Dr John Straube, P.Eng.
Principal, Building Science Corporation
Associate Professor, University of Waterloo

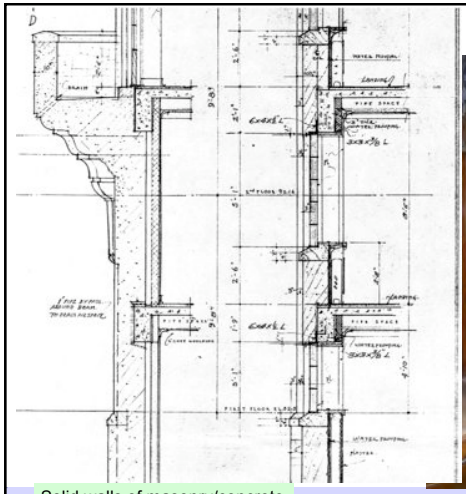
Healthy, Durable, Energy Efficient More Sustainable Buildings:

Big Changes and Future Trends

www.BuildingScience.com

Solid masonry

Building Science.com



Wet Applied Plaster

Solid walls of masonry/concrete

3

Old Growth Timber

Building Science.com 4

This is what wood framing should look like

Pre-WWII Buildings

- Masonry and old-growth solid timber structures
- Plaster is the dominant interior finish
- No added insulation (or very little)
- No vapor barriers
- Heating systems only, some natural ventilation
- No air conditioning
- Few explicit air-tightening details
- Few ducts, pipes, wires, controls, gas, cables,etc

Building Science.com 11

Five Fundamental Changes

1. Increasing Thermal Resistance
2. Changing Permeance of Enclosure Linings
3. Water/Mold Sensitivity of Materials
4. Moisture Storage Capacity
5. 3-D Airflow Networks

Building Science.com 12

1. Thermal

- Old buildings used energy leakage to dry materials and assemblies
- Increased airtightness
  - Reduces drying, interior RH increases
- Increased insulation = less drying
  - Colder exterior, colder interior
  - Wider swings
- White roofs, efficient lights, etc

Building Science.com 13

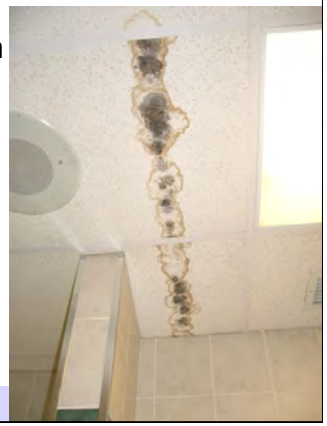
2. Vapor Permeability

- Low vapor permeance exterior layers
  - Metal panels, precast concrete
  - OSB and foam vs skip wood sheathing
- Low vapor permeance interior layers
  - Polyethylene,
  - vinyl wall paper
  - Vinyl sheet flooring

Building Science.com

3. Water/Mold Sensitivity

- Moisture= mold growth
- Wood products
  - New growth vs old
  - Processing: plywood, OSB, particle board
  - Paper, Veneers
- Finishes
  - Drywall, ceiling tile



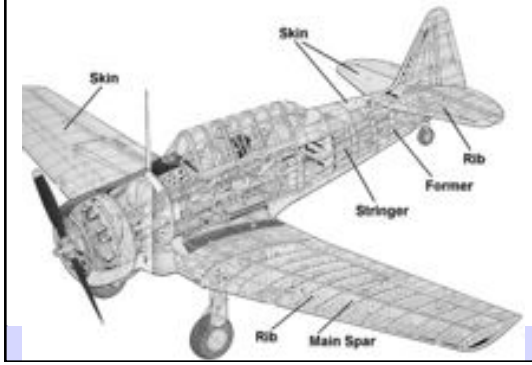
Building Science.com

4. Moisture Storage Capacity

- Old
  - Concrete block / terra cotta
  - Rough cut wood / skip sheathing
- New
  - Steel stud lined with gypsum board
- Orders of magnitude change in moisture storage capacity!
- But, future is likely more hollow/lightweight

Building Science.com 16

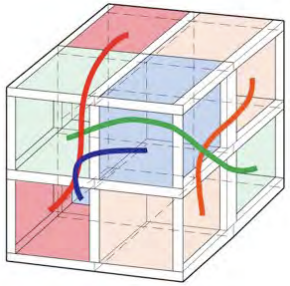
Lightweight hollow structures are environmentally preferred (lower resource use) if the material has low embodied energy and pollution



17

5. Three-D Airflow Networks

- Hollow enclosure
- Airflow+complexity



Hollow Buildings

Interconnected interstitial voids

19

Five Fundamental Changes

1. Increasing Thermal Resistance
2. Changing Permeance of Enclosure Linings
3. Water/Mold Sensitivity of Materials
4. Moisture Storage Capacity
5. Hollow, Airflow connected light structures

Building Science.com 20

Addressing these changes

- Enhance design for durability
  - . . . and we need more insulation & airtightness
- Need better moisture control
  - rain, airtight, construction moisture control
- Allow drying of moisture
  - Use vapor barriers with care, consider ventilation
- Materials and systems must work better together

Building Science.com 21

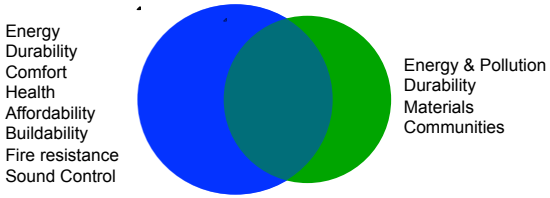
Building Science vs Tradition

- Can no longer "learn by trying"
  - Too slow
  - Failures of thousands of buildings = $$
- Need to understand what we are doing from *first* principles
  - Design for predictable performance
- This is Building Science
  - Physics + construction technology + experience

Building Science.com 22

Building Science=Green Buildings

- Building Science?
  - The science of making buildings that work
- Green Buildings?
  - Buildings that reduce environmental damage



- Less impact for same function = **efficient**

23/175

Building Science.com 24

Buildings & the Environment

- Largest single global industry
- Hence, buildings consume resources
  - Lots of materials
  - Lots of energy
  - Lots of money
  - Pollute, displace, and destroy habitats
- Last a long time: A “durable good”
  - Running shoe (1 yr), car (10 yr), bldg (100yr?)
- Hence - more careful long-term design
  - i.e. societal involvement is justified

Green Buildings

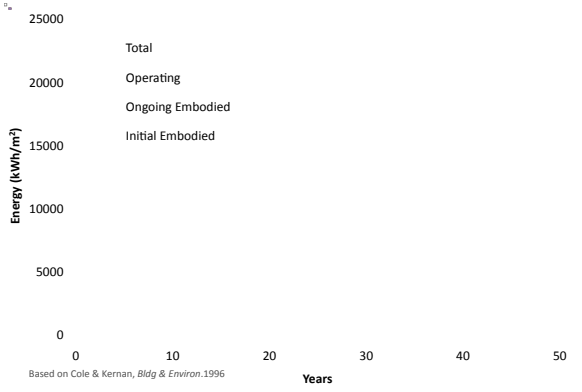
- Impact the environment less in construction, operation, end of life

Damage Components

- Resource Extraction
  - Cutting trees, mining, drilling oil, etc.
- Processing
  - Refining, melting, etc. Pollutants and energy
- Transportation
  - Mass and Mode (ship/truck) and Mileage
- Construction
  - Energy, worker transport
- Operational Energy

The Majority of Impact

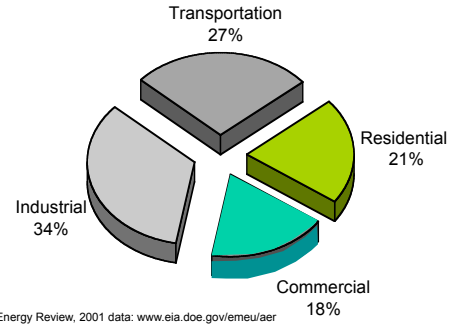
Office Building Example



Based on Cole & Kernan, *Bldg & Environ*.1996

Building Energy Use

Primary Energy Consumption by Sector, 2001

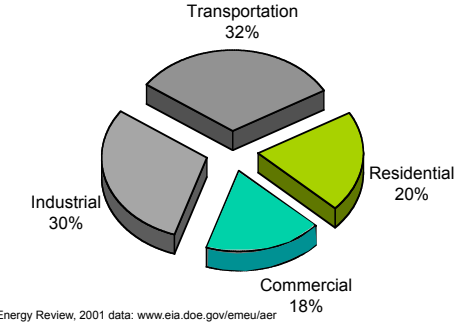


Source: EIA, Annual Energy Review, 2001 data: www.eia.doe.gov/emeu/aer

www.BuildingScience.com Buildings,Energy, Environment No. 29/84

Building Carbon Emissions

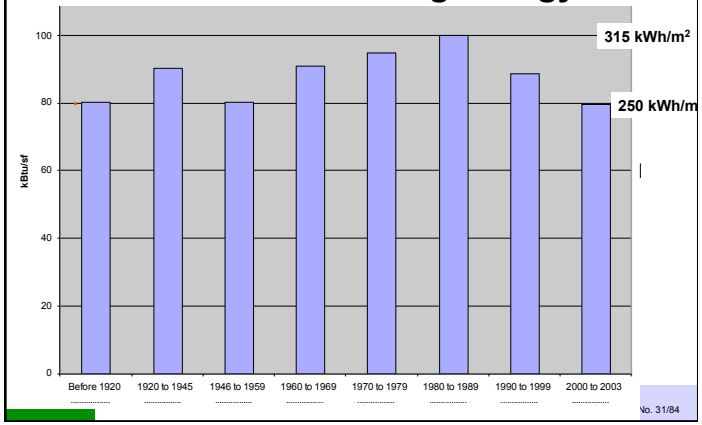
Carbon Dioxide Emissions from Energy Consumption by Sector, 2001



Source: EIA, Annual Energy Review, 2001 data: www.eia.doe.gov/emeu/aer

www.BuildingScience.com Buildings,Energy, Environment No. 30/84

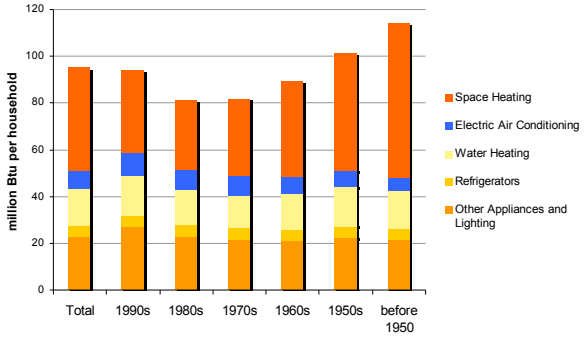
US Commercial Building Energy Use



No. 31/84

How Old and New Houses Use Ene

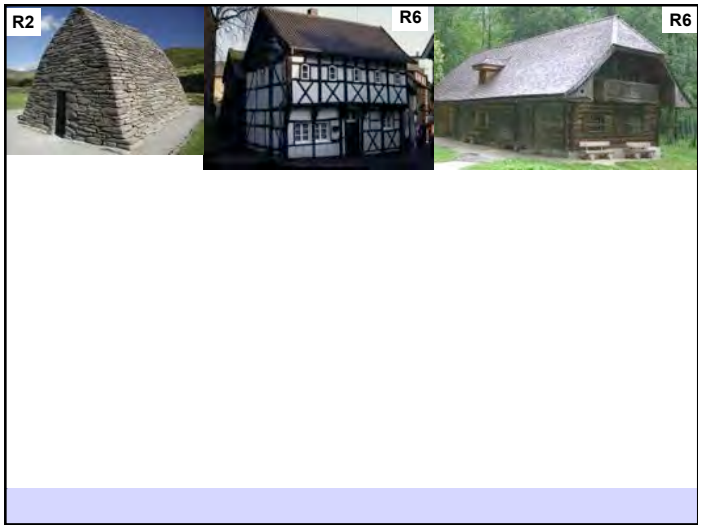
Total Btu Consumption per Household, 2001

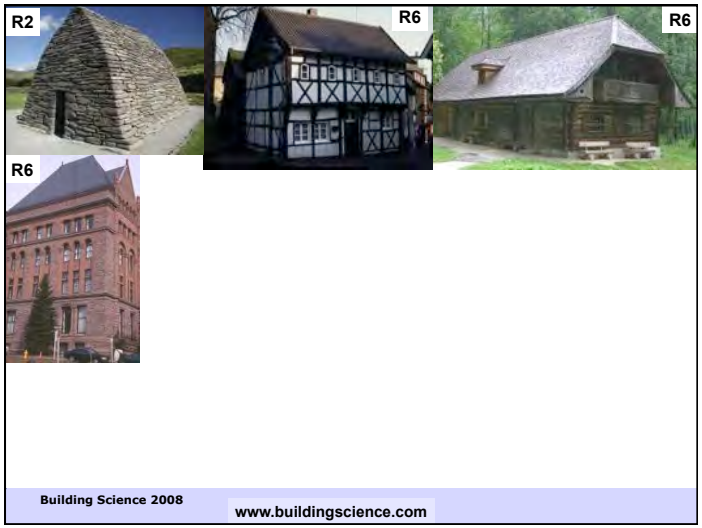


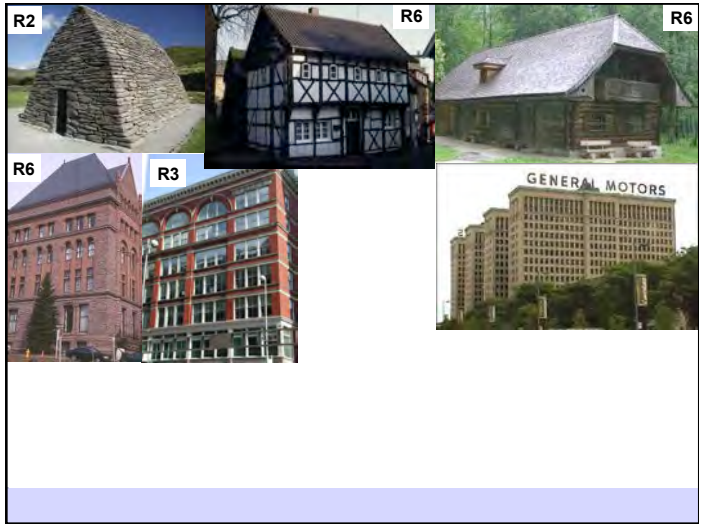
Source: US Census Bureau, Annual Housing Survey: http://www.census.gov/hhes/www/housing/ahs/ahs.html

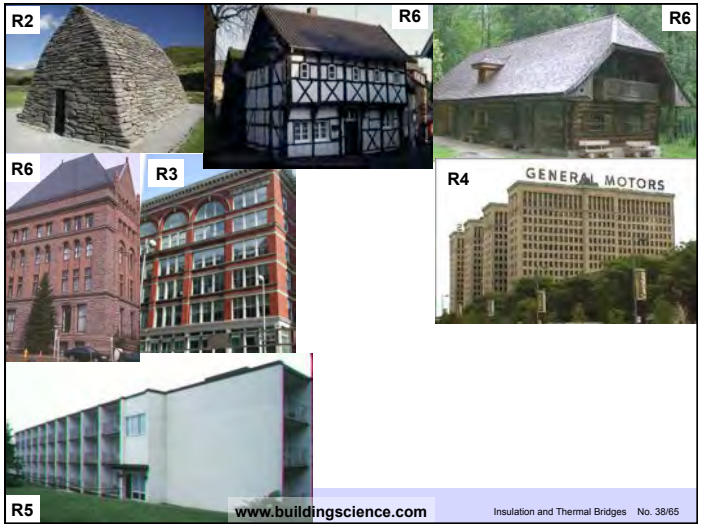

R2
on - History

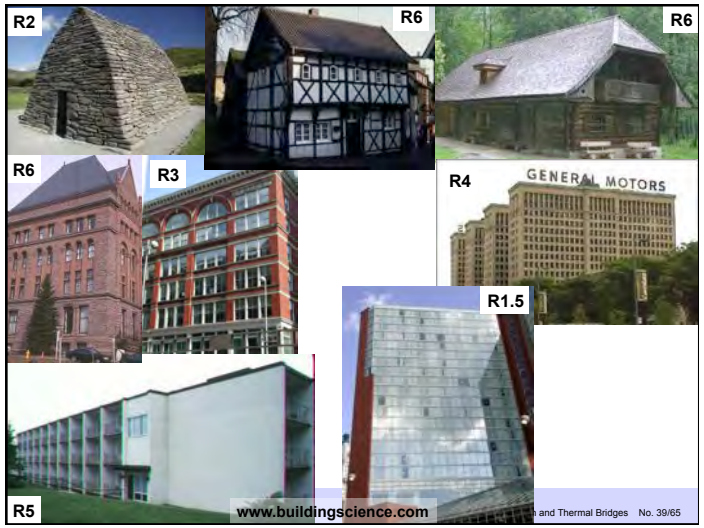

R2
R6

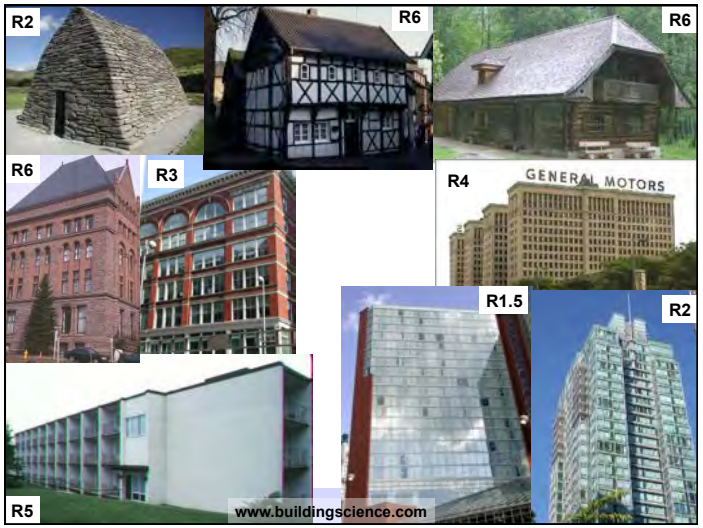

R2
R6
R6


R2
R6
R6
R6
Building Science 2008
www.buildingscience.com


R2
R6
R6
R6
R3
GENERAL MOTORS


R2
R6
R6
R6
R3
R4
GENERAL MOTORS
R5
www.buildingscience.com
Insulation and Thermal Bridges No. 38/65


R2
R6
R6
R6
R3
R4
GENERAL MOTORS
R1.5
R5
www.buildingscience.com
and Thermal Bridges No. 39/65


R2
R6
R6
R6
R3
R4
GENERAL MOTORS
R1.5
R2
R5
www.buildingscience.com

Fixing this mess

- More Insulation
- Better Airtightness
- Better Glazing of the right quantity
- Simple HVAC, Simple Controls

Building Science.com 41

Energy Efficiency & Durability

- Better insulation means
  - – Colder exterior and/or interior surface
  - – Colder surfaces mean
    - = more likely condensation
    - = higher RH = higher moisture content
  - – More extreme variations at exterior
- Therefore more insulation reduces durability!
- Air leakage dried as well as wets
  - – Airtightness increases indoor humidity

www.BuildingScience.com Buildings,Energy, Environment No. 42/84

The Rules

Heat Flow Is From Warm To Cold

Moisture Flow Is From Warm To Cold

Moisture Flow Is From More To Less

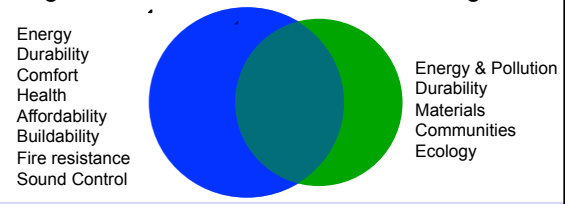
Air Flow Is From A Higher Pressure To A Lower Pressure

Gravity Always Acts Down

Building Science Corporation 43

Building Science=Green Buildings

- Building Science?
  - – The science of making buildings that work
- Green Buildings?
  - – Buildings that reduce environmental damage



- Less impact for same function = **efficient**

44/175

Fundamental Goals

Safe

Healthy

Comfortable

Durable

Affordable

Environmentally Responsible

Building Science.com 45

The Rules

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 Always Acts Down

Building Science Corporation 46

Joseph Lstiburek, Ph.D., P.Eng
John Straube, Ph.D., P.Eng

Building Science

Environmental Separation

presented by www.buildingscience.com

Building Functions

- Much more more than shelter
- Function of a building:

"Provide the desired environment for human use and occupancy"

"Durability, Convenience, and Beauty"
Vitruvius, 70 BC

Building Science.com Enclosures No. 48 /

Building Components

- Buildings are made of several large systems
- Can be grouped in four categories
  - Superstructure
  - Service Systems
  - Fabric
  - Enclosure

Building Science.com Enclosures No. 49 /

The Enclosure: An Environmental Separator

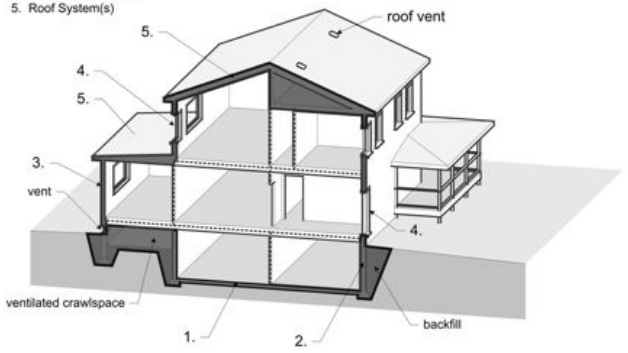
- The part of the building that physically ***separates*** the ***interior*** and ***exterior*** environments.
- Includes all of the parts that make up the wall, window, roof, floor, etc… from the innermost to the outermost layer.
- Sometimes, interior partition also are environmental separators (pools, rinks, etc.)

Building Science.com Enclosures No. 50 /

Building Enclosure Components:

1. Basement Floor System(s)
2. Foundation Wall System(s)
3. Above Grade Wall System(s)
4. Windows and Doors
5. Roof System(s)

Where is inside?
Where is outside?



Building Science 2008 Enclosures No. 51 /

Climate Site

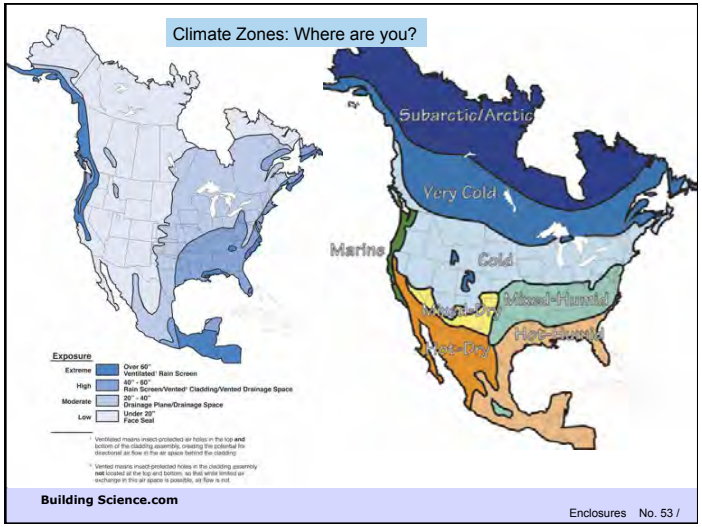
- Design for
  - Climate zone
  - Site
  - Building height, shape, complexity

Seattle ≠ Sacramento
Miami ≠ Minneapolis
Edmonton ≠ Toronto

Marcus Vitruvius Pollio

These are properly designed, when due regard is had to the country and climate in which they are erected. For the method of building which is suited to Egypt would be very improper in Spain, and that in use in Pontus would be absurd at Rome: so in other parts of the world **a style suitable to one climate, would be very unsuitable to another**: for one part of the world is under the sun's course, another is distant from it, and another, between the two, is temperate.

Building Science .com Enclosures No. 52 /



Building Science.com Enclosures No. 53 /

Climate Load Modification

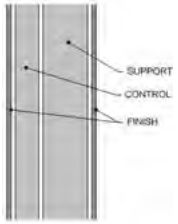
- Building & Site (overhangs, trees…)
  - Creates microclimate
- Building Enclosure (walls, windows, roof…)
  - Separates climates
  - Passive modification
- Building Environmental Systems (HVAC…)
  - Use energy to change climate
  - Active modification

Building Science 2008 Enclosures No. 54 /

Basic Functions of the Enclosure

- 1. Support
  - Resist and transfer physical forces from inside and out
- 2. Control
  - Control mass and energy flows
- 3. Finish
  - Interior and exterior surfaces for people
- Distribution – a building function

Functional Layers

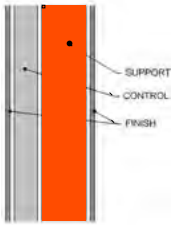


Building Science 2008 Enclosures No. 55 /

Basic Enclosure Functions

- **Support**
  - **Resist & transfer physical forces from inside and out**
    - Lateral (wind, earthquake)
    - Gravity (snow, dead, use)
    - Rheological (shrink, swell)
    - Impact, wear, abrasion
- Control
  - Control mass and energy flows
- Finish
  - Interior and exterior surfaces for people

Functional Layers

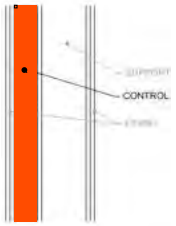


Building Science 2008 Enclosures No. 56 /

Basic Enclosure Functions

- Support
  - Resist & transfer physical forces from inside and out
- **Control**
  - **Control mass and energy flows**
    - **Water/Rain** (and soil moisture)
      - Drainage plane, capillary break, etc.
    - **Air**
      - Continuous air barrier
    - **Heat**
      - Continuous layer of insulation
    - **Vapor**
      - Balance of wetting/drying
- Finish
  - Interior and exterior surfaces for people

Functional Layers

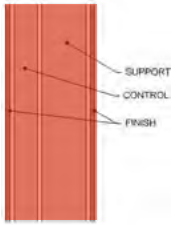


Building Science 2008 Enclosures No. 57 /

Other Control . . .

- Support
- **Control**
  - **Fire**
    - **Penetration**
    - **Propagation**
  - **Sound**
    - **Penetration**
    - **Reflection**
  - **Light**
    - **Diffuse/glare**
    - **View**
- Finish

Functional Layers

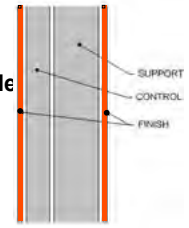


Building Science 2008 Enclosures No. 58 /

Basic Enclosure Functions

- Support
  - Resist & transfer physical forces from inside and out
- Control
  - Control mass and energy flows
- **Finish**
  - **Interior & exterior surfaces for people**
    - Color, speculance
    - Pattern, texture

Functional Layers



Building Science 2008 Enclosures No. 59 /

Distribution

- A *Building* Function imposed on enclosure
- Distribute services or utilities to from through, within, the enclosure, e.g.,
  - Power
  - Communication
  - Water (Potable, sewage, etc.)
  - Gas
  - Conditioned air ◄
  - Cold or hot water ◄

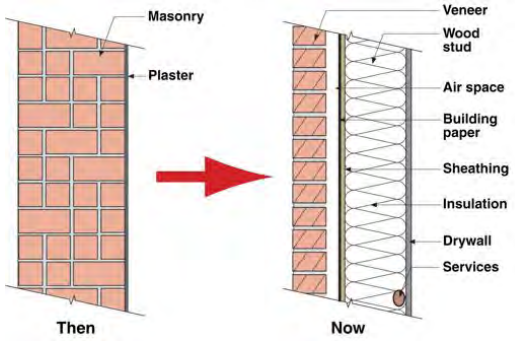
Building Science 2008 Enclosures No. 60 /

History of Control Functions

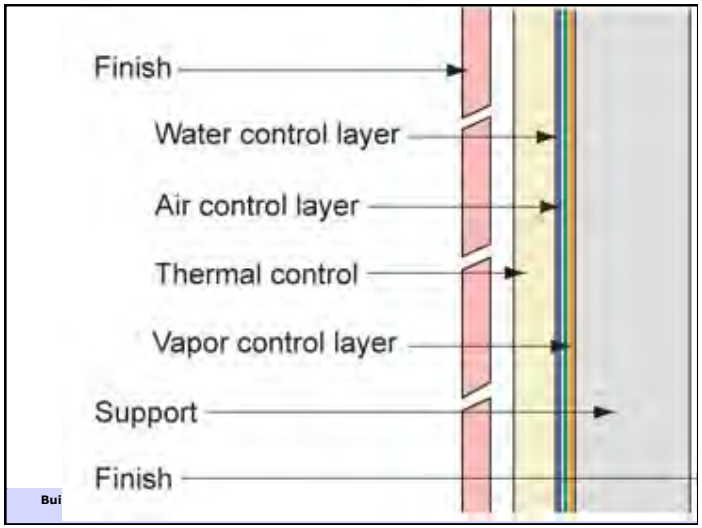
- Older Buildings
  - One layer does everything
- Newer Building
  - Separate layers,
    . . . separate functions

Building Science 2008

Changes

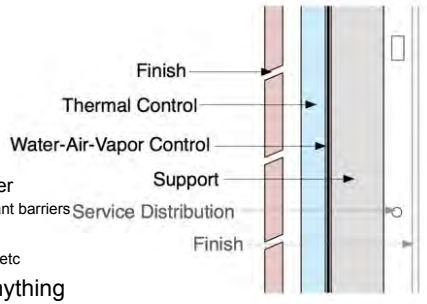


Building Science 2008 Enclosures No. 62 /



The "Perfect Wall"

- Finish of whatever
- Control continuity
  - Rain control layer
    - Perfect barrier
    - Drained with gap
    - Storage
  - Air control layer
  - Thermal control layer
    - Aka insulation, radiant barriers
  - Vapor control layer
    - Retarders, barriers, etc
- Structure can be anything

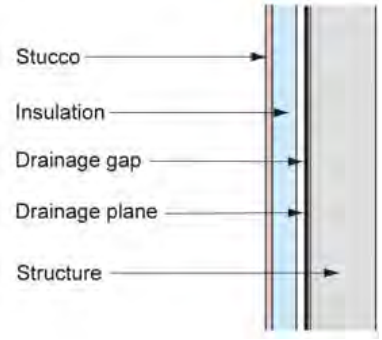


Fire Control may be needed
Sound Control optional

Building Science.com 64

Different Arrangements

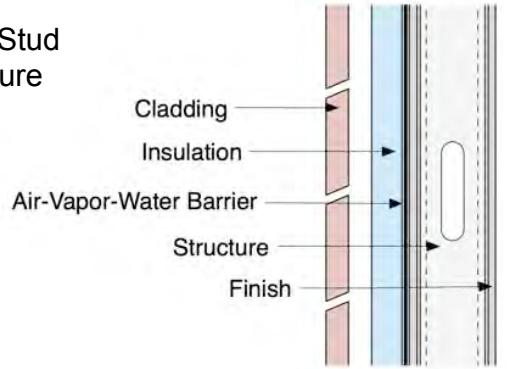
- Almost perfect



Building Science.com 65

Perfect Wall

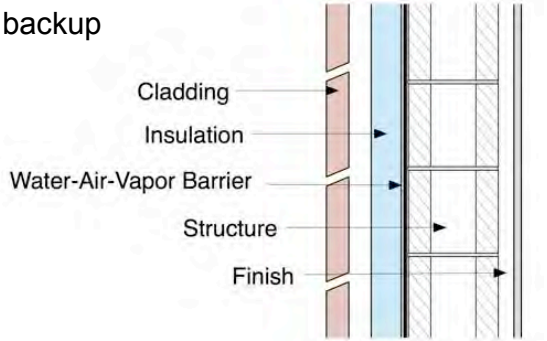
- Steel Stud Structure



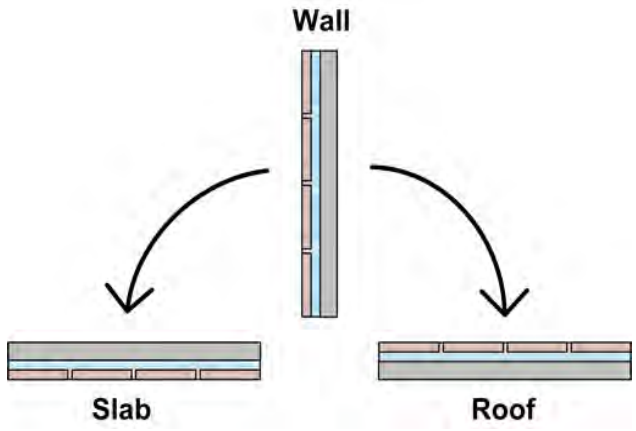
Building Science.com 66

Perfect Wall

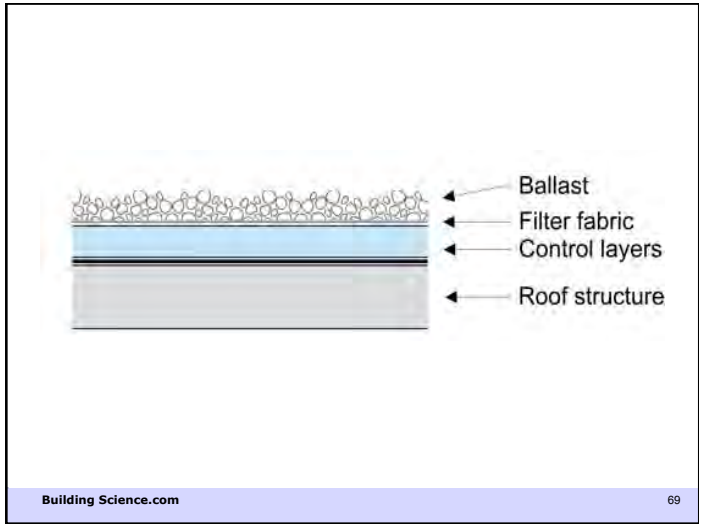
- CMU backup

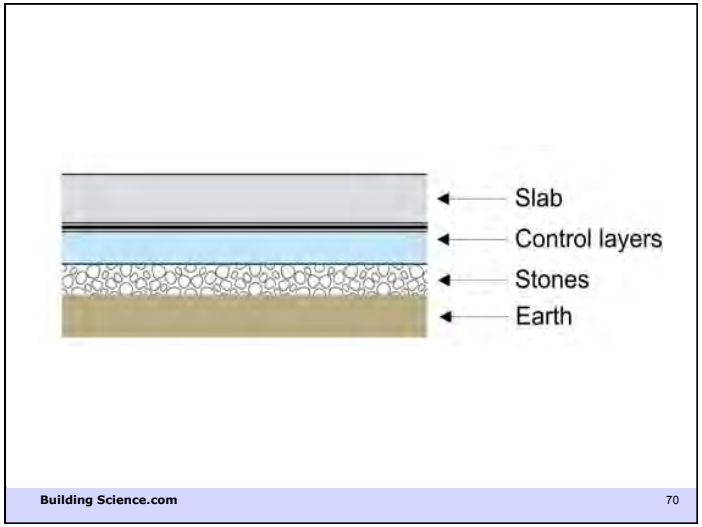


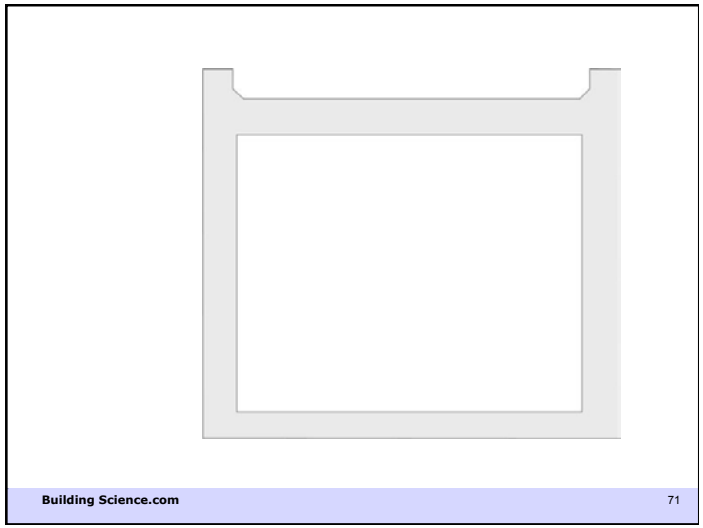
Building Science.com 67

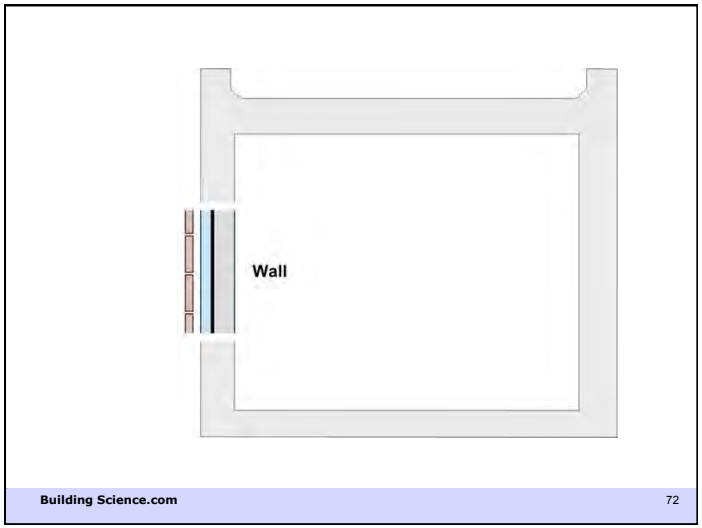


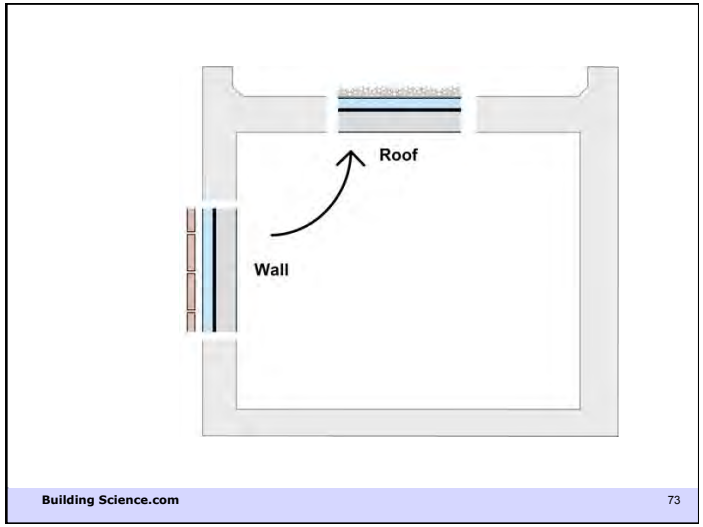
Building Science.com 68

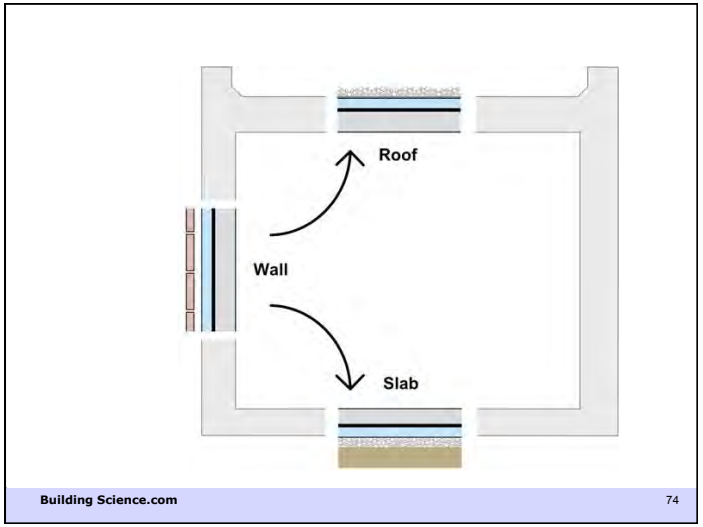

Ballast
Filter fabric
Control layers
Roof structure
Building Science.com
69

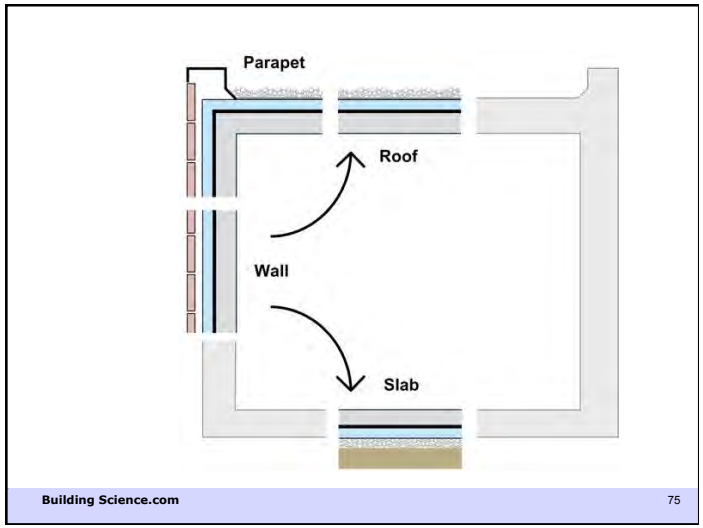

Slab
Control layers
Stones
Earth
Building Science.com
70

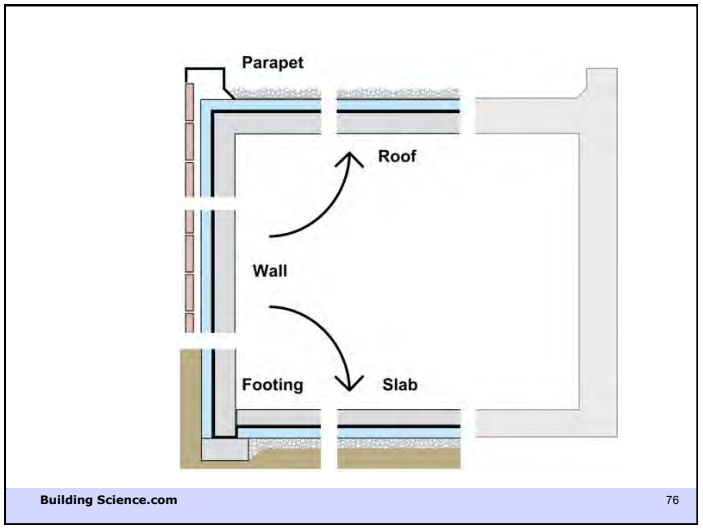

Building Science.com
71

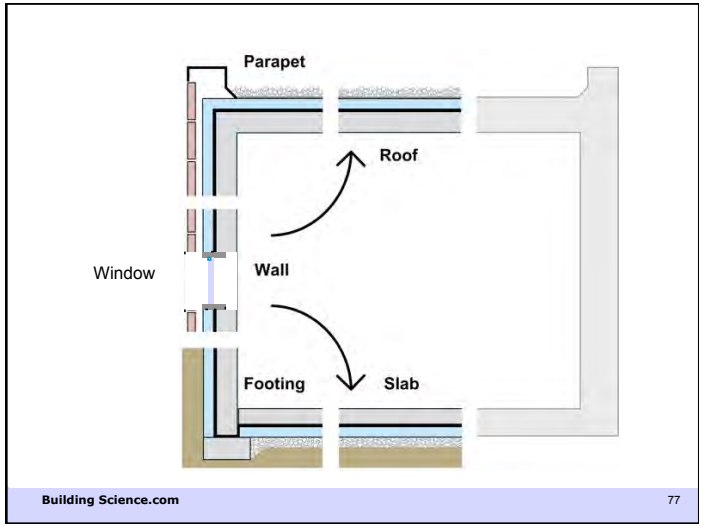

Wall
Building Science.com
72


Roof
Wall
Building Science.com
73

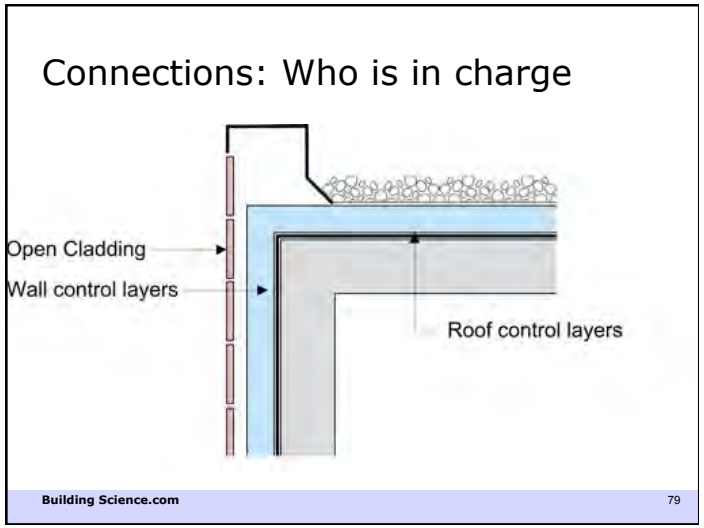

Roof
Wall
Slab
Building Science.com
74

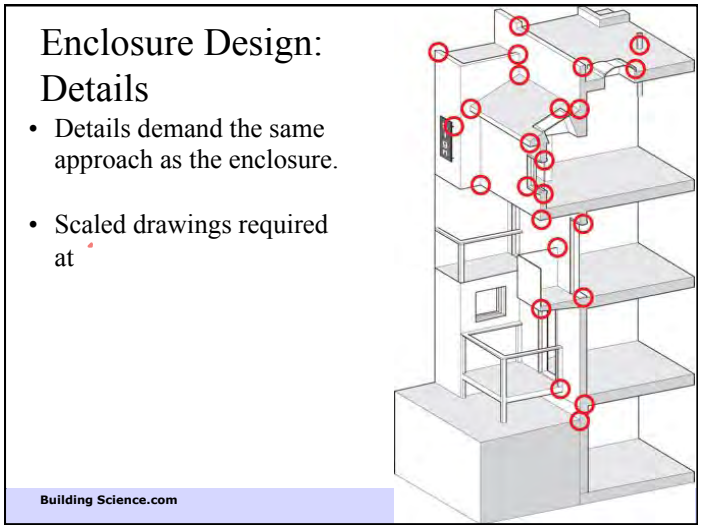

Parapet
Roof
Wall
Slab
Building Science.com
75


Parapet
Roof
Wall
Footing
Slab
Building Science.com
76

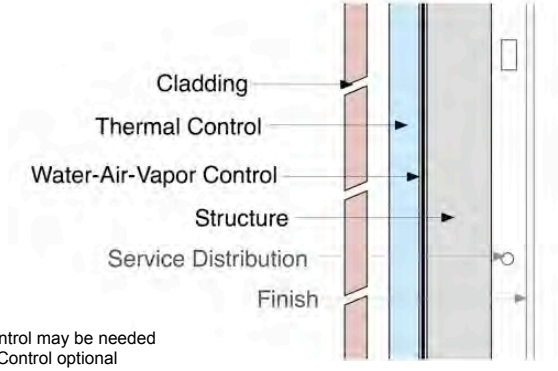

Parapet
Roof
Window
Wall
Footing
Slab
Building Science.com
77


Enclosures No. 78 /


Connections: Who is in charge
Open Cladding
Wall control layers
Roof control layers
Building Science.com
79


Enclosure Design: Details
• Details demand the same approach as the enclosure.
• Scaled drawings required at
Building Science.com

Perfect Wall expanded

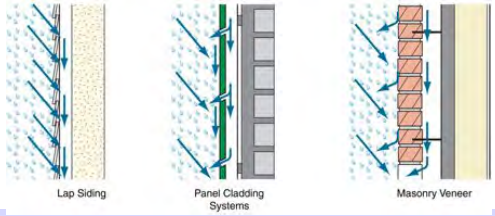


Fire Control may be needed
Sound Control optional

Building Science.com 81

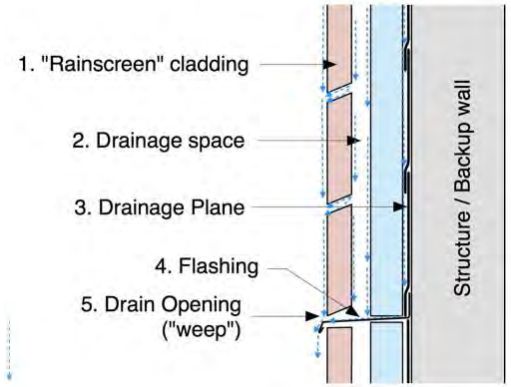
1. Water / Rain Control

- Drained systems preferred
- Account for joints and penetrations as well as installation defects and material failure

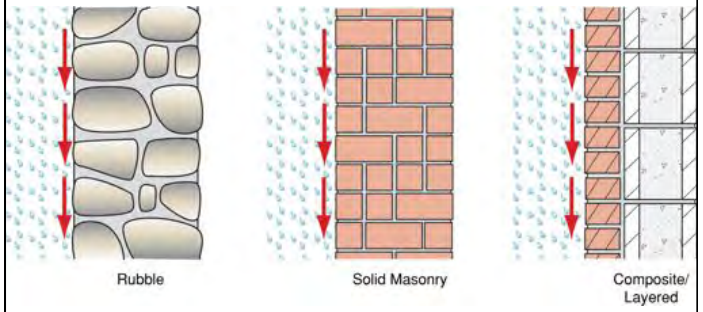


Building Science.com 82

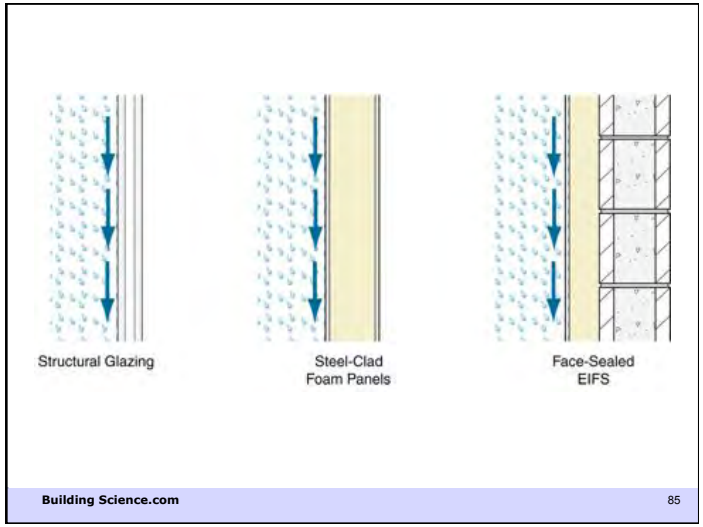
"Rainscreen" or "Drained" System

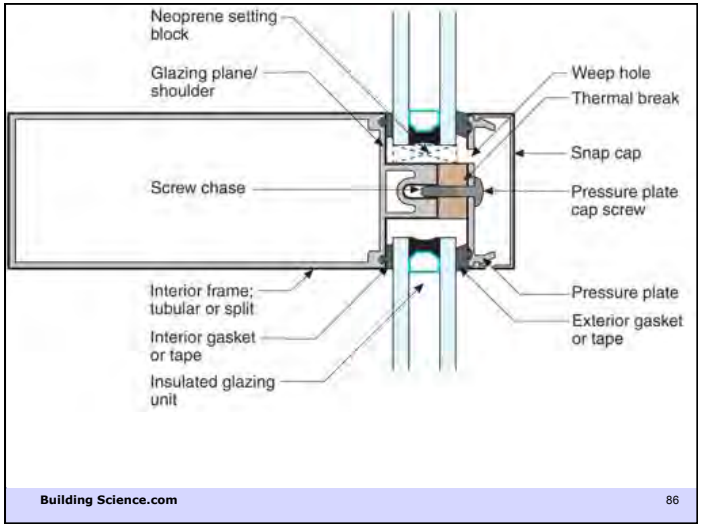


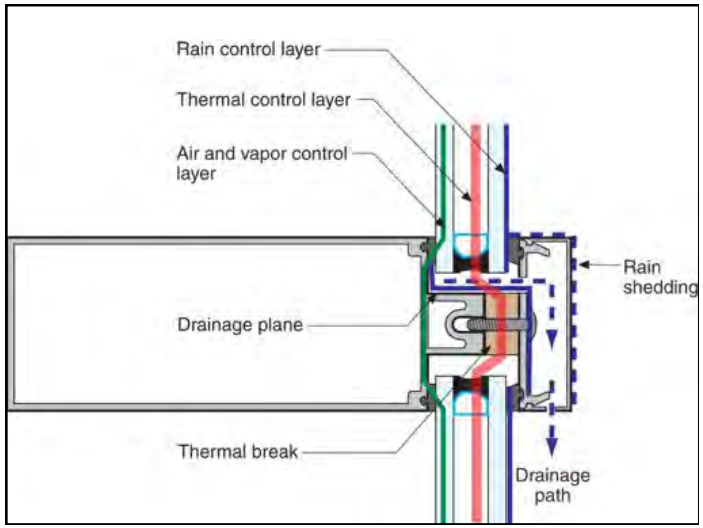
Building Science.com 83



Building Science.com 84







2. Airflow control

- Airtightness critical for all climates
  - Control condensation and energy waste critical in cold climates
- Airflow Control Layer
  - Practically, an air barrier system
- Cant be TOO tight
  - But must provide ventilation

88/175

Airtightness

- Materials not important, *system* is
- GSA and Army Corp requiring testing to tightness targets now
  - 0.40 and 0.25 cfm/sf@75 Pa respectively
- IECC/IRC likely to require soon
  - Measured at 50 Pa in houses

Building Science.com 89

3. Thermal control

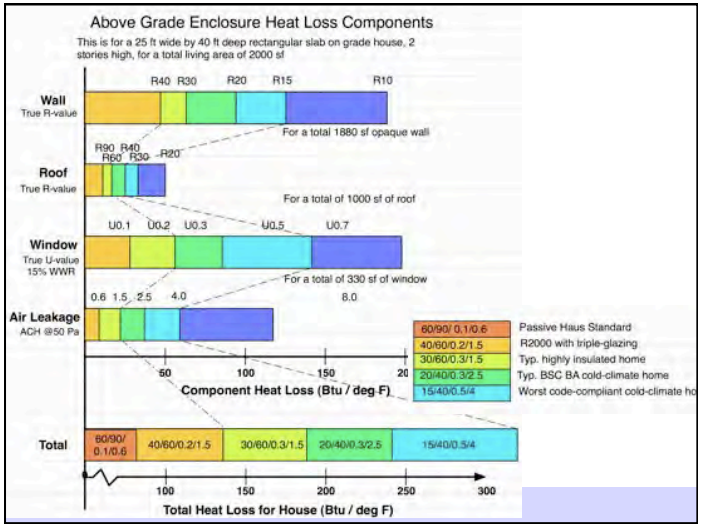
- Resists heat loss/gain = energy savings
  - Large temperature differences: cold and hot climates, roofs (hot)
  - Less important in warm-humid and mixed climates
- Warms surfaces = durability
  - Avoids condensation in hot and cold weather
  - = a durability and health strategy
  - Keep structure warm and dry and stable

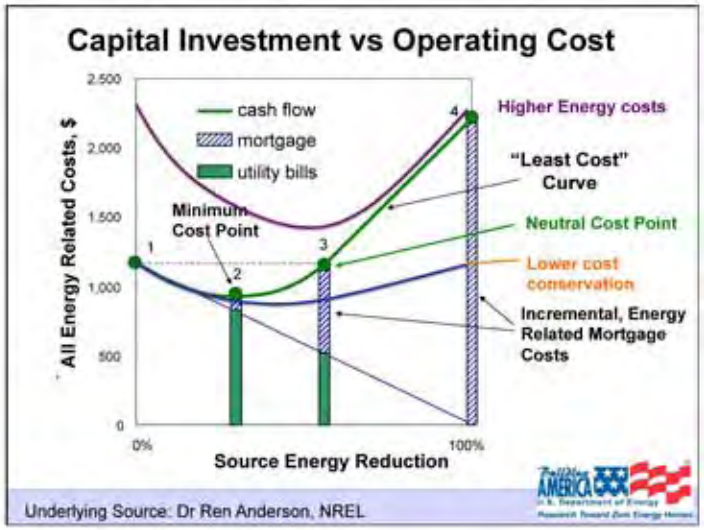
11-07-12

Insulation

- How much? Use much *more than normal practise*
- Comfort & moisture –
  - **True** R5-10 is usually enough, but …..
- For energy / environment
  - As much as practical
- Practical constraints likely the limit
  - How much space available in studs?
  - Fastening, windows: exterior sheathing of 1.5”/4”
- Increased insulation should reduce HVAC capital as well as operating!

Building Science



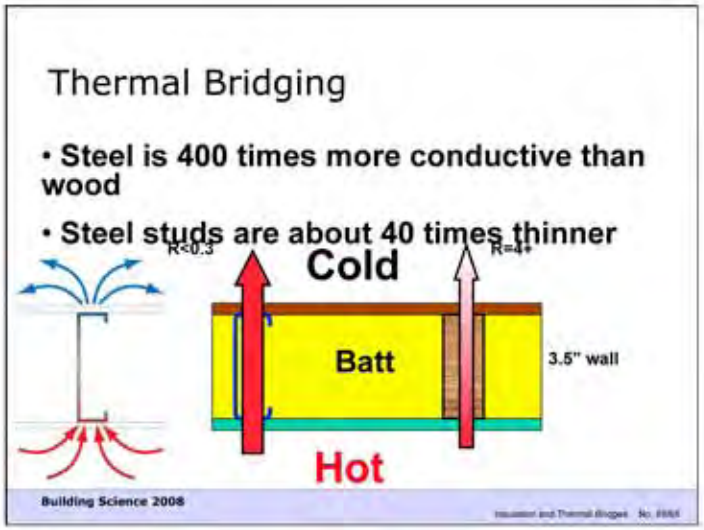

Capital Investment vs Operating Cost
All Energy Related Costs, $
2,500
2,000
1,500
1,000
500
0
cash flow
mortgage
utility bills
Minimum Cost Point
"Least Cost" Curve
Higher Energy costs
Neutral Cost Point
Lower cost conservation
Incremental, Energy Related Mortgage Costs
1
2
3
4
0%
100%
Source Energy Reduction
Underlying Source: Dr Ren Anderson, NREL

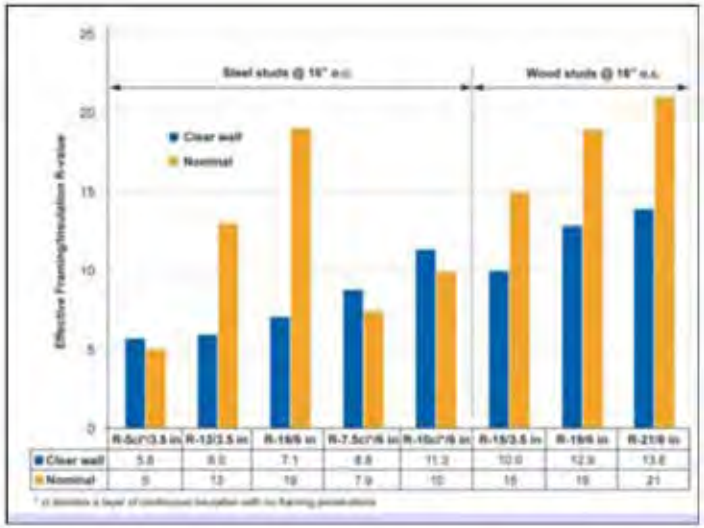

It's More Than Insulation!
• Thermal bridges provide shortcut for heat through insulation
• Heat passes through the structural members
• Common offenders
– Floor and balcony slabs
– Shear walls
– Window frames
– Steel studs
Building Science.com

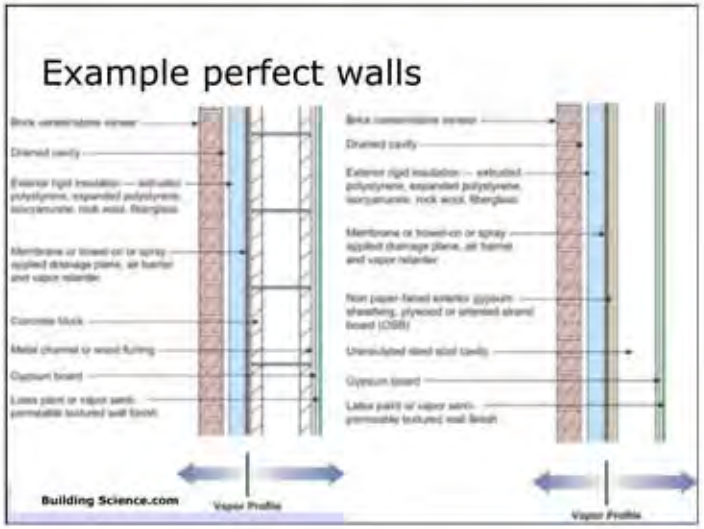

Find the thermal bridge


Find the thermal bridge
Building Science 2008


Building Science 2008
Insulation and Thermal Bridges No. 9705

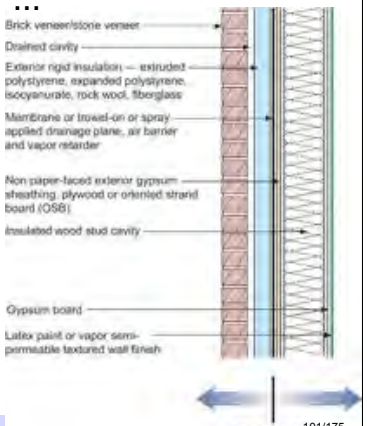

Thermal Bridging
• Steel is 400 times more conductive than wood
• Steel studs are about 40 times thinner
R<0.3
Cold
R=4+
Batt
3.5" wall
Hot
Building Science 2008


Steel studs @ 16" o.c.
Wood studs @ 16" o.c.
Clear wall
Nominal
Effective Framing/Insulation R-value
25
20
15
10
5
0
R-5ci*/3.5 in
R-13/3.5 in
R-19/6 in
R-7.5ci*/6 in
R-15ci*/6 in
R-15/3.5 in
R-19/6 in
R-21/9 in
Clear wall 5.8 8.0 7.1 8.8 11.2 10.0 12.9 13.6
Nominal 5 13 19 7.9 15 15 19 21

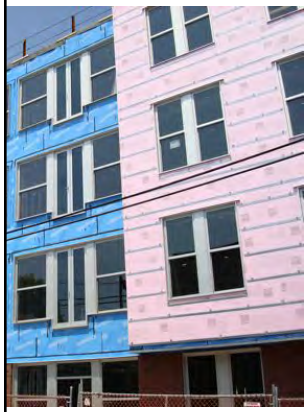

Example perfect walls
Building Science.com
Vapor Profile
Vapor Profile

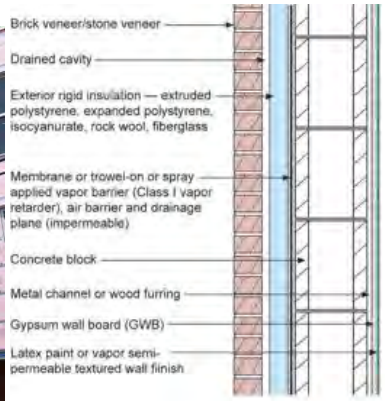
More challenging …

- Hybrid Compromise
  - – Wood framing
  - – High R-value steel
    - Eg 50%R outside
  - – R-value on outside
    - Varies with climate + interior conditions



101/175





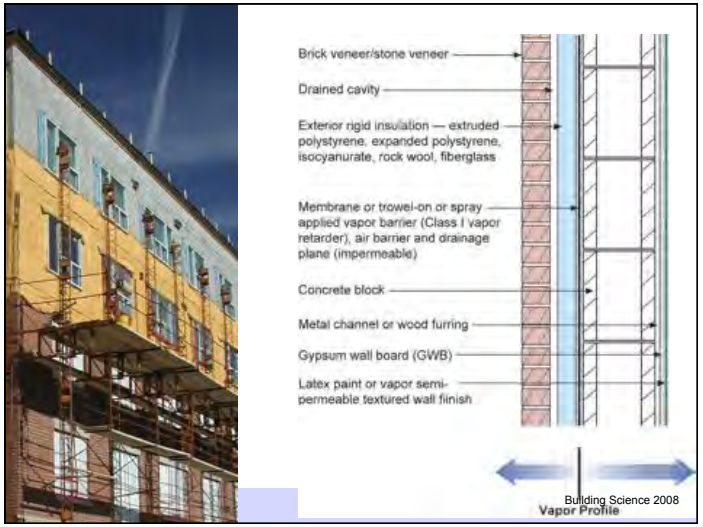
Building Science.com

Building Science Corporation 2010

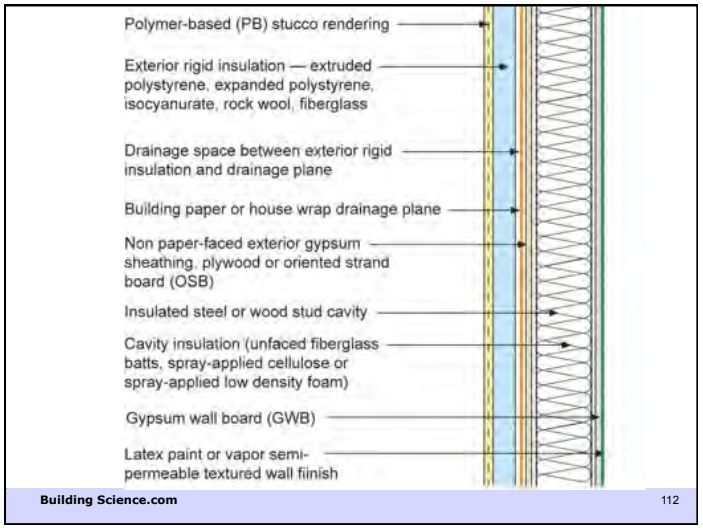
Joseph Lstiburek 104

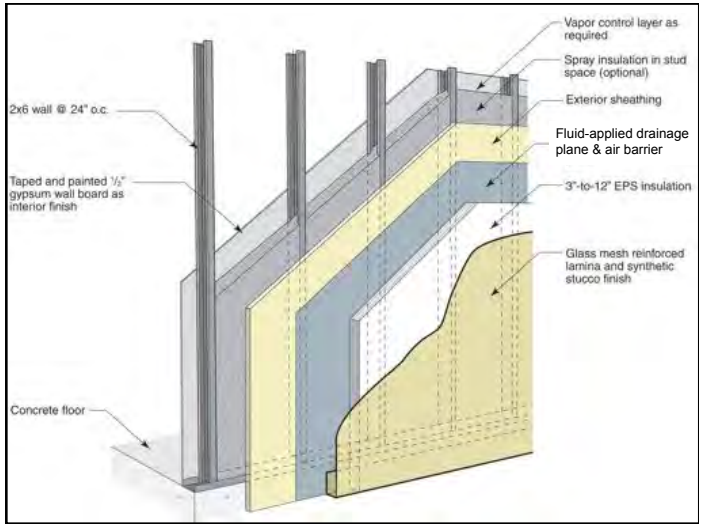
Building Science Corporation
2010
Joseph Lstiburek 105

Building Science Corporation
106

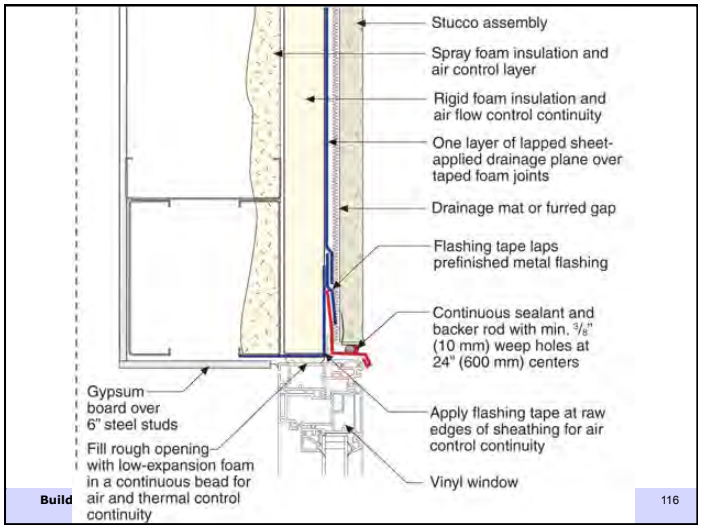

Brick veneer/stone veneer
Drained cavity
Exterior rigid insulation — extruded polystyrene, expanded polystyrene, isocyanurate, rock wool, fiberglass
Membrane or trowel-on or spray applied vapor barrier (Class I vapor retarder), air barrier and drainage plane (impermeable)
Concrete block
Metal channel or wood furring
Gypsum wall board (GWB)
Latex paint or vapor semi-permeable textured wall finish
Building Science 2008
Vapor Profile


Building Science.com


Polymer-based (PB) stucco rendering
Exterior rigid insulation — extruded polystyrene, expanded polystyrene, isocyanurate, rock wool, fiberglass
Drainage space between exterior rigid insulation and drainage plane
Building paper or house wrap drainage plane
Non paper-faced exterior gypsum sheathing, plywood or oriented strand board (OSB)
Insulated steel or wood stud cavity
Cavity insulation (unfaced fiberglass batts, spray-applied cellulose or spray-applied low density foam)
Gypsum wall board (GWB)
Latex paint or vapor semi-permeable textured wall finish
Building Science.com
112

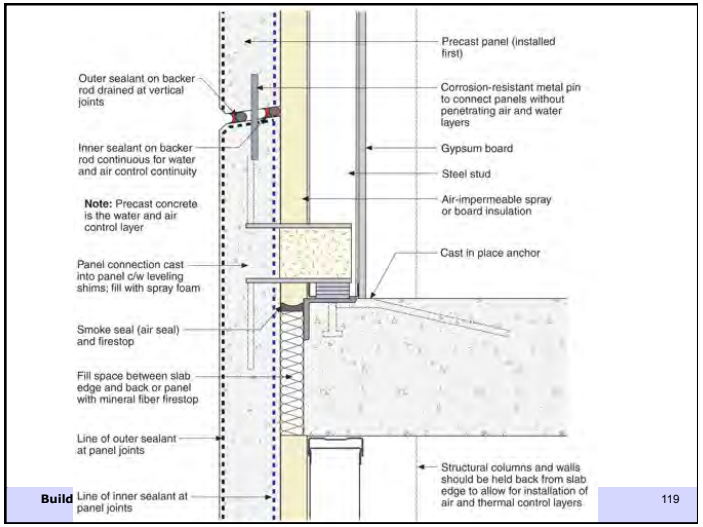

Vapor control layer as required
Spray insulation in stud space (optional)
Exterior sheathing
Fluid-applied drainage plane & air barrier
3"-to-12" EPS insulation
Glass mesh reinforced lamina and synthetic stucco finish
2x6 wall @ 24" o.c.
Taped and painted ½" gypsum wall board as interior finish
Concrete floor


Building Science.com
114

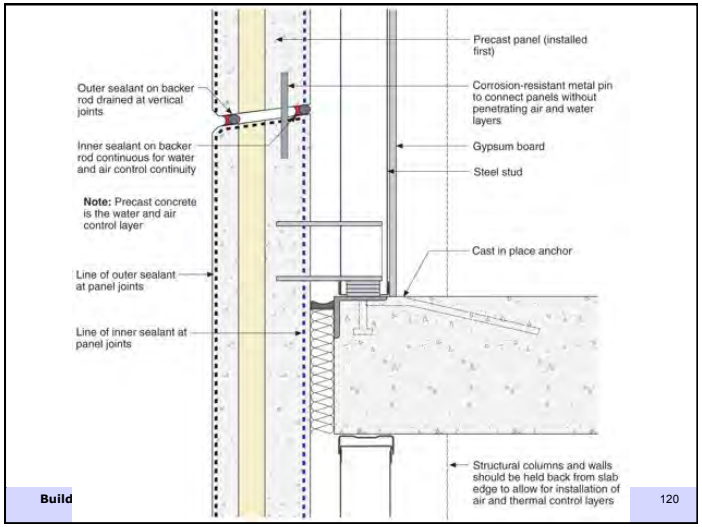

Stucco assembly
Spray foam insulation and air control layer
Rigid foam insulation and air flow control continuity
One layer of lapped sheet-applied drainage plane over taped foam joints
Drainage mat or furred gap
Flashing tape laps prefinished metal flashing
Continuous sealant and backer rod with min. 3/8" (10 mm) weep holes at 24" (600 mm) centers
Gypsum board over 6" steel studs
Fill rough opening with low-expansion foam in a continuous bead for air and thermal control continuity
Apply flashing tape at raw edges of sheathing for air control continuity
Vinyl window
Build
116

Building Science.com 117

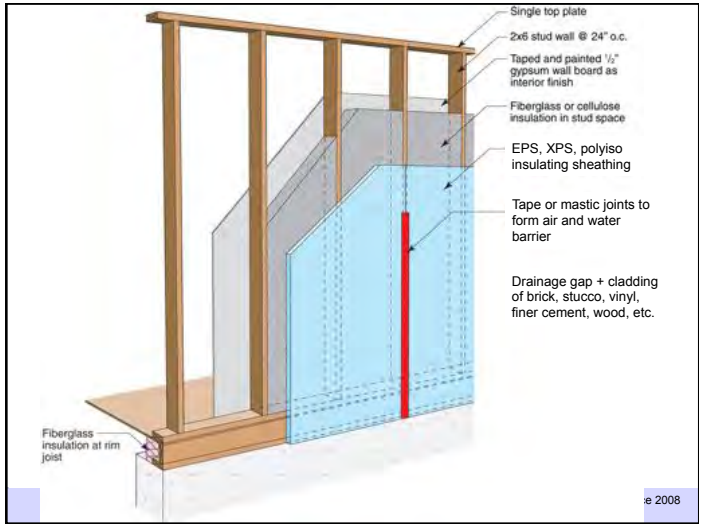
Building Science.com 118



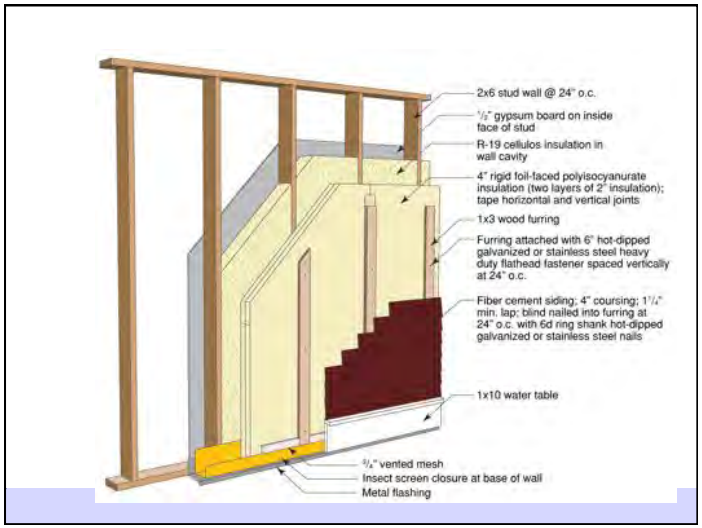
Build 119

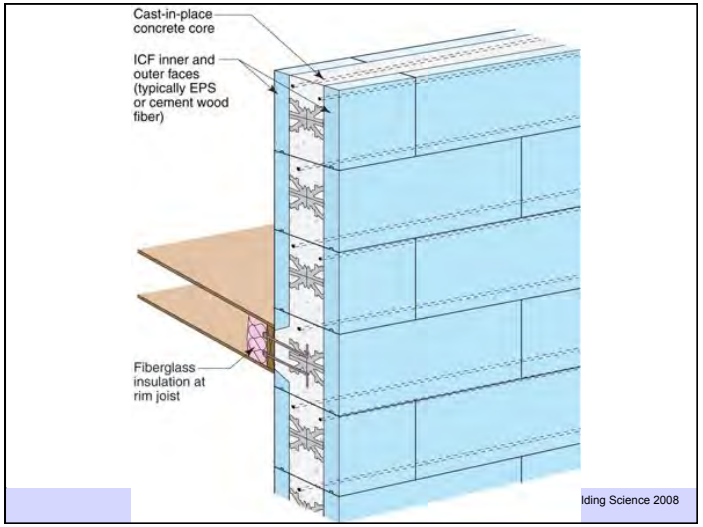


Build 120


Single top plate
2x6 stud wall @ 24" o.c.
Taped and painted ½" gypsum wall board as interior finish
Fiberglass or cellulose insulation in stud space
EPS, XPS, polyiso insulating sheathing
Tape or mastic joints to form air and water barrier
Drainage gap + cladding of brick, stucco, vinyl, finer cement, wood, etc.
Fiberglass insulation at rim joist
e 2008

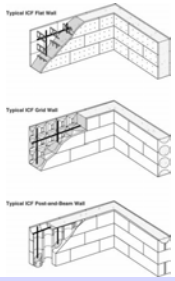

Brick veneer/stone veneer
Drained cavity
Exterior rigid insulation — extruded polystyrene, expanded polystyrene, isocyanurate, rock wool, fiberglass
Membrane or trowel-on or spray applied drainage plane, air barrier and vapor retarder
Non paper-faced exterior gypsum sheathing, plywood or oriented strand board (OSB)
Insulated wood stud cavity


2x6 stud wall @ 24" o.c.
½" gypsum board on inside face of stud
R-19 cellulos insulation in wall cavity
4" rigid foil-faced polyisocyanurate insulation (two layers of 2" insulation); tape horizontal and vertical joints
1x3 wood furring
Furring attached with 6" hot-dipped galvanized or stainless steel heavy duty flathead fastener spaced vertically at 24" o.c.
Fiber cement siding; 4" coursing; 1¼" min. lap; blind nailed into furring at 24" o.c. with 6d ring shank hot-dipped galvanized or stainless steel nails
1x10 water table
¾" vented mesh
Insect screen closure at base of wall
Metal flashing



Insulated Concrete Forms

- Excellent enclosure system
- Concrete acts as air barrier
- No vapor barrier needed
- Expensive, but high performance

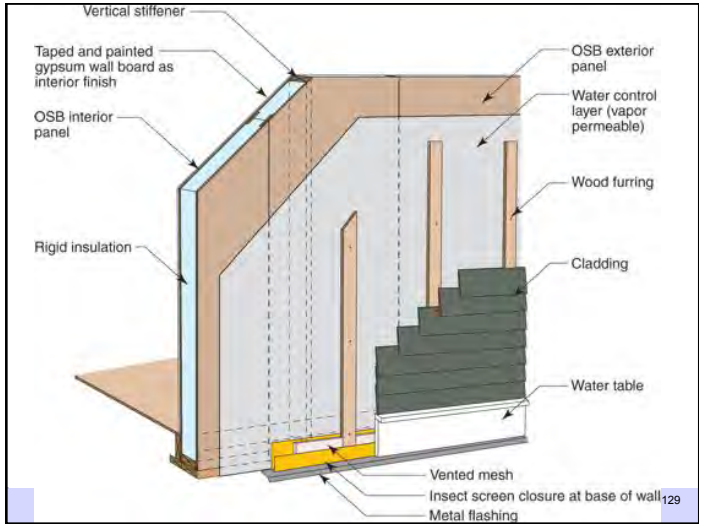


Building Science 2008

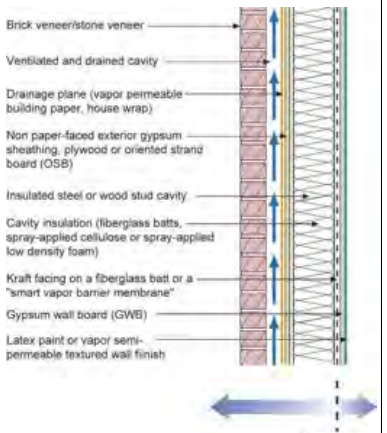
Structural Insulated Panels

- Advantages
  - Superior blanket of insulation
  - if no voids then no convection or windwashing
  - May seal OSB joints for excellent air barrier system
- Therefore, done right = excellent
- Small air leaks at joints in roofs can cause problems
- Don't get them too wet from rain
  - Low perm layers means limited drying

Building Science 2008 Insulation and Thermal Bridges No. 128/65



Vapour Profiles
In Wall Assemblies:



End of Section

Building Science.com 132