October 12, 2010
Peter Baker, P.Eng.
Building Science Corporation

Residential Energy Performance Association of New Hampshire

Wall and Roof Systems

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Presentation Overview

- Context for Residential Construction
- The Ideal Building Enclosure
- Moisture Control
- Energy Transfer
- Wall Systems
- Roof System/Attic Systems

Context for Residential Construction

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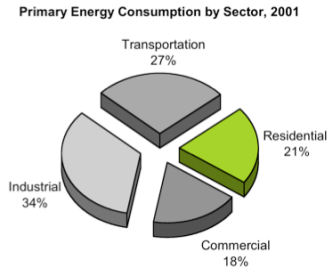
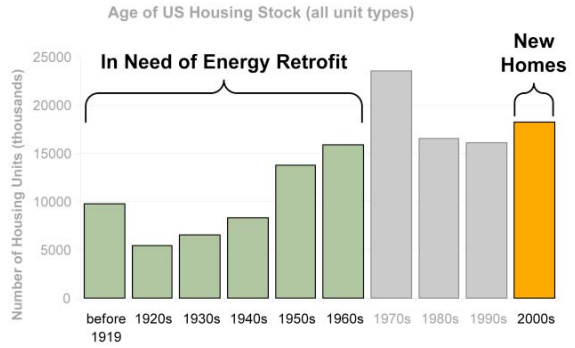
Energy Use

- Energy is a big consideration in new construction and building retrofits



Building Energy Use



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Building Retrofit Opportunities

- There are approximately 60 million units of housing in the U.S. that were built prior to 1960.
- Most of these will need major systems replaced in the near future.
- As siding, windows, roof claddings, mechanicals replaced, opportunities arise to reduce the overall energy use of these homes

CAPTURE OPPORTUNITIES !

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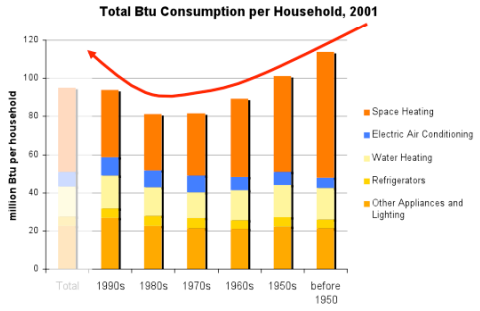
Home Energy Use



Source: US Census Bureau, Annual Housing Survey: http://www.census.gov/hhes/www/housing/ahs/ahs.html

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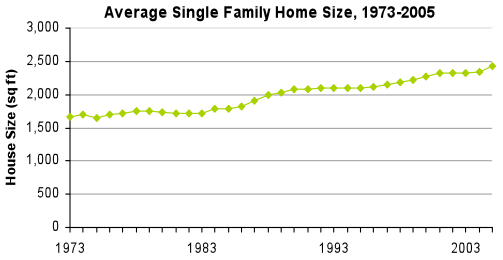
More Efficient, but Bigger

- Average House Size in **1940:** **~1100 sq ft**[1]
- Average House Size in 1973: **1660 sq ft**[2]
- Average House Size in **2005:** **2434 sq ft**



1. Wilson, Alex and Jessica Boehland "Small is Beautiful" *Journal of Industrial Ecology*, Vol 9, No 1-2. 2005
2. EIA, Annual Energy Review, 2001 data: www.eia.doe.gov/emeu/aer

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Home Energy Use

- Significant portion of the total energy use
- Need to reduce energy
- New buildings should consider not just current standards and requirements but future needs
- Retrofit buildings should look for opportunities to bring levels above current standards as well

Building Service Life

- Any new construction or significant reworking of an assembly/system essentially inoculates that assembly/ system from further improvement for the services life
- Consider service life of measures
- Will components of an assembly provide appropriate performance for the full service life

Building Enclosure

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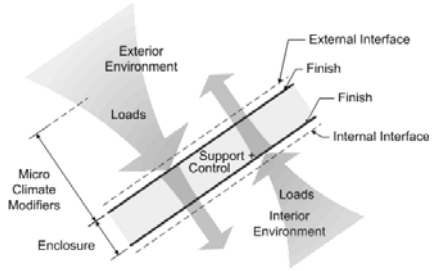
Building Enclosure

- Key Requirements
  - Control rain and ground water (including snow)
  - Control heat flow, airflow, and water vapor flow
  - Control light and solar radiation
  - Control noise and vibrations
  - Control contaminants, environmental hazards and odors, insects, rodents and vermin
  - Control fire
  - Provide strength and rigidity
  - Be durable
  - Be aesthetically pleasing
  - Be economical

Building Enclosure

- Rain Control Layer
- Vapor Control Layer
- Air Control Layer
- Thermal Control Layer



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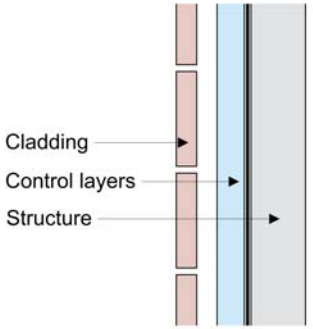
The Ideal Building Enclosure



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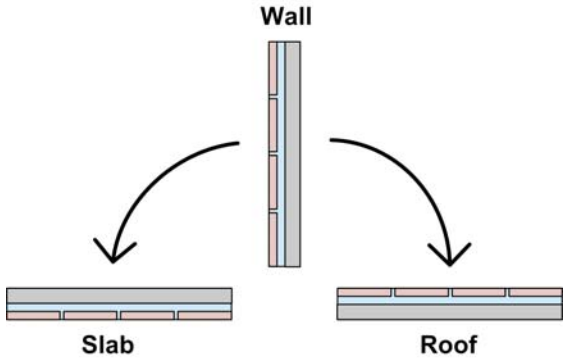

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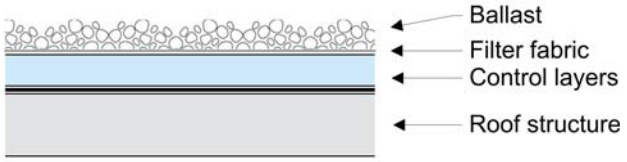

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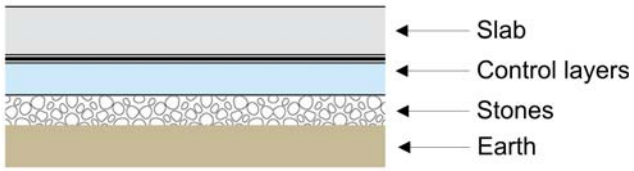

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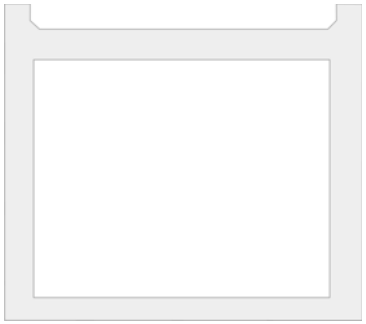

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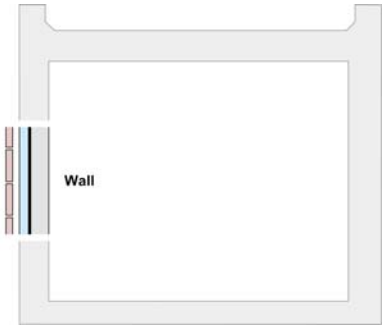

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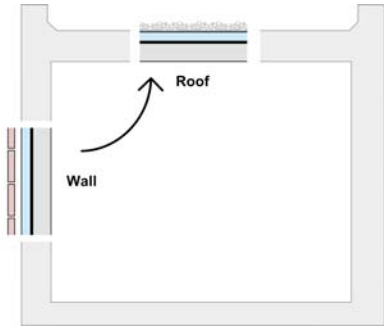

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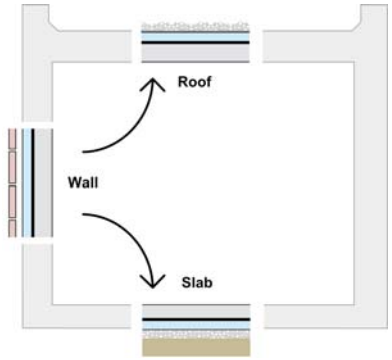

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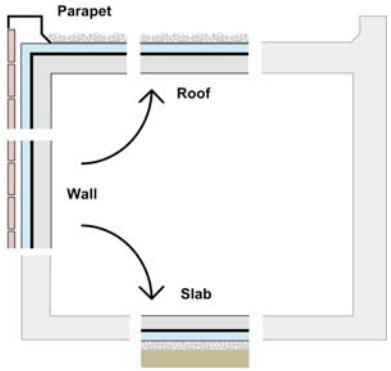

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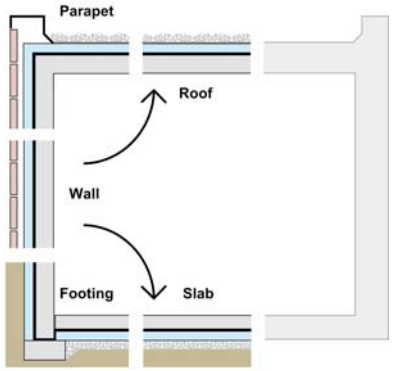

Physics

- Heat Flow Is From Warm To Cold
- Moisture Flow Is From Warm To Cold
- Moisture Flow Is From More To Less
- Air Flow Is From A Higher Pressure to a Lower Pressure
- Gravity Acts Down

Moisture Control

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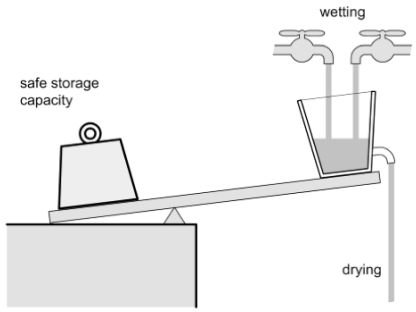
Moisture Control

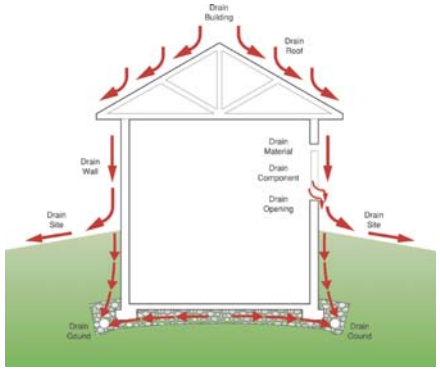
- The Moisture Balance



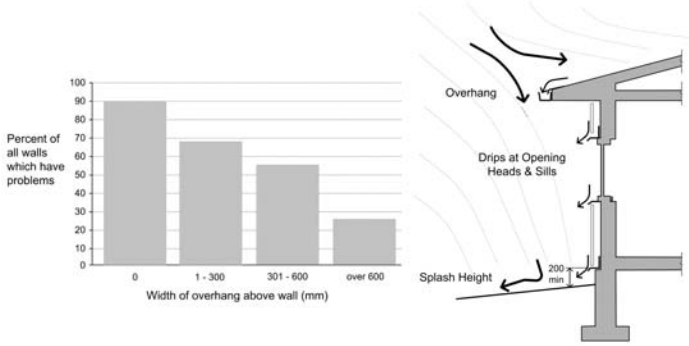
Moisture Control

- Wetting
  - Liquid Water Management
    - Rain/Snow
    - Ground water
  - Condensation
    - Air Leakage
    - Vapor Diffusion
- Storage
- Drying
  - Drainage
  - Ventilation
  - Vapor Diffusion

Water Management

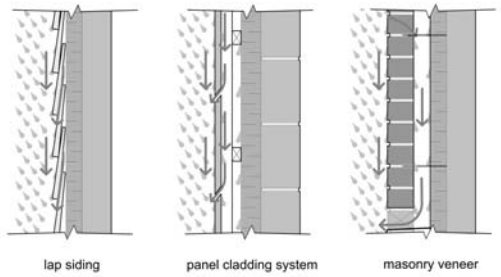


Water Management



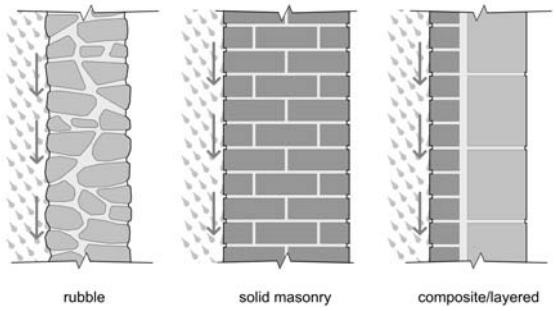
Water Management

- Drained Assemblies



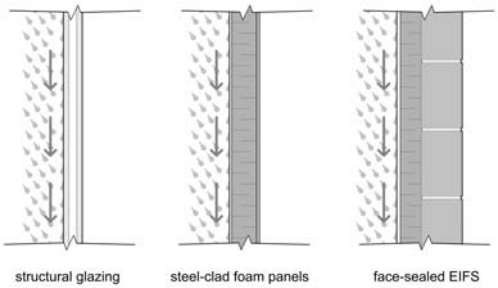
Water Management

- Mass Walls



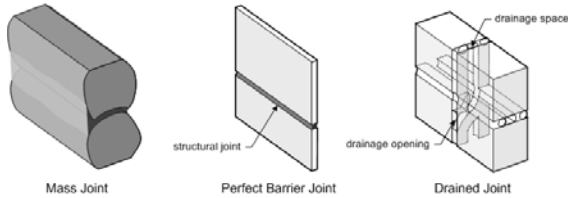
Water Management

- Barrier Walls

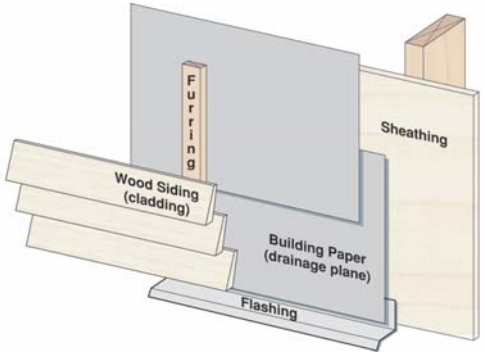


Water Management

- Water Managed Joints



Water Management



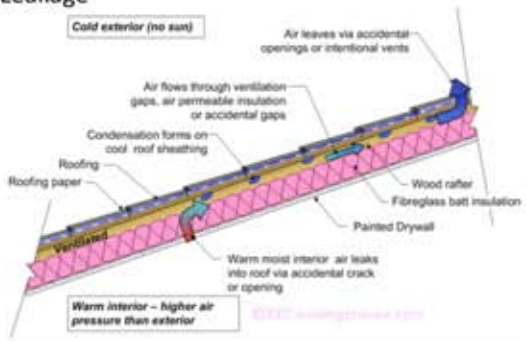
Water Management

Vapor Management

- Air leakage
  - Can transport significant amounts of water vapor
  - Driven by air pressure differences
  - Requires a pathway
- Vapor Diffusion
  - Typically slow transport of water vapor – though it can act continuously for long periods of time
  - Driven by partial vapor pressure differences
  - Function of material property and area

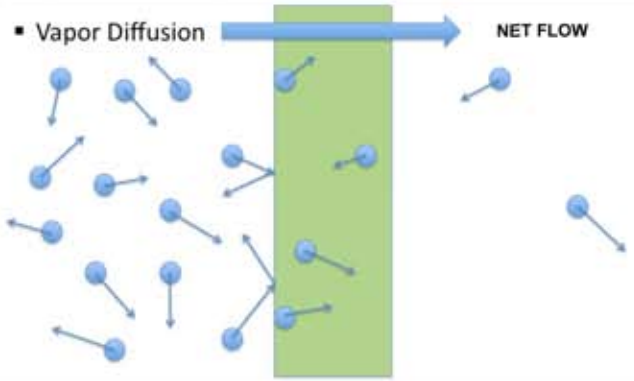
Vapor Management

- Air Leakage

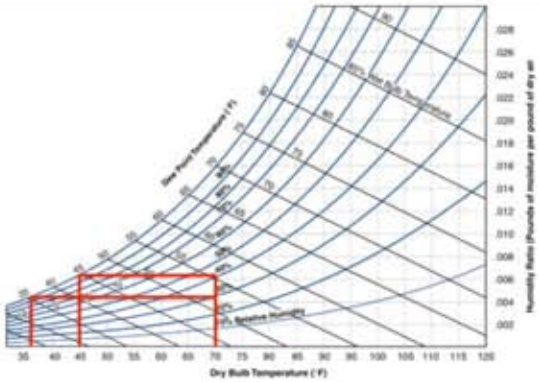


Vapor Management

- Vapor Diffusion

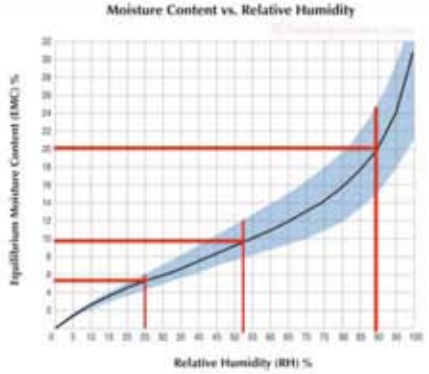


Vapor Management



Vapor Management

- Wood

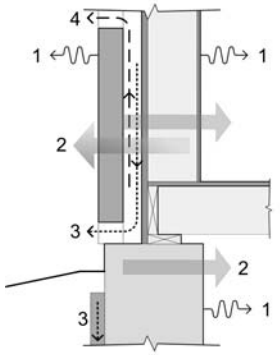


Moisture Storage

- High Storage
  - Masonry
  - Concrete
- Moderate Storage
  - Wood (Cellulose)
- No Storage
  - Glass(Including Fiberglass insulation)
  - Metal

Drying

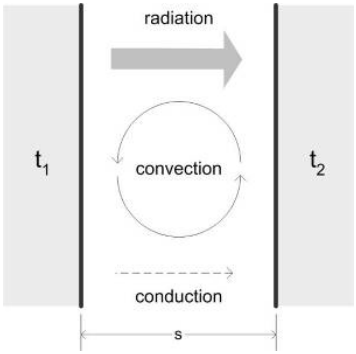
- Drainage
- Ventilation
- Vapor Diffusion



Thermal Control

Basic Heat Flow

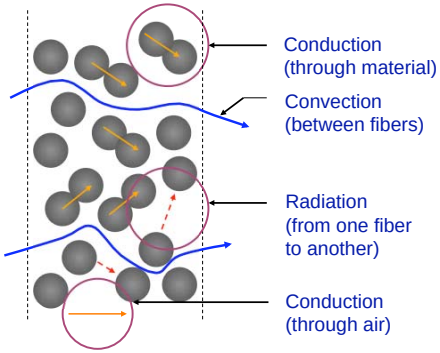
- Conduction
- Convection
- Radiation



Heat Flow in Materials

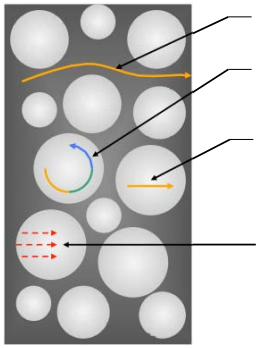
- Function of:
  - Material Type
  - Density and pore structure
  - Moisture content
  - Temperature difference
- Combination of:
  - Conduction through material and air (or other gas)
  - Convection in pores
  - Radiation through pores

Heat Flow in Materials



HYPOTHETICAL FIBEROUS MATERIAL

Heat Flow in Materials

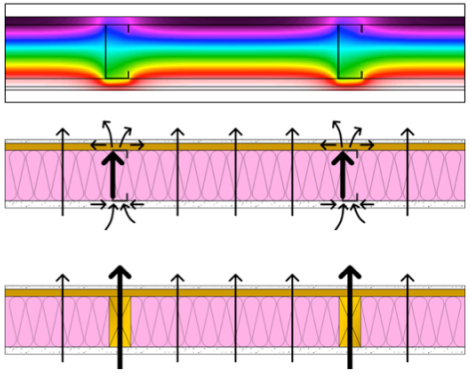


HYPOTHETICAL POROUS MATERIAL

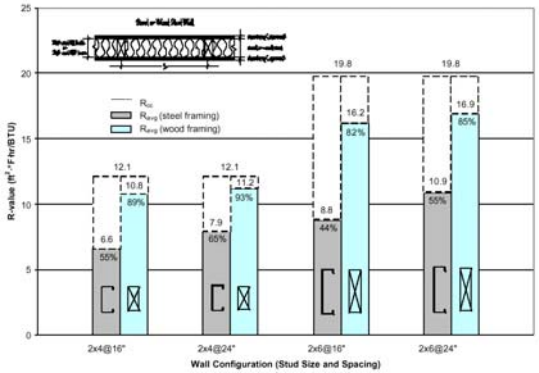
Heat Flow in Materials

- R-Value or RSI
  - Gives heat flow as “equivalent conductance”
  - Includes all three modes of heat transfer
  - Rarely includes thermal bridging or three dimensional heat flow
  - Never intended to include airtightness or mass

Conductance Through the Enclosure



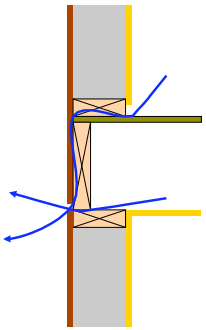
Conductance Through the Enclosure



Conductance Through the Enclosure

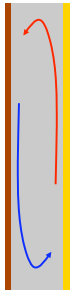
Convection Through the Enclosure

- Commonly referred to as “Air Leakage”
- Driven by air pressure differences
  - Wind
  - Mechanical
  - stack effect
- Large energy impacts (can account for 30% of the heating and cooling energy

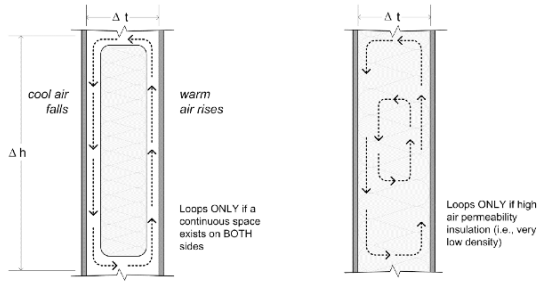


Convection Within the Enclosure

- Commonly referred to as "Convective Loops"
- Driven by natural buoyancy - warm air will rise
- Short circuits insulation
- R-value does not take into account the potential of movement of air within an assembly.



Convection Within the Enclosure



A: Air Loops Around Insulation B: Air Loops Through Insulation

Convection Within the Enclosure

Convection Within the Enclosure

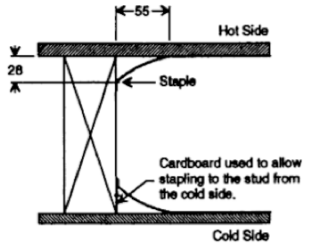
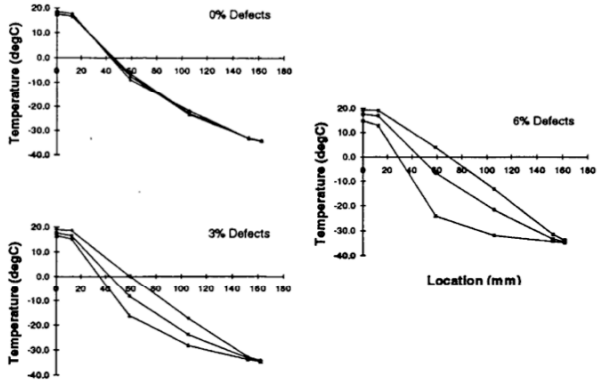


FIGURE 3. Detail of 6% installation defect.

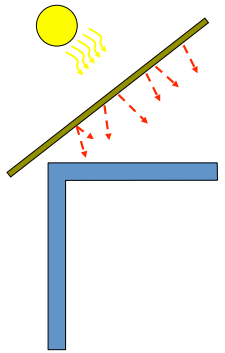
Brown and Bomberg 1993

Convection Within the Enclosure



Radiation

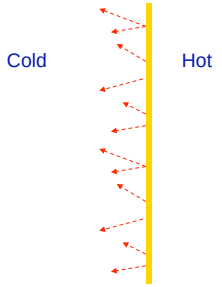
- Net radiant flow across a clear cavity
- Emissivity is expressed as a fraction of energy emitted when compared to the radiation from a black body
- Common in attics



Radiation

Radiation

- Must have an airspace for radiant products to work
- While low emitting, radiant products are often highly conductive
- Energy will be conducted to other materials in contact with radiant product (framing, dirt)



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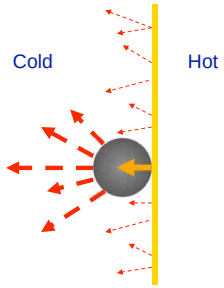

Insulation Types

- Cavity
  - Mineral Fiber Batts
  - Blown/Spray Mineral Fiber
  - Blown/Spray Cellulose
  - Cotton
  - Open Cell Spray Polyurethane
  - Closed Cell Spray Polyurethane

Insulation Types

- Insulating Sheathing
  - Medium Density Mineral Fiber
  - Expanded Polystyrene
  - Extruded Polystyrene
  - Polyisocyanurate
  - Closed Cell Spray Polyurethane

Performance

- Mineral Fiber Batts (Glass/Rock/Slag)
  - R/inch = 2.8 to 3.7
  - Air Permeable
  - Vapor Permeable
  - No moisture storage capacity
  - Uneven cavity fill (difficult to fit around obstructions)
- Blown/Spray Mineral Fiber (Glass/Rock/Slag)
  - R/inch = 2.8 to 3.7
  - Air Permeable
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  - No moisture storage capacity
  - Even Cavity Fill (net/adhesive holds fibers in place)

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Performance

- Blown/Spray Cellulose
  - R/inch = 3.0 to 3.7
  - Air Permeable (higher density = some resistance to air flow)
  - Vapor Permeable
  - Some moisture storage capacity
  - Even Cavity Fill (net/adhesives hold fibers in place)
- Cotton
  - R/inch = 3.0 to 3.7
  - Air Permeable (Some resistance to air flow)
  - Vapor Permeable
  - Some Moisture Storage Capacity
  - Even Cavity Fill

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Performance

- Open Cell Spray Polyurethane
  - R/inch = 3.6 to 3.8
  - Air Impermeable (good air barrier <0.01 lps/m2 @ 75 Pa, controls convective loops)
  - Vapor Permeable
  - Moisture Resistant
  - Even Cavity Fill (expands to fill voids)
- Closed Cell Spray Polyurethane
  - R/inch = 5.8 to 6.8
  - Air Impermeable (good air barrier <0.01 lps/m2 @ 75 Pa, controls convective loops)
  - Vapor Semi-impermeable (1 – 2 perms for 2" thickness)
  - Moisture Resistant
  - Even Cavity Fill (expands to fill voids)

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Performance

- Medium Density Mineral Fiber (Glass/Rock/Slag)
  - R/inch = 4.0 to 4.4
  - Air Permeable (resistance to wind washing)
  - Vapor Permeable
  - Moisture Resistant (good drainage for rock/slag)
- Expanded Polystyrene
  - R/inch = 3.6 to 4.4
  - Air Impermeable (air barrier if joints taped?)
  - Vapor Semi-impermeable (3 – 4 perms)
  - Moisture Resistant

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Performance

- Extruded Polystyrene
  - R/inch = 5.0
  - Air Impermeable (air barrier if joints taped?)
  - Vapor Semi-impermeable (0.5 perms for 2" thickness)
  - Moisture Resistant
- Polyisocyanurate
  - R/inch = 6.0 to 6.5
  - Air Impermeable (air barrier if joints taped?)
  - Vapor Semi-Impermeable or Impermeable (<1 glass fiber faced, 0.03 perms for foil faced)
  - Moisture Resistant

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Performance

- Closed Cell Spray Polyurethane
  - R/inch = 5.8 to 6.8
  - Air Impermeable (good exterior air barrier system <0.01 lps/m2 @ 75 Pa)
  - Vapor Semi-impermeable (1 - 2 perms for 2" thickness)
  - Moisture Resistant (can act as a drainage plane behind a cladding system)

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Wall Assemblies

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Wall Assemblies

- How much insulation?
- Comfort & moisture –
  - **True** R-10 is usually enough in Zone 6, but …..
- For energy / environment / economics
  - as much as *practical*
- Practical constraints likely the limit
  - How much space available in studs?
  - Moisture concerns
  - Fastening, windows: exterior sheathing of 1.5”/4”
- Increased insulation can reduce HVAC purchase/install cost as well as operating!

Wall Assemblies

- Add up the R-values of the layers to get the total R-value of the assembly
- **BUT** the actual thermal resistance of an assembly is affected by
  - **Thermal Bridges**
  - **Thermal Mass**
  - **Air Leakage**

True R-value

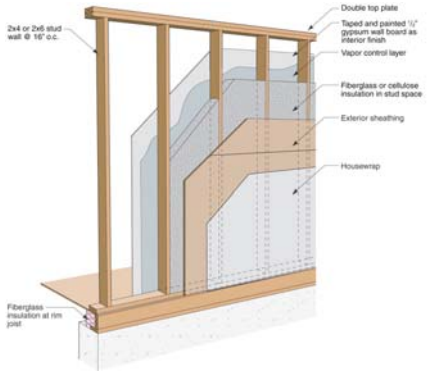
- Includes realistic framing factors
  - 3D heat loss
  - Realistic framing factors
  - (16% advanced framing, 25% normal)
- Should include airtightness
  - But we don't have a metric yet
- Durability also matters
  - No one metric will work

Durability

- Condensation occurs on cold surface
- Drying occurs slowly when cold
- Ergo... Insulating makes things wetter!
- Air & water vapor moves through fiberglass and cellulose
- Foam stops air and slows vapor

Wall Assemblies

- Wood framed wall with cavity insulation



Wall Assemblies

- Cavity Insulation Options
  - Fiberglass/Cellulose/Cotton/Open Cell SPF/Closed Cell SPF
  - Combinations?
- Retrofits change the dynamic of the wall assembly
  - How is the moisture balance affected?
- Building operation is changing to meet peoples comfort needs
  - Can't guarantee interior environmental conditions
  - Look for more resistant/robust assemblies

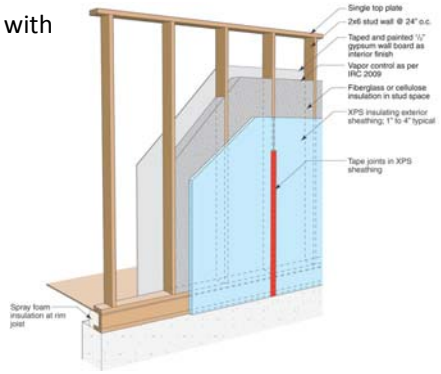
Wall Assemblies

Wall Assemblies

- Retrofits?
  - Address water management concerns – required for all
  - How will it affect the drying of the assembly?
  - Will it reduce wetting?
  - What about built in moisture?
  - Cladding impacts?
  - Other elements?

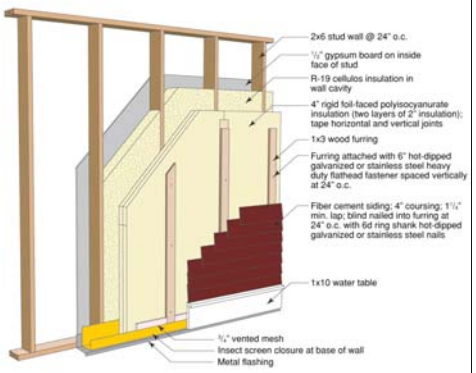
Wall Assemblies

- Wood framed wall with exterior insulating sheathing



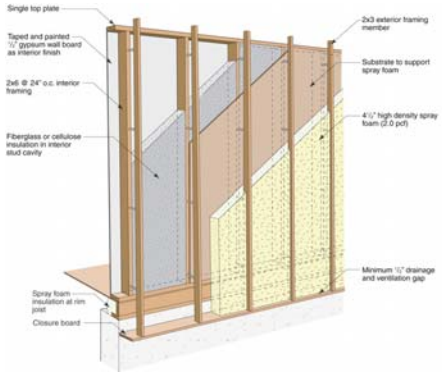
Wall Assemblies

- Wood framed wall with thick exterior insulating sheathing



Wall Assemblies

- Wood framed wall with exterior closed cell spray foam insulation and drainage plane



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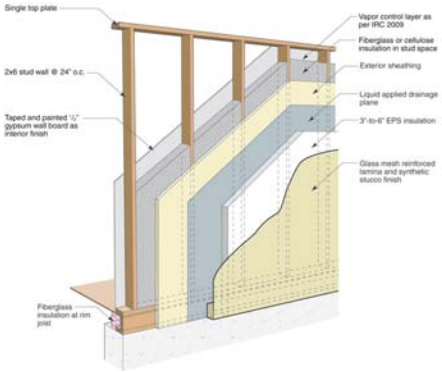
Wall Assemblies

- Wood framed wall with EIFS cladding



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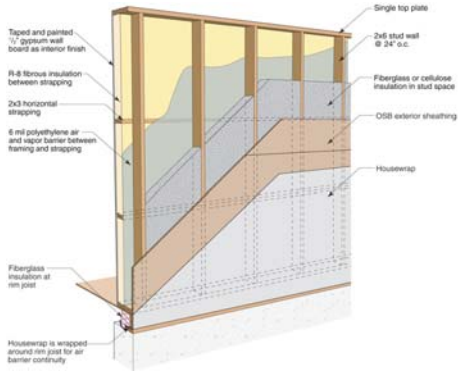
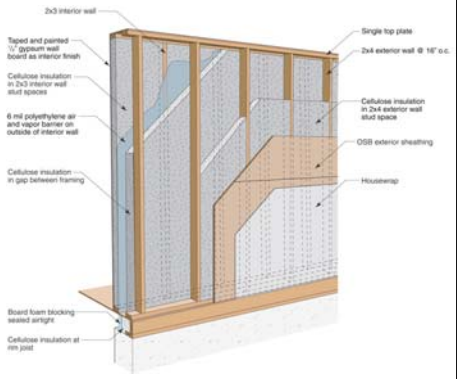
Wall Assemblies

- Wood framed wall with interior horizontal strapping



Wall Assemblies

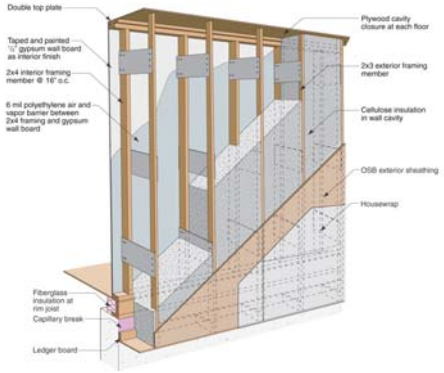
- Double stud wall



Construction issues

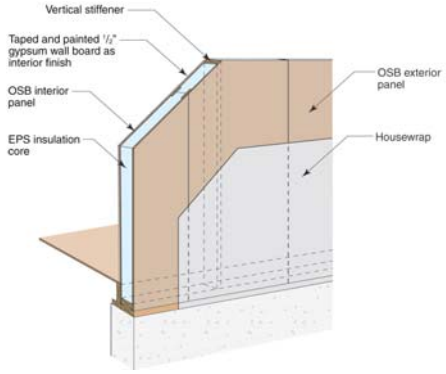
Wall Assemblies

- Larsen truss wall



Wall Assemblies

- SIP wall



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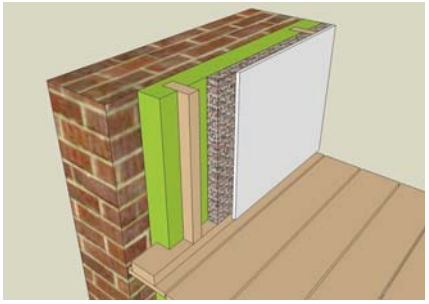
Wall Assemblies

- Mass Wall



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Roof Assemblies

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Roof Assemblies

- How much insulation?
- For energy / environment / economics
  - as much as *practical*
- Practical constraints likely the limit
  - How much space available?
  - Rafter depth
  - Moisture concerns
  - Vented/Unvented – material deterioration?
- Increased insulation can reduce HVAC purchase/install cost as well as operating!

Vented Attics

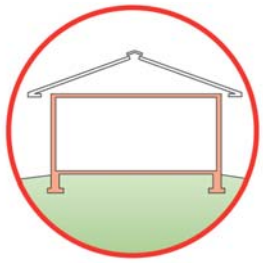
- Why ventilate?
  - Remove excess heat and moisture
  - Prolong service life of shingles
  - Control ice damming

Vented Attics

- Retrofits
  - Can re-roof whenever, with whatever
  - Deal with moisture, then add insulation
    - Rain leaks, air leaks
  - If possible, keep ventilated attic
    - Inspect ceiling plane, plug all holes with caulking and foam
    - Consider 1" of spray foam air barrier
    - Blow in minimum R60 cellulose, R75-R100 sensible

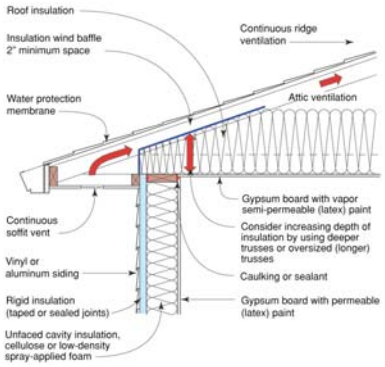
Roof Assemblies

- Common assembly
- Easy to get higher levels of insulation
- Need to provide an air seal the ceiling plane



Vented attic with insulation at ceiling; mechanical equipment should be located inside the conditioned space; can also have a tray ceiling

Roof Assemblies



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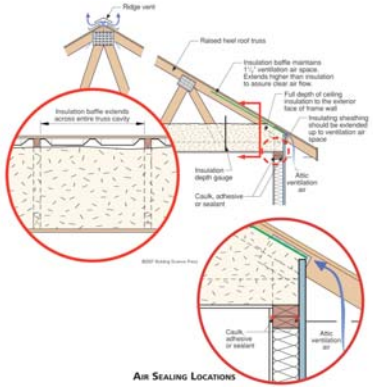
Roof Assemblies



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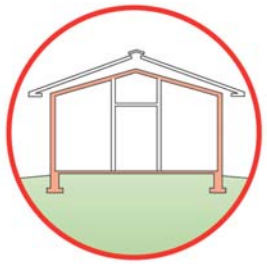
Roof Assemblies

- Cathedral ceilings are common in New England
- Rafter depth can create a challenge for insulation thickness while still providing ventilation
- Air sealing occurs at the ceiling plane



Vented attic with cathedral ceiling; mechanical equipment should be located inside the conditioned space

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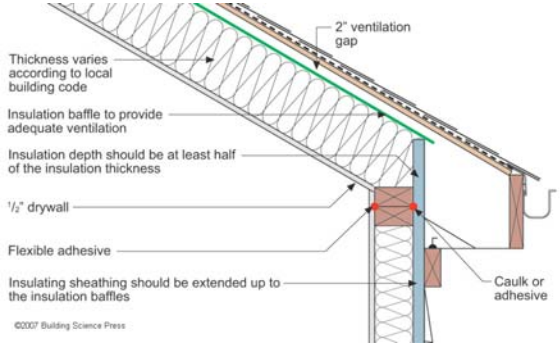
Roof Assemblies



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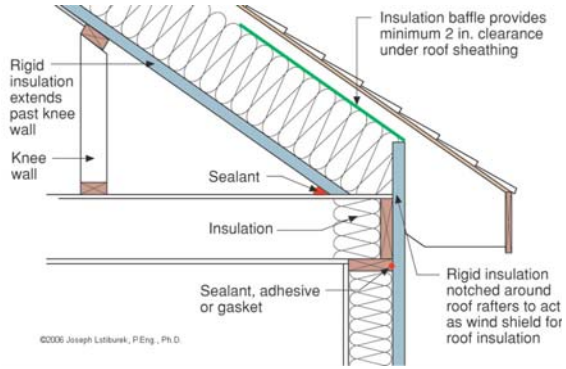
Roof Assemblies



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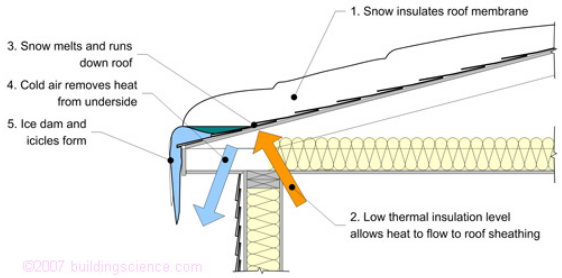
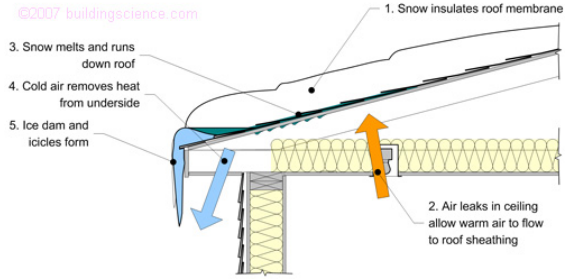
Roof Assemblies

Ice Damming



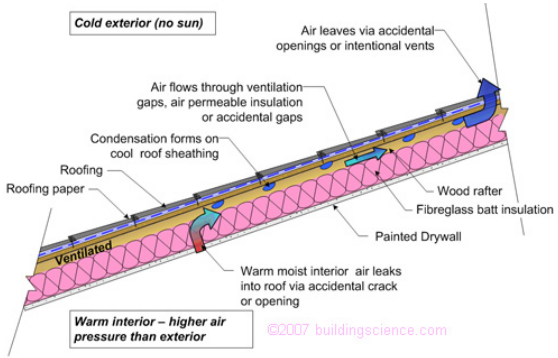
Ice Damming



Ice Damming

Ice Damming

Condensation



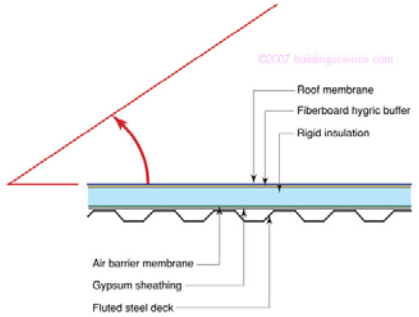
Condensation

Unvented Roof

- Why use a hot roof?
  - Mechanical in the attic
  - Complicated ceiling geometry make air sealing difficult
  - Control ice dams?
- Why not to use a hot roof?
  - Control of ice dams?
  - Reduced shingle life?

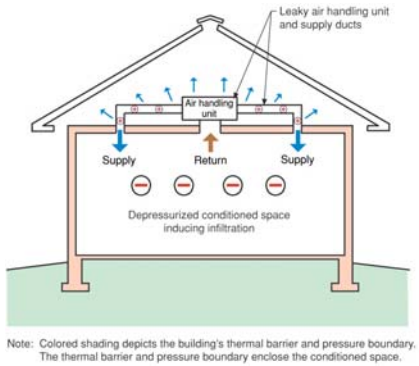
Unvented Roof

- Long history of performance



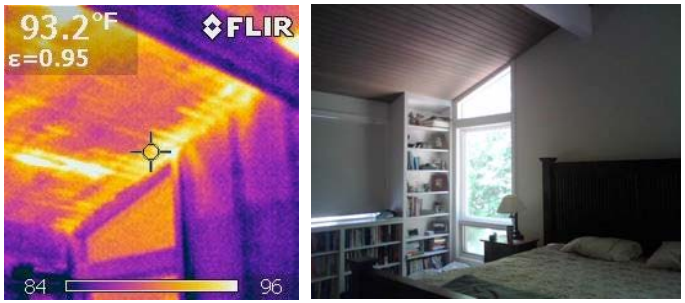
Unvented Roof

Unvented Roof

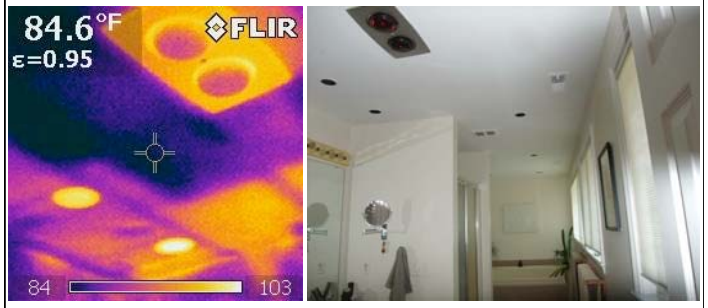


Note: Colored shading depicts the building's thermal barrier and pressure boundary. The thermal barrier and pressure boundary enclose the conditioned space.

Why an Unvented Roof?



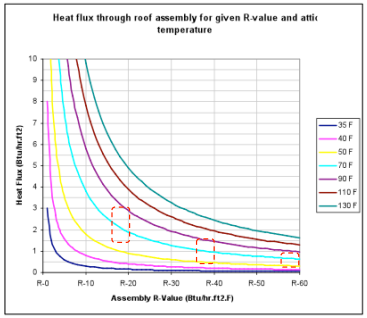
Why an Unvented Roof?



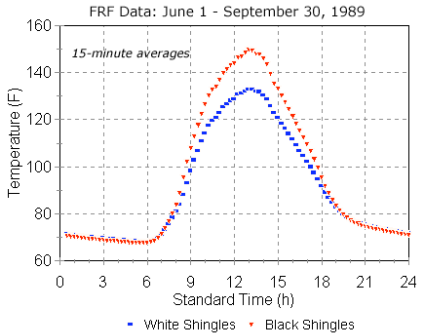
Why an Unvented Roof?

Unvented Roof

- Ice Damming
  - Function of rate of heat loss through thermal insulation – Heat Flux
  - Cannot prevent snow melt – can reduce the rate to the point where ice dams will not form
  - Empirical evidence has demonstrated good success



Shingle Temperature



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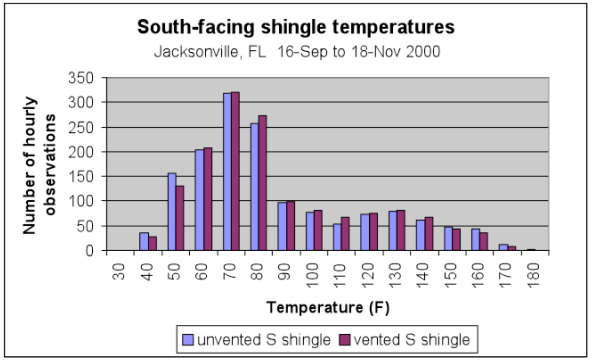
Shingle Temperature



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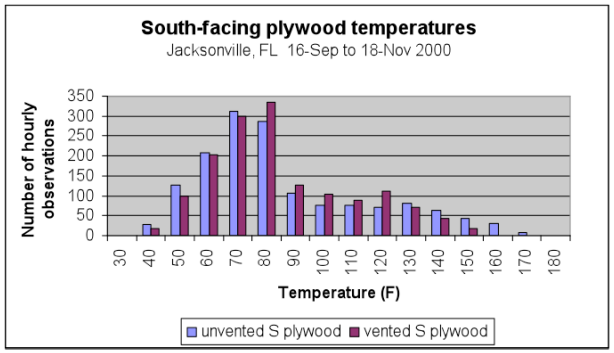
Shingle Temperature



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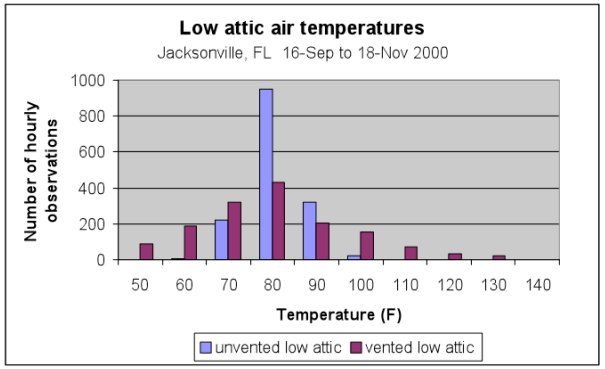
Shingle Temperature



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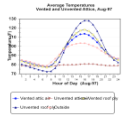


Building Code

Excerpt from 2006 IRC

SECTION R806
ROOF VENTILATION

R806.1 Ventilation required. Enclosed attics and enclosed rafter spaces formed where ceilings are applied directly to the underside of roof rafters shall have cross ventilation for each separate space by ventilating openings protected against the entrance of rain or snow. Ventilating openings shall be provided with corrosion-resistant wire mesh, with $^1/_8$ inch (3.2 mm) minimum to $^1/_4$ inch (6 mm) maximum openings.

R806.2 Minimum area. The total net free ventilating area shall not be less than $^1/_{150}$ of the area of the space ventilated except that reduction of the total area to $^1/_{300}$ is permitted, provided that at least 50 percent and not more than 80 percent of the required ventilating area is provided by ventilators located in the upper portion of the space to be ventilated at least 3 feet (914 mm) above the eave or cornice vents with the balance of the required ventilation provided by eave or cornice vents. As an alternative, the net free cross-ventilation area may be reduced to $^1/_{300}$ when a vapor barrier having a transmission rate not exceeding 1 perm (5.7×10^{-11} kg/s · m² · Pa) is installed on the warm-in-winter side of the ceiling.

Building Code

Excerpt from 2006 IRC

R806.4 Conditioned attic assemblies. Unvented conditioned attic assemblies (spaces between the ceiling joists of the top story and the roof rafters) are permitted under the following conditions:

1. No interior vapor retarders are installed on the ceiling side (attic floor) of the unvented attic assembly.
2. An air-impermeable insulation is applied in direct contact to the underside/interior of the structural roof deck. "Air-impermeable" shall be defined by ASTM E 283.

   Exception: In Zones 2B and 3B, insulation is not required to be air impermeable.

Building Code

Excerpt from 2006 IRC

4. In Zones 3 through 8 as defined in Section N1101.2, sufficient insulation is installed to maintain the monthly average temperature of the condensing surface above 45°F (7°C). The condensing surface is defined as either the structural roof deck or the interior surface of an air-impermeable insulation applied in direct contact with the underside/interior of the structural roof deck. "Air-impermeable" is quantitatively defined by ASTM E 283. For calculation purposes, an interior temperature of 68°F (20°C) is assumed. The exterior temperature is assumed to be the monthly average outside temperature.

Building Code

Excerpt from 2007 IRC Supplement

R806.4 Unvented attic assemblies. Unvented attic assemblies (spaces between the ceiling joists of the top story and the roof rafters) shall be permitted if all the following conditions are met:

1. The unvented attic space is completely contained within the building thermal envelope.
2. No interior vapor retarders are installed on the ceiling side (attic floor) of the unvented attic assembly.
3. Where wood shingles or shakes are used, a minimum ¼ inch (6 mm) vented air space separates the shingles, or shakes and the roofing underlayment above the structural sheathing.
4. In climate zones 5, 6, 7 and 8, any air-impermeable insulation shall be a vapor retarder, or shall have a vapor retarder coating or covering in direct contact with the underside of the insulation.
5. Either items a, b or c shall be met, depending on the air permeability of the insulation directly under the structural roof sheathing.
   a. Air-impermeable insulation only. Insulation shall be applied in direct contact to the underside of the structural roof sheathing.
   b. Air-permeable insulation only. In addition to the air-permeable installed directly below the structural sheathing, rigid board or sheet insulation shall be installed directly above the structural roof sheathing as specified in Table R806.4 for condensation control.
   c. Air-impermeable and air-permeable insulation. The air-impermeable insulation shall be applied in direct contact to the underside of the structural roof sheathing as specified in Table R806.4 for condensation control. The air-permeable insulation shall be installed directly under the air-impermeable insulation.

TABLE R806.4
INSULATION FOR CONDENSATION CONTROL

CLIMATE ZONE	MINIMUM RIGID BOARD OR AIR-IMPERMEABLE INSULATION *R*-VALUE [a]
2B and 3B tile roof only	0 (none required)
1, 2A, 2B, 3A, 3B, 3C	R-5
4C	R-10
4A, 4B	R-15
5	R-20
6	R-25
7	R-30
8	R-35

a. Contributes to but does not supersede Chapter 11 energy requirements.

Building Code

Excerpt from 7th Edition Mass Code for 1 and 2-family dwellings

SECTION 5806
ROOF VENTILATION

5806.1 Ventilation required. Enclosed attics and enclosed rafter spaces formed where ceilings are applied directly to the underside of roof rafters shall have cross ventilation for each separate space by ventilating openings protected against the entrance of rain or snow. Ventilating openings shall be provided with corrosion-resistant wire mesh, with $^1/_8$ inch (3.2 mm) minimum to $^1/_4$ inch (6.4 mm) maximum openings.

Exceptions:

1. *Roof assemblies where an expanding spray foam insulation material, providing at least 40 percent of the total R-value of the required insulation, is in direct contact with the underside of the roof deck and adjacent framing members. If the permeability of the foam material is less than 2 perm-inch, no vapor barrier is necessary.*
2. *Roof assemblies where a board foam plastic insulation material, providing at least 40 percent of the total R-value of the required insulation, is placed on top of the roof deck. If the permeability of the foam material is less than 2 perm-inch, no vapor barrier is necessary.*

Building Code

Excerpt from 2006 IRC

R314.5.3 Attics. The thermal barrier specified in Section 314.4 is not required where attic access is required by Section R807.1 and where the space is entered only for service of utilities and when the foam plastic insulation is protected against ignition using one of the following ignition barrier materials:

1. 1.5-inch-thick (38 mm) mineral fiber insulation;
2. 0.25-inch-thick (6.4 mm) wood structural panels;
3. 0.375-inch (9.5 mm) particleboard;
4. 0.25-inch (6.4 mm) hardboard;
5. 0.375-inch (9.5 mm) gypsum board; or
6. Corrosion-resistant steel having a base metal thickness of 0.016 inch (0.406 mm).

The above ignition barrier is not required where the foam plastic insulation has been tested in accordance with Section R314.6.

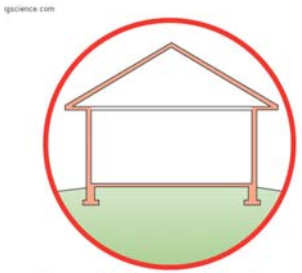
Building Code

Excerpt from 2006 IRC

R314.6 Specific approval. Foam plastic not meeting the requirements of Sections R314.3 through R314.5 shall be specifically approved on the basis of one of the following approved tests: NFPA 286 with the acceptance criteria of Section R315.4, FM4880, UL 1040 or UL 1715, or fire tests related to actual end-use configurations. The specific approval shall be based on the actual end use configuration and shall be performed on the finished foam plastic assembly in the maximum thickness intended for use. Assemblies tested shall include seams, joints and other typical details used in the installation of the assembly and shall be tested in the manner intended for use.

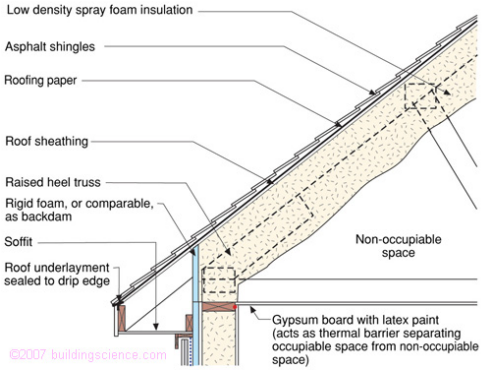
Roof Assemblies

- Insulation at the roof plane
- Thickness is not a function of the rafter depth
- Material type may have other requirements for ignition, thermal barrier, or vapor control



Un-vented attic; mechanical equipment can be located inside the conditioned attic.

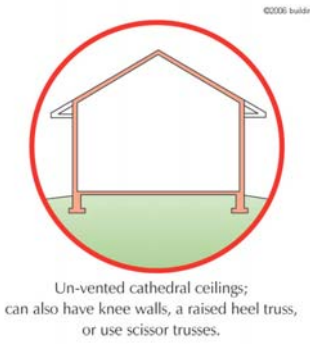
Roof Assemblies



Roof Assemblies

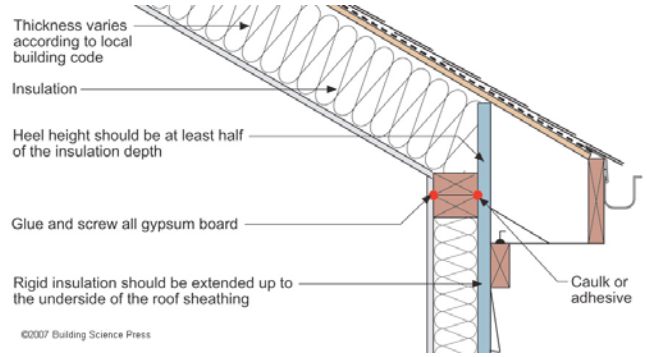
Roof Assemblies

- Insulation at the plane of the roof deck
- Interior insulation thickness limited by rafter depth – though possible for additional insulation to be added to the interior of the framing
- Exterior insulation is possible



Un-vented cathedral ceilings; can also have knee walls, a raised heel truss, or use scissor trusses.

Roof Assemblies



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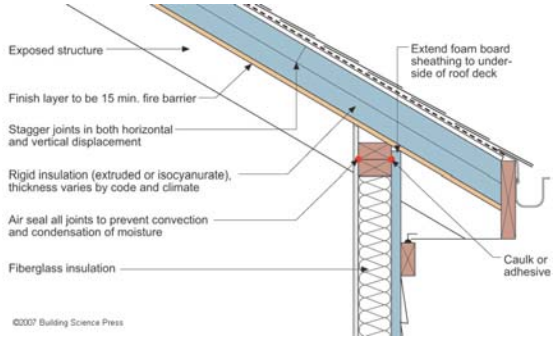
Roof Assemblies



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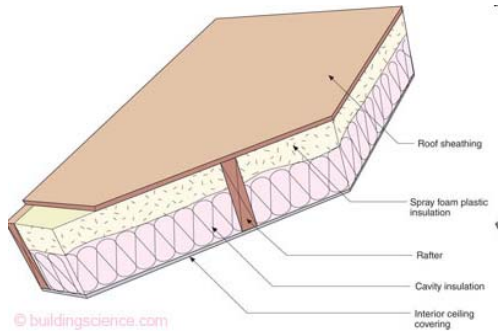
Roof Assemblies



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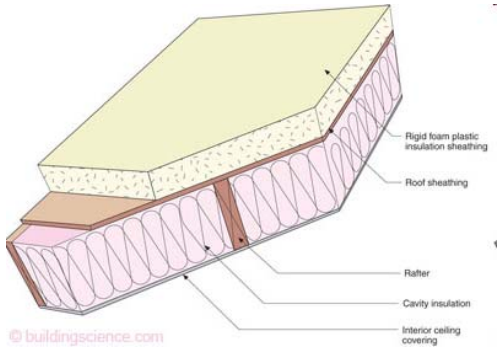
Roof Assemblies



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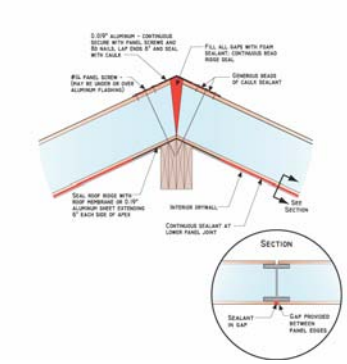
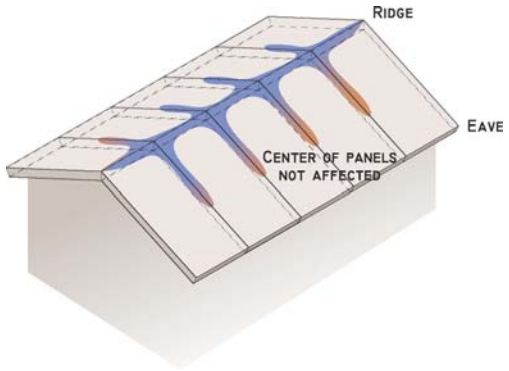
SIP Roofs

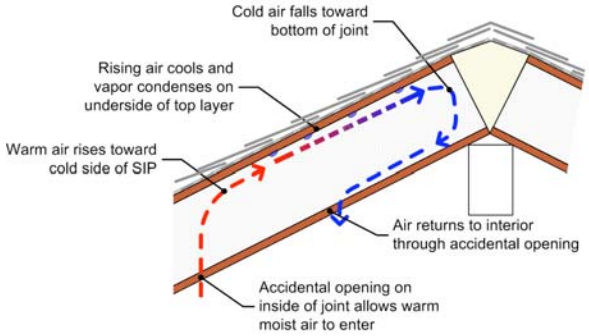


SIP Roofs

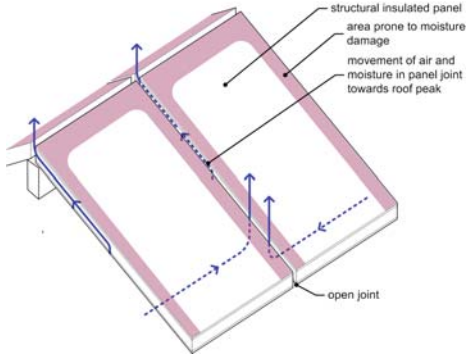


SIP Roofs

SIP Roofs



SIP Roofs



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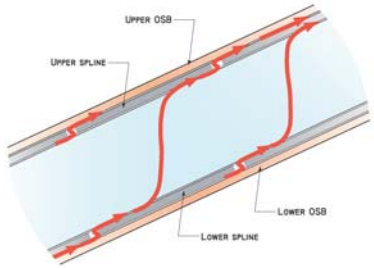
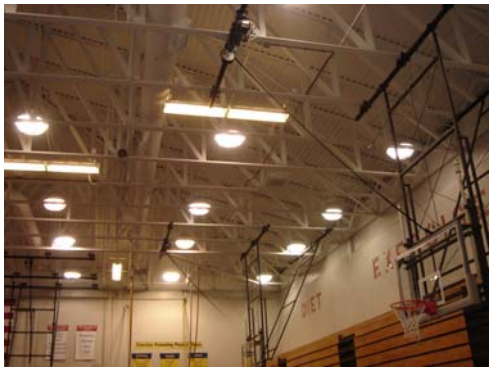


SIP Roofs



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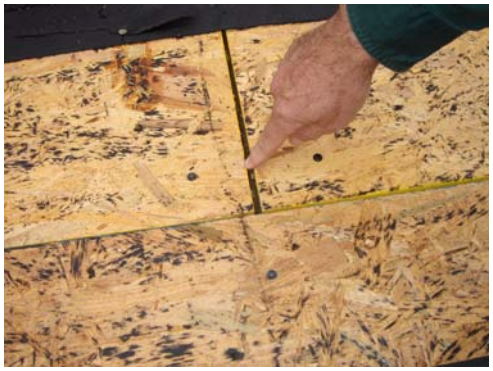
Building Science Corporation REPA October 12, 2010 163



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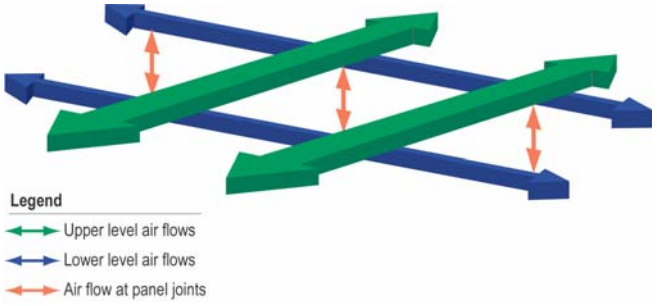

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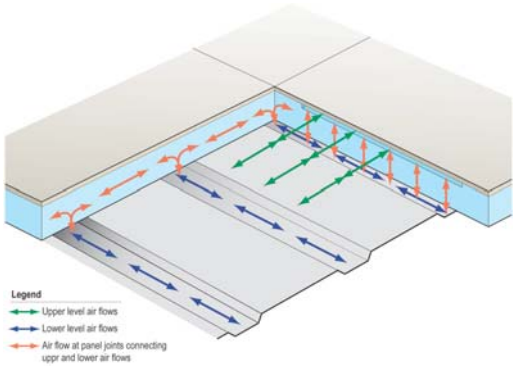

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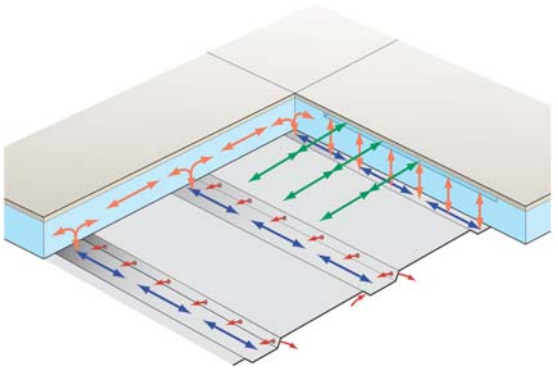

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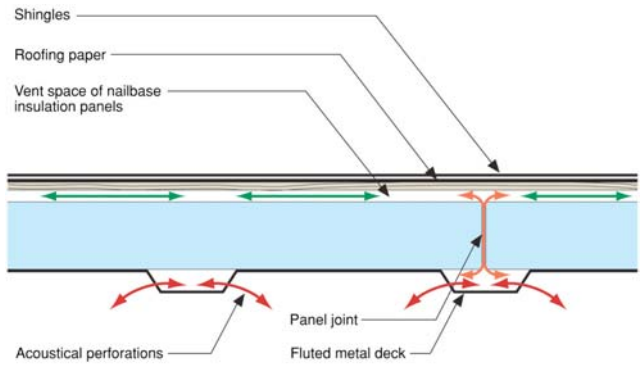

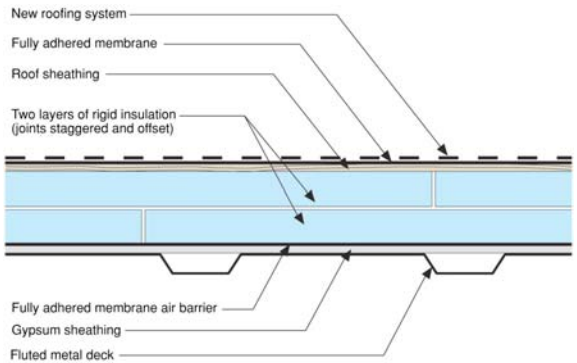

Questions?

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