Durability and Moisture Management in Net Zero Commercial Buildings

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Principal, RDH Building Science
Professor, University of Waterloo
→ Technical risk
  → Likelihood and significance of poor technical performance
→ Not schedule or budget related
→ Avoiding = one of our core values to clients
Section 1: From Current Code Requirements to Net Zero Buildings
Space heating dominates building energy use in Canada

(NRCAn 2008)
Space heating load primarily due to: poor insulation, windows, & air leakage

Space heating dominates, even for offices

207 million m²
Average 394 kWh/m²

Source: NRCan Office of Energy Efficiency
Trends

→ Higher insulation levels
  → over R=20/RSI3.5
→ Higher air tightness levels
  → Testing commercial buildings
→ Effective R-values
  → Account for thermal bridging
→ Wood-frame 4–6 storey, residential
→ Sub/Urban infill
→ Moving towards Net Zero Energy
National Building Code of Canada

→ Pan-Canadian Framework on Clean Growth and Climate Change calls for
→ adoption of “net-zero energy” ready

Critical Path to 2030

GOAL: Federal, provincial, and territorial governments will work to develop and adopt increasingly stringent model building codes, starting in 2020, with the goal that provinces and territories adopt a “net-zero energy ready” model building code by 2030.

nrcan.gc.ca/pathwayto2030

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<tbody>
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<td>Raising the efficiency bar for new buildings</td>
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<td>Getting Net-Zero Energy Ready</td>
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<td>Code Compliance Assistance Program Launch</td>
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<tr>
<td>Model Net Zero Energy Ready (NZER) Codes for Homes and Buildings</td>
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<td>Publish More Stringent Codes</td>
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<td>Publish Additional Tiers of NZER Codes</td>
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<td>Adoption of More Stringent Codes</td>
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<td>Research, Development and Demonstration (RD&amp;D) Projects to Lower Incremental Costs of Building to NZER</td>
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<td>First Set of Co-Funding Agreements Signed</td>
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<td>Expansion of Local Energy Efficiency Partnership</td>
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<tr>
<td>Supporting Materials for Adoption, Building Officials and Code Compliance</td>
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</table>

Making New Buildings More Energy Efficient

NZER model code adopted for new homes and buildings in jurisdictions that have adopted it

Potential GHG reductions*: 5.6 MT
What is Net Zero Energy Building?

→ Simple: *A Building that produces as much energy as it consumes over the year*

→ Complications
  
  → Can you buy renewable power from elsewhere? (e.g., wind in PEI for Montreal building)
  
  → Is energy production only ON *building* or on *site*?
  
  → Are imported renewables allowed (wood, ethanol)?
  
  → Next year, or typical year’s weather?
  
  → What kind of occupancy?
<table>
<thead>
<tr>
<th>Option Number</th>
<th>NZEB Supply-Side Options</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Reduce site energy use through energy efficiency and demand-side renewable building technologies.</td>
<td>Daylighting; insulation; passive solar heating; high-efficiency heating, ventilation, and air-conditioning equipment; natural ventilation, evaporative cooling; ground-source heat pumps; ocean water cooling</td>
</tr>
</tbody>
</table>

### On-Site Supply Options

<table>
<thead>
<tr>
<th>Option Number</th>
<th>Description</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Use RE sources available within the building footprint and connected to its electricity or hot/chilled water distribution system.</td>
<td>PV, solar hot water, and wind located on the building</td>
</tr>
<tr>
<td>2</td>
<td>Use RE sources available at the building site and connected to its electricity or hot/chilled water distribution system.</td>
<td>PV, solar hot water, low-impact hydro, and wind located on parking lots or adjacent open space, but not physically mounted on the building</td>
</tr>
</tbody>
</table>

### Off-Site Supply Options

<table>
<thead>
<tr>
<th>Option Number</th>
<th>Description</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Use RE sources available off site to generate energy on site and connected to the building's electricity or hot/chilled water distribution system.</td>
<td>Biomass, wood pellets, ethanol, or biodiesel that can be imported from off site, or collected from waste streams from on-site processes that can be used on site to generate electricity and heat</td>
</tr>
<tr>
<td>4</td>
<td>Purchase recently added off-site RE sources, as certified from Green-E (2009) or other equivalent REC programs. Continue to purchase the generation from this new resource to maintain NZEB status.</td>
<td>Utility-based wind, PV, emissions credits, or other “green” purchasing options. All purchases must be certified as renewable energy. A building could then purchase electricity from its power provider, or purchase power from wind turbines or PV arrays that can generate good solar or wind energy. The power generated can be used on site as needed. The power can be used to generate electricity for on-site use, or sold back to the grid.</td>
</tr>
</tbody>
</table>
MOHAWK COLLEGE
THE JOYCE CENTRE FOR PARTNERSHIP AND INNOVATION

McCallum Sather / B+H Architects. 96 000 sq ft
Project Successes

Process:

- Establishing the Energy Budget at the project inception became a huge design driver

Impacts: Net Zero Targets Achievable

- Net Zero Energy
- CaGBC Net Zero Carbon

35% WWR, R-7 window, R-25 wall, R-40 roof
Average enclosure R-10 (windows + opaque)
Energy use: 71 kWh/m²/yr
Energy production: 71 kWh/m²/yr on-site
High performance enclosure

R-7 Curtainwall

R-25 Precast
3+4 PIC+3
→ Primary components: 
   *Enclosure, Structure, Services and Fabric*

→ NZE adds
   *Renewable Energy*

→ NZE focus on
   1. Enclosure
   2. Energy
   3. then Services
Early-Stage Decisions

→ Important decisions are often at start of design
→ Assuming .. Site is known, program fixed, and area estimated.
→ Form (Box? Egg?)
→ Space Dimensions
→ Structural Systems
→ Window Area
→ Enclosure attributes
→ HVAC… later
→ Details .. later
Low Energy: Enclosure First

→ Low-energy buildings focus on high-performance enclosures first
→ Allows more affordable, often more efficient and simpler HVAC
→ Design to lower:
  → Heat loss (UA + air leakage)
  → Heat Gain (Window area time SHGC)
Enclosure Focus Areas for Low Energy

- Improved Air Barrier Systems & Whole Building Testing/Commissioning
- Improved insulation levels in roofs
- Higher Performance Windows & Thermally Improved Installation Details
- Careful selection of glazing, shading and overheating potential
- Improved insulation levels in walls, and floors & reduced thermal bridging
The Road to *Net Zero* Performance Housing

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<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td><strong>ERS 50...</strong></td>
<td><strong>ERS 80</strong></td>
<td><strong>ERS 86-89</strong></td>
<td><strong>ERS 100</strong></td>
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<tr>
<td><strong>Attics</strong></td>
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<tr>
<td>R-12 to R-20</td>
<td>R-40 to R-50</td>
<td>R-60 to R-80</td>
<td>R-60 to R-80</td>
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<tr>
<td>R-8 to R-12</td>
<td>R-12 to R-20</td>
<td>R-30 to R-40</td>
<td>R-30 to R-40</td>
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<tr>
<td>R-0</td>
<td>R-0</td>
<td>R-10 to R-15</td>
<td>R-10 to R-15</td>
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<tr>
<td><strong>Walls Above Grade</strong></td>
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<td><strong>Foundation Walls</strong></td>
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<tr>
<td><strong>Slab</strong></td>
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<tr>
<td><strong>Airtightness:</strong></td>
<td>AVG 5 ACH</td>
<td>&lt;3.5 ACH</td>
<td>&lt;1.5 ACH</td>
</tr>
</tbody>
</table>
Role of Factors on Energy use

→ Window area is the largest practical factor
  → Less window area reduces energy use, improves thermal comfort, and costs less
→ Shape and orientation are less important, but can be useful to reduce cost and save energy
→ HVAC and details can be chosen later in process
Common Codes in Canada

- ASHRAE 90.1–20xx
- NECB 20xx
- Provincial
  - Quebec
    - “Regulation Respecting Energy Conservation in New Buildings Act.”
  - Ontario SB–10
- Enhanced
  - Net Zero Energy
  - Passive House, Energy Stu
  - Living Building Challenge
Climate Zone obviously matters

Most codes use some version of this map (not Quebec, now)
How Codes Work

→ There is no “code R-value your wall must meet”
→ Code official (“Authority Having Jurisdiction”) ask designers to “demonstrate compliance” to code
→ Designers must know the thermal performance of their enclosures to:
  → compare to tabulated values
  → provide information to energy modelers
→ Level of detail in “calculations” depend on code and AHJ
Code Compliance Paths

**Prescriptive**
- Installs R-value
- Limited flexibility, restrictive
- No calcs

- Overall U-value
- Many combinations possible, simple calcs

**Trade-off**
- Simple
- Easy, calcs account for different WWR. Cant trade walls & roofs

**Performance**
- Hourly energy model of whole building
- Most flexible, hourly computer model, detailed information, difficult to do early stage, requires expertise.

*Mandatory minimum HVAC Lighting assumed*
Energy Modeling

→ Allows for great flexibility
→ Model code minimum building, including all HVAC, lighting, DHW, etc. (“Reference Building”)
→ Demonstrate Design Building is same or lower energy use
→ Often require too much information at early stage.
→ Can’t wait for modeling to make important design decisions
→ Black box models often cloud understanding
Energy Models: not very accurate

Low-energy Buildings are harder

Section 2: Net Zero Building Enclosures
Building Enclosures

→ Enclosure separates indoors from outdoors
→ Important component
  → Appearance
  → Comfort
  → Durability / maintenance
  → Energy!
→ Common source of problems
  → Leaks, comfort, mold, cladding failure, etc
→ Critical for low-energy buildings
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

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 ped...
Basic Enclosure Functions

→ Support
  → Resist & transfer physical forces from inside and out

→ Control
  → Control mass and energy flows
    › 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
→ **Support**

→ **Control**
  
  → **Fire**
  
  › Penetration
  
  › Propagation

→ **Sound**
  
  › Penetration
  
  › Reflection

→ **Light**
  
  › Diffuse/glare
  
  › View

→ **Finish**
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
History of

→ Older Buildings
   → One layer does everything

→ Newer Building
   → Separate layers,
       . . . separate functions
Cladding

1. Water Control
2. Air Control
3. Thermal Control
4. Vapor Control

Support

Service Distribution

Interior Finish

Ideal Enclosure / Perfect Wall
Complexity increases detailing effort, risk of failure, and reduces performance
• Details demand the same approach as the enclosure.

• Scaled drawings required at
  - change in plane
  - change in material
  - change in trade
What is a high performance enclosure?

→ High levels of control (heat, air, rain)
→ **But**, poor continuity limits performance
→ & Poor continuity causes most problems too:
   → E.g. air leakage condensation
   → Rain leakage
   → Surface condensation
   → Cold windows
→ Thus: *continuity + high levels of control*
Insulation in stud cavity

→ Need vapor permeable air–water membrane
→ Wood studs usually have cavity insulation

- Higher R–values
- Can use lower cost fiber insulation
- Reduces wall thickness
Exterior Insulation

→ Wood frame, split-insulated. With batt inside frames
Resource: Low-Energy Design Guide


→ For up to 6-storey Wood-frame Buildings
→ Focus on highly insulated wood-frame assemblies to meet current and upcoming energy codes
→ Strategies, assemblies & many building enclosure details provided
→ Sequential detailing for windows and other complicated details
Thermal Control

→ Insulation
→ Thermal bridging
The Ideal Enclosure / Perfect Wall

Cladding

1. Water Control
2. Air Control
3. Thermal Control
4. Vapor Control

Support

Service Distribution

Interior Finish
Thermal Control

→ Critical part of low-energy buildings in Canada

→ Significant quantities of insulation ....
  → Key is to get it continuous – avoid metal and concrete thermal bridges!
  → Airtight – don’t bypass insulation with air!

→ Many choices for insulation products
## Choices: Insulation *Materials*

<table>
<thead>
<tr>
<th>Materials</th>
<th>Examples</th>
<th>Moisture</th>
<th>Fire</th>
<th>Vapor Permeance</th>
<th>Air Permeance</th>
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</thead>
<tbody>
<tr>
<td>Mineral fiber</td>
<td>Fiberglass, stone, slag</td>
<td>Tolerant</td>
<td>Non-combustible</td>
<td>high</td>
<td>high</td>
</tr>
<tr>
<td>Organic Fiber</td>
<td>Cellulose, cotton, wool, straw</td>
<td>Sensitive</td>
<td>Combustible</td>
<td>high</td>
<td>high</td>
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<tr>
<td>Plastic foam</td>
<td>Polystyrene, polyurethane, polyisocyanurate</td>
<td>Tolerant</td>
<td>Combustible</td>
<td>Low-medium</td>
<td>low</td>
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<tr>
<td>Mineral foam</td>
<td>Foamglass, pumice, airkrete, aerogel</td>
<td>Tolerant</td>
<td>Non-combustible</td>
<td>low</td>
<td>low</td>
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</table>
## Choices: *Form* of Insulation

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<thead>
<tr>
<th>Form</th>
<th>Installation</th>
<th>Limits to use</th>
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<tbody>
<tr>
<td>Loose</td>
<td>poured or blown</td>
<td>may settle, easily compressed</td>
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<tr>
<td>Batt</td>
<td>friction fit</td>
<td>held in place by friction, easily compressed</td>
</tr>
<tr>
<td>Roll</td>
<td>friction fit / mechanically attached</td>
<td>as for batts</td>
</tr>
<tr>
<td>Board</td>
<td>mechanically, adhesively attached</td>
<td>resistant to mechanical pressure</td>
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<tr>
<td>Spray</td>
<td>spray in place</td>
<td>sticks to adjoining surfaces, resilient</td>
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</table>
Insulations: R/inch compared

- Fiberglass HD batt
- Stonewool batt
- Stonewool rigid
- XPS
- EPS HD
- EPS
- polyiso
- cSPF
- oSPF
- cellulose
Making Choices

- Factors *other than R-value* are usually most important
  - Fire resistance
  - Moisture tolerance
  - Physical strength
  - Vapor permeance
  - Air permeance

- Most insulation products are very inexpensive relative to other building products
Thermal Bridging

→ Manage to get effective R-value
→ Increasing code restrictions
Calculating R-value: the good old days

→ Just add the layer $R$-values.

\[ R_{\text{total}} = R_1 + R_2 + R_3 + R_4 + R_5 + R_6 + R_7 \]
Example Assembly R-value

Values from tables

<table>
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<tr>
<th>Layer</th>
<th>R-value</th>
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<tr>
<td>Exterior air film</td>
<td>0.16</td>
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<tr>
<td>5” (125 mm) concrete panel</td>
<td>0.30</td>
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<tr>
<td>2” (51 mm) XPS insulation</td>
<td>10.0</td>
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<tr>
<td>5/8” (15 mm) GWB</td>
<td>0.10</td>
</tr>
<tr>
<td>Interior air film</td>
<td>0.68</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>11.2</strong></td>
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</tbody>
</table>

U = 1/R_{total}
U = 1/11.2 = 0.089
Real walls are often not simple layers
Thermal Bridging

→ A local area of the enclosure that has higher heat loss

→ Thermal bridging at structural penetrations
Thermal bridging at structural penetrations

Hard / impossible to get continuous

1. Intermediate Floors
2. Baconies, Projections, Shades
3. Parapets
4. Window and Door perimeter
5. Internal Walls to External Walls
6. At Grade

Floors, roofs, slabs cause penetrations
1. Cladding attachments
2. Windows and doors
3. Balconies and canopies

Cladding attachment can cause thermal bridging

Much easier to get continuous
Thermal bridging of framing

- Codes NECB / ASHRAE 90.1... requires thermal bridging of framing studs be accounted for

- Typically, $\frac{2}{3}$ to $\frac{3}{4}$ of batt insulation R-value is lost by placing between steel studs
Find the thermal bridge
Accounting for framing

→ We can convert 3-D frames into a layer
→ Note the poor performance of steel stud framing with batt insulation

<table>
<thead>
<tr>
<th>Cavity Depth</th>
<th>Rated Cavity R-value</th>
<th>Layer R\textsubscript{cw} -value @ 16 inch centres</th>
<th>Layer RSI\textsubscript{cw} @ 405 mm centres</th>
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</thead>
<tbody>
<tr>
<td>In</td>
<td>mm</td>
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<tr>
<td>2.5</td>
<td>64</td>
<td>Empty</td>
<td>0.75</td>
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<td></td>
<td>0.13</td>
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<tr>
<td>3.5</td>
<td>89</td>
<td>Empty</td>
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<td>R-13</td>
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<td>R-15</td>
<td>6.4</td>
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<tr>
<td>6.0</td>
<td>152</td>
<td>Empty</td>
<td>0.84</td>
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<td></td>
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<td>R-19</td>
<td>7.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>R-21</td>
<td>7.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>R-24 (4” ccSPF)</td>
<td>7.6</td>
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</tbody>
</table>

This assumes 16” o.c. studs… in reality, many more studs used and R-value drops

Note: “ccSPF” is closed cell Sprayed Polyurethane Foam insulation
Then add GWB, sheathing, cladding and airfilms
Exterior insulation can be added to other layers R-values.
Continuous Insulation (ci)

→ Example:
  → steel-studs with R–19 batt have a value of about R–7.1 (see table)
  → Addition of 2” of stonewool means
    R–value = 7.1* 2X R–4/inch = R–15.1
  → Addition of 2.5 of XPS provides
    R–value = 7.1* 2.5 X R–5/inch = R–19.6

→ But, cladding attachment, balconies, etc have an impact
Calculating Thermal Bridging

→ Chi-factor


Heat flow with floor and balcony intersection

Clear Field heat flow

Additional heat flow due to thermal bridging at floor and balcony intersection
→ Resources:
thermal bridging guides

Owens Corning® Canada
Building Envelope
Thermal Bridging Guide
Example

Metal panel

Drainage cavity

Intermittent thermally isolated aluminum bracket

Vertical aluminum rail

Ecotouch Pink fiberglass batt insulation/air gap

Thermafiber RainBarrier 45 mineral wool semi rigid insulation

Exterior sheathing

Gypsum board

Vertical aluminum rail embedment depth varies (see appendix)
<table>
<thead>
<tr>
<th>Scenario</th>
<th>Exterior Insulation Thickness Inches (mm)</th>
<th>Exterior Insulation Nominal R-value hr·ft²·ºF/Btu (m²K/W)</th>
<th>Assembly</th>
<th>U-value Btu/hr·ft²·ºF (W/m²K)</th>
<th>Highest Applicable Climate Zone per NECB 2015¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air in Stud Cavity</td>
<td>2&quot; (50.8) 5&quot; (127)</td>
<td>R-8.6 (1.51) R-21.5 (3.79)</td>
<td>R-10.2 (1.80) R-18.0 (3.16)</td>
<td>0.098 (0.557) 0.056 (0.316)</td>
<td>None None</td>
</tr>
<tr>
<td>R-19 (3.35 RSI) Batt Insulation in Stud Cavity</td>
<td>1.5&quot; (38.1) 2&quot; (50.8) 3&quot; (76.2) 4&quot; (101.6) 5&quot; (127)</td>
<td>R-6.5 (1.14) R-8.6 (1.51) R-12.9 (2.27) R-17.2 (3.03) R-21.5 (3.79)</td>
<td>R-17.1 (3.01) R-18.2 (3.20) R-20.5 (3.60) R-23.2 (4.09) R-25.8 (4.54)</td>
<td>0.059 (0.333) 0.055 (0.313) 0.049 (0.278) 0.043 (0.245) 0.039 (0.220)</td>
<td>None 4 5 6 6</td>
</tr>
<tr>
<td>R-20 (3.52 RSI) Batt Insulation in Stud Cavity</td>
<td>1.5&quot; (38.1) 2&quot; (50.8) 3&quot; (76.2) 4&quot; (101.6) 5&quot; (127.0)</td>
<td>R-6.5 (1.14) R-8.6 (1.51) R-12.9 (2.27) R-17.2 (3.03) R-21.5 (3.79)</td>
<td>R-17.3 (3.05) R-18.4 (3.25) R-20.7 (3.65) R-23.5 (4.13) R-26.0 (4.59)</td>
<td>0.058 (0.327) 0.054 (0.308) 0.048 (0.274) 0.043 (0.242) 0.038 (0.218)</td>
<td>None 4 5 6 6</td>
</tr>
<tr>
<td>R-22 (3.87 RSI) Batt Insulation in Stud Cavity</td>
<td>1.5&quot; (38.1) 2&quot; (50.8) 3&quot; (76.2) 4&quot; (101.6) 5&quot; (127.0)</td>
<td>R-6.5 (1.14) R-8.6 (1.51) R-12.9 (2.27) R-17.2 (3.03) R-21.5 (3.79)</td>
<td>R-17.9 (3.15) R-18.9 (3.34) R-21.2 (3.73) R-24.0 (4.23) R-26.6 (4.68)</td>
<td>0.056 (0.318) 0.053 (0.300) 0.047 (0.268) 0.042 (0.237) 0.038 (0.214)</td>
<td>None 4 5 6 6</td>
</tr>
<tr>
<td>R-24 (4.23 RSI) Batt Insulation in Stud Cavity</td>
<td>1.5&quot; (38.1) 2&quot; (50.8) 3&quot; (76.2) 4&quot; (101.6) 5&quot; (127)</td>
<td>R-6.5 (1.14) R-8.6 (1.51) R-12.9 (2.27) R-17.2 (3.03) R-21.5 (3.79)</td>
<td>R-18.4 (3.23) R-19.4 (3.42) R-21.7 (3.81) R-24.4 (4.30) R-27.0 (4.76)</td>
<td>0.054 (0.309) 0.051 (0.292) 0.046 (0.262) 0.041 (0.233) 0.037 (0.210)</td>
<td>None 4 4 5 6 7</td>
</tr>
</tbody>
</table>

Buy R-5 get R1.2

¹NECB = National Energy Code for Buildings.
Wood studs.. Better performance

- Brick veneer
- Drainage cavity
- Heckmann Pos-i-Tie veneer anchoring system
- Foamular extruded polystyrene rigid insulation (XPS) Type 3
- Wood sheathing
- Ecotouch Pink fiberglass batt insulation
- Gypsum board

varies with studs

16" [406]
# High R-values w/only R-10 ci

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Exterior Insulation Thickness Inches (mm)</th>
<th>Exterior Insulation Nominal R-value hr·ft²·°F/Btu (m²K/W)</th>
<th>Assembly</th>
<th>Highest Applicable Climate Zone per NECB 2015¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-19 (3.35 RSI) Batt² Insulation in Stud Cavity Studs @ 16” o.c.</td>
<td>2” (50.8)</td>
<td>R-10 (1.76)</td>
<td>R-29.6 (5.21)</td>
<td>0.034 (0.192)</td>
</tr>
<tr>
<td></td>
<td>3” (76.2)</td>
<td>R-15 (2.64)</td>
<td>R-33.6 (5.92)</td>
<td>0.030 (0.169)</td>
</tr>
<tr>
<td></td>
<td>4” (101.6)</td>
<td>R-20 (3.52)</td>
<td>R-37.4 (6.59)</td>
<td>0.027 (0.152)</td>
</tr>
<tr>
<td>R-19 (3.35 RSI) Batt² Insulation in Stud Cavity Studs @ 24” o.c.</td>
<td>2” (50.8)</td>
<td>R-10 (1.76)</td>
<td>R-30.6 (5.39)</td>
<td>0.033 (0.185)</td>
</tr>
<tr>
<td></td>
<td>3” (76.2)</td>
<td>R-15 (2.64)</td>
<td>R-35.0 (6.16)</td>
<td>0.029 (0.162)</td>
</tr>
<tr>
<td></td>
<td>4” (101.6)</td>
<td>R-20 (3.52)</td>
<td>R-39.1 (6.89)</td>
<td>0.026 (0.145)</td>
</tr>
<tr>
<td>R-22 (3.87 RSI) Batt² Insulation in Stud Cavity Studs @ 16” o.c.</td>
<td>2” (50.8)</td>
<td>R-10 (1.76)</td>
<td>R-31.7 (5.58)</td>
<td>0.032 (0.179)</td>
</tr>
<tr>
<td></td>
<td>3” (76.2)</td>
<td>R-15 (2.64)</td>
<td>R-35.8 (6.30)</td>
<td>0.028 (0.159)</td>
</tr>
<tr>
<td></td>
<td>4” (101.6)</td>
<td>R-20 (3.52)</td>
<td>R-39.6 (6.97)</td>
<td>0.025 (0.144)</td>
</tr>
<tr>
<td>R-22 (3.87 RSI) Batt² Insulation in Stud Cavity Studs @ 24” o.c.</td>
<td>2” (50.8)</td>
<td>R-10 (1.76)</td>
<td>R-33.0 (5.82)</td>
<td>0.030 (0.172)</td>
</tr>
<tr>
<td></td>
<td>3” (76.2)</td>
<td>R-15 (2.64)</td>
<td>R-37.3 (6.58)</td>
<td>0.027 (0.152)</td>
</tr>
<tr>
<td></td>
<td>4” (101.6)</td>
<td>R-20 (3.52)</td>
<td>R-41.3 (7.28)</td>
<td>0.024 (0.137)</td>
</tr>
<tr>
<td>R-24 (4.23 RSI) Batt² Insulation in Stud Cavity Studs @ 16” o.c.</td>
<td>2” (50.8)</td>
<td>R-10 (1.76)</td>
<td>R-33.2 (5.84)</td>
<td>0.030 (0.171)</td>
</tr>
<tr>
<td></td>
<td>3” (76.2)</td>
<td>R-15 (2.64)</td>
<td>R-37.1 (6.53)</td>
<td>0.027 (0.153)</td>
</tr>
<tr>
<td></td>
<td>4” (101.6)</td>
<td>R-20 (3.52)</td>
<td>R-41.0 (7.21)</td>
<td>0.024 (0.139)</td>
</tr>
<tr>
<td>R-24 (4.23 RSI) Batt² Insulation in Stud Cavity Studs @ 24” o.c.</td>
<td>2” (50.8)</td>
<td>R-10 (1.76)</td>
<td>R-34.7 (6.11)</td>
<td>0.029 (0.164)</td>
</tr>
<tr>
<td></td>
<td>3” (76.2)</td>
<td>R-15 (2.64)</td>
<td>R-39.0 (6.86)</td>
<td>0.026 (0.146)</td>
</tr>
<tr>
<td></td>
<td>4” (101.6)</td>
<td>R-20 (3.52)</td>
<td>R-42.9 (7.56)</td>
<td>0.023 (0.132)</td>
</tr>
</tbody>
</table>

¹ Compared to above grade wall for maximum U-factor in Table 3.2.2.2
² Installed R-value. Rated R-20 Fiberglass Batt is compressed to R-19 when installed in a 5.5-inches wood studs cavity
### Screws at 12" o.c. have almost no impact

### Exterior Insulation

<table>
<thead>
<tr>
<th>Exterior Insulation Thickness</th>
<th>Exterior Insulation Nominal R-value hr-ft²·°F/Btu (m²K/W)</th>
<th>Assembly R-value hr-ft²·°F/Btu (m²K/W)</th>
<th>U-value Btu/hr-ft²·°F (W/m²K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1x4&quot; (1x101.6mm)</td>
<td>R-20 (3.52)</td>
<td>R-20.8 (3.67)</td>
<td>0.048 (0.272)</td>
</tr>
<tr>
<td>2x3&quot; (2x76.2mm)</td>
<td>R-30 (5.28)</td>
<td>R-30.5 (5.36)</td>
<td>0.033 (0.186)</td>
</tr>
<tr>
<td>2x4&quot; (2x101.6mm)</td>
<td>R-40 (7.04)</td>
<td>R-39.8 (7.02)</td>
<td>0.025 (0.142)</td>
</tr>
</tbody>
</table>

**Legend:**
- **Roof membrane and cover board**
- **Steel fasteners**
- **Foamular extruded polystyrene rigid insulation (XPS) Type 4**
- **Roof sheathing**
- **Steel deck**
Fenestration

→ Total Area (WWR)
→ Thermal Quality
Windows & Glazing: Key Considerations

→ Window-to-Wall Ratio
Window Performance is Important

→ Code-approved windows have $U_{SI}$ values of about 2.5 W/m$^2$K ... this is R–2.3

→ Windows and curtainwalls with R–2.5 to R3.5 comprise most installed

→ To achieve higher R-values, different frames and triple-glazing needed
Average R-value

R−20.4 wall 65% of Area + R−2.6 window 35% of Area = Window $U_{SI} = 2.2$ or R−2.6
Average R-value

R–20.4 wall

65% of Area

R–2.6 window

35% of Area

= 

R–6.0

100% of Area

Window $U_{SI} = 2.2$ or R–2.6
Example Low-energy Office Building

Adding window area = more energy for heating & cooling

Mid-size cold-climate (Sweden) low-energy office building
Note: true R20 walls, R3.5 windows, daylighting controls, and demand-controlled ventilation.

Poirazis et al 2008
Window-to-Wall Ratios

- $R = 20$, $U = 0.3$
- $R = 10$, $U = 0.4$
- $R = 10$, $U = 0.3$
- $R = 10$, $U = 0.2$
- $R = 20$, $U = 0.2$
- $R = 20$, $U = 0.4$

**High Performance**

- $R_{ww} = 10$, $U_v = 0.2$
- $R_{ww} = 10$, $U_v = 0.3$
- $R_{ww} = 10$, $U_v = 0.4$
- $R_{ww} = 20$, $U_v = 0.2$
- $R_{ww} = 20$, $U_v = 0.3$
- $R_{ww} = 20$, $U_v = 0.4$
High Performance Windows & Glazing

→ Triple glazing with argon fill, warm edge spacers and 2–3 low-e coatings
  → Possibly quad IGUs in far North
→ Punched window options (domestic & imported)
  → Insulated fiberglass, insulated vinyl, vinyl/aluminum
→ Curtainwall options
  → Imported thermally broken aluminum
  → Options for wood veneer (aluminum glazing components)
    fiberglass/vinyl
Better Windows

R–20.4 Wall [65% of Area] + R–4 [35% of Area] = R–8.4 [100% of Area]

Better windows, and almost 30% reduction in heat loss
→ Ensure continuity of water, air, and thermal control
→ Note difference to window / storefront
Windows Placement in Rough Openings

Optimal placement aligns window with insulation
Path forward

- Better insulated windows
- Triple-glazed
- Carefully designed installation to avoid water, air, and thermal leaks
Airflow Control

→ Air Barriers
→ Convection and Windwashing
Air Barriers

→ Air Barrier Systems must:
  → Be Continuous
  → Be Durable
  → Resist Structural Loads – Stiffness & Strength for Design Wind Load
  → Be Airtight
→ May need to allow vapor diffusion drying and act as/with Water Control
→ Wind loads on mid-rise buildings can be significant and approaches used for low-rise wood-frame may not be appropriate
Why is Air Leakage Control is Important – Preventing Building Enclosure Failures
Air Barriers Are Systems

Materials

Components

Accessories

Whole Building Airtightness
Water Barriers & Air Barriers

→ Often combine functions for same product
  → E.g. liquid–applied and adhered sheets

→ Requirements of both functions required
  → Water: Gravity lapped, connected to flashing
  → Air: sealed, supported

→ Conflicts: connected to interior of window for air, but shed to the exterior flashing at window head
Shift to the Exterior Air Barrier

→ Industry shift from the use of interior air barrier approaches (poly, drywall) to exterior sheathing approaches as the primary air barrier element

→ BUT! still need to maintain a reasonable degree of airtightness at interior side of cavity insulation in cold climates (convection suppressor)

→ Vapor barrier/retarder at interior side depending on insulation ratio & type

With enough exterior insulation – risk for condensation at sheathing decreases, as does need for interior air tightness
Air Barrier/WRB Placement Considerations

- **Interior (stud) insulated**
- **Split (exterior & stud) insulated**
- **Exterior insulated**
Why Exterior Air Barriers vs. Interior?
Air Barrier: As Good as Weakest Detail
Continuity Detailing

→ Early
→ Plan
→ Label drawings

→ Often
→ Schematic
→ Details
→ On-site
Air Leak Locations – Mid to High-rise

If leakage areas were identified, what were the most common problem areas?

- Roof to wall transitions: 45%
- Base of wall or floor line transitions: 10%
- Mechanical penetrations: 45%
- Dampers: 35%
- Soffits: 15%
- Vented roof assemblies: 10%
Continuity Detailing at EVERY Detail
Exterior Air Barrier Systems

→ Exterior air barrier approaches (at sheathing plane) rely on rigidity of wood/gypsum sheathing

→ **Sealed sheathing membrane approach**
  → Mechanically Attached Sheets (Taped & Sealed), $
  → Self-adhered Membranes, $$$
  → Liquid/Fluid Applied, $$$$+

→ **Sealed sheathing approach** (plywood/OSB/gypsum)
  → Sealed joints (good sealant or tapes), $

→ **Sealed foam insulation** $
Mechanically Attached Air (&Water?) Barrier

- Loose sheet mechanically attached to wall with cap staples/nails and sealed with tapes, self-adhered membrane and sealants
Challenges with Mechanically Attached Membranes & Wind During Construction
Fully-adhered vs mechanical attached
Fully-adhered vs mechanical attached
Fully-adhered vs mechanical attached
Fully-adhered vs mechanical attached
Exterior Insulation Sandwich Support for Mechanically Attached Air Barriers
Sprayfoam Air Barrier between studs

→ Careful with Application

Airseal required between all wood-wood joints
Trends in Air Barrier Systems

→ Exterior Sprayfoam
→ Air and Water Control
Trends in Air Barrier Systems

→ Sealed Exterior Foam Sheathing
→ Air and Water Control
XPS *can* be air water barrier

→ Requires care at all details
Sealed Foam Sheathing: AB + WRB

→ **Systems** and compatible components are key
Airtightness Does Not Happen By Accident

Multiple trades, multiple stages of construction require focus and commitment
Experience with Large Buildings

Setting targets results in lower measured leakage

- **No Requirement, Post 2000 Construction** (31 Buildings)
- **USACE** (245 Buildings)
- **Washington** (38 Buildings)

Based on RDH testing and research from the US
How Well Is the Industry Doing – WA State

Airtightness [L/(s·m²) @ 75 Pa]

- Liquid Applied (10 Buildings)
- Sealed Sheathing (11 Buildings)
- Sheet Applied (28 Buildings)
- Curtain Wall/Window Wall/Storefront (15 Buildings)

WA State Requirement

- Leakiest tested
- Median & 1st/3rd quartile range
- Tightest tested

Passive House Range equivalent ~ 0.6 ACH₅₀

54 Buildings, Oct 2015 RDH SEA Data
→ Set targets (codes may impose)
→ Field Test
→ Repeat

→ Massive benefits for energy, better HVAC design, and reduced condensation risks
  → Known, predictable airtightness more important than super low numbers
Section 3: Durability in Highly Insulated Buildings
Durability

→ Most concerns are related to moisture
  → Rot, corrosion, mould

→ High Insulated Enclosures can be more at risk
  → Increasing insulation reduces heat flow
  → Lower heat flow means less drying
→ Response: more resilient design and/or better quality control
The Moisture Balance

- Wetting
- Wetting
- Safe Storage Capacity
- Drying
The Moisture Balance

Safe Storage Capacity

Wetting

Wetting

Drying
The Moisture Balance

Condensation
- air convection
- vapor diffusion

Safe Storage Capacity

Wetting

Rain
- absorption
- penetration

Wetting

Plumbing

Built-in

Drying
- Drainage
- Air convection
- Evaporation-Diffusion
Moisture Balance

→ Select materials to tolerate moisture expected
→ Rain management is most important
  → Flashing, drainage, penetrations
→ Air leakage condensation next
  → Air barriers, exterior insulation
→ Remember: Construction moisture
  → Management, drying
→ Allow drying by vapor diffusion
  → None of us is perfect
Air Leakage Condensation & exterior insulation
Question: Where does condensation occur?

Answer: on a cold solid surface
Significance of air flow

**Wall 1**
- Vapor diffusion only
- $V_B = 60 \text{ ng/Pa s m}^2$

**Wall 2**
- Vapor diffusion only
- $V_B = 600 \text{ ng/Pa s m}^2$

**Wall 3**
- Air leakage only
- $V_B = 6 \text{ ng/Pa s m}^2$

Exterior

$T = 0^\circ F / -18^\circ C$
$RH = 80\%$

48 grams / month = 3 tablespoons

538 grams / month = 2.4 cups

22,200 grams / month = 98 cups

Interior

$T = 70^\circ F / 21^\circ C$
$RH = 35\%$

1 in$^2$ opening
10 Pa pressure

It is air barrier, not vapor barrier, that matters most
Air Leakage Condensation: Control Strategies

1. “Plug all holes” – an air barrier system
   → Hard to be perfect, so …

2. Control driving forces
   → HVAC pressure differences, stack effect, wind
   → Reduce interior moisture (control interior RH!)

3. Control Temperature of condensing surface
   → insulated sheathing, special heating, etc.
Wall w/o Insulated Sheathing

Air leakage

Cold = Condensation

Vapour Diffusion
Wall with Insulated Sheathing

- Air leakage

- Vapour Diffusion

- Warm = no condensation
\[ T_{\text{back of sheathing}} = T_{\text{interior}} - (T_{\text{interior}} - T_{\text{exterior}}) \frac{R_{\text{batt}}}{R_{\text{total}}} \]
**Insulation Ratios**

<table>
<thead>
<tr>
<th>Indoor RH</th>
<th>20%</th>
<th>30%</th>
<th>40%</th>
<th>50%</th>
<th>60%</th>
</tr>
</thead>
<tbody>
<tr>
<td>T_{outdoor} (°C)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0.12</td>
<td>0.32</td>
<td>0.47</td>
<td>0.60</td>
</tr>
<tr>
<td>-10</td>
<td>0.23</td>
<td>0.40</td>
<td>0.54</td>
<td>0.64</td>
<td>0.73</td>
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<tr>
<td>-20</td>
<td>0.41</td>
<td>0.55</td>
<td>0.65</td>
<td>0.73</td>
<td>0.80</td>
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<tr>
<td>-30</td>
<td>0.53</td>
<td>0.64</td>
<td>0.72</td>
<td>0.78</td>
<td>0.84</td>
</tr>
<tr>
<td>-40</td>
<td>0.66</td>
<td>0.70</td>
<td>0.76</td>
<td>0.82</td>
<td>0.86</td>
</tr>
</tbody>
</table>

*prudent to assess w/ temperature dependent insulation R-value*
Vapor diffusion & foam sheathing
Vapour Retarder / Barrier Materials

- Concrete, glass, metal <0.1
- Impermeable peel & stick <1
- Polyethylene sheet 3
- Vapour Barrier Paint, smart vapour retarder
- Vinyl Wallpaper 10–30
- Plywood/OSB (at low RH levels) 20–60
- XPS, 60–90/ inch
- Closed-cell sprayfoam 60–120 / inch
Super-Insulation Strategies

→ All exterior insulation is moisture safest
→ Split and thick walls require care in vapor diffusion control, drying

Thick wall approach

Split Insulation Approach
North and south elevations were used for testing
Natural weather exposure (Southern Ontario)
Interior Conditions: 21 °C, 40% RH (winter)
High R-value Wall Research

2x6 Datum

Double Stud

Split – Polyiso

Split – XPS

Split – Mineral Wool

R–24 (installed)

R–35 (installed)

I–Joist similar

R–35 (installed)

R–35 (installed)

R–34 (installed)
Test walls in test hut

3 exterior insulated samples
Finished, under test
Air Leakage Apparatus

- Inject room air at bottom of wall
- Control air flow path using upper air relief hole
- Represents air leakage at electrical outlet
North Side OSB Moisture Content

Many results, here is one example....

Moisture Content - Lower OSB

- Double Stud
- I-Joist
- Datum
- Polysio
- XPS
- Rockwool

Equilibrium Phase
Air Injection Phase
Drying Phase

Enough exterior insulation avoids air leakage condensation risk
Insulation Variables – Double Stud Walls/SIPs

<table>
<thead>
<tr>
<th>Insulation Type</th>
<th>Effective R-value @ Standard 24°C</th>
<th>Effective R-value @ Cold -20°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.5” Dense-packed (4pcf) cellulose (CFI), 6.5” gap between 2x4s</td>
<td>R-38</td>
<td>R-41</td>
</tr>
<tr>
<td>13” Open-cell ½ pcf sprayfoam (ocSPF), 6” gap between 2x4s</td>
<td>R-37</td>
<td>R-40</td>
</tr>
<tr>
<td>5” Closed-cell 2 pcf sprayfoam (ccSPF) and 7” Dense-packed (4pcf) cellulose (CFI), 5” gap between 2x4s</td>
<td>R-38</td>
<td>R-40</td>
</tr>
<tr>
<td>8” EPS SIPs</td>
<td>R-32</td>
<td>R-40</td>
</tr>
</tbody>
</table>
All walls will perform adequately under normal operating conditions and perfect air tightness, well below 20% MC.
Deep stud insulated walls with cellulose or fiberglass are high risk from any small air leaks—exterior insulation and ocSPF or ccSPF cavity fill help reduce this risk.
Section 4: Getting into the Details
Enclosure assemblies

→ Walls
→ Roofs
→ Basements and Slab
Cladding attachment
Many Cladding Attachment Options

- Vertical Z-girts
- Horizontal Z-girts
- Crossing Z-girts
- Galvanized/Stainless Clip & Rail
- Aluminum Clip & Rail
- Thermally Improved Clip & Rail
- Non-Conductive Clip
- Long Screws through Insulation
Summary of Cladding Support Performance

- Continuous Vertical Z-Girt
- Continuous Horizontal Z-Girt
- Aluminum T-Clip
- Intermittent Galvanized Clip
- Stainless Steel Clip
- Isolated Galvanized Clip
- Fiberglass Clip Galv. Screws
- Galvanized Screws
- Fiberglass Clip SS Screws
- Stainless Steel Screws
- Fiberglass Clip No Through Screws

Percent Effectiveness of Exterior Insulation (Typical Range)
Cladding Attachment: Screws through Insulation

Longer cladding
Fasteners directly through rigid insulation (up to 2” for light claddings)

Long screws through vertical strapping and rigid insulation creates truss – short cladding fasteners into vertical strapping

Rigid shear block type connection through insulation, short cladding fasteners into vertical strapping
What about Really Thick Exterior Insulation?

Displacement (mm)

0.00 0.13 0.25 0.38 0.51 0.64 0.76

Load (kg)

3 inch 6 inch 9 inch 12 inch
Spandrels

Nominal R–14
Actual R–4.0 Assembly: U–0.250 BTU/hr–ft$^2$–°F
Even R-20 spandrel < R-5

Figure 1: Diminishing Rate of Return of Spandrel Section Overall Thermal Reaction.  
Source: Morrison–Hershfield
Cladding Attachment: Masonry Ties & Shelf Angles

Brick ties
10–30% loss for most galvanized ties,
5–10% loss for stainless steel

Continuous shelf angles
~40–50% R-value loss

Shelf angle on stand-offs
only ~15%–20 R-value loss
Relieving Angles

“The Ugly”

“The Bad”

“The Good”
Architectural Precast
Outer sealant on backer rod

Outward slope is preferred but horizontal is acceptable

Inner sealant on backer rod continuous for water and air control continuity

Outer seal drained at vertical joints

Note: Precast concrete is the water and air control layer between joints

Panel connection cast into panel c/w leveling shims; fill with spray foam to control convection of air

Smoke seal (air seal) and firestop

Fill space between slab edge and back or panel with mineral fiber firestop

Line of outer sealant at panel joints as rainscreen and finish

Line of inner sealant at joints: air seal and drainage plane

Precast panel (installed first)

Steel alignment plate completely sealed from interior air by spray foam

Gypsum board

Steel stud

Air-impermeable spray or board insulation

Cast in place anchor

Ensure airflow control continuity from the wall past the slab (including behind any columns)

Structural columns and walls should be held back from slab edge to allow for installation of air and thermal control layers

Modern Approach
High thermal
Excellent air / water
Durable
Multi-wythe Insulated Sandwich panels

- Outer sealant on backer rod
- Outward slope is preferred but horizontal is acceptable
- Inner sealant on backer rod continuous for water and air control continuity
- Outer seal drained at vertical joints
  **Note:** Precast concrete is the water and air control layer between joints
- Line of outer sealant at panel joints
- Line of inner sealant at panel joints
- Smoke seal and firestop as required

**Complete prefab high-performance enclosure**

- Precast panel (installed first)
- Steel alignment plate
- Gypsum board
- Steel stud
- Ensure smoke seal and firestop continuity at vertical joints
- Cast in place anchor

**R-10 to R-30+**

- Structural columns and walls should be held back from slab edge to allow for installation of connections
Some owners insist on it. Eg. US Federal Government (GSA)
The “Perfect” Roof?: Protected Membrane Roof

Ballast (rock, pavers, earth)

Filter fabric

Extruded polystyrene insulation

Thermal control

Water–air–vapor control

Planar roof structure sloped at min. 2% toward drains

Drainage gap, i.e., drainage mat or grooved insulation

Ballast=heavy

Premium insulation cost

Fully-adhered roof membrane
Plaza Decks and PMR
The tried and true, light-weight alternate

Questions:
Membrane chemistry?
Membrane color?
Attachment?
R-value?
Air barrier?
Vapor barrier?

High R-value Roof Assemblies

Code Minimum Insulated Low-Slope Roofs

- **Conventional**
  - Simple design
  - Standard details with deeper structure

- **Inverted/PMR**
  - Least durable but least expensive
  - Simple design
  - Standard details with deeper structure

- **Vented**
  - More complex design

**Exterior Insulated+ (conventional or inverted/PMR)**
- Best durability but most expensive
- Some challenges with more layers of insulation & detailing
- Simple design

**Deeper Joist/Truss – (vented or unvented)**
- Least durable but least expensive
- Simple design
- Standard details with deeper structure

**Split Insulated (unvented)**
- Decent durability
- Moderate cost
- More complex design
Insulating Sloped & Compact Roofs

New Challenges:
- Getting to higher R-values (R-60 to R-100+)
- Vapour control?
- Air Barrier & Air Permeable insulation
- Constructability & Thickness
- Roofing Materials
- Roof Venting
- Interior Services
Unvented Exterior insulated roof
Good continuity of water, air, vapor

8" concrete foundation wall
Protection board to 6" (150 mm) below grade
Drainage mat
4" XPS rigid insulation (R-20)
Dampproofing (water control layer drainage plane)
Capillary break
Granular fill
2" XPS rigid insulation (R-10)

Modest thermal bridge

Note: A continuous air-vapor control layer (e.g. heavy poly) can be used below the slab (never below the insulation) and sealed to the wall for slightly improved performance). Insulating under and around the footing is feasible and may be worth doing in very cold climates.

Air control should be made continuous by sealing the wall to the slab.
Exterior Insulation

→ Bituminous air–water–vapor barrier on concrete
Interior Insulation Solution

- Poured concrete foundation wall
- Rigid vapor semi-permeable insulation; R-7.5 to R-20 (XPS, EPS, PIC)
- 2x4 steel stud or 2x4/2x6 wood stud wall with fibrous insulation
- Gypsum board with latex paint vapor control (no polyethylene or aluminum foil barriers)
- Capillary break
- Drainage layer over dampproofing
- Granular fill

1” to 4” EPS, XPS or ccSPF
→ Airtightness still important
→ Radon control, moisture part of airtightness
ccSPF as on-grade insulation
Conclusions

→ High performance enclosures are the future
→ Eventually Net Zero, or close, will be the norm
→ Modern principles of building enclosure design can be extended to deliver the future
   → Higher R-value
   → Limited thermal bridges
   → Excellent Airtightness
→ Usually, exterior continuous insulation
Exterior Water-Air-Thermal Barriers