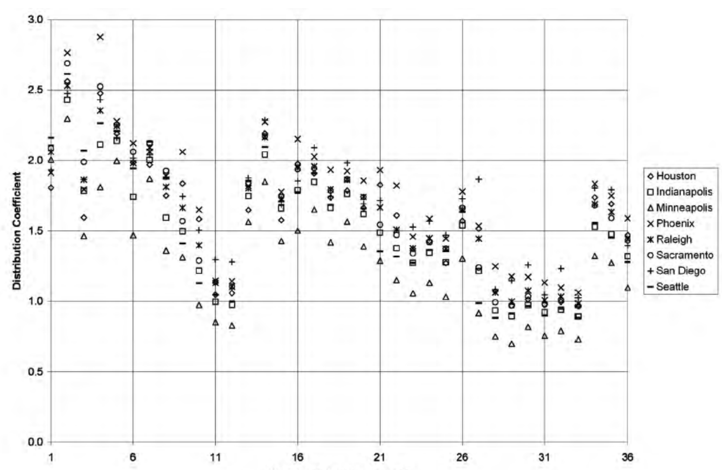
- Average of the reference system exposure from all climates
- Each exposure scenario has a different reference exposure

Airflow Ratio Calculation

- An airflow ratio is calculated for each system and exposure scenario



Airflow Ratio Results – Volume Weighted Sources



System Coefficients

- Similar systems perform similarly: single-point exhaust, multi-point supply, etc.
- Systems grouped by characteristic appropriate for a standard and the airflow ratios averaged to get a system coefficient

Conclusions

- A method for comparing different ventilation systems has been demonstrated
- System coefficients range from 1 to about 3 with the given reference system using volume-weighted contaminant sources

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Questions?

3. PROJECT 3: DEHUMIDIFICATION PERFORMANCE ADVANCED SYSTEM RESEARCH

3.1 Executive Summary

Overview

Energy-efficient houses in warm, humid climates have low sensible heat gain. Low sensible heat gain is good for reducing cooling costs, but contributes to part load moisture control challenges. Especially during Spring and Fall seasons, as well as rainy periods and summer nights, there are a significant number of hours where little or no sensible cooling is needed but moisture removal is still needed due to internal moisture generation and outside air exchange. Conventional cooling equipment is equipped mostly for reducing air temperature (sensible cooling), with only about 20 to 30 percent of its capacity typically designed for removing moisture (latent cooling). This results in periods of high indoor relative humidity.

Enhanced space conditioning equipment can slow the indoor fan and stage the compressor to remove more moisture while the system is cooling for longer periods, but, regardless, it continues to cool in order to dehumidify. In efficient, low heat gain houses in warm-humid climates, when no cooling is needed but moisture removal alone is needed, the solution has been to employ systems that can remove moisture while supplying room neutral temperature or warmer air. That has been in the form of stand-alone dehumidifiers, or dehumidifiers integrated with the central space conditioning system, or central cooling systems with condenser reheat capability.

There is a significant lack of performance information to characterize these equipment options in residential buildings. The Building America Program has been obtaining some performance data through field and laboratory testing. Current standards for performance ratings, and methods of test, do not account for a wide enough range of test conditions to allow a designer or analyst to know what to expect for moisture removal capacity and moisture removal efficiency over a range of operating conditions and operating states. The goal of this project is achieve an industry-based standard for rating residential dehumidifier performance with a large enough set of test conditions to allow designers to understand the expected performance and correctly apply the right equipment in the field. It is also anticipated that more test conditions will enable better performance mapping of the equipment for better energy and humidity control modeling of high-performance buildings.

Key Results

Currently, we have drafted both a performance rating standard and a method of test standard. These documents need to be refined under the guidance of an AHRI committee for the performance rating, and under the guidance of an ASHRAE committee for the method of test. Contacts have been made in both organizations and efforts will continue to see the committees formed and progressing with these documents. There is support for this from industry and manufacturing partners.

Gate Status

The following sections evaluate the research project results based on performance benefits and the ability to develop performance specifications for advanced systems.

1. *Source Energy Savings and Whole Building Benefits (“must meet”)*

This project meets the Gate 1B "must meet" requirement for source energy savings. The performance rating standard will assist HVAC system designers to properly apply dehumidification systems in the most efficient ways.

2. Performance-Based Code Approval ("must meet")

This project meets the Gate1B "must meet" requirement for performance-based safety, health and building code requirements for new homes. The system is fully compliant with all relevant performance-based codes.

3. Prescriptive-Based Code Approval ("should meet")

This project meets the Gate1B "should meet" requirement for prescriptive-based safety, health and building code requirements for new homes. The system is fully compliant with all relevant prescriptive-based codes.

4. Cost Advantage ("should meet")

This project meets the Gate 1B "should meet" requirement for strong potential to provide cost benefits relative to current systems. A dehumidification system tested to a new expanded performance rating standard may have a slightly higher first cost, but should provide operating cost benefits through more appropriate application of the system and knowledge of its dehumidification efficiency under multiple operating conditions.

5. Reliability Advantage ("should meet")

Compared to products not tested to an expanded set of test conditions, products tested to and expanded performance rating standard should more likely meet the Gate 1B "should meet" requirement to meet reliability, durability, ease of operation, and net added value requirements for use in new homes.

6. Manufacturer/Supplier/Builder Commitment ("should meet")

This project meets the Gate 1B "should meet" requirement of manufacturer commitment since manufacturing partners are helping to push the new performance rating standard forward through AHRI.

7. Gaps Analysis ("should meet")

Current gaps for this project include:

a) getting the right mix of people together between AHRI and ASHRAE to benefit from the proponents of related existing performance rating standards and methods of test so as to gain from their experience;

b) achieving consensus among participants concerning the appropriate information to include in either a performance rating or a method of test; and

c) achieving consensus on how many and what standard test conditions should be included.

We see no major market barriers to this project, but minor market barriers could include trying to broaden the standard to include desiccant dehumidifiers and standard cooling systems that are not dedicated dehumidifiers but cool to dehumidify.

Conclusions

The goal of this project is to reach publication of a new performance rating standard and method of test standard to facilitate appropriate application of residential dehumidifiers in high-performance homes. This will provide accurate means to compare multiple efficient and cost effective paths to control indoor humidity in homes, year round, yielding confidence to continue pushing ahead with efficiency improvements that reduce sensible cooling load. The efforts made toward establishing a coherent industry based performance rating and method of test standard will continue and will yield long-term benefits due to quantifiable and appropriate application of whole-building dehumidification systems for high-performance homes. Realistic performance maps can also be developed from more detailed test data to support accurate modeling efforts.

Research Approach and Results to Date

3.1.1. New Standard Test Conditions

BSC has been leading the effort on behalf of the Building America Program to achieve an industry-based standard for rating residential dehumidifier performance. The process started by developing a rationale and specification for more test conditions than what current standards call for. These recommended new test conditions are listed in Tables 3.1 thru 3.3.

Referring to Table 3.1, the Test 1a to 1c outdoor and indoor conditions are intended to represent summer peak cooling conditions in warm- humid climates. The Test 2a to 2c outdoor and indoor conditions are intended to represent summer off-peak cooling conditions, such as during summer nights and overcast or rainy periods. The Test 3a to 3c outdoor and indoor conditions are intended to represent spring/fall off-peak cooling conditions when the outside temperature is close to room temperature but the outdoor still humidity remains high. The Test 4a to 4c outdoor and indoor conditions are intended to represent winter periods in warm-humid climates when the outside air temperature is lower than room temperature but the outdoor humidity remains above indoors.

	Outdoor T/RH/Tdp (F/%/F)	Inlet T/RH/Tdp (F/%/F)	Outlet T/RH/Tdp (F/%/F)	Indoor Wet-coil Airflow (cfm)	Sensible Cooling Capacity[1] (Btu/h)	Latent Cooling Capacity (Btu/h)	Moisture Removal Capacity (L/h)	Total Power (kW)	Moisture Removal Efficiency[2] (L/kW-h)
Test 1a	95/58/78	80/60/65							
Test 1b	""	78/55/61							
Test 1c	""	75/50/55							
Test 2a	80/85/75	80/60/65							
Test 2b	""	78/55/61							
Test 2c	""	75/50/55							
Test 3a	75/85/70	78/60/63							
Test 3b	""	78/55/61							
Test 3c	""	75/50/55							
Test 4a	65/90/62	72/60/57							
Test 4b	""	70/52/52							
Test 4c	""	68/45/46							

[1] Negative cooling capacity denotes net heat added from inlet to outlet

[2] Same units as the USDOE and USEPA Energy Factor for dehumidifiers

[3] All tests with steady wet coil

Table 3.1: Recommended new standard test conditions and reporting results, for rating residential dehumidifier performance, for units with both indoor and outdoor heat transfer components

Referring to Table 3.2, the Test 1 to 7 indoor conditions are intended to represent a range of indoor temperature and humidity combinations commonly found in warm-humid climates. The range extends from the AHAM test conditions of 80 F and 60% RH for dehumidifiers to conditions representing wintertime in warm-humid climates where dehumidification may be used to address interior window condensation.

	Inlet T/RH/Tdp (F/%/F)	Outlet T/RH/Tdp (F/%/F)	Indoor Wet-coil Airflow (cfm)	Sensible Cooling Capacity (Btu/h)	Latent Cooling Capacity[1] (Btu/h)	Moisture Removal Capacity (L/h)	Total Power (kW)	Moisture Removal Efficiency[2] (L/kW-h)
Test 1	80/60/65							
Test 2	78/60/63							
Test 3	78/55/61							
Test 4	75/50/55							
Test 5	72/60/57							
Test 6	70/52/52							
Test 7	68/45/46							

[1] Negative cooling capacity denotes net heat added from inlet to outlet

[2] Same units as the USDOE and USEPA Energy Factor for dehumidifiers

[3] All tests with steady wet coil

Table 3.2. Recommended new standard test conditions and reporting results, for rating residential dehumidifier performance, for units with only indoor heat transfer components

Referring to Table 3.3, the Test 1 to 4 indoor conditions are intended to represent a range of temperature and humidity combinations commonly found when controlling basement moisture.

	Inlet T/RH/Tdp (F/%/F)	Outlet T/RH/Tdp (F/%/F)	Indoor Wet-coil Airflow (cfm)	Sensible Cooling Capacity[1] (Btu/h)	Latent Cooling Capacity (Btu/h)	Moisture Removal Capacity (L/h)	Total Power (kW)	Moisture Removal Efficiency[2] (L/kW-h)
Test 1	65/50/46							
Test 2	65/60/51							
Test 3	70/50/51							
Test 4	70/60/56							

[1] Negative cooling capacity denotes net heat added from inlet to outlet
[2] Same units as the USDOE and USEPA Energy Factor for dehumidifiers
[3] All tests with steady wet coil

Table 3.3. Recommended new standard test conditions and reporting results, for rating residential dehumidifier performance, for basement units

3.1.2. Modifying AHRI Standard 210/240

Initially, the intention was to restrict the scope of the new rating performance standard to electrically operated refrigerant vapor compression systems, either dehumidifier systems that were independent of a central cooling system or part of a central cooling system. In other words, it would be for any equipment that dehumidifies (AC systems) or dedicated dehumidification equipment (dehumidifiers).

AC systems may have enhanced dehumidification capability through the common method of lowering evaporator fan speed, to the newer methods of condenser reheat (subcooling only, or with partial or full condensing). AC systems that just lower evaporator fan speed would still provide more than 60% of the total cooling capacity as sensible cooling, having outlet air colder than inlet air. AC systems with process air condenser reheat could adjust the outlet air temperature to be colder, equal to, or warmer than inlet air. In the case where outlet air was warmer than inlet air, a negative sensible cooling capacity would be recorded, meaning that heat was added to the process air.

Because conventional AC systems would be included in the new residential dehumidifier performance rating standard, the AHRI Standard 210/240 "Performance Rating Of Unitary Airconditioning and Airsource Heat Pump Equipment" was first considered to be the base standard to work from. The AHRI Standard 210/240 was then modified to redact unnecessary portions and to add new portions, including the new standard test conditions given in Tables 3.1 to 3.3. A draft of that document is provided in Section 0.

3.1.3. Modifying ASHRAE Standard 37

Upon presenting a draft of the approach to modify AHRI Standard 210/240 to the Building America Working Group, there was a strong suggestion that the new standard should be a method of test (MOT) standard rather than a rating standard. There was also a strong suggestion that the new dehumidifier standard should be inclusive of desiccant dehumidifiers. ASHRAE Standard 37 is the primary MOT relied upon by AHRI 210/240. It already covered much of what we wanted to describe for unitary AC equipment. So, that led to another draft dehumidifier performance standard derived from modifying ASHRAE Standard 37 "Methods of Testing for Rating Electrically Driven Unitary Air-Conditioning and Heat Pump Equipment." A draft of that document is provided in Section 3.4.2.

At that point, the developing standard was a method of test (not a rating) to cover all residential equipment that removes moisture from process air. Basically, using the air-enthalpy method, keeping track of moisture removal, sensible cooling, net sensible heat added if applicable, and energy consumption, all at multiple specified environmental operating conditions.

In terms of a rating, based on overall annual energy use prediction, the thinking was that the method of test could provide data to complete equipment performance maps that could be input into annual simulations for rating purposes.

3.1.4. Building America Expert Meeting on "Residential Dehumidifier Performance: Modeling, Lab Testing, And Method Of Test Development"

BSC held a Building America Expert Meeting on the topic, "Residential Dehumidifier Performance: Modeling, Lab Testing, And Method Of Test Development." The meeting was held on Friday morning, 6/19/2009 in Louisville in advance of the ASHRAE Summer Annual Meeting technical program.

The objective of the session was to present and discuss recent developments in modeling and lab testing of residential dehumidification equipment, as well as ongoing efforts to develop a standard method of test. TRNSYS was the primary modeling platform presented. The goal was to provide Building America teams with necessary tools and performance information to make informed choices in the design and application of dehumidification in net-zero energy homes.

The following are key points addressed at this meeting:

1. In order to develop a building simulation model for any HVAC system, a performance map must created from either measured data or a more detailed equipment model. Regression analysis or lookup tables are generally the most common approach to accomplish this task. In addition, many HVAC systems inherently include control algorithms that describe how the system responds to the building loads and operating conditions.

2. There are different data needs for simulating various systems: 1) stand alone dehumidifiers, 2) spilt system dehumidifiers, 3) air conditioners with enhanced dehumidification features, and 4) dedicated outdoor air systems that pre-treat ventilation air. Each control state must be characterized. The specific needs for laboratory measured data will be discussed including the range of data needed and how these needs could fit into a method of test (MOT).

3. Current HVAC equipment EER & SEER test methods do not include accurate evaluations of dehumidification performance. This motivates laboratory evaluation at a wider range of test conditions to develop performance maps. NREL has begun a program of laboratory performance testing the dehumidification performance of residential HVAC equipment. The data will illuminate energy simulations and allow better comparisons between divergent technologies for Net-Zero Energy Homes. Recent experimental results will be presented to show laboratory capabilities and difficulties in obtaining test data at the proposed matrix of test conditions.

4. A standard method of test (MOT) is needed to better evaluate and compare the performance of residential dehumidification equipment, and to eventually allow more detailed modeling toward a standard rating. Testing dehumidification equipment at a number of environmental conditions is critical. Ongoing work has produced a preliminary draft MOT. ASHRAE TC 8.10 may be willing to sponsor a new SPC to pursue this formally. With an industry consensus MOT in place, resultant test data would feed into detailed modeling to allow development of a new rating standard.

A full summary report on the meeting is provided in Section 3.4.3. An important outcome of that meeting towards achieving an industry based standard on residential dehumidifier performance was guidance on how to improve the draft MOT derived from ASHRAE Standard 37.

3.1.5. Meetings with ASHRAE Technical Committees

Both ASHRAE Technical Committee (TC) 8.12 Desiccant Dehumidification Equipment & Components and TC 8.10 Mechanical Dehumidification Equipment and Heat Pipes provided time for BSC to discuss the intentions and progress of the new draft dehumidification performance standard. After meeting with both committees, a number of things became clear:

1. The focus of those committees was primarily for commercial equipment. Residential equipment was a low priority.

2. There was a lot of new work going on with dehumidification standards (both MOT and Ratings). A number of draft standards were in progress for pool dehumidifiers, dedicated outdoor air systems, and desiccant dehumidifiers. What we were doing was probably overlapping in a number of ways with what was currently in progress in ASHRAE committees.

3. TC 8.10 minimized the need for a new MOT standard for dehumidifiers. There was a strong suggestion, amidst some opposition, that an MOT should not cover test conditions but just the methods of performing the tests. A new Rating standard would be needed to expand standard test conditions, and the Air-conditioning, Heating, and Refrigeration Institute (AHRI) would be the entity responsible for that. Since the primary reason for developing the new dehumidifier standard was to expand the number or test conditions (state points) it was agreed that BSC would focus on working with AHRI on this project rather than ASHRAE. A few of the TC membership from the dehumidifier industry offered to help with coordinating an AHRI committee on the subject.

3.1.6. Summary of Rating and MOT Standards Related to Dehumidification

After the Building America Expert Meeting and the meetings with the ASHRAE technical committees, it became clear that there was a need to organize all the dehumidification related standards, whether existing or in progress, or whether a rating or a method of test. Tables 4 through 8 provide that information, grouped by major topic area. There are still some gaps in information regarding some of the AHRAE and AHRI works-in-progress that need to be understood.

3.2 Next Steps

The next steps in this process include working closely with AHRI to come to a conclusion concerning whether the new dehumidifier performance standard should be a AHRI rating or an ASHRAE MOT. If AHRI agrees to develop a new rating standard, it would need to form a committee which would be responsible for developing the new standard. The experience we have gained and the contacts we have made should make that process move more quickly and smoothly next year.

Standard	Title	Purpose/Scope Other/Comments
ANSI/AHAM DH-1-1992/1986 Rating	Dehumidifiers	Purpose: This standard establishes a uniform, repeatable procedure for measuring the capacity and energy input of dehumidifiers under specified test conditions. Scope: This standard applies to dehumidifiers as defined in 3.1 and includes definitions, performance test procedures, and safety. 3.1 Se1f-Contained, Electrically-operated, Mechanically-Refrigerated Dehumidifier. Other: Single test condition: Dry-bulb temperature 80F (26.7C), Wet-bulb temperature 69.6F (20.9C), Relative humidity 60% 6 hour steady state test
CAN/CSA-C749-1994 Rating (Based on ANSI/AHAM DH-1)	Performance of Dehumidifiers	This Standard specifies performance requirements for factory made dehumidifiers having a rated daily water-removal capacity of up to 30 L (63.4 US pints). Included are uniform procedures for measuring the (a) capacity; and (b) minimum energy factor (EF).

Table 3.4. Standards on Dehumidifiers

Standard	Title	Purpose/Scope Other/Comments
ASHRAE 190 MOT (draft)	Method of Testing for Rating Indoor Pool Dehumidifiers for Moisture Removal Capacity and Moisture Removal Efficiency	Purpose: The purpose of this standard is to prescribe test methods for determining the moisture removal and efficiency for indoor pool dehumidifiers. Scope: This Standard (a) established uniform methods of testing to obtain rating data; (b) specifies test equipment for performing such tests; (c) specifies data required and calculation to be used; and (d) list and defines the terms used in testing. For purposes of this standard, indoor pool dehumidifiers are defined as equipment to provide the function of dehumidifying , air circulation, air reheating and may include the function of air cooling, air filtration, pool water heating and air-to-air heat recovery.

ARI 910-2006	Performance of Indoor Pool Dehumidifiers	Purpose: The purpose of this standard is to establish for Indoor Pool Dehumidifiers: definitions; classifications; test requirements; rating requirements; minimum data requirements for Published Ratings; operating requirements; marking and nameplate data; and conformance conditions. Scope: This standard applies to factory-made residential, commercial and industrial Indoor Pool Dehumidifiers, as defined in Section 3. This standard applies to **electrically operated, vapor-compression refrigeration systems**. 3.2 Indoor Pool Dehumidifier. A type of air-cooled or water-cooled electrically operated, vapor compression refrigeration system; factory assembled as a single package or split system, which includes an indoor cooling/dehumidifying coil, an air reheat coil, compressor(s) and an air moving device. It may also include a Refrigerant Heat Recovery Unit, an auxiliary refrigerant condenser, Economizer, and an air-to-air heat recovery device. It shall provide the function of dehumidifying, air circulation, air reheating and may include the function of air-cooling, air-cleaning, pool water heating and air-to-air heat recovery.

Table 3.5. Standards on Pool Dehumidifiers

Standard	Title	Purpose/Scope Other/Comments
ASHRAE 174 MOT (Draft)	Method of Test for Rating Desiccant Based Dehumidification Equipment	Purpose: This standard provides test methods for rating the performance of desiccant based dehumidification equipment. Scope: This method of test applies to dehumidification equipment operating at atmospheric pressure using desiccants combined with other components to produce dehumidified air that is to be provided to a conditioned space.
ARI 940-1998 Rating	Dehumidification Components (Relies on 174 MOT)	Includes multiple test conditions. According to Harry Milliken presentation, when combining Std 940 test conditions with Std 340/360 (commercial unitary equip.), up to 25% outside air can be accommodated before needing dedicated outside air unit. Purpose. The purpose of this standard is to establish for thermally regenerated dynamic desiccant dehumidification components: definitions; classification requirements for testing and rating; minimum data requirements for published ratings; marking and nameplate data; and conformance conditions. Scope. This standard applies to factory manufactured, thermally regenerated, dynamic desiccant components operating at atmospheric pressure as defined in Section 3. Only the desiccant containing component is subject to this standard. Blowers, heat exchangers, evaporative coolers, drive motors, etc. are not rated within this standard, but may be subject to other ARI standards.

Table 3.6. Standards on Desiccant Dehumidification Equipment

Standard	Title	Purpose/Scope Other/Comments
AHRI 220P (or 920P, the document uses both, 920 also	DX Dedicated Outside Air Systems – Testing and	Purpose. The purpose of this standard is to establish for Dedicated Outside Air Systems: definitions; symbols and constants; classifications; test requirements; rating requirements; minimum data requirements for Published Ratings; operating

shows up as a standard on solar hot water)	Rating for Performance	requirements; marking and nameplate data; and conformance conditions. Scope. This standard applies to factory-assembled commercial or industrial Dedicated Outside Air Systems as defined in Section 3. Applicability. ARI Standard 210/240, ARI Standard 340/360, and ANSI/ARI/ASHRAE ISO Standard 13256-1 shall not apply to commercial or industrial equipment covered by this Standard. Energy Source. This standard applies to equipment that includes **electrically operated, vapor-compression refrigeration systems**. Installation. Dedicated Outside Air Systems are intended for ducted or non-ducted installation with field or factory supplied grilles.
ASHRAE 198 or 190??? MOT (used by ARI 910)	DX DOAS Equipment	Need to get copy of this. Check with Harry/Craig/Keith at Desert Aire

Table 3.7: Standards on Dedicated Outdoor Air Systems (DOAS)

Standard	Title	Purpose/Scope Other/Comments
ARI 210/240-2006 Rating	Performance Rating Of Unitary Airconditioning and Airsource Heat Pump Equipment	Purpose: The purpose of this standard is to establish, for Unitary Air-Conditioners and Air-Source Unitary Heat Pumps: definitions; classifications; test requirements; rating requirements; minimum data requirements for Published Ratings; operating requirements; marking and nameplate data; and conformance conditions. Scope: This standard applies to factory-made Unitary Air-Conditioners and Air-Source Unitary Heat Pumps as defined in Section 3. 3.1 Air-Source Unitary Heat Pump. One or more factory-made assemblies which normally include an indoor conditioning coil(s), compressor(s), and outdoor coil(s), including means to provide a heating function. They shall provide the function of air heating with controlled temperature, and may include the functions of air-cooling, air-circulating, air-cleaning, dehumidifying or humidifying. 3.16 Unitary Air-Conditioner. One or more factory-made assemblies which normally include an evaporator or cooling coil(s), compressor(s), and condenser(s). Either alone or in combination with a heating plant, the functions are to provide air-circulation, air cleaning, cooling with controlled temperature and dehumidification, and may optionally include the function of heating and/or humidifying.
ASHRAE 37-2005 MOT	Methods of Testing for Rating Electrically Driven Unitary Air-Conditioning and Heat Pump Equipment	Purpose: The purpose of this standard is to provide test methods for determining the cooling capacity of unitary air-conditioning equipment and the cooling or heating capacities, or both, of unitary heat pump equipment. Scope: This standard applies to **electrically driven mechanical-compression** unitary air conditioners and heat pumps consisting of one or more assemblies that include an indoor air coil(s), a compressor(s), and an outdoor coil(s).
ARI 310/380-2004 Rating	Standard For Packaged Terminal Air-	Purpose. The purpose of this Standard is to establish the following for packaged terminal air-conditioner and heat pump equipment: test requirements, rating requirements, minimum

	Conditioners And Heat Pumps	data requirements for published ratings, operating requirements, marking and nameplate data, and conformance conditions. Scope. This Standard applies to factory-manufactured residential, commercial, and industrial packaged terminal air-conditioners and heat pumps as defined in Clause 3.
AHRI 340/360-2007	Performance Rating of Commercial and Industrial Unitary Air-Conditioning and Heat Pump Equipment	

3.8. Standards on Unitary Cooling and Heat Pump Equipment

3.3 Conclusions/Remarks

The goal of this project is to reach publication of a new performance rating standard and method of test standard to facilitate appropriate application of residential dehumidifiers in high-performance homes. This will provide accurate means to compare multiple efficient and cost effective paths to control indoor humidity in homes, year round, yielding confidence to continue pushing ahead with efficiency improvements that reduce sensible cooling load. The efforts made toward establishing a coherent industry based performance rating and method of test standard will continue and will yield long-term benefits due to quantifiable and appropriate application of whole-building dehumidification systems for high-performance homes. Realistic performance maps can also be developed from more detailed test data to support accurate modeling efforts.

Currently, we have drafted both a performance rating standard and a method of test standard. These documents need to be refined under the guidance of an AHRI committee for the performance rating, and under the guidance of an ASHRAE committee for the method of test. Contacts have been made in both organizations and efforts will continue to see the committees formed and progressing with these documents. There is support for this from industry and manufacturing partners.

3.4 Appendices

3.4.1. Standard for Performance Rating Of Electrically Operated Dehumidifying Equipment (DRAFT); adapted from AHRI Standard 210/240

3.4.2. Method of Testing for Residential Dehumidifiers for Moisture Removal (DRAFT); adapted from ASHRAE Standard 37

3.4.3. Final Report on the Expert Meeting for “Residential Dehumidifier Performance: Modeling, Lab Testing, And Method Of Test Development”

3.4.1. Standard for Performance Rating Of Electrically Operated Dehumidifying Equipment (DRAFT); adapted from AHRI Standard 210/240

PERFORMANCE RATING OF ELECTRICALLY OPERATED DEHUMIDIFYING EQUIPMENT

Commenter suggestion to re-title to: METHOD OF TEST FOR ELECTRICALLY OPERATED DEHUMIDIFYING EQUIPMENT. The MOT would describe how to make the measurements but not set a performance standard. [The ARI Standard 210/240 from which this draft was modeled uses the "performance rating" terminology but does not specify the DOE minimum performance level.] Commenter also suggests looking at referencing ASHRAE Standard 37 (Methods of testing for rating electrically driven unitary air conditioning and heat pump equipment) in order to reduce text here.

1. Purpose

1.1 Purpose.
The purpose of this standard is to establish, for dehumidifying equipment: definitions; classifications; test requirements; rating requirements; minimum data requirements for Published Ratings; operating requirements; marking and nameplate data; and conformance conditions.

1.1.1 Intent.
This standard is intended for the guidance of the industry, including manufacturers, engineers, installers, contractors and users.

1.1.2 Review and Amendment.
This standard is subject to review and amendment as technology advances.

2. Scope

2.1 Scope.
This standard applies to the following factory-made vapor compression refrigeration dehumidifying equipment as defined in Section 3:

a) Unitary Cooling Unit;
b) Unitary Cooling and Dehumidification Unit;
~~b)~~c) Unitary Dehumidification Unit; and
~~c)~~d) Unitary Air-Source Unitary Heat Pump Unit.

Commenter suggestion to simplify this to systems that remove moisture by cooling air below its dew-point. That would eliminate desiccant systems [but not heat activated absorption systems].

2.1.1 Energy Source
This standard applies only to electrically operated vapor compression refrigeration dehumidifying systems.

2.2 Exclusions

2.2.1 This standard does not apply to the rating and testing of individual assemblies, such as condensing units or coils, for separate use.

2.2.2 This standard does not apply to heat operated cooling/heat pump equipment.

2.2.3 This standard does not apply to equipment with capacities of 65,000 Btu/h [19,000 W] or greater.

2.2.4 This standard does not apply to: water-source heat pumps, ground water-source heat pumps, and ground source closed-loop heat pumps.

3. Definitions

All terms in this document shall follow the standard industry definitions in the current edition of ASHRAE Terminology of Heating, Ventilation, Air- Conditioning and Refrigeration, unless otherwise defined in this section.

3.4 Moisture Removal Efficiency (MRE).

A ratio of the water removal rate in liters/h to the power input value obtained at any given Rating Condition expressed in l/(kW-h).

3.4.1 Standard Moisture Removal Efficiency

A ratio of the water removal rate in liters/h to power input value obtained at Standard Rating Conditions expressed in l/(kW-h).

3.5 Dehumidification Efficiency Ratio (DER)

A ratio of the latent cooling rate in Btu/h to the power input value in watts at any given set of Rating Conditions expressed in Btu/(W·h).

3.5.1 Standard Dehumidification Efficiency Ratio

A ratio of the latent cooling rate in Btu/h to the power input value in watts at Standard Rating Conditions expressed in Btu/(W·h).

3.6 Energy Efficiency Ratio

A ratio of the total (combined sensible and latent) cooling rate in Btu/h to the power input value in watts at any given set of Rating conditions expressed in Btu/(W-h).

[alternate: Energy efficiency ratio (EER) means the ratio of the average rate of space cooling delivered to the average rate of electrical energy consumed by the air conditioner or heat pump. These rate quantities must be determined from a single test or, if derived via interpolation, must be tied to a single set of operating conditions. EER is expressed in units of Btu/W-h. When determined for a ducted unit tested without an indoor fan installed, EER must include the section 3.3 and 3.5.1 default values for the heat output and power input of a fan motor.]

3.7 Published Rating
A statement of the assigned values of those performance characteristics, under stated Rating Conditions, by which a unit may be chosen to fit its application. These values apply to all units of like nominal capacity and type (identification) produced by the same manufacturer. As used herein, the term Published Rating includes the rating of all performance characteristics shown on the unit or published in specifications, advertising, or other literature controlled by the manufacturer, at stated Rating Conditions.

3.7.1 Application Rating
A rating based on tests performed at Application Rating Conditions (other than Standard Rating Conditions).

3.7.2 Standard Rating
A rating based on tests performed at Standard Rating Conditions.

3.8 Rating Conditions (commenter suggestion to delete this definition)
Any set of operating conditions under which a single level of performance results and which causes only that level of performance to occur.

3.8.1 Standard Rating Conditions~~.~~ (commenter suggestion to delete this definition))
~~-~~Rating Conditions used as the basis of comparison for performance characteristics.

3.10 "Shall" or "Should" (commenter suggestion to delete this definition)
~~.-~~"Shall" or "should" shall be interpreted as follows:

3.10.1 Shall (commenter suggestion to delete this definition)
~~.-~~Where "shall" or "shall not" is used for a provision specified, that provision is mandatory if compliance with the standard is claimed.

3.10.2 Should (commenter suggestion to delete this definition)
~~.-~~"Should" is used to indicate provisions which are not mandatory but which are desirable as good practice.

3.13 Standard Air
Dry ~~A~~air ~~weighing~~with a density of 0.075 lb/ft3 [1.2 kg/m3] ~~which approximates dry air~~ at 70°F [21°C] and at a barometric pressure of 29.92 in Hg [101.3 kPa].

3.16 Unitary Cooling Unit (Commenter suggests deleting all the following definitions)
One or more factory-made assemblies which normally include an air distribution fan, evaporator or cooling coil(s), compressor(s), ~~-~~and condenser(s). Where such equipment is provided in more than one assembly, the separated assemblies are to be designed to be used together, and the requirements of rating outlined in this standard are based upon the use of these assemblies in operation together.

3.16.1 Functions
Either alone or in combination with a heating plant, the function is to provide cooling and dehumidification.

3.17 Unitary Cooling and Dehumidification Unit.
One or more factory-made assemblies which normally include an air distribution fan, evaporator or cooling coil(s), compressor(s), condenser(s), and may include a condenser reheat coil. Where such equipment is provided in more than one assembly, the separated assemblies are to be designed to be used together, and the requirements of rating outlined in this standard are based upon the use of these assemblies in operation together.

3.17.1 Functions
Either alone or in combination with a heating plant, the function is to provide dehumidification or cooling and dehumidification.

3.18 Air-Source Unitary Heat Pump
One or more factory-made assemblies which normally include an air distribution fan, indoor conditioning coil(s), compressor(s), and outdoor coil(s), including means to provide a heating function. When such equipment is provided in more than one assembly, the separated assemblies shall be designed to be used together, and the requirements of rating outlined in the standard are based upon the use of matched assemblies.

3.18.1 Functions
The function is to provide heating, cooling, and dehumidifying.

4. Classifications
Equipment covered within the scope of this standard shall be classified as shown in Table ~~???~~xx (to be created).

5. Test Requirements (commenter suggestion to more explicitly state that the actual measurment/step-by-step procedures are in Std. 37)
All Standard Ratings shall be verified by tests conducted in accordance with the test methods and procedures as described in this standard and its appendices. Air-cooled units shall be tested in accordance with ANSI/ASHRAE Standard 37 and with Appendices C and D. Water-cooled and

evaporative-cooled condensing units shall be tested in accordance with ANSI/ASHRAE Standard 37.

6. Rating Requirements

6.1 Standard Ratings.
Standard Ratings shall be established at the Standard Rating Conditions specified in 6.1.3. Standard Ratings relating to cooling or moisture removal rates shall be net values, including the effects of circulating-fan heat. Power input shall be the total power input to the compressor(s) and fan(s), plus controls and other items required as part of the system for normal operation.

Standard Ratings of units which do not have indoor air-circulating fans furnished as part of the model, i.e., split systems with indoor coil alone, shall be established by subtracting from the total cooling rate 1,250 Btu/h per 1,000 cfm (0.366 W/cfm) [775 W/m3/s]. Total power input for both heating and cooling shall be increased by 0.366 W/cfm [226 W/m3/s] of indoor air circulated. (commenter suggestion to change to: …1500 Btu/h per 1,000 cfm (0.44 W/cfm) [925 W/m3/s]. Total power input for both heating and cooling shall be increased by 0.5 W/cfm [238 W/m3/s] of indoor air circulated.

6.1.1 Values of Standard Ratings
These ratings shall be expressed only in terms of:

a) airflow through the indoor coil reported in cubic feet per minute (cfm) to a resolution of 10 cfm;
b) sensible cooling capacity reported in British thermal unit per hour (Btu/h) to a resolution of 10 Btu/h (sensible cooling capacity will be negative if the outlet air is warmer than the inlet air);
c) latent cooling capacity reported in Btu/h to a resolution of 20 Btu/h;
d) latent cooling capacity reported in liter per hour (l/h) to a resolution of 0.01 l/h;
e) total power reported in watts (W) to a resolution of 3 W;
f) Moisture Removal Efficiency (MRE) reported in liter per kilowatt-hour (l/kW·h) to a resolution of 0.01;
g) Dehumidification Efficiency Ratio (DER) reported in British thermal unit per watt-hour (Btu/W-h) to a resolution of 0.05; and
h) Energy Efficiency Ratio (EER) reported in British thermal unit per watt-hour (Btu/W-h) to a resolution of 0.05.

6.1.3 Standard Rating Tests
Table 6-1 shows the test conditions which are required to determine values of standard ratings.

Table 6.1 Test conditions to determine values of standard ratings for units with both indoor and outdoor heat transfer components

	Outdoor T/RH/Tdp (F/%/F)	Inlet T/RH/Tdp (F/%/F)
Test 1a	95/58/78	80/60/65
Test 1b	""	78/55/61
Test 1c	""	75/50/55
Test 2a	80/85/75	80/60/65
Test 2b	""	78/55/61
Test 2c	""	75/50/55
Test 3a	75/85/70	78/60/63
Test 3b	""	78/55/61
Test 3c	""	75/50/55
Test 4a	65/90/62	72/60/57
Test 4b	""	70/52/52
Test 4c	""	68/45/46

[1] Negative cooling capacity denotes net heat added from inlet to outlet
[2] Same units as the USDOE and USEPA Energy Factor for dehumidifiers
[3] All tests with steady wet coil

Commentor suggestions:
Use ARI outdoor condition of 67 Tdp

Table 6.2 Test conditions to determine values of standard ratings for units with only indoor heat transfer components

	Inlet T/RH/Tdp (F/%/F)
Test 1	80/60/65
Test 2	78/60/63
Test 3	78/55/61
Test 4	75/50/55
Test 5	72/60/57
Test 6	70/52/52
Test 7	68/45/46

[1] Negative cooling capacity denotes net heat added from inlet to outlet
[2] Same units as the USDOE and USEPA Energy Factor for dehumidifiers
[3] All tests with steady wet coil

Table 6.3 Test conditions to determine values of standard ratings for basement units

	Inlet T/RH/Tdp (F/%/F)
Test 1	65/50/46
Test 2	65/60/51
Test 3	70/50/51
Test 4	70/60/56

[1] Negative cooling capacity denotes net heat added from inlet to outlet
[2] Same units as the USDOE and USEPA Energy Factor for dehumidifiers
[3] All tests with steady wet coil

6.1.3.2 Electrical Conditions
Standard Rating tests shall be performed at the nameplate rated voltage(s) and frequency. For air-cooled equipment which is rated with 208-230 V dual nameplate voltages, Standard Rating tests shall be performed at 230 V. For all other dual nameplate voltage equipment covered by this standard, the Standard Rating tests shall be performed at both voltages or at the lower of the two voltages if only a single Standard Rating is to be published.

6.1.3.3.1 Cooling and Dehumidification Air Volume Rate

6.1.3.3.1.1 Cooling and Dehumidification Air Volume Rate for Ducted Units (commenter suggestion to define Ducted Units)
The manufacturer must specify the cooling air volume rate and the external static pressure.

a. For ducted units that are tested with a fixed-speed, multi-speed, or variable speed variable-air-volume-rate indoor fan installed, the measured external static pressure must be equal to or greater than 0.5 inch w.c. (125 Pa).

6.1.3.3.1.2 Cooling Air Volume Rate for Non-ducted Units
For non-ducted units, the cooling air volume rate is the air volume rate that results during each test when the unit is operated with all of its normal grilles and air filter components in place.

6.1.3.4 Outdoor-Coil Airflow Rate
All Standard Ratings for systems with an outdoor coil shall be determined at the outdoor-coil airflow rate specified by the manufacturer where the fan drive is adjustable. Where the fan drive is non-adjustable, they shall be determined at the outdoor-coil airflow rate inherent in the equipment when operated with all of the resistance elements associated with inlets, louvers, and any ductwork and attachments considered by the manufacturer as normal installation practice. Once established, the outdoor coil air circuit of the equipment shall remain unchanged throughout all tests prescribed herein.

6.1.3.5 Requirements For Separated Assemblies
All Standard Ratings for equipment in which the outdoor section is separated from the indoor section shall be determined with at least 25 ft [7.6 m] of interconnection tubing on each line of the size recommended by the manufacturer. Such equipment in which the interconnection tubing is furnished as an integral part of the machine not recommended for cutting to length shall be tested with the complete length of tubing furnished, or with 25 ft [7.6] of tubing, whichever is greater. At least 10 ft [3.0 m] of the interconnection tubing shall be exposed to the outside conditions. The line sizes, insulation, and details of installation shall be in accordance with the manufacturer's published recommendation.

6.3 Application Ratings.

Ratings at conditions of temperature or airflow rate other than those specified in Table 6.1 may be published as Application Ratings, and shall be based on data determined by the prescribed methods.

6.4 Publication Of Ratings.
Wherever Application Ratings are published or printed, they shall include, or be accompanied by the Standard Ratings, clearly designated as such, including a statement of the conditions at which the ratings apply.

6.4.1 Capacity Designation
The capacity designation used in published specifications, literature or advertising, controlled by the manufacturer, for equipment rated under this standard, shall be expressed only in Btu/h [W] at the Standard Rating Conditions.

6.5 Tolerances (commenter suggestion that this section may not be needed or is confusing)
To comply with this standard, measured test results shall not be less than 95% of Published Ratings for performance ratios and capacities.

7. Minimum Data Requirements for Published Ratings

7.1 Minimum Data Requirements for Published Ratings.
As a minimum, Published Ratings shall consist of the following information:

Table 7-1. Minimum Data Requirements for Published Ratings for units with both indoor and outdoor heat transfer components

	Outdoor T/RH/Tdp (F/%/F)	Inlet T/RH/Tdp (F/%/F)	Outlet T/RH/Tdp (F/%/F)	Indoor Wet-coil Airflow (cfm)	Sensible Cooling Capacity[1] (Btu/h)	Latent Cooling Capacity (Btu/h)	Moisture Removal Capacity (L/h)	Total Power (kW)	Moisture Removal Efficiency[2] (L/kW-h)
Test 1a	95/58/78	80/60/65							
Test 1b	""	78/55/61							
Test 1c	""	75/50/55							
Test 2a	80/85/75	80/60/65							
Test 2b	""	78/55/61							
Test 2c	""	75/50/55							
Test 3a	75/85/70	78/60/63							
Test 3b	""	78/55/61							
Test 3c	""	75/50/55							
Test 4a	65/90/62	72/60/57							
Test 4b	""	70/52/52							
Test 4c	""	68/45/46							

[1] Negative cooling capacity denotes net heat added from inlet to outlet

[2] Same units as the USDOE and USEPA Energy Factor for dehumidifiers

[3] All tests with steady wet coil

Table 7-2. Minimum Data Requirements for Published Ratings for units with only indoor heat transfer components

	Inlet T/RH/Tdp (F/%/F)	Outlet T/RH/Tdp (F/%/F)	Indoor Wet-coil Airflow (cfm)	Sensible Cooling Capacity (Btu/h)	Latent Cooling Capacity[1] (Btu/h)	Moisture Removal Capacity (L/h)	Total Power (kW)	Moisture Removal Efficiency[2] (L/kW-h)
Test 1	80/60/65							
Test 2	78/60/63							
Test 3	78/55/61							
Test 4	75/50/55							
Test 5	72/60/57							
Test 6	70/52/52							
Test 7	68/45/46							

[1] Negative cooling capacity denotes net heat added from inlet to outlet
[2] Same units as the USDOE and USEPA Energy Factor for dehumidifiers
[3] All tests with steady wet coil

Table 7-3. Minimum Data Requirements for Published Ratings for basement units

	Inlet T/RH/Tdp (F/%/F)	Outlet T/RH/Tdp (F/%/F)	Indoor Wet-coil Airflow (cfm)	Sensible Cooling Capacity[1] (Btu/h)	Latent Cooling Capacity (Btu/h)	Moisture Removal Capacity (L/h)	Total Power (kW)	Moisture Removal Efficiency[2] (L/kW-h)
Test 1	65/50/46							
Test 2	65/60/51							
Test 3	70/50/51							
Test 4	70/60/56							

[1] Negative cooling capacity denotes net heat added from inlet to outlet
[2] Same units as the USDOE and USEPA Energy Factor for dehumidifiers
[3] All tests with steady wet coil

Commenter suggestions:
Check with EPA and DOE on use of Energy Factor (EF) instead of MRE.
What about water heating by desuperheating? Could add column for hot water heating capacity, with text footnote for applicability.

7.2 Capacity and Efficiency Designations
All minimum data designations shall be published in the manufacturer's specifications and literature.

7.2.1 Indoor Airflow
The airflow of the indoor supply air fan shall be reported for all test conditions in units of cfm.

7.2.2 Sensible Cooling Capacity
The sensible cooling capacity shall be reported in Btu/h at all test conditions regardless of whether the capacity is positive, negative, or zero, for all test conditions. Dehumidification equipment that supplies air that is warmer than the equipment inlet air will report a negative cooling capacity.

7.2.3 Latent Capacity
The latent (moisture) removal capacity shall be reported for all test conditions in units of Btu/h and l/h for all test conditions.

7.2.4 Total Power
The total system power (indoor and outdoor units as applicable) shall be reported in units of kW for all test conditions.

7.2.6 Moisture Removal Efficiency
The Moisture Removal Efficiency shall be reported in units of l/(kW-h) for all test conditions.

7.2.7 Dehumidification Efficiency Ratio
The dehumidification efficiency ratio, as a ratio of latent capacity to latent power, shall be reported in units of Btu/W-h for all test conditions.

7.2.8 Energy Efficiency Ratio
The energy efficiency ratio, as a ratio of total capacity to total power, shall be reported in units of Btu/W-h for all test conditions.

7.3 Rating Claims. All claims to ratings within the scope of this standard shall include the statement "Rated in accordance with Standard ??? ". All claims to ratings outside the scope of this standard shall include the statement: "Outside the scope of Standard ???". Wherever Application Ratings are published or printed, they shall include a statement of the conditions at which the ratings apply.

8. Operating Requirements

8.1 Operating Requirements
Unitary equipment shall comply with the provisions of this section such that any production unit will meet the requirements detailed herein.

8.2 Maximum Operating Conditions Test

Unitary equipment shall pass the following maximum operating conditions test with an indoor-coil airflow rate as determined under ??? (need to complete this).

8.2.1 Temperature Conditions
Temperature conditions shall be maintained as shown in Tables ??? (need to complete this).

8.2.2 Voltages
The test shall be run at the minimum utilization voltage based upon the unit's nameplate rated voltage(s). This voltage shall be supplied at the unit's service connection and at rated frequency.

8.2.3 Procedure
The equipment shall be operated for one hour at the temperature conditions and voltage specified.

8.2.4 Requirements
The equipment shall operate continuously without interruption for any reason for one hour.

8.3.2.2 The power supplied to single phase equipment shall be adjusted just prior to the shut-down period (8.3.3.2) so that the resulting voltage at the unit's service connection is 86% of nameplate rated voltage when the compressor motor is on locked-rotor. (For 200V or 208V nameplate rated equipment the restart voltage shall be set at 180V when the compressor motor is on locked rotor). Open circuit voltage for threephase equipment shall not be greater than 90% of nameplate rated voltage.
8.3.2.3 Within one minute after the equipment has resumed continuous operation (8.3.4.3), the voltage shall be restored to the values specified in 8.3.2.1.

8.3.3 Procedure.

8.3.3.1 The equipment shall be operated for one hour at the temperature conditions and voltage(s) specified.

8.3.3.2 All power to the equipment shall be shut off for a period sufficient to cause the compressor to stop (not to exceed five seconds) and then restored.

8.3.4 Requirements.

8.3.4.1 During both tests, the equipment shall operate without failure of any of its parts.

8.3.4.2 The equipment shall operate continuously without interruption for any reason for the one hour period preceding the power interruption.

8.3.4.3 The unit shall resume continuous operation within two hours of restoration of power and shall then operate continuously for one half hour. Operation and resetting of safety devices prior to establishment of continuous operation is permitted.

8.4 Low-Temperature Operation Test (commenter suggestion to delete all of sections 8.4 and 8.5)
Unitary equipment shall pass the following low-temperature operation test when operating with initial airflow rates as determined in Table 6.1 and with controls and dampers set to produce the maximum tendency to frost or ice the evaporator, provided such settings are not contrary to the manufacturer's instructions to the user.

8.4.1 Temperature Conditions
Temperature Conditions shall be maintained as shown in Table ??? (need to complete this).

8.4.2 Procedure
The test shall be continuous with the unit on the cooling cycle, for not less than four hours after establishment of the specified temperature conditions. The unit will be permitted to start and stop under control of an automatic limit device, if provided.

8.4.3 Requirements.

8.4.3.1 During the entire test, the equipment shall operate without damage or failure of any of its parts.

8.4.3.2 During the entire test, the air quantity shall not drop more than 25% from that determined under the Standard Rating test.

8.4.3.3 During the test and during the defrosting period after the completion of the test, all ice or meltage must be caught and removed by the drain provisions.

8.5 Insulation Effectiveness Test
Unitary equipment shall pass the following insulation effectiveness test when operating with airflow rates as determined in 6.1.3.3 and 6.1.3.4 with controls, fans, dampers, and grilles set to produce the maximum tendency to sweat, provided such settings are not contrary to the manufacturer's instructions to the user.

8.5.1 Temperature and Moisture Conditions
Temperature and moisture conditions shall be maintained as shown in Table 6-1.

8.5.2 Procedure
After establishment of the specified temperature and moisture conditions, the unit shall be operated continuously for a period of four hours.

8.5.3 Requirements.
During the test, no condensed water shall drop, run, or blow off from the unit casing.

8.6 Tolerances.
The conditions for the tests outlined in Section 8 are average values subject to tolerances of ± 1.0°F [± 0.6°C] for air dry-bulb and dew-point temperatures, ±2% for air relative humidity, and ± 1.0% of the reading for voltages.

9. Marking and Nameplate Data

9.1 Marking and Nameplate Data
As a minimum, the nameplate shall display the manufacturer's name, model designation, and electrical characteristics. Nameplate voltages for 60 Hertz systems shall include one or more of the equipment nameplate voltage ratings shown in Table 1 of ARI Standard 110. Nameplate voltages for 50 Hertz systems shall include one or more of the utilization voltages shown in Table 1 of IEC Standard 60038.

10. Conformance Conditions

10.1 Conformance
While conformance with this standard is voluntary, conformance shall not be claimed or implied for products or equipment within the standard's Purpose (Section 1) and Scope (Section 2) unless such product claims meet all of the requirements of the standard and all of the testing and rating requirements are measured and reported in complete compliance with the standard. Any product that has not met all the requirements of the standard shall not reference, state, or acknowledge the standard in any written, oral, or electronic communication.

3.4.2. Method of Testing for Residential Dehumidifiers for Moisture Removal (DRAFT); adapted from ASHRAE Standard 37

Draft product of Building America Dehumidification Working Group, Armin Rudd—lead.
For internal use only

Method of Test~~ing~~ing for ~~Rating~~ Residential Dehumidifiers for Moisture Removal ~~Capacity and Moisture Removal Efficiency~~

FORWARD

…

1. PURPOSE

1.1. This standard establishes an ASHRAE standard method of determining the moisture removal capacity and moisture removal ~~efficiency~~efficacy of residential dehumidifiers at a range of specified test conditions.

2. SCOPE

2.1 This Standard applies to residential dehumidifying equipment that removes moisture ~~by cooling air below its dew-point or by desiccant adsorption~~ from process air that can be measured by the air enthalpy method. The equipment may consist of one or more separate assemblies located indoors or outdoors. Where more than one separate assembly is used, they shall be designed to be used together.

2.2 For purposes of this standard, a residential dehumidifier provides air dehumidification and may also provide ~~additional functions of:~~ air cooling, air heating, air circulation, air filtration, air-to-air heat recovery, ~~and~~ water heating.

3.1 DEFINITIONS

3.1 Definitions are given in ASHRAE Standard 37-2005, ARI Standard 210/240, and additionally as follows below:

moisture removal ~~efficiency~~efficacy (MRE): a ratio of the water removal rate in liters/h to the power input value obtained at any given Rating Condition expressed in l/(kW-h). Dehumidification Efficacy (DHE)?

~~***dehumidification efficiency ratio (DER):*** a ratio of the latent cooling rate in Btu/h to the power input value in watts at any given set of Rating Conditions expressed in Btu/(W·h).~~

energy efficiency ratio: a ratio of the combined sensible plus latent) cooling rate in Btu/h to the power input value in watts at any given set of Rating conditions expressed in Btu/(W-h).

standard air: dry air with a density of 0.075 lb/ft3 [1.2 kg/m3] at 70°F [21°C] and at a barometric pressure of 29.92 in Hg [101.3 kPa].

Possibly add heat added per lb of water removed, kind of a new consumer rating value

4. CLASSIFICATIONS

4.1 Component Arrangement:

4.2 Method of Outdoor Coil Heat Exchange:

5. INSTRUMENTS

5.1 Instruments for measuring temperature, pressure, differential pressure, air flow, electrical power, voltage, volatile refrigerant flow, liquid flow, rotational speed, time, mass, and volatile refrigerant mass composition shall be as specified in Section 5 of ASHRAE Standard 37-2005.

6. AIRFLOW AND AIR DIFFERENTIAL PRESSURE MEASUREMENT APPARATUS

6.1 Airflow and air differential pressure measurement apparatus shall be as specified in Section 6 of ASHRAE Standard 37-2005.

7. METHOD OF TESTING AND CALCULATION

7.1 Standard Test Methods. The methods of testing and calculation shall be as specified in Section 7 of ASHRAE Standard 37-2005, except as otherwise specified here.

7.1.1

7.2 Applicability of Test Methods.

7.2.1

7.2.2

7.2.3 The methods described in this standard may be used to test dehumidifying equipment with heat rejection to at least one of, or a combination of: outdoor air heat rejection; indoor air reheating, and water heating. The air-enthalpy method shall be used for both the indoor and outdoor equipment sections. Condensate flow measurement is required in all cases.

7.3.4 Net-Air Reheating Calculations.

7.4.5 Moisture Removal Capacity Calculations.

7.2 Water Heating Calculations. Calculate water heating capacity according to Equation 1.

$$q_w = c_w w_w (t_{w.in} - t_{w.out}) \quad (1)$$

8. TEST PROCEDURES

The test procedures will be as specified in Section 8 of ASHRAE Standard 37-2005 and as otherwise specified herein.

9. DATA TO BE RECORDED

Data to be recorded shall be as specified in Section 9 of ASHRAE Standard 37-2005 and as otherwise specified in Table 2.

9.2 Test Tolerances. All test observations shall be within the tolerances specified in Section 9.2 of ASHRAE Standard 37-2005 and as specified in Table 3, as appropriate to the test methods, type of equipment, and type of test.

Table 2. Data to be recorded in addition to data recorded as specified in Section 9.1 of ASHRAE Standard 37-2005

Item	Units		Comment
	English	SI	
Date			
Observer			

10. TEST RESULTS

10.1 Test Requirements.

10.1.1 The results of a test shall express quantitatively the effects produced upon air by the equipment tested. For given test conditions, the capacity test results shall include each of the following quantities that are applicable to cooling, dehumidifying, air heating or water heating and to the type of equipment tested:

(1) Moisture removal capacity (condensate), pint/h [L/h]

(2) Air-reheating capacity, Btu/h [W]
(3) Water heating capacity, Btu/h [W]

a) airflow through the indoor coil reported in cubic feet per minute (cfm) to a resolution of 10 cfm;
b) sensible cooling capacity reported in British thermal unit per hour (Btu/h) to a resolution of 10 Btu/h (sensible cooling capacity will be negative if the outlet air is warmer than the inlet air);
c) latent cooling capacity reported in Btu/h to a resolution of 20 Btu/h;
d) latent cooling capacity reported in liter per hour (l/h) to a resolution of 0.01 l/h;
e) total power reported in watts (W) to a resolution of 3 W;
f) Moisture Removal Efficiency (MRE) reported in liter per kilowatt-hour (l/kW·h) to a resolution of 0.01;
g) Dehumidification Efficiency Ratio (DER) reported in British thermal unit per watt-hour (Btu/W-h) to a resolution of 0.05; and
h) Energy Efficiency Ratio (EER) reported in British thermal unit per watt-hour (Btu/W-h) to a resolution of 0.05.

	Outdoor T/RH/Tdp (F/%/F)	Indoor Return T/RH/Tdp (F/%/F)	Indoor Supply T/RH/Tdp (F/%/F)	Indoor Wet-coil Airflow (cfm)	Sensible Cooling Capacity (Btu/h)	Latent Cooling Capacity (Btu/h)	Heating Added In Dehum (Btu/h)	Moisture Removal Capacity (L/h)	Total Power (kW)	Moisture Removal Efficiency[1] (MRE) (L/kW-h)	Dehum Efficiency Ratio (DER) (Btu/W-h)	Energy Efficiency Ratio (EER) (Btu/W-h)
Test 1	95/58/78	80/60/65 78/55/61 75/50/55										
Test 2	80/85/75	80/60/65 78/55/61 75/50/55										
Test 3	75/85/70	78/60/63 78/55/61 75/50/55										
Test 4	65/90/62	72/60/57 70/52/52 68/45/46										
Test 5 (opt)		65/55/49										

[1] Same as the Energy Factor used for dehumidifiers by Energy Star

10.2 Calculations of Results.

10.2.1 Moisture Removal Capacity shall be determined by the volume of moisture collected by the condensate measurement method.

10.2.2 Moisture Removal Efficiency shall be calculated by dividing the Moisture Removal Capacity divided by the total input power.

11. TEST CONDITIONS

Table 11.1 Standard test conditions

	Outdoor T/RH/Tdp (F/%/F)	Indoor T/RH/Tdp (F/%/F)	
Test 1	95/58/78	80/60/65 78/55/61 75/50/55	cooling design conditions
Test 2	80/85/75	80/60/65 78/55/61 75/50/55	cooling part-load: summer nights/rainy periods
Test 3	75/85/70	78/60/63 78/55/61 75/50/55	cooling part-load: spring/fall
Test 4	65/90/62	72/60/57 70/52/52 68/45/46	no cooling: spring/fall/winter
Test 5 (opt)		65/55/49[1]	cold climate basement conditions

[1] Single unit basement dehumdifier condition

May be able to combine Test 2 and Test 3.
If the equipment cannot operate at any standard test condition, then note that in reporting the results.
May be run at additional non-standard test conditions.

10. LETTER SYMBOLS USED IN EQUATIONS

10.1 Symbols used in this appendix **are in ASHRAE Standard 37-2005 or are defined as follows:**

11. REFERENCE PROPERTIES AND DATA

11.1 Thermodynamic Properties of Air.

11.1.1 The thermodynamic properties of air-water vapor mixture shall be obtained from the equations in the Psychrometric chapter in *2009 ASHRAE Handbook, Fundamentals*.

11.2 Thermodynamic Properties of Water and Steam.

11.2.1 The thermodynamic properties of water and steam shall be obtained from the *2009 ASHRAE Handbook, Fundamentals*.

11.3 Thermodynamic Properties of Volatile Refrigerants.

11.3.1 The thermodynamic properties of volatile refrigerants may be obtained from the *2009 ASHRAE Handbook, Fundamentals* or from an established refrigerant property database.

13. REFERENCES

Copy references from ASHRAE Standard 37-2005

3.4.3. Final Report on the Expert Meeting for “Residential Dehumidifier Performance: Modeling, Lab Testing, And Method Of Test Development”

Final Report on the Expert Meeting for RESIDENTIAL DEHUMIDIFIER PERFORMANCE: MODELING, LAB TESTING, AND METHOD OF TEST DEVELOPMENT

Building Science Corporation Industry Team

23 August 2009

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EXECUTIVE SUMMARY

1. Title: Final Report on the Expert Meeting for RESIDENTIAL DEHUMIDIFIER PERFORMANCE: MODELING, LAB TESTING, AND METHOD OF TEST DEVELOPMENT (Gate 1B)

2. Overview: The Building Science Consortium held an Expert Meeting on Residential Dehumidifier Performance: Modeling, Lab Testing, And Method Of Test Development on 19 June 2009 at the Galt House hotel in Louisville, Kentucky. To make it easier for key industry personnel to participate, the expert meeting was held the morning immediately before the afternoon ASHRAE SSPC 62.2 meetings in advance of the ASHRAE technical program. Planned speakers included Hugh Henderson, Jr. of CDH Energy Corp., Dane Christensen of the National Renewable Energy Laboratory, and Armin Rudd of Building Science Corporation.

3. Key Results: Key results from this meeting were: 1) a greater understanding of the availability of and need for tools and methods to evaluate indoor humidity control systems in building energy simulations; 2) a greater understanding of laboratory testing capabilities that both exist and are needed to develop more detailed dehumidification equipment performance maps and to supplement field testing; and 3) more buy-in and assistance from ASHRAE and AHRI industry participants in moving forward with approaches for developing a dehumidification equipment method of test standard and a performance rating standard.

4. Gate Status: This project meets the “must meet” and “should meet” criteria for Gate 1B. The project provides source energy and whole building performance benefits by allowing building efficiency improvements that further reduce the sensible cooling requirement while providing a sure means to properly handle the unchanged moisture removal requirement, thereby reducing the source energy needed to condition the house. The project also meets the performance-based safety, health, and building code requirements for use in new homes, as it directly attempts to improve the indoor air quality, comfort, and durability of residential buildings. For the same reason, this project meets the prescriptive-based code requirements. The project will be cost-neutral for new homes, as builders will still be free to choose from a variety of dehumidification systems. The project will increase reliability by increasing the likelihood of proper indoor moisture control. Finally, the project does not require any new products to be manufactured, and suppliers, manufactures, and builders will continue responding to market forces as they always do. As part of the effort in responding to market forces, the project continues to work with industry partners to improve product features and capabilities.

5. Conclusions: The key gaps that remain are obtaining enough detailed performance data to adequately compare the dehumidification performance of different systems as they will typically operate in residential buildings, standardizing test methods and performance ratings, and pushing the limits of equipment efficiency, system integration, and cost reduction. Expected benefits include energy savings (due to lower cooling requirements without creating a moisture control problem especially in humid climates), reliability (due to improved indoor humidity control), durability (due to lower chances of moisture damage), and expected value to builders, contractors, and homeowners (due to improved occupant satisfaction).

INTRODUCTION

The Building Science Consortium held an Expert Meeting on Residential Dehumidifier Performance: Modeling, Lab Testing, And Method Of Test Development on 19 June 2009 at the Galt House hotel in Louisville, Kentucky. To make it easier for key industry personnel to participate, the expert meeting was held the morning immediately before the afternoon ASHRAE SSPC 62.2 meetings in advance of the ASHRAE technical program. There were 25 in attendance. Invited speakers gave presentations in their particular area of expertise. The presentations were followed by discussion with the expert audience.

A summary of the individual presentations and major discussion points is provided in the sections below.

The final agenda for the meeting is listed in Appendix A. A list of attendees for the meeting is given in Appendix B. The presentations are included in Appendices C through E.

PRESENTATIONS

Speaker 1: Hugh Henderson, Jr., P.E., CDH Energy Corp.

Presenter bio: Hugh is a founding principal of CDH Energy Corp., an energy consulting firm Cazenovia, NY. With a master's degree in mechanical engineering from Cornell University, Hugh has been working in the building space conditioning field for over 20 years. Prior to CDH Energy, Hugh worked for Carrier Corporation, the Florida Solar Energy Center, and the Fleming Group. Hugh has developed and published widely recognized algorithms for modeling part load latent capacity of DX cooling systems.

Presentation Title: *Data Needs for Modeling Dehumidification and Cooling Systems.*

Presentation Summary:

Mr. Henderson presented how the TRNSYS based ResDH program that he has developed over several years incorporates the control algorithms and performance data of various dehumidification systems into a whole-building energy simulation.

To develop a building simulation model for any HVAC system, a performance map must created from either measured data or a more detailed equipment model. Regression analysis or lookup tables are generally the most common approach to accomplish this task. In addition, many HVAC systems inherently include control algorithms that describe how the system responds to the building loads and operating conditions. The presentation described the different data needs for simulating various systems: 1) stand alone dehumidifiers, 2) spilt system dehumidifiers, 3) air conditioners with enhanced dehumidification features, and 4) dedicated outdoor air systems that pre-treat ventilation air. The specific needs for laboratory measured data were discussed including the range of data needed and how these needs could fit into a standard method of test.

Mr. Henderson made the following key points during his presentation:

- Data sources for creating performance maps can be measured or simulated, or a combination of the two, yielding semi-empirical, which generally works better.
- Regression models or other means then generate the maps using the best independent variables (Tdb, Tdp, Twb, RH) to represent dependent variables such as outlet temperature, power draw, total capacity, sensible capacity, and latent capacity.
- Changes in operating state caused by equipment controls need to be characterized with individual performance maps. Dehumidification examples of different control states are: compressor staging, airflow reduction, refrigerant reheat systems (spanning from subcooling reheat to partial condensing reheat to full condensing reheat with and without hot gas modulation) and hybrid desiccant units.
- Part load effects need to be accounted for such as: startup efficiency, shut-down latent degradation (evaporation from coil), and thermostat "droop" as the space temperature changes with loading.
- Multiple equipment configurations need to be addressed also (i.e. ventilation or recirculation mode, integrated or not-integrated with central system fans, interactions with other equipment or building components, etc).
- Currently we have focused on recirculation dehumidification systems for residential buildings, but we should consider establishing test conditions for systems that may bring in 100% outdoor air. In very low load houses, conditioning the outside air may be the primary means of space conditioning.
- Testing for too many conditions may be overly burdensome. Testing for two or three conditions may be enough. Currently, manufacturers test only at the single rating condition then simulate performance from there to provide extended performance data. Although there is no standard for doing this, it has generally worked pretty well. However, the best approach might be a blend laboratory tests and simulated data, using the model to fill in testing gaps.
- Perhaps developing a better standard for creating performance maps through modeling (using a model like the ORNL heat pump design model) would reduce the need for testing at off-rating conditions.
- In 1992, Hugh published a semi-empirical air conditioner model that is now in USDOE's EnergyPlus. The model uses the apparatus dew point (ADP) and bypass factor (BF) approach. From knowing one operating condition you get the BF. From knowing the bypass factor you get the ADP and the performance at all other operating conditions. However, you need a different performance map for each control state. The simulation switches between the different maps depending on the control state.
- When using a short simulation time step (<15 min), the traditional degradation coefficient (C_d) used in the current rating standard is not applicable anymore. You need to calculate the time constant from C_d and use that to obtain performance at part load operation using a short time step. Also, using a short time step (<= 2 min) allows more accurate calculation of evaporation rates from wet coils.

<u>Participant questions and discussion:</u>

Questions, comments and answers were as follows:

- Q: Does the ResDH model iterate between the building load and the HVAC system? A: Yes.
- Q: Does the EnergyPlus building simulation program do that also? A: Pretty sure the answer is yes but should ask Don Shirey at the Florida Solar Energy Center.

Speaker 2: Dane Christensen, National Renewable Energy Laboratory

Presenter bio: Dane joined NREL in 2008. His expertise is in equipment testing and integration, and is currently focused on performance of emerging technologies in HVAC and Dehumidification across varied loading conditions. He supports technical efforts for the Building America Program and conducts finite element modeling for building energy simulation. Prior to joining NREL, Dane worked at Atec, Inc., designing test and support equipment for turboshaft engines. He has 18 publications and has earned 2 patents.

Presentation Title: *Laboratory Testing of Dehumidification Equipment*

Presentation Summary:

Mr. Christensen began with an overview of the USDOE Building America including the research being conducted to achieve zero net energy homes by the target year 2020. During the rest of his presentation, he gave details of the setup and capability of the HVAC testing laboratory at NREL, and recent results from testing the Thermastor Ultra-Aire dehumidifier in a standalone configuration.

Current HVAC equipment EER & SEER test methods do not include accurate evaluations of dehumidification performance. This motivates laboratory evaluation at a wider range of test conditions to develop performance maps. NREL has begun a program of laboratory performance testing the dehumidification performance of residential HVAC equipment. The data will illuminate energy simulations and allow better comparisons between divergent technologies for Net-Zero Energy Homes. Recent experimental results were presented to show laboratory capabilities and difficulties in obtaining test data at the proposed matrix of test conditions.

Mr. Christensen made the following key points during his presentation:

- A key net zero energy technology gap is very high performance AC systems which control humidity and provide 30% reduction in annual energy use, with an incremental cost of $1000 or less, relative to a current SEER 18/EER 13.4 system with ducts located in conditioned space.
- A Building America home with 50% savings over Benchmark will have significantly reduced sensible loads and roughly equivalent latent loads. Right-sizing leads to reduced equipment size. The equipment can’t keep up with dehumidification requirements, humidity builds, causing high-RH excursions. Thus, these houses need equipment with on-demand dehumidification or at least enhanced dehumidification options/controls.
- The Thermastor Ultra-Aire dehumidifier was the first dehumidifier tested in the NREL HVAC lab. The test protocol was designed to obtain performance data for a wide range of operating conditions as opposed to the single state point (80^{o}F dry-bulb, 69.6^{o}F wet-bulb, converts to 60% RH) specified by the American Home Appliance Manufacturers (AHAM) standard (ANSI/AHAM DH-1-1992). The wider range of dehumidifier test conditions has been proposed by the Building America working group on dehumidification led by Building Science Corporation.
- The laboratory setup consisted of a system to continuously condition the inlet airstream to the dehumidifier. This allowed relatively quick changes from one test condition to another, compared to a traditional environmental chamber with slow response time.

- The equipment performance was measured at twelve test conditions, and checked by computing an air mass balance, a moisture balance, and a total energy balance.
- A six coefficient regression model was used to create the equipment performance map (in terms of power, efficiency, total load removal, sensible load removal, and latent load removal) as a function of inlet dry-bulb temperature and inlet dew-point temperature.
- Typically, a good HVAC lab will achieve accuracy within 5%. The NREL lab has been able to achieve a repeatable 2% accuracy. The performance map shows excellent fit to the measured data.
- The dehumidifier model/performance map is being put into Energy Plus.
- In general, what is needed for appropriate modeling of dehumidification equipment is: extensive ratings tables at a broad range of temperature and humidity, time constants derived from cycling data, evaluation at all control states (i.e. fan cycling, delays, steps, and capacity staging).

Questions, comments, and answers were as follows:

Mr. Christensen considered the following questions and comments after his presentation:

- Question: Will adding more "boxes," such as separate dehumidifiers, ultimately be successful due to owner maintenance costs? Answer: Proper maintenance of the additional air filter will be the primary requirement in this case.
- Question: Much more complicated systems are emerging that will need testing. Will the NREL lab be capable of testing those systems also? Answer: In time, yes. The current system can be used effectively to test standalone dehumidifiers, but an outdoor section chamber will be necessary to test split systems.
- Comment: A dialogue should be opened with existing testing labs regarding the greatly increased number of test conditions. There will be a learning curve to increase accuracy for humidity measurements and energy balances, and to reduce the testing time through process air treatment versus the room/environmental chamber method.

Speaker 3: Armin Rudd, Building Science Corporation

Presenter bio: Armin Rudd is a Principal at Building Science Corporation where he joined in 1999. Prior to that he worked at the Florida Solar Energy Center, a research institute of the University of Central Florida. He has worked in the field of buildings research and consulting for over 20 years. Armin has a wide range of experience in residential and commercial buildings, and has been especially focused on space conditioning systems, ventilation, and product development. He has authored many technical publications, is a regular presenter at national conferences.

Presentation Title: *Development of a Standard Method of Test for Residential Dehumidification Equipment*

Presentation Summary:

Mr. Rudd presented an overview of residential dehumidification systems typically being installed in current high-performance homes, then he summarized on-going work being conducted within the USDOE Building America program to develop a standard method of test for residential dehumidification equipment. Such a standard method of test (MOT) is needed to better evaluate and compare the performance of residential dehumidification equipment, and to eventually allow more detailed modeling toward a standard rating. Testing dehumidification equipment at a number of environmental conditions is critical to characterize actual performance for proper space conditioning system design and evaluation. Ongoing work has produced a preliminary draft MOT. ASHRAE TC 8.10 may be willing to sponsor a new SPC to pursue this formally. With an industry consensus MOT in place, resultant test data would feed into detailed modeling to allow development of a new rating standard.

Mr. Rudd made the following key points during his presentation:

- High-performance homes have low sensible heat gain but latent gain remains mostly unchanged. This causes periods of high indoor relative humidity unless supplemental humidity control is employed, separate from sensible cooling operation.
- A number of supplemental dehumidification systems have been successfully employed in high-performance homes. These have ranged from:
    - Unducted standalone dehumidifiers in interior mechanical closets, either in or near the central system return air path; to
    - Ducted standalone dehumidifiers integrated with the central duct system, to;
    - Supplemental dehumidification integrated into a central split heat pump system utilizing modulating hot gas for condenser reheat.
- Those systems have been field monitored, but more controlled and accurate laboratory testing would enhance our understanding of their performance, and in less time.
- Moving forward, we are working to create a framework in which to evaluate the performance of a range of supplemental dehumidification systems as they are applied to high-performance homes. This will entail developing engineering criteria for obtaining standardized extended performance data in laboratories, and conducting field evaluations that will also serve as a reality check for modeling efforts towards a new rating standard.
- Planned process steps to achieve that include:
    - Settle on an approach to establish performance and testing requirements for humidity control equipment in high performance homes in hot-humid climates, which includes defining the minimum whole house performance goal. The initial performance goal in Building America is to limit the duration of indoor RH greater than 60% to 4 hours or less, while meeting Energy Star dehumidification efficiency requirements for latent cooling.
    - Define a test method and rating method that that provides a consistent basis of comparison of performance between different types of equipment.
    - Demonstrate that the method works based on lab tests and field tests in high performance homes.
    - Hold meetings with stakeholders to build consensus for performance goals and test methods.
    - Integrate equipment performance maps into annual energy simulations which would support the rating procedures
    - Publish test methods, rating procedures, and test/analysis results.
- It is critical that designers specifying dehumidification equipment have the performance data necessary to properly apply the equipment for the way it will be used. A range of test conditions should be representative of climate, season-of-year, interior temperature and humidity set-points, and the sensible and latent loads.
- A draft method of test has been developed. A series of test conditions includes those that would cover: design cooling conditions; part-load cooling conditions representing

summer nights and rainy periods; part-load conditions representing spring and fall shoulder seasons; dehumidification-only conditions in spring/fall; and basement dehumidification conditions.

- At each test condition, test results for rating purposes would include:
  - Dry-bulb temperature, dew-point temperature, and relative humidity of the air leaving the dehumidification equipment
  - Indoor unit airflow. Measured with coil fully wet if using equipment that cools air to its dew-point temperature to condense water on a heat exchange coil.
  - Latent, sensible, and total cooling capacity.
  - Heat added if the air leaving the equipment is warmer than the air entering the equipment.
  - Volumetric moisture removal capacity
  - Total equipment power draw
  - Moisture removal efficiency (same units as Energy Factor)
  - Dehumidification efficiency ratio

Questions, comments, and answers were as follows:

Mr. Rudd considered the following questions and comments after his presentation:

- Comment: Moisture Removal Efficiency should be Moisture Removal Efficacy since it is not dimensionless.
- Comment: There is either a need to define "residential" since it is used in the title. Consider definitions used in ASHRAE 90.2 and codes, etc.
- Q: Should there be a need for a capacity limit, say single-phase electrical connection and less than 65 kBtu/h? A: My preference would be to not have a limitation on capacity but to state that any dehumidification equipment applied in residential use should be tested according to the standard.

- Comment: There is a need to test at 100% outside air conditions for equipment that will be applied in ventilation mode.
- Comment: When writing the scope, only specifically include equipment functions that are covered by the standard, then add a generic statement such as, "…and may provide other functions like filtration…"
- Comment: The "heat added" test result could be normalized by mass of water removed.
- Comment: The table of test conditions is large and more confusing than it needs to be. For example, if there is no outdoor unit, then outdoor conditions don't matter. So, use different tables in different sections for:
  - No outdoor unit, not designed for low temperature basement use;
  - No outdoor unit, designed for low temperature basement use;
  - Outdoor unit plus indoor unit; and
  - Any unit designed for 100% outside air.
- For desiccant dehumidification equipment, there should be another inlet test condition at 78 F dry-bulb, 55 F dew-point, 45% relative humidity.
- Comment: A method of test should not specify a range of test conditions but should only define the test. A range of test conditions should be left to a performance rating standard. The draft we are working with today is a combination of both and should be separated.

FOLLOW-UP WORK

BSC will have meetings during the ASHRAE conference in Louisville with technical committees TC 8.12 (Desiccant Dehumidification Equipment and Components) and TC 8.10 (Mechanical Dehumidification Equipment and Heat Pipes) to generate interest concerning starting an SPC for the standard method of test development. AHRI will be contacted concerning the development of a new performance rating standard for residential dehumidifiers.

Appendix A: Expert Meeting Agenda

INVITATION and AGENDA

Building America Expert Meeting

RESIDENTIAL DEHUMIDIFIER PERFORMANCE: MODELING, LAB TESTING, AND METHOD OF TEST DEVELOPMENT

Meeting Manager: Armin Rudd, Building Science Corp.
Date/Time: **Friday, 19 June 2009, 8:00 am to 12 pm**
(light breakfast refreshments after 7:45 am)
Location: Louisville, ASHRAE Summer Annual Meeting
The Galt House Hotel, Ballroom B

Featured Speakers:

- Hugh Henderson, Jr., CDH Energy Corp.
- Dane Christensen, National Renewable Energy Laboratory
- Armin Rudd, Building Science Corp.

The objective of this session is to present and discuss recent developments in modeling and lab testing of residential dehumidification equipment, as well as ongoing efforts to develop a standard method of test. TRNSYS will be the primary modeling platform presented. The goal is to provide Building America teams with necessary tools and performance information to make informed choices in the design and application of net-zero energy homes.

Key points regarding this meeting:

1. To develop a building simulation model for any HVAC system, a performance map must created from either measured data or a more detailed equipment model. Regression analysis or lookup tables are generally the most common approach to accomplish this task. In addition, many HVAC systems inherently include control algorithms that describe how the system responds to the building loads and operating conditions.

This presentation will describe the different data needs for simulating various systems: 1) stand alone dehumidifiers, 2) spilt system dehumidifiers, 3) air conditioners with enhanced dehumidification features, and 4) dedicated outdoor air systems that pre-treat ventilation air. The specific needs for laboratory measured data will be discussed including the range of data needed and how these needs could fit into a method of test (MOT).

2. Current HVAC equipment EER & SEER test methods do not include accurate evaluations of dehumidification performance. This motivates laboratory evaluation at a wider range of test conditions to develop performance maps. NREL has begun a program of laboratory performance testing the dehumidification performance of residential HVAC equipment. The data will illuminate energy simulations and allow better comparisons between divergent technologies for Net-Zero Energy Homes. Recent experimental results will be presented to show laboratory capabilities and difficulties in obtaining test data at the proposed matrix of test conditions.

3. A standard method of test (MOT) is needed to better evaluate and compare the performance of residential dehumidification equipment, and to eventually allow more detailed modeling toward a standard rating. Testing dehumidification equipment at a number of environmental conditions is critical. Ongoing work has produced a preliminary draft MOT. ASHRAE TC 8.10 may be willing to sponsor a new SPC to pursue this formally. With an industry consensus MOT in place, resultant test data would feed into detailed modeling to allow development of a new rating standard.

<u>Invitees:</u>

Participants will be key people working in the indoor air quality, comfort, and space conditioning fields. Participants are invited from the following groups: Building America teams, ASHRAE and AHRI standards and technical committee members and participants, residential HVAC and construction industry, national and state government laboratories and agencies, university researchers, energy efficiency organizations, and building consultants.

<u>Meeting Agenda:</u>

- 8:00 am to 8:05 am, Welcome and Meeting Introduction

- Presentations

    - 8:05 to 8:45, (40 min) Hugh Henderson, *Data Needs for Modeling Dehumidification and Cooling Systems*.
    - 8:45 to 8:55, (10 min) Questions and discussion

    - 8:55 to 9:35, (40 min) Dane Christensen, *Laboratory Testing of Dehumidification Performance*.
    - 9:35 to 9:45, (10 min) Questions and discussion

    - 9:45 to 10:00, (15 min) Break

    - 10:00 to 10:30 (30 min) Armin Rudd, *Development of a Standard Method of Test for Residential Dehumidification Equipment*.

- Group discussion and advancement of the draft MOT, 10:30 to 11:45
- Wrap up, action items, and follow-up plan, 11:45 to 12:00

Bios

Hugh Henderson: Hugh is a founding principal of CDH Energy Corp., an energy consulting firm Cazenovia, NY. With a master's degree in mechanical engineering from Cornell University, Hugh has been working in the building space conditioning field for over 20 years. Prior to CDH Energy, Hugh worked for Carrier Corporation, the Florida Solar Energy Center, and the Fleming Group. Hugh has developed and published widely recognized algorithms for modeling part load latent capacity of DX cooling systems.

Dane Christensen: Dane joined NREL in 2008. His expertise is in equipment testing and integration, and is currently focused on performance of emerging technologies in HVAC and Dehumidification across varied loading conditions. He supports technical efforts for the Building America Program and conducts finite element modeling for building energy simulation. Prior to joining NREL, Dane worked at Atec, Inc., designing test and support equipment for turboshaft engines. He has 18 publications and has earned 2 patents.

Armin Rudd: Armin Rudd is a Principal at Building Science Corporation where he joined in 1999. For 12 years prior to that, he was at the Florida Solar Energy Center, a research institute of the University of Central Florida. He has worked in the field of buildings research and consulting for over 20 years. Armin has a wide range of experience in residential and commercial buildings, and has been especially focused on space conditioning systems, ventilation, and product development. He has authored many technical publications, is a regular presenter at national conferences, and holds 10 patents.

Appendix B: Expert Meeting Attendee List (based on sign-in sheet)

Last name	First name	Company
Baxter	Van	ORNL
Crawford	Roy	Trane
Domanski	Piotr	NIST
Drumheller	Craig	NAHB RC
Emmerich	Steve	NIST
Fairey	Philip	FSEC
Ferguson	Julie	Applied Dehumdification, Inc.
Harriman	Lew	Mason Grant
Henderson	Hugh	CDH Energy
Hoeschele	Marc	Davis Energy Group
Kosar	Douglas	Gas Technology Institute
Logee	Terry	USDOE
Payne	Vance	NIST
Raymer	Paul	Heyoka Solutions
Rudd	Armin	Building Science Corp.
Sherman	Max	LBNL
Stevens	Don	Panasonic
Uselton	Dutch	Lennox
Walker	Iain	LBNL
Werling	Eric	USEPA
Wilcox	Bruce	
Williamson	Jennifer	PNNL

Appendix C: Presentation 1

Data Needs for Modeling Dehumidification and Cooling Systems

Building America Expert Meeting

June 19, 2009

Hugh I Henderson, Jr., P.E.

CDH Energy Corp.

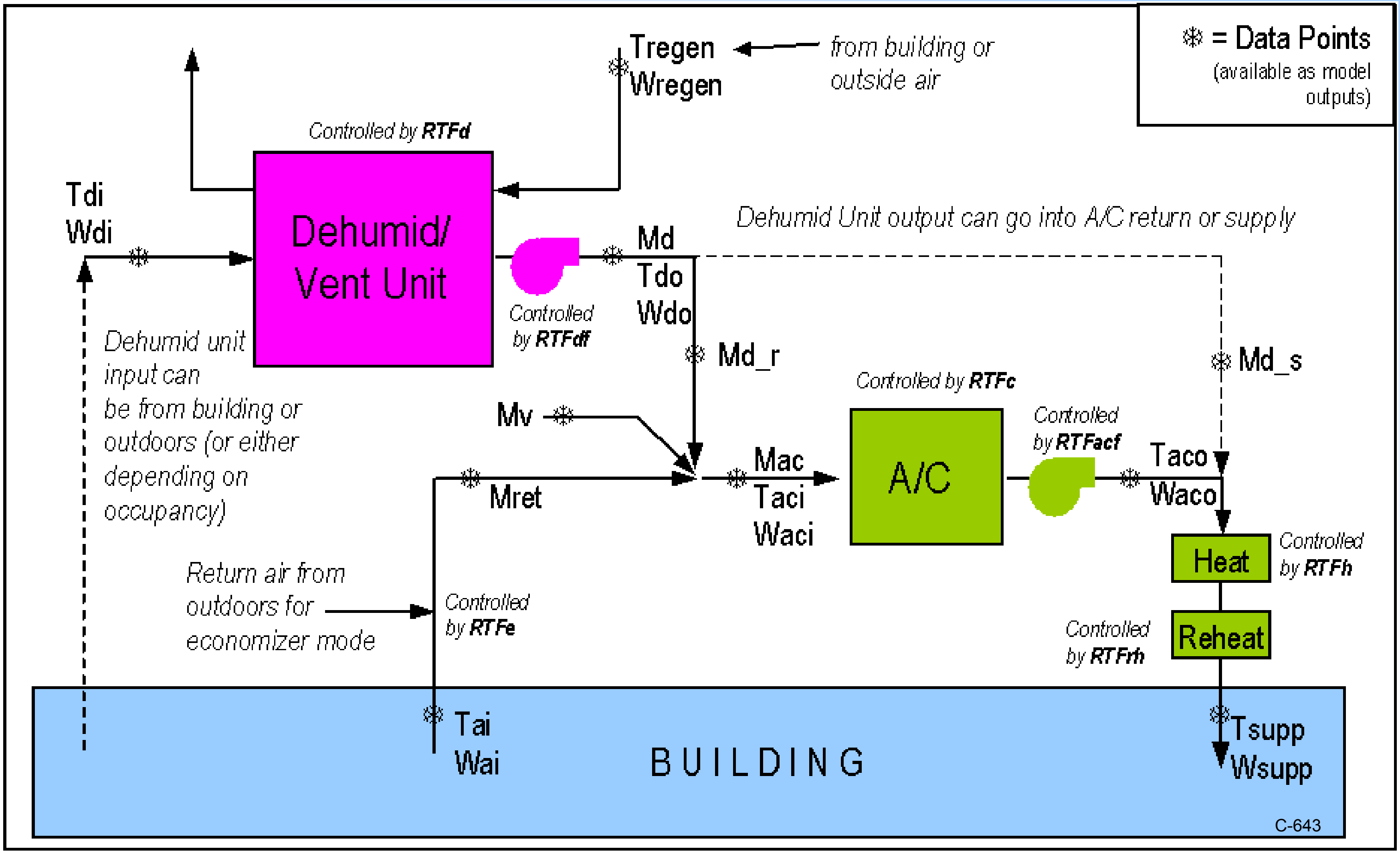
Cazenovia, NY

www.cdhenergy.com

Overview

- Performance Maps for Components
  - Measured vs. simulated data sources
  - Regression maps vs. other means
  - Empirical vs. semi-empirical
- Representing Different Types of Systems
  - Best independent variable (RH, DPT, WB, etc)
- Equipment Controls and Configuration
  - Change state in response to environment, loading, or state of other equipment
  - Arrangement of multiple components in system
  - Equipment-building interactions

Simulation Framework
model from Henderson and Sand (2003)

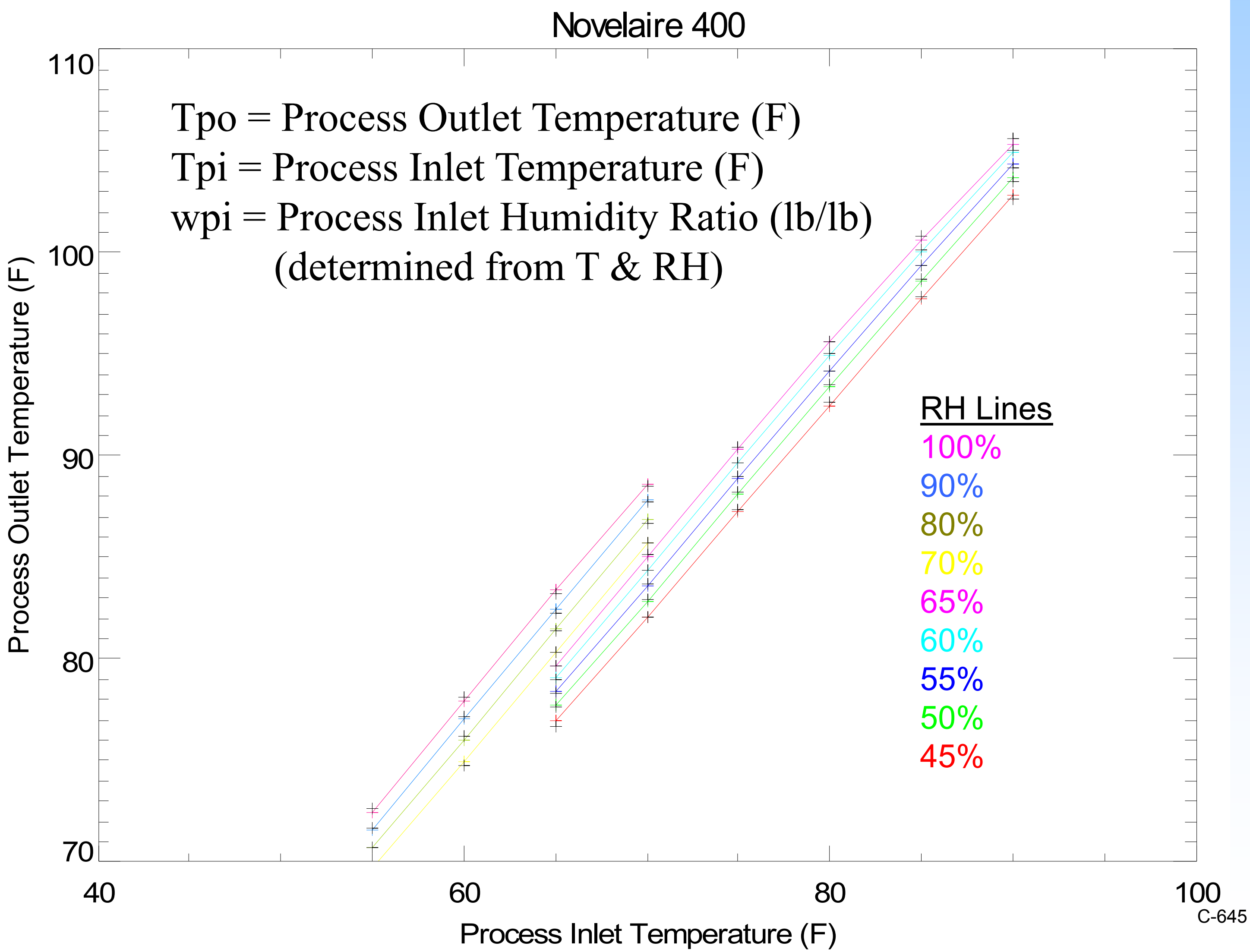


Developing Performance Maps

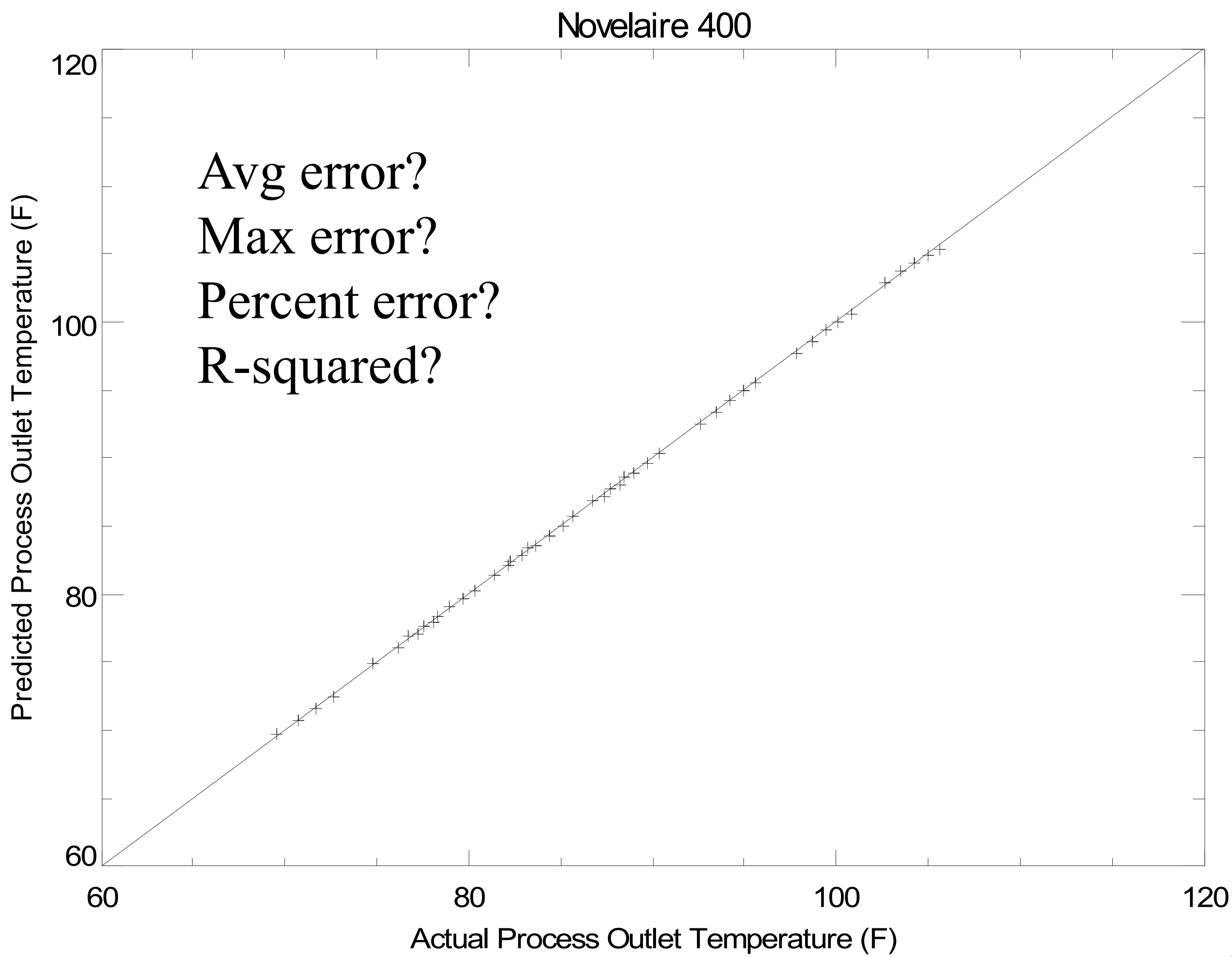
- Choose best dependent variables
  - Leaving conditions (T & w)
  - Total, Latent and sensible capacity
  - Usually need 3 variables to fully describe a AC or DH capacity & efficiency
- Choose best independent variables
  - Humidity: dew pt, RH, humidity ratio, WB
  - What provides the best fit
  - Physical performance expectations
    - E.g., Total Capacity = F(WB) $\neq$ F(DB, WB)

Typical Performance Map

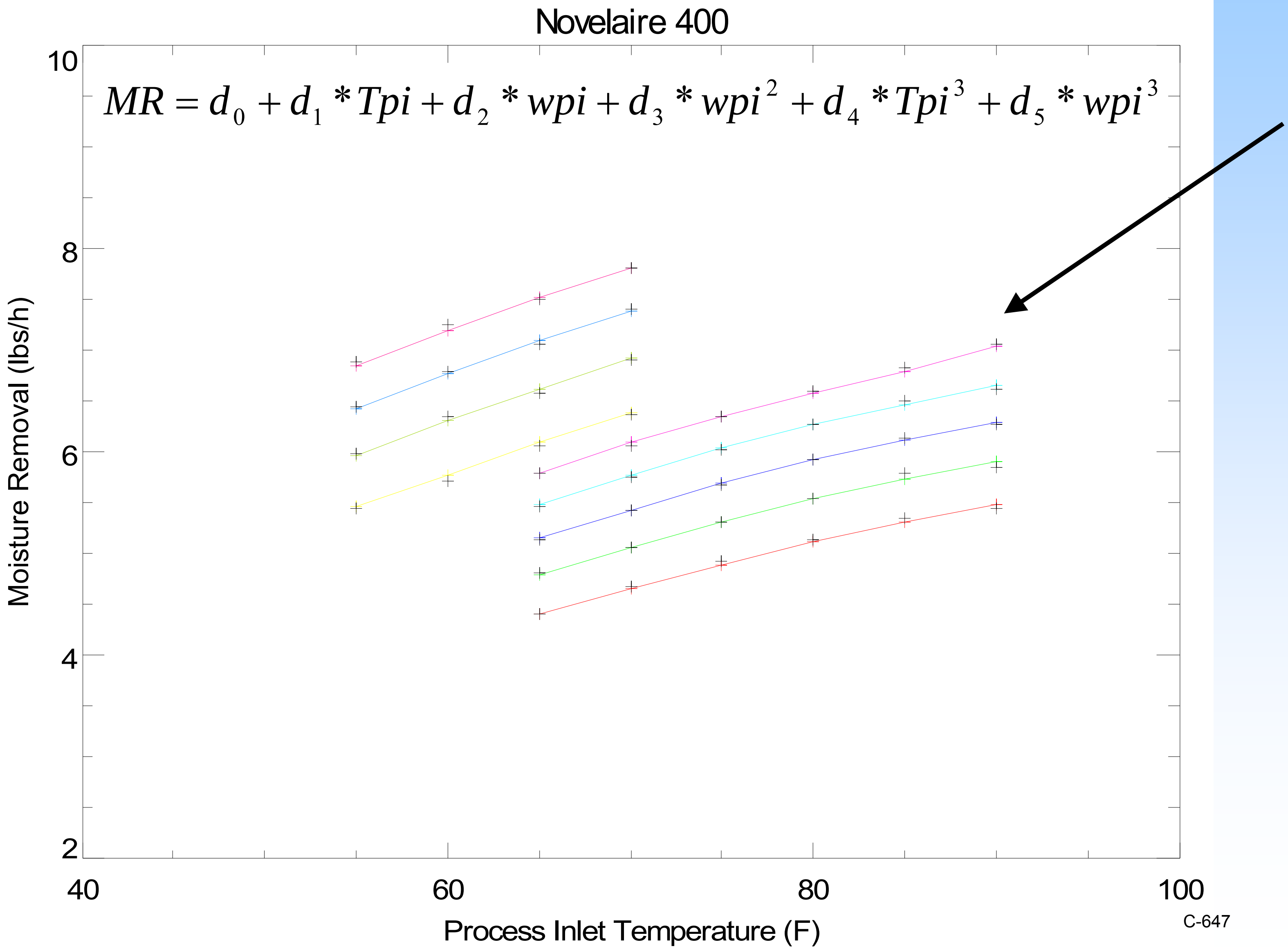
$$Tpo = c_0 + c_1 * Tpi + c_2 * wpi + c_3 * Tpi^2 + c_4 * wpi^2$$



How Good is the Resulting Model?

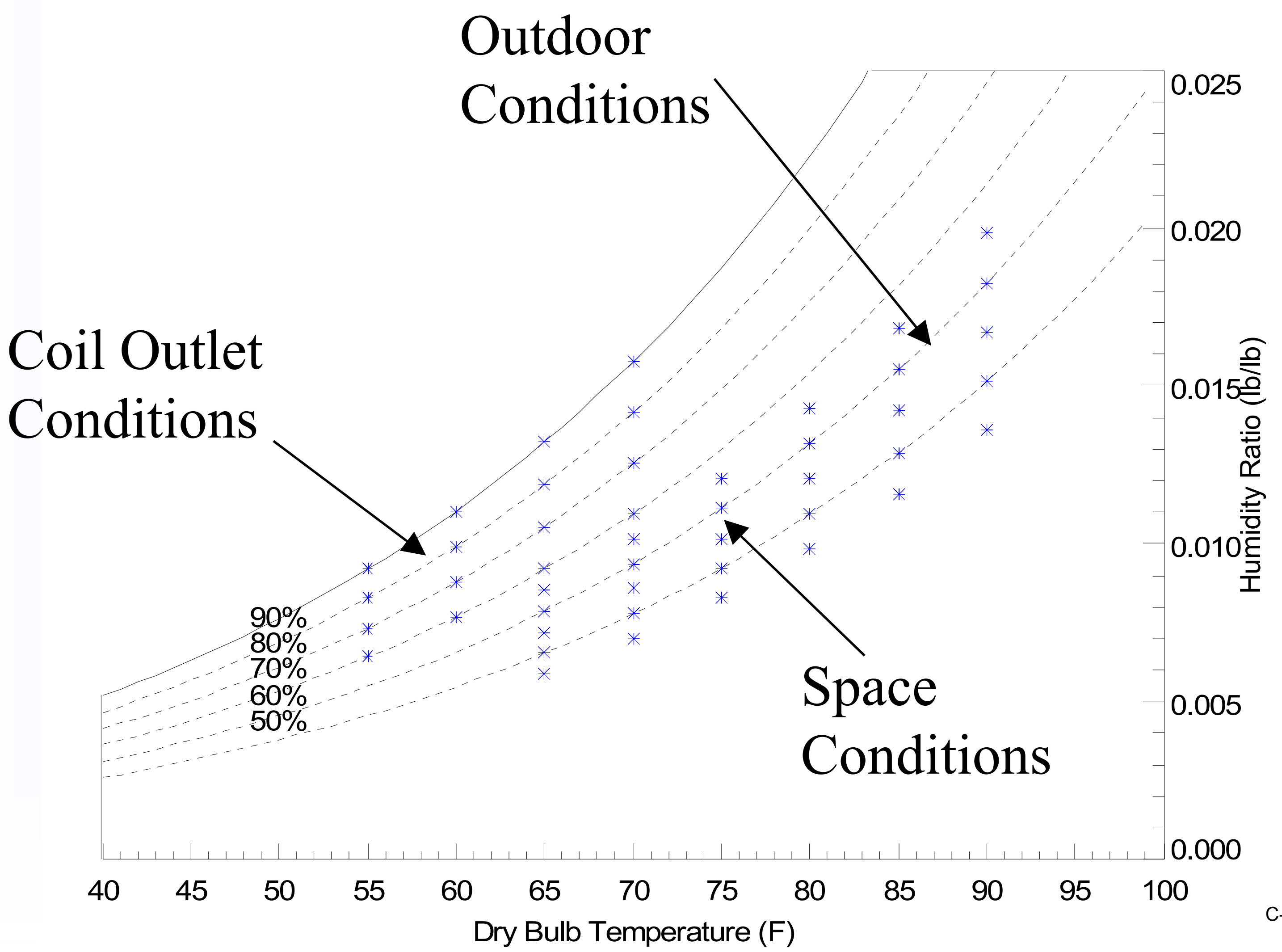


Slightly Non-Physical Behavior



Range of Inlet Conditions

How will the Component Be Applied?



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How Comprehensive is The Performance Map?

- Apply to all configurations?
  - inlet from space, from outdoors, from coil outlet
- Various airflows and hardware options
  - different air flows, imbalanced flows, regeneration temperatures, wheel thicknesses
- Can it be normalized to represent different sizes?
  - same model applies for 1, 5, or 50 tons?

Different Products – Different Needs

- Easy: Stand-alone Dehumidifier
  - Ductless = constant air flow, operates at space conditions
  - Few possibilities, easy to make a map
- Harder: Commercial Desiccant Unit
  - Could pull air from space or from outdoors
  - Could operate at different airflow rates
  - Could have imbalanced flows
  - Regeneration temperatures might be fixed or vary with ambient or loading
  - Controls maintain constant supply air temperature

Manufacturer's Performance Data

Typically Generated with Algorithm

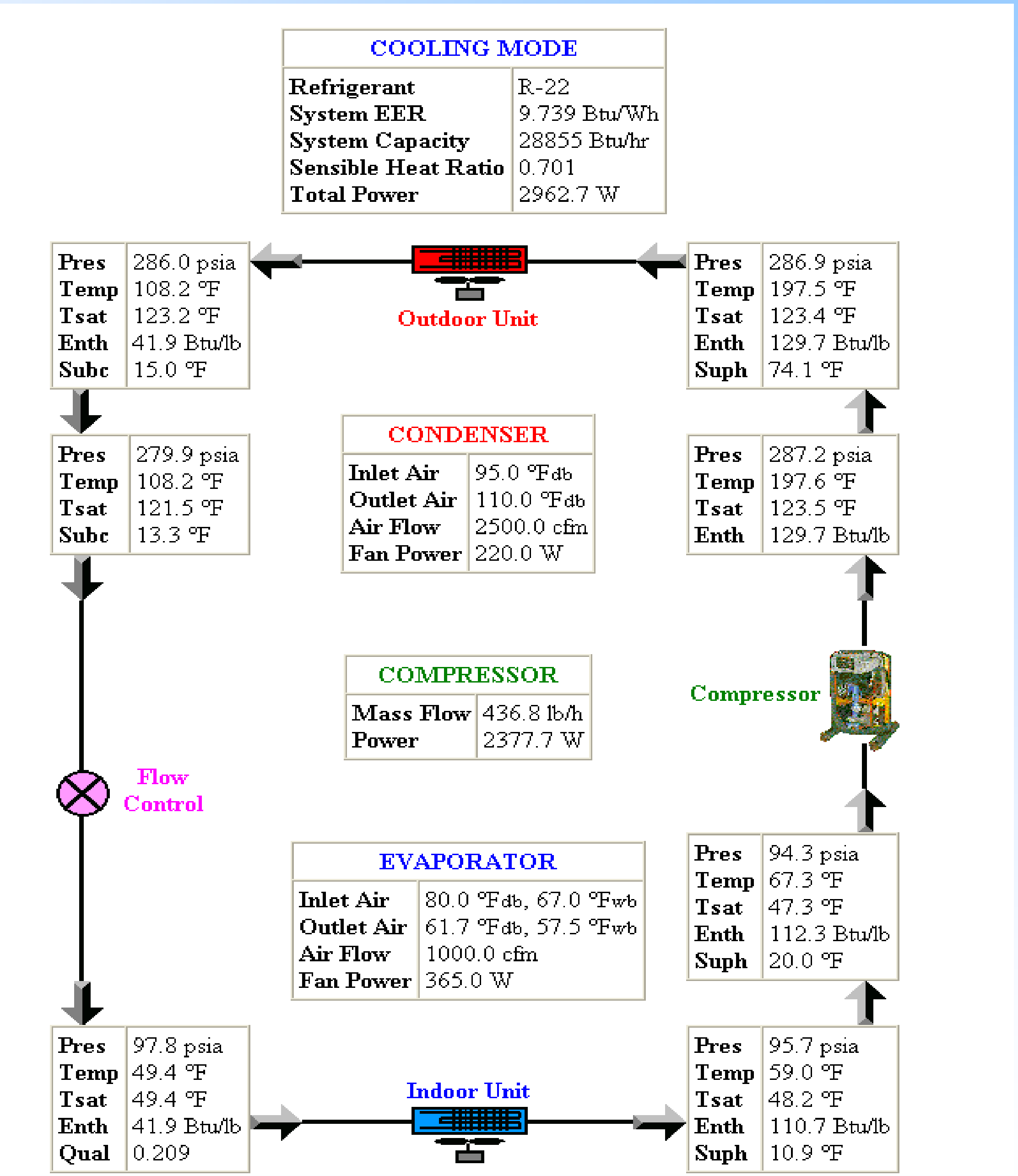
48TF004 (3 TONS)										
Temp (F) Air Entering Condenser (Edb)		Air Entering Evaporator — Cfm/BF								
		900/0.11			1200/0.14			1500/0.17		
		Air Entering Evaporator — Ewb (F)								
		72	67	62	72	67	62	72	67	62
75	TC	42.8	38.9	35.0	44.8	40.8	37.0	45.8	41.9	38.2
	SHC	20.0	24.5	28.7	21.8	27.5	32.8	23.0	30.0	36.0
	kW	2.91	2.81	2.70	2.99	2.88	2.78	3.02	2.92	2.82
85	TC	40.8	36.9	33.3	42.5	38.7	35.0	43.6	39.9	36.1
	SHC	19.4	23.7	27.9	21.0	26.8	31.8	22.6	29.7	35.1
	kW	3.14	3.01	2.90	3.20	3.08	2.97	3.24	3.14	3.02
95	TC	38.7	34.9	31.4	40.4	36.6	33.0	41.4	37.6	34.1
	SHC	18.6	22.9	27.0	20.3	26.0	30.9	22.0	28.8	34.0
	kW	3.35	3.21	3.09	3.42	3.29	3.16	3.47	3.35	3.22
105	TC	36.5	32.8	29.2	38.1	34.3	30.9	39.0	35.2	32.4
	SHC	17.8	22.1	25.9	19.6	25.2	29.8	21.2	28.0	32.3
	kW	3.55	3.41	3.27	3.63	3.49	3.35	3.68	3.54	3.43
115	TC	34.3	30.7	26.9	35.7	32.1	28.8	36.5	32.9	30.6
	SHC	17.0	21.3	24.8	19.0	24.4	28.8	20.5	27.1	30.6
	kW	3.76	3.60	3.45	3.84	3.68	3.54	3.88	3.74	3.64

Source of Data

- Virtually all manufacturers publish "simulated" performance data
  - There is no rating standard for how to present this data
- Only rating points are fully based on measured data
- Is this a bad thing?
  - Mature, well understood products may not need measured data for every point in a performance table or map
  - There is a difference between certified data, published data, and "just" data

ORNL
AC Model

- Best approach might blend a mix of laboratory tests and simulated data
- Use model to fill in gaps



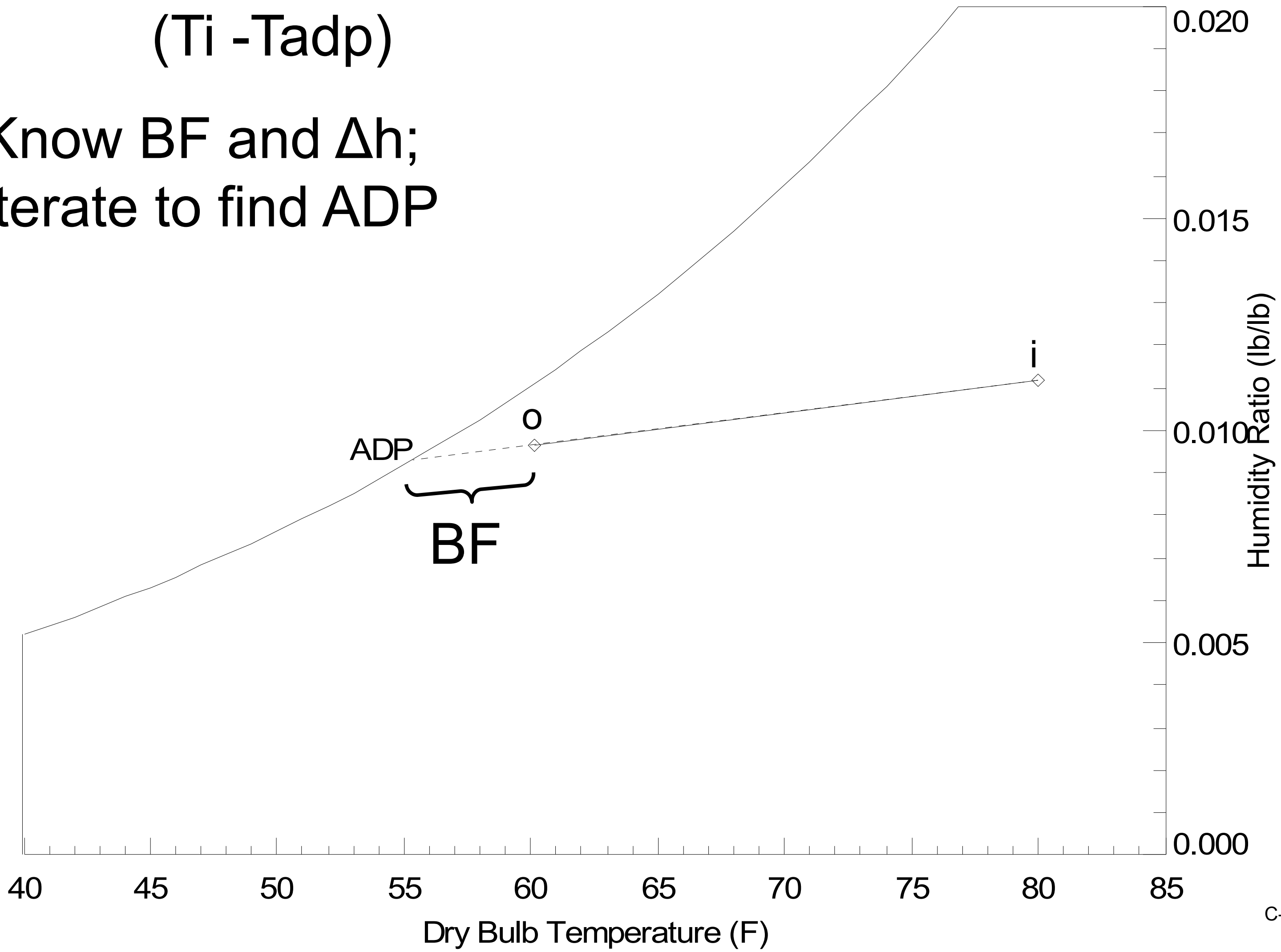
Semi-Empirical Model: AC

- Empirical
  - $QT/QT_{rated} = F(DBO, WBI, CFM_{ton})$
  - $kW/kW_{rated} = F(DBO, WBI, CFM_{ton})$
- Find sensible and latent breakout with physical model
  - Use apparatus dew point and bypass factor (ADP/BF) method; predicts coil dryout
  - Use rated SHR to find “rated” BF
- Then build entire performance map from one rating point

ADP/BF Approach

$$BF = \frac{(T_o - T_{adp})}{(T_i - T_{adp})} = F(cfm)$$

Know BF and Δh;
iterate to find ADP



Equipment with Different States

Integrating control issues

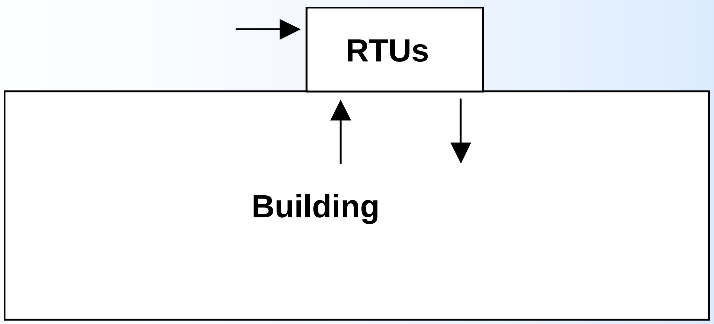
- Examples
  - Subcool/reheat systems, hybrid desiccant units, condenser reheat systems
- Component changes "state"
  - Switch between multiple performance maps
- What drives "state" change
  - Ambient temperature (easy)
  - Space conditions (when space is "overcooled")
  - State of other components (change state when AC is on)

Iterations required

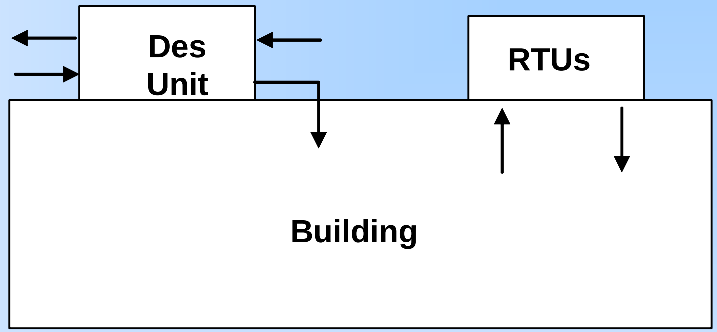
Easy or Hard: Condenser Reheat

- Simple Way (desuperheating reheat):
  - Use AC performance map
  - Some condenser heat is added into air stream
  - Probably works for small amounts of reheat
    - Reheat does not change AC coil performance
- Hard Way (full condensing):
  - As more reheat is used, AC performance changes (condensing temperature changes)
  - More complicated with modulating
    - Continuous function or 2-3 state maps?

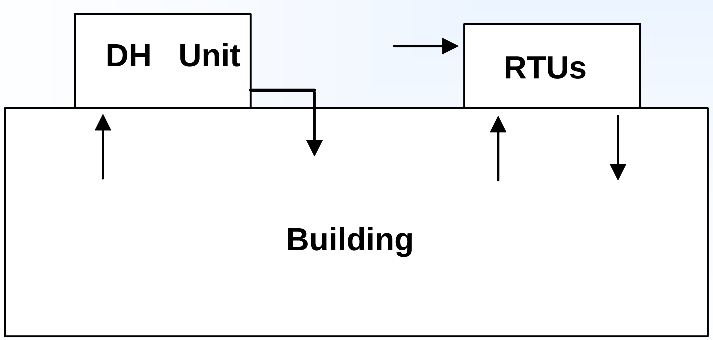
Possible Configurations



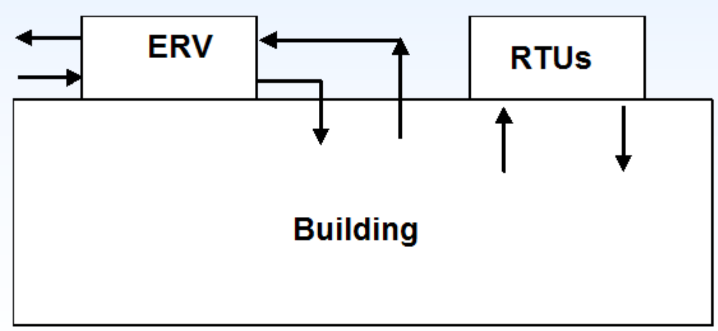
AC Only



AC w/ DH venting



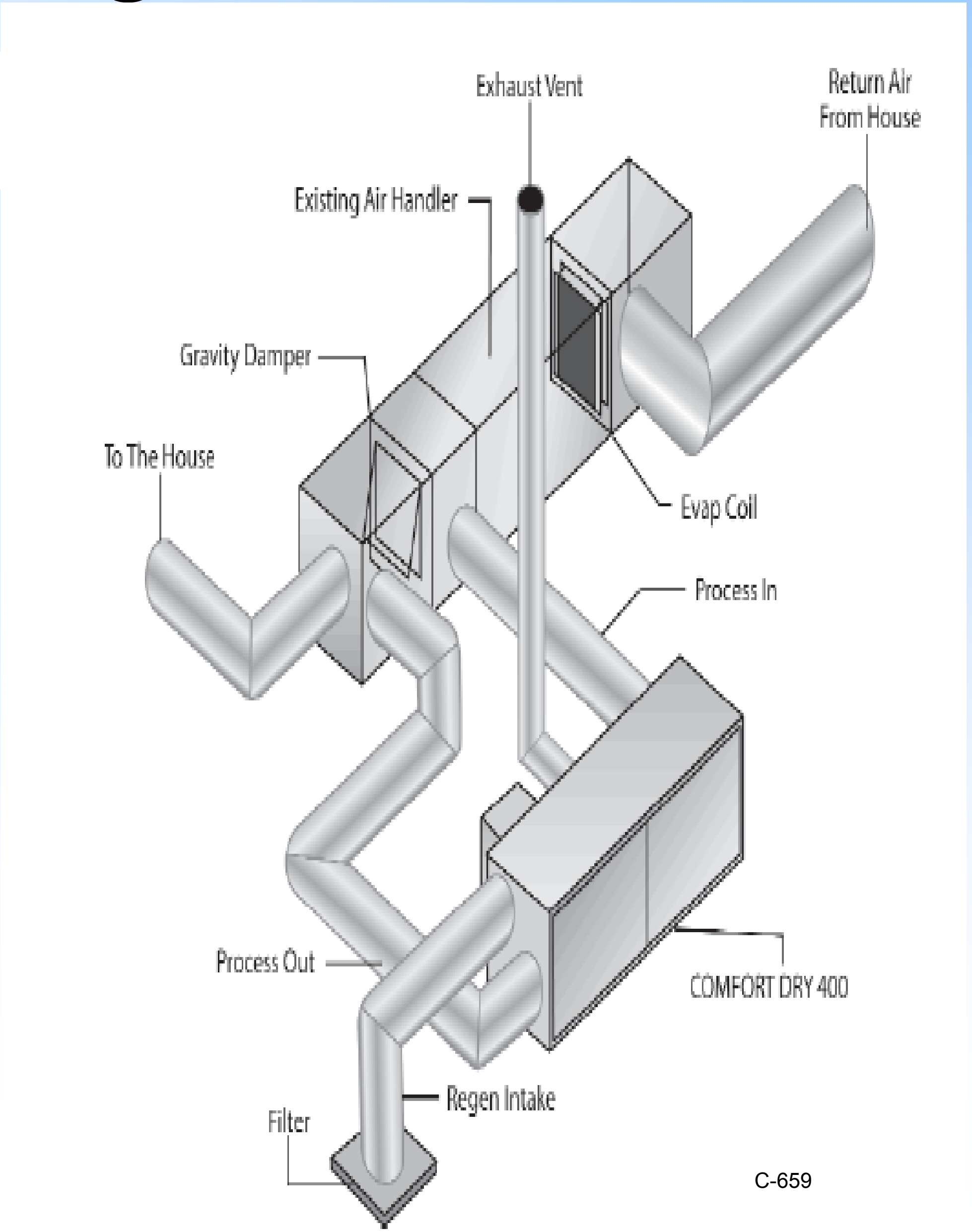
AC w/ DH



AC w/ ERV

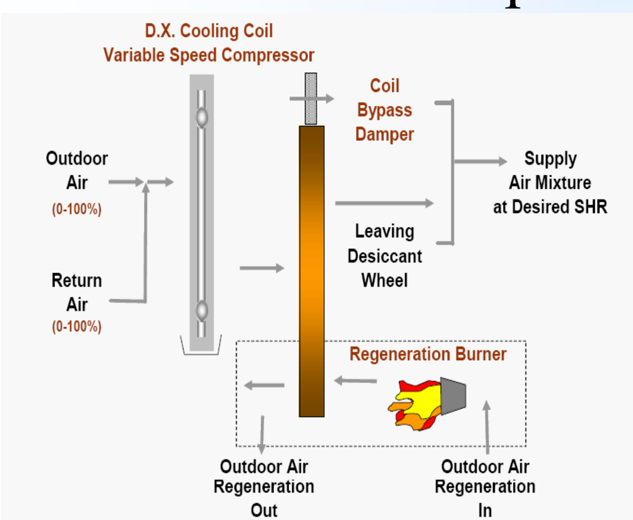
Component Configuration Issues

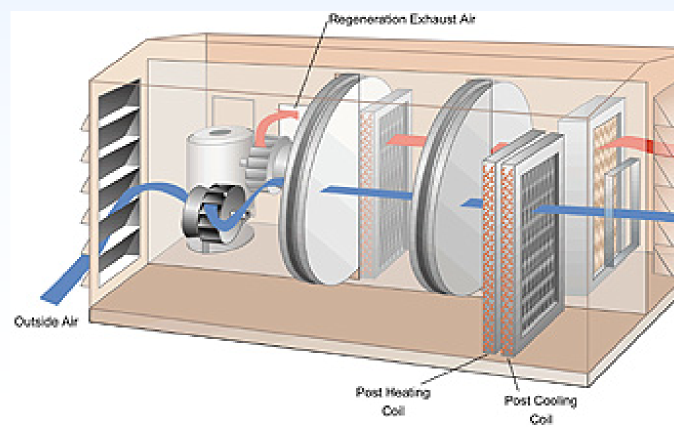
- Novelaire suggests putting desiccant unit in AC supply stream
  - Desiccant likes cold, high RH air
- DH Runs independently
  - DH might see return or supply air conditions…. or in between



Commercial Hybrid Units

- Can combine multiple components (desiccant, HX, DX coil) into one bigger component
- Integrate some controls into component:
  - Constant supply air set point
  - Hot gas bypass
  - Changes of state (based on no-iterative conditions, e.g., outdoor temperature)

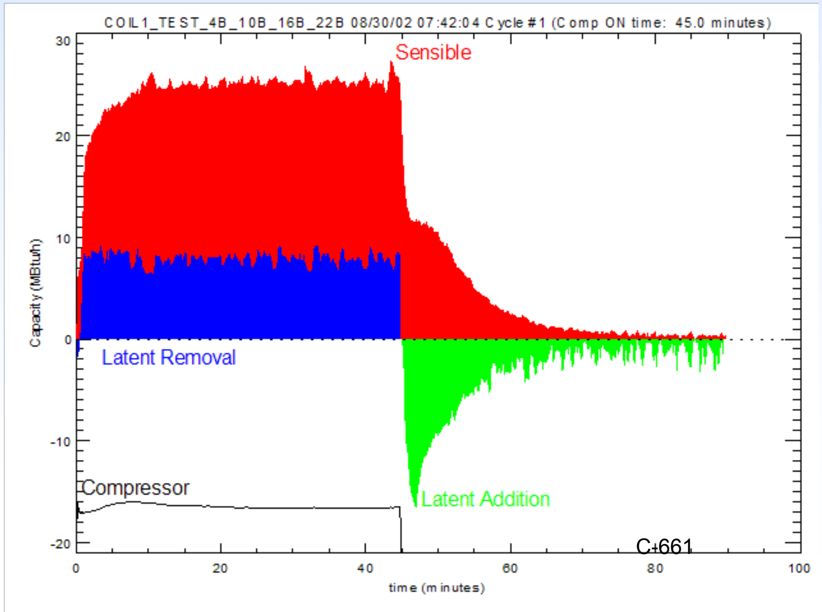




C-660

Part-load Load Effects

- Part load efficiency degradation
- Part load latent degradation (i.e., off-cycle moisture evaporation)
- Thermostat “droop”; space temperature changes with loading
- Independent ventilation controls (recycler)
- Hot gas bypass controls



Summary

- Performance for the Component
  - Need data to represent range of expected operating conditions (maybe a mix of measured and simulated)
  - Choose good independent and dependent variables
  - semi-empirical models are better
  - Normalize models where possible
- Integration, Configuration and Control
  - Often the hardest part
  - How component works with other components and within building system

Appendix D: Presentation 2

Not available at this time, pending approval by NREL.

Appendix E: Presentation 3

U.S. Department of Energy
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Building Technologies Program

Building America
U.S. Department of Energy
Research Leading to Zero Energy Homes

Residential Dehumidifier Performance: Field Testing and Method Of Test Development

By:
Armin Rudd
Building Science Corp.
www.buildingscience.com

For:
Building America Expert Meeting
Louisville
19 June 2009

Stand-alone dehumidifier
Installed in mechanical closet, in central system return air path

C-666

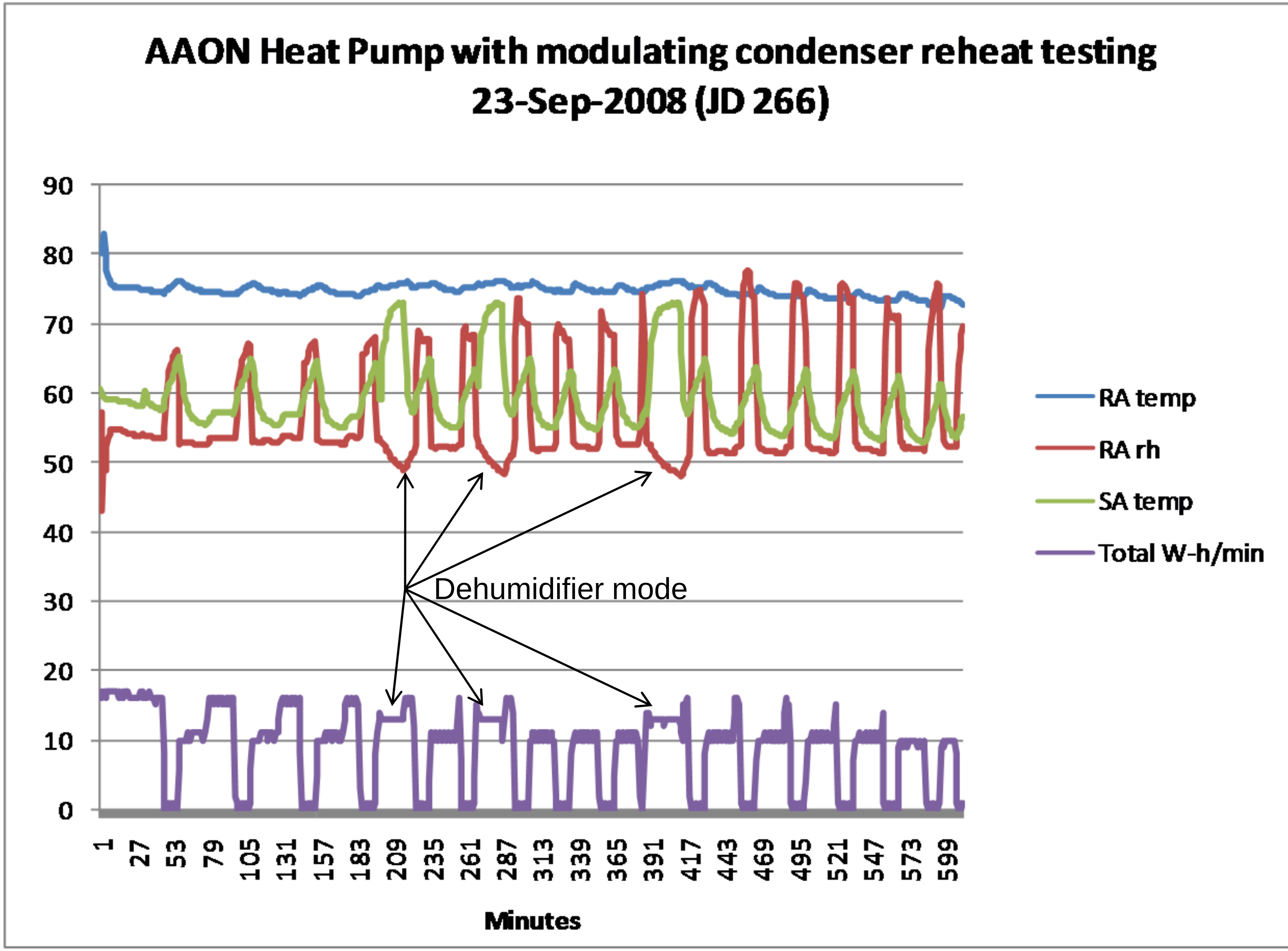
Stand-alone dehumidifier, installed in attic
Ducted to living space and central system supply

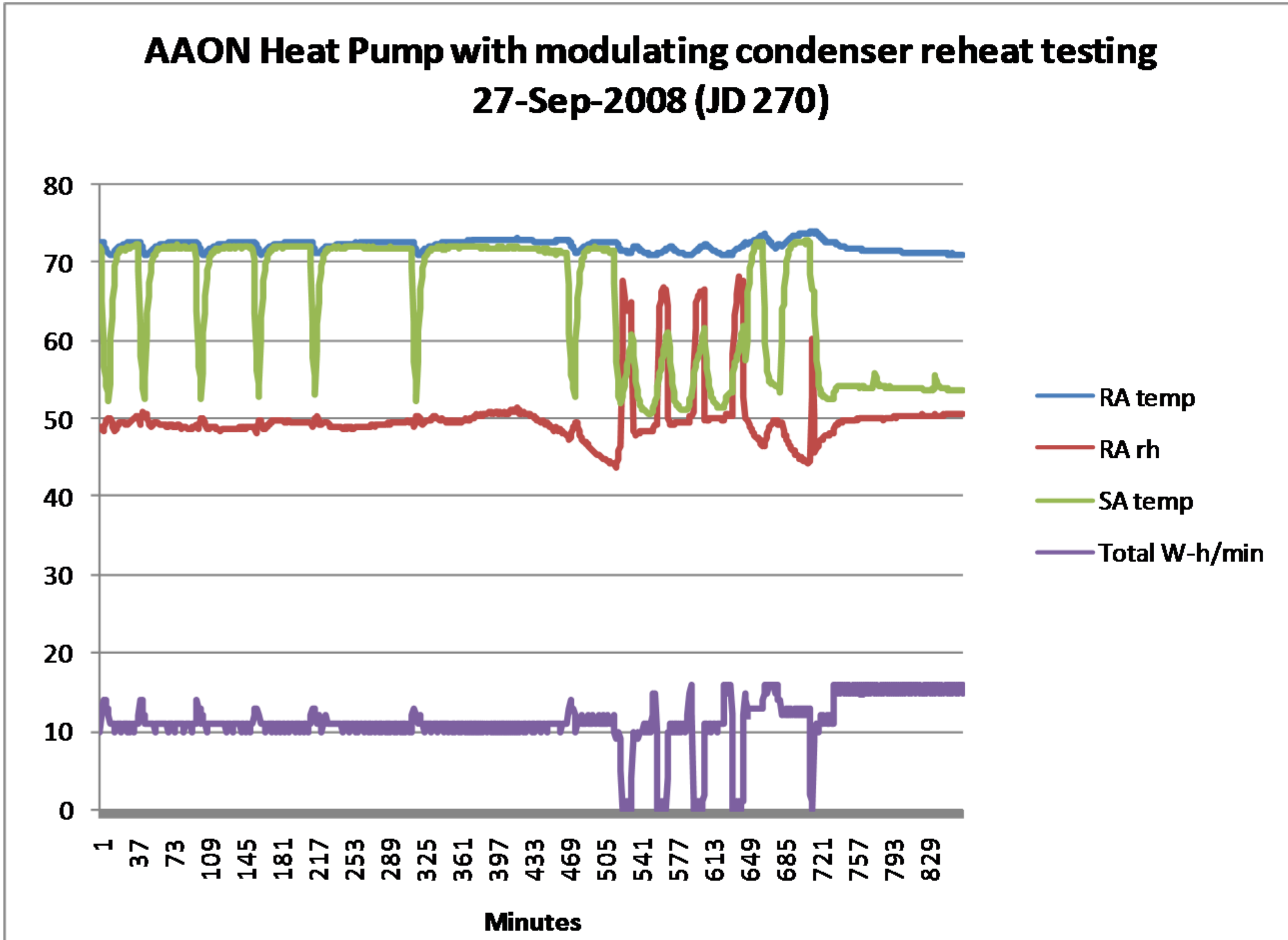
Stand-alone dehumidifier, installed in conditioned space
Ducted and integrated with central system

DX cooling system with modulating hot gas condenser reheat for dedicated dehumidification mode

3-pipe system

FSEC Manufactured Housing LAB
Cocoa, FL


AAON Heat Pump with modulating condenser reheat testing
23-Sep-2008 (JD 266)
90
80
70
60
50
40
30
20
10
0
1
27
53
79
105
131
157
183
209
235
261
287
313
339
365
391
417
443
469
495
521
547
573
599
Minutes
Dehumidifier mode
RA temp
RA rh
SA temp
Total W-h/min


AAON Heat Pump with modulating condenser reheat testing
27-Sep-2008 (JD 270)
80
70
60
50
40
30
20
10
0
1
37
73
109
145
181
217
253
289
325
361
397
433
469
505
541
577
613
649
685
721
757
793
829
Minutes
RA temp
RA rh
SA temp
Total W-h/min

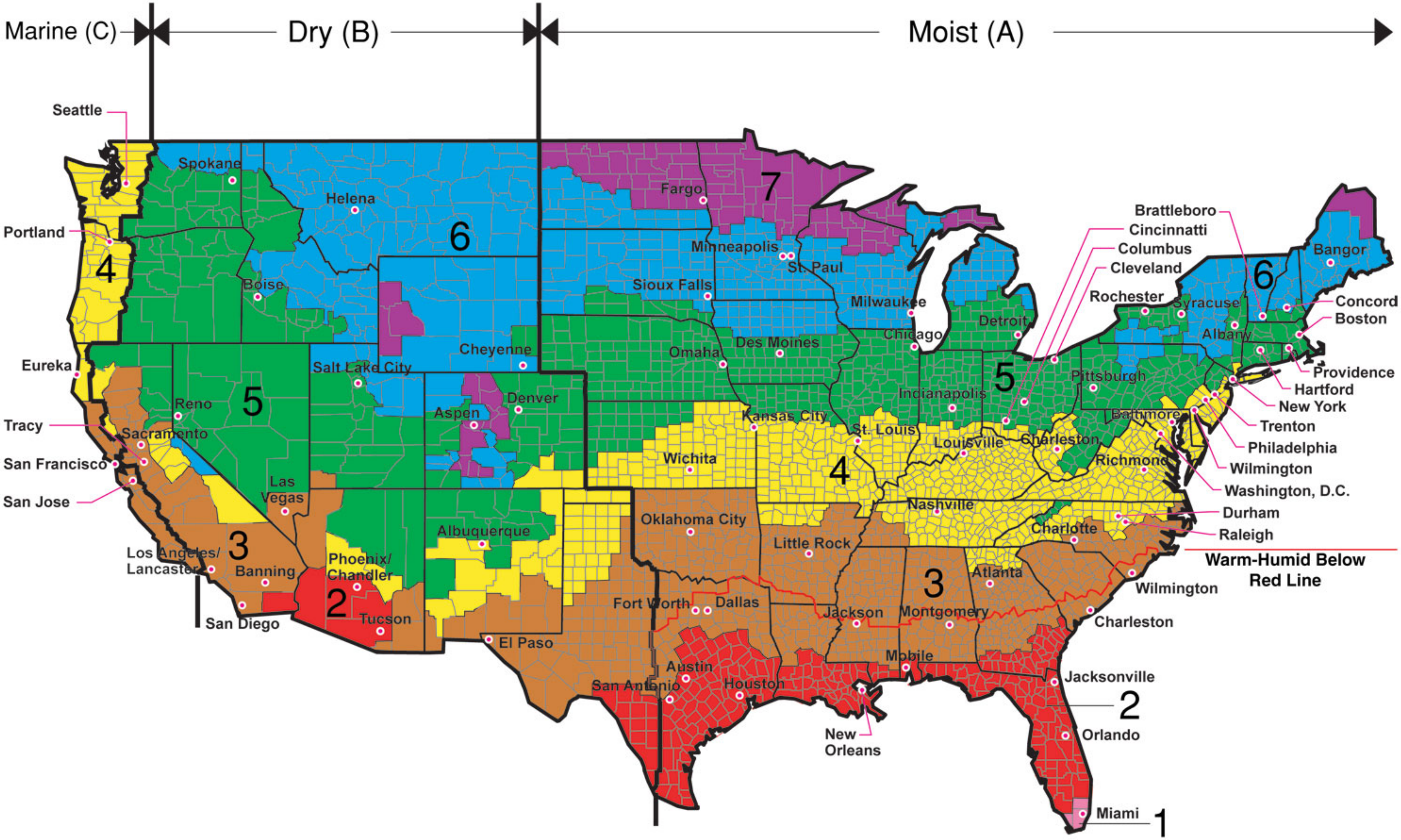
Summary to this point

- **Where we have been** is to demonstrate that there is a certain need for dehumidification separate from cooling in high-performance, low sensible gain houses in humid climates. We have also worked with manufacturers providing stand-alone dehumidifier solutions, and have developed and tested our own integrated system.
- **Where we are right now** is: existing packaged dehumidifier equipment, and single-system integrated approach.
- **Where we are going** is to create a framework in which to evaluate the performance of a range of supplemental dehumidification systems as they are applied to high-performance homes. This will entail developing engineering criteria for obtaining standardized extended performance data in laboratories (MOT), and conducting field evaluations that will also serve as a reality check for modeling efforts towards a new rating standard.

Approach to establish performance and testing requirements for humidity control equipment in high performance homes in hot-humid climates

- Define the minimum whole house performance goal
  - for example: Limit duration of indoor RH >60% to 4 hours or less, while meeting Energy Star dehumidification efficiency requirements for latent cooling and SEER 13 efficiency requirement for total cooling.
- Define a test method that that provides a consistent basis of comparison of performance between different types of equipment
- Demonstrate that the method works based on lab tests and field tests in high performance homes
- Hold meetings with stakeholders to build consensus for performance goals and test methods
- Begin to adapt the field test data to models to provide basis for equipment rating (further testing may be needed)
- Integrate equipment performance maps into annual energy simulations which would support the rating procedures
- Publish test methods, rating procedures, and test/analysis results

Regional ratings may be important



All of Alaska in Zone 7 except for the following Boroughs in Zone 8: Bethel, Dellingham, Fairbanks, N. Star, Nome North Slope, Northwest Arctic, Southeast Fairbanks, Wade Hampton, and Yukon-Koyukuk

Zone 1 includes: Hawaii, Guam, Puerto Rico, and the Virgin Islands

Method of Testing for Rating Residential Dehumidifiers for Moisture Removal Capacity and Moisture Removal Efficiency

FORWARD

...

1. PURPOSE

1.1. The purpose of this standard is to prescribe test methods for determining the moisture removal capacity and moisture removal efficiency for residential dehumidifiers.

2. SCOPE

2.1 This Standard applies to residential dehumidifying equipment that removes moisture by cooling air below its dew-point. The equipment may consist of one or more separate assemblies located indoors or outdoors. Where more than one separate assembly is used, they shall be designed to be used together.

2.2 For purposes of this standard, residential dehumidifiers provides air dehumidification and may provide additional functions of: air cooling, air heating, air circulation, air filtration, air-to-air heat recovery, and water heating.

3.1 DEFINITIONS

ARI Standard 210/240 test conditions

Table 3. Cooling Mode Test Conditions for Units Having a Single-Speed Compressor and a Fixed-Speed Indoor Fan, a Constant Air Volume Rate Indoor Fan, or No Indoor Fan

Test Description	Air Entering Indoor Unit				Air Entering Outdoor Unit			
	Dry-Bulb		Wet-Bulb		Dry-Bulb		Wet-Bulb	
	F	C	F	C	F	C	F	C
A Test - required (steady, wet coil)	80	26.7	67	19.4	95	35	75.0(1)	23.9(1)
B Test - required (steady, wet coil)	80	26.7	67	19.4	82	27.8	65.0(1)	18.3(1)
C Test - optional (steady, dry coil)	80	26.7			82	27.8		
D Test - optional (cyclic, dry coil)	80	26.7			82	27.8		

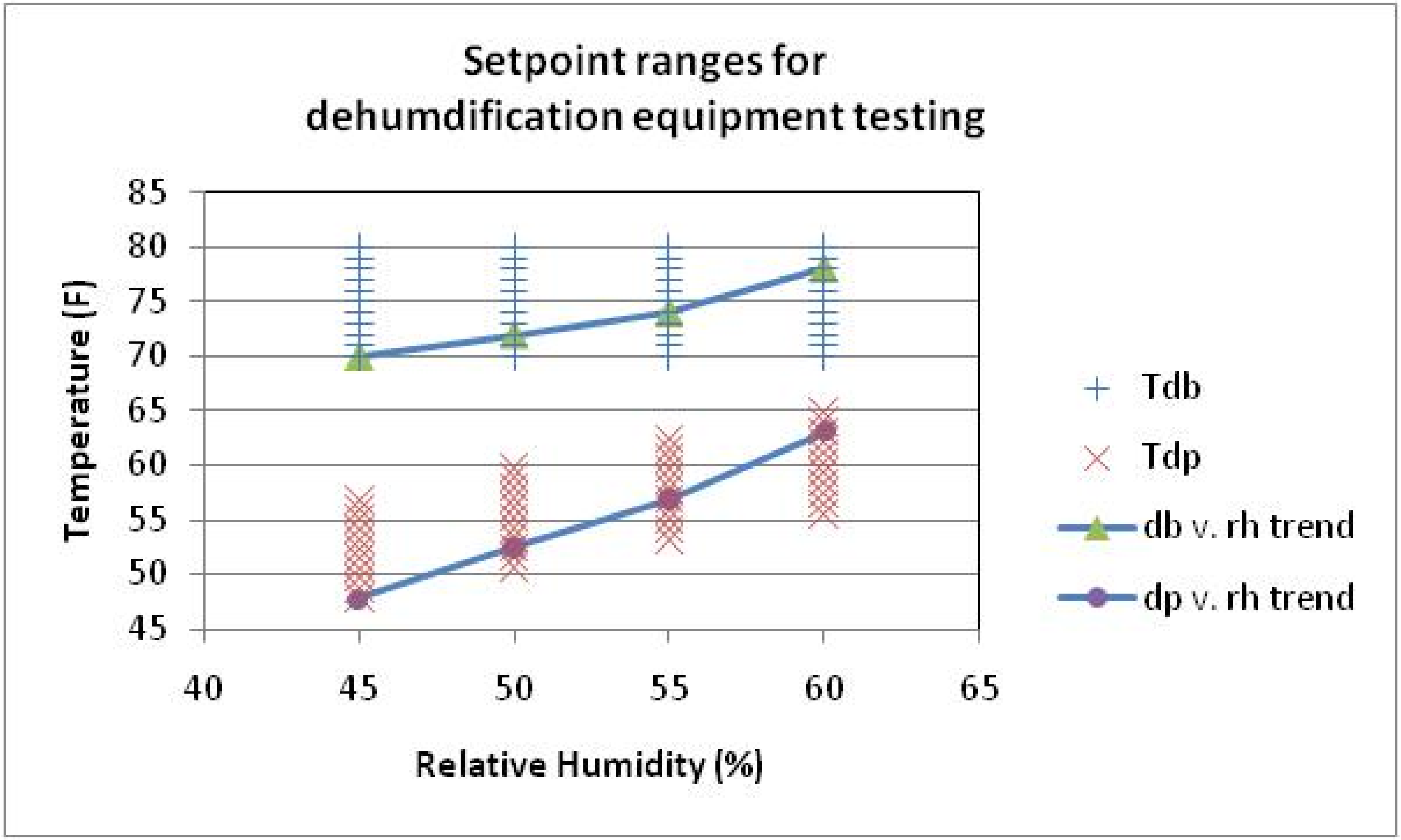
Notes: (1) The specified test condition only applies if the unit rejects condensate to the outdoor coil.

Cd = degradation coefficient, you want that to be low, default=0.25
PLF = part load factor (at 50% load), you want that to be high

PLF = 1 - 0.5(Cd)

SEER = PLF * EER

Humidity control setpoints for testing



Humidity control setpoints for testing

	Outdoor T/RH/Tdp (F/%/F)	Indoor T/RH/Tdp (F/%/F)	
Test 1	95/58/78	80/60/65 78/55/61 75/50/55	cooling design conditions
Test 2	80/85/75	80/60/65 78/55/61 75/50/55	cooling part-load: summer nights/rainy periods
Test 3	75/85/70	78/60/63 78/55/61 75/50/55	cooling part-load: spring/fall
Test 4	65/90/62	72/60/57 70/52/52 68/45/46	no cooling: spring/fall/winter
Test 5 (opt)		65/55/49[1]	cold climate basement conditions

[1] Single unit basement dehumdifier condition

Dehumidification equipment test results

	Outdoor T/RH/Tdp (F/%/F)	Indoor Return T/RH/Tdp (F/%/F)	Indoor Supply T/RH/Tdp (F/%/F)	Indoor Wet-coil Airflow (cfm)	Sensible Cooling Capacity (Btu/h)	Latent Cooling Capacity (Btu/h)	Heat Added In Dehum (Btu/h)	Moisture Removal Capacity (L/h)	Total Power (kW)	Moisture Removal Efficiency[1] (MRE) (L/kW-h)	Dehum Efficiency Ratio (DER) (Btu/W-h)	Energy Efficiency Ratio (EER) (Btu/W-h)
Test 1	95/58/78	80/60/65 78/55/61 75/50/55										
Test 2	80/85/75	80/60/65 78/55/61 75/50/55										
Test 3	75/85/70	78/60/63 78/55/61 75/50/55										
Test 4	65/90/62	72/60/57 70/52/52 68/45/46										
Test 5 (opt)		65/55/49										

[1] Same as the Energy Factor used for dehumidifiers by Energy Star