7th Annual North American Passive House Conference
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# Performance of 8 Passive House Envelopes in Cold Climates

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Passive House Institute US

# Session Learning Objectives:

- Understand the significance of accurately calculating R-values using 2-dimensional calculation protocols, and the benefits of using continuous insulation for overall R-value performance.

- Identify common linear thermal bridges in a residential envelope, and identify the steps that can be taken to minimize thermal bridging at these locations.

- Identify and understand the significance of an envelope's "critical layer" in terms of moisture performance. What steps can be taken to minimize the risk of moisture damage and/or mold growth in the critical layer?

- Develop a general understanding of the embodied energy and embodied carbon in common envelope materials. Answer the question of whether or not Passive House envelopes built with these materials exhibit life-cycle carbon savings and energy savings compared to standard homes?

# Outline

1. Background
2. Review
3. Case studies & envelope selection
4. Section 1 – 2-D R-value calculations
5. Section 2 – Thermal bridging (THERM simulations)
6. Section 3 – Hygrothermal performance (WUFI simulations)
7. Section 4 – Life cycle environmental impacts (Athena models)

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6. Section 3 – Hygrothermal performance (WUFI simulations)
7. Section 4 – Life cycle environmental impacts (Athena models)

The goal is not to pick a winner, but to use the comparison to investigate issues common to all passive house envelopes. Also, to highlight the strengths and weaknesses of different envelope types.

# Background

- B.A. in physics and math from St. Olaf College, 2001
- Worked as a framer building homes from 2002 - 2005
- Began work on Master's thesis in 2007
- Fulbright scholarship to complete thesis and study cold climate envelopes in Norway in 2010/2011

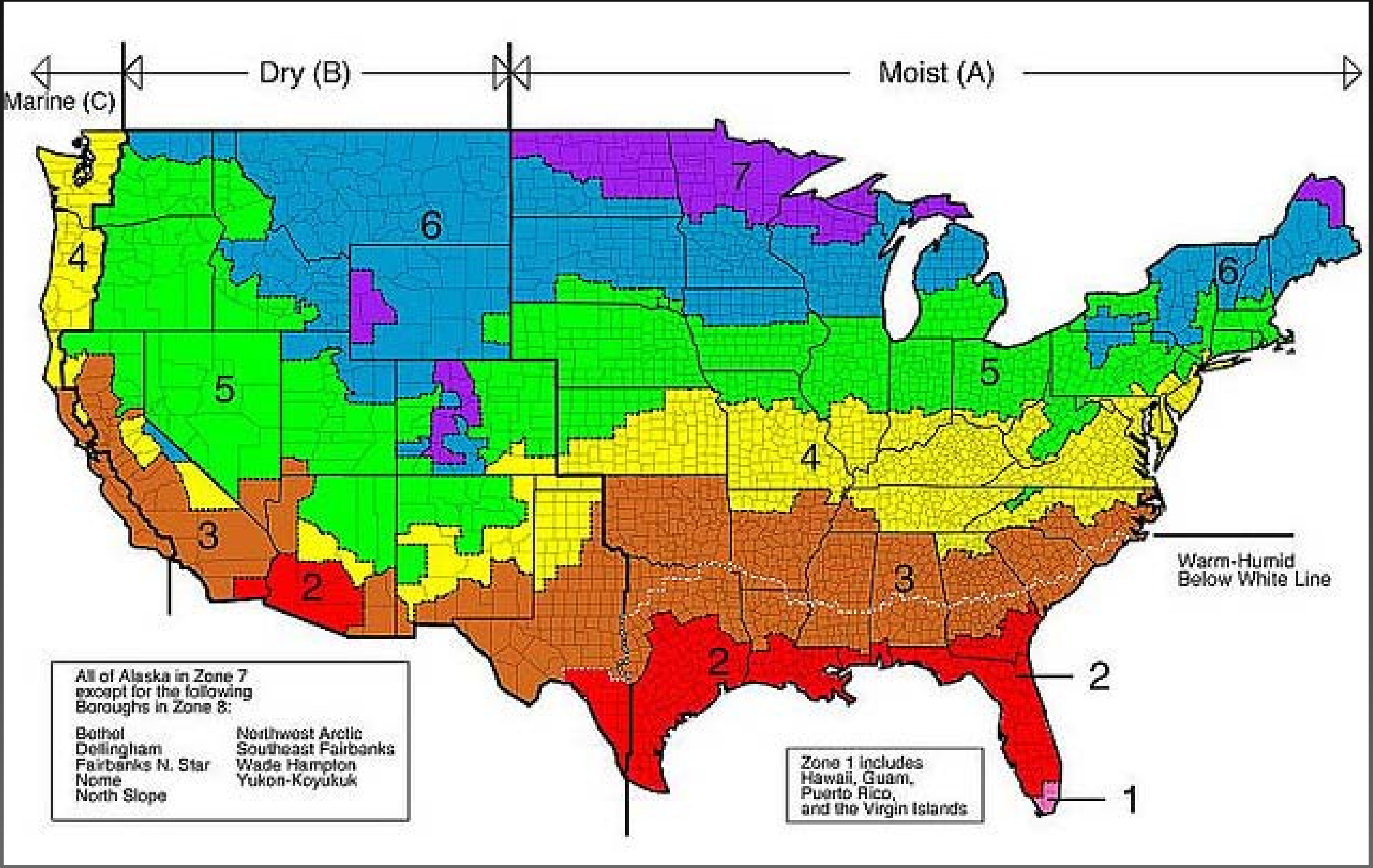
# Background

- In Norway, studied at the Center for Zero Emissions Buildings (ZEB)

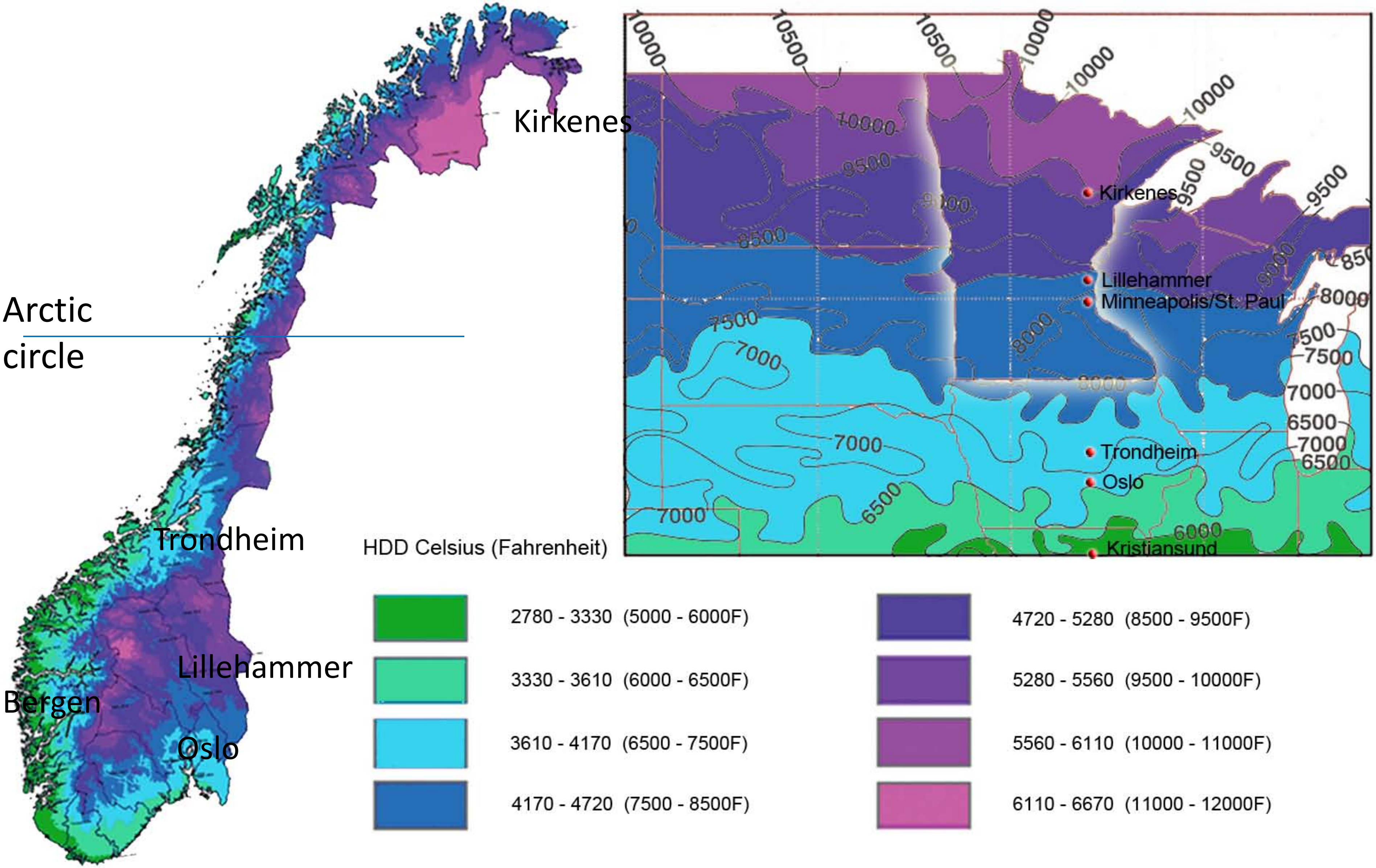
- Housed within the Norwegian technical university, NTNU, in Trondheim

- ZEB has close ties with SINTEF Byygforsk – SINTEF is similar to the Buildings Technology Center (BTC) at ORNL, but greater cooperation between industry and university research. Also responsible for national building/energy code development.

# Review – "Cold Climate" - for these purposes, primarily Climate Zones 6,7, plus Scandinavia



# Review- climate comparison



# Case Studies – IECC climate zone 5,6

| Project: Smith House | Location: Urbana, IL - HDD 6359 | | Envelope types | R-value |
|---|---|---|---|---|
|  | | Wall | 12" TJI balloon frame insulated with blown fiberglass + exterior EPS | R-60 |
| | | Roof | 16" TJI insulated with blown fiberglass | R-60 |
| | | Floor slab | concrete insulated with EPS | R-56 |
| | | Notes | First Passive House constructed in North America | |

TJI frame w blown fiberglass

| Project: Passive House in the Woods | Location: Hudson, WI - HDD 7866 | | Envelope types | R-value |
|---|---|---|---|---|
|  | | Wall | 11" ICF (6" concrete) 5" EPS integral to ICF + exterior EPS | R-70 |
| | | Roof | light frame wood truss insulated with exterior polyisocyanurate | R-95 |
| | | Floor slab | concrete insulated with XPS | R-60 |
| | | Notes | First certified Passive House in Wisconsin | |

ICF w exterior EPS

# Case Studies – IECC climate zone 6

| Project: Wilder House 1 Location: St. Paul, MN - HDD 7980 | | Envelope types | R-value |
|---|---|---|---|
|  | Wall | 1.5" thick structural engineered panel (SEP panel) | R-17 |
| | | insulated with exterior XPS (SEP-ETMMS) | |
| | Roof | solid wood rafters with 0.75" thick SEP panel | R-28 |
| | | insulated with exterior XPS (SEP-ETMMS) | |
| | Floor slab | concrete | R-10 |
| | | insulated with XPS | |
| | Notes | Not designed as a Passive House | |

SEP panel w exterior rigid foam

| Project: GO Logic Passive Location: Belfast, ME - HDD 7852 | | Envelope types | R-value |
|---|---|---|---|
|  | Wall | 6.5" urethane SIP panel + interior 2x4 stud wall | R-50 |
| | | 5.5" urethane foam integral to SIP + interior blown cellulose | |
| | Roof | 24" wood scissor truss | |
| | | insulated with blown cellulose | R-80 |
| | Floor slab | concrete | ? |
| | | insulated with EPS | |
| | Notes | First certified Passive House in Maine | |

SIP panel

# Case Studies – IECC climate zone 7

| Project: BioHaus | Location: Bemidji, MN - HDD 9869 | Envelope types | R-value |
|---|---|---|---|
|  | Wall 1 | advanced 2x12 stud wall framing<br>insulated with open cell SPF + exterior EPS | R-70 |
| | Wall 2 | advanced 2x6 stud wall framing<br>insulated with open cell SPF + exterior VIP | R-70 |
| | Roof 1 | flat roof, 12" TJI<br>insulated with open cell SPF + exterior VIP | R-100 |
| | Roof 2 | flat roof, 12" TJI + 8" perpendicular sleeper trusses<br>insulated with open cell SPF | R-100 |
| | Floor slab | concrete, insulated with EPS | R-55 |
| | Notes | First certified Passive House in North America | |

Advanced framing w spray foam

| Project: Skyline House | Location: Duluth, MN - HDD 9818 | Envelope types | R-value |
|---|---|---|---|
|  | Wall | double 2x4 stud wall framing<br>insulated with blown cellulose | R-55 |
| | Roof | Light frame wood truss with cold attic<br>insulated with blown cellulose | R-95 |
| | Floor slab | concrete<br>insulated with XPS | R-60 |
| | Notes: | Narrowly missed Passive House certification | |

Double stud w blown cellulose

# Case Studies – Scandinavian climates

| Project: Ranheimsveien 149 Location: Trondheim, Norway - HDD 7200 | Envelope types | R-value |
|---|---|---|
| Wall | advanced 2x6 stud wall framing | R-63 |
| | insulated with ? + exterior mineral wool (flexvegg) | |
| Roof 1 | 5.5" massivtre element, flat roof | R-87 |
| | insulated with exterior mineral wool | |
| Roof 2 | 5.5" massivtre element + 20" furring trusses | R-87 |
| | insulated with exterior blown cellulose | |
| Floor slab | concrete | R-71 |
| | insulated with some type of polystyrene | |
| Notes | Meets Norwegian national Passivhus Standard | |

Massivtre w exterior mineral wool

| Project: Stenagervaenget 37 Location: Vejle, Denmark - HDD 6500 (approx.) | Envelope types | R-value |
|---|---|---|
| Wall | prefab stud wall panel with interior cross strapping | R-67 |
| | insulated with mineral wool + exterior mineral wool | |
| Roof | prefab wood roof panel | R-75 |
| | insulated with mineral wool + exterior mineral wool | |
| Floor slab | concrete | R-83.5 |
| | insulated with EPS | |
| Notes | Komfort Husene, also Certified Passive House | |

Advanced frame and interior cross strapping w mineral wool

# Case Studies – Scandinavian climates

| Project: Stenagervaenget 28 Location: Vejle, Denmark - HDD 6500 (approx.) | | Envelope types | R-value |
|---|---|---|---|
|  | Wall | 4" porous concrete block wall with brick cladding insulated with mineral wool | R-68 |
| | Roof | light frame wood truss insulated with mineral wool | R-78 |
| | Floor slab | concrete insulated with EPS | R-83.5 |
| | Notes | Komfort Husene, also Certified Passive House | |

Concrete mass wall w exterior mineral wool

Average R-values of cold-climate Passive House case studies

- Above grade wall: R-62.9 — Target: R-60
- Roof: R-83.8 — Target: R-80
- Floor slab: R-67 — Target: R-60

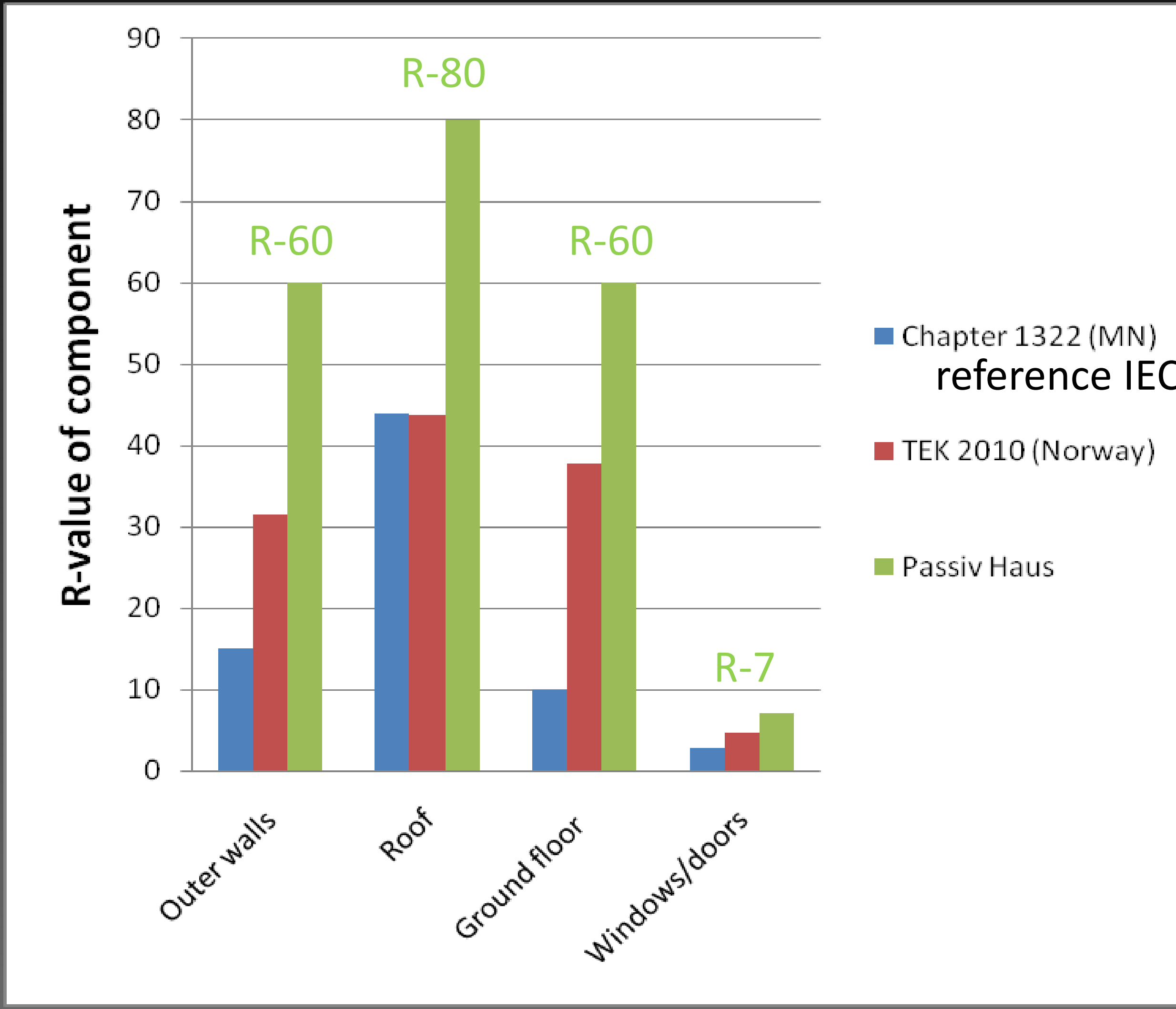
Average air tightness

- 0.46 ACH @50Pa — Requirement: 0.6

# Case Studies – results and comparison

**Envelope:**

- Walls – R-60 (4x higher)
- Roof = R-80 (2x higher)
- Floor slab = R-60 (6x higher)

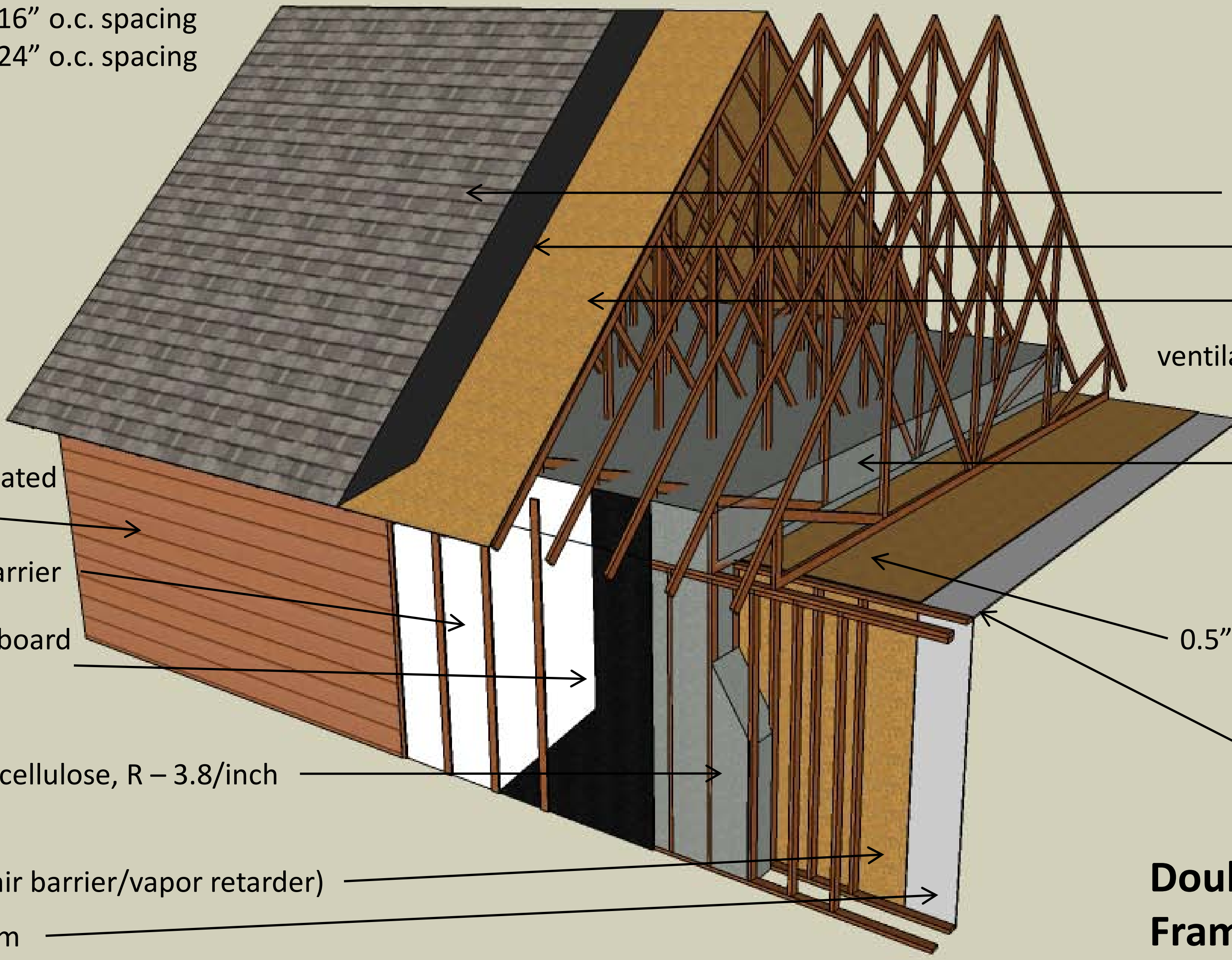



# High Performance Envelopes

*What are the concerns?*

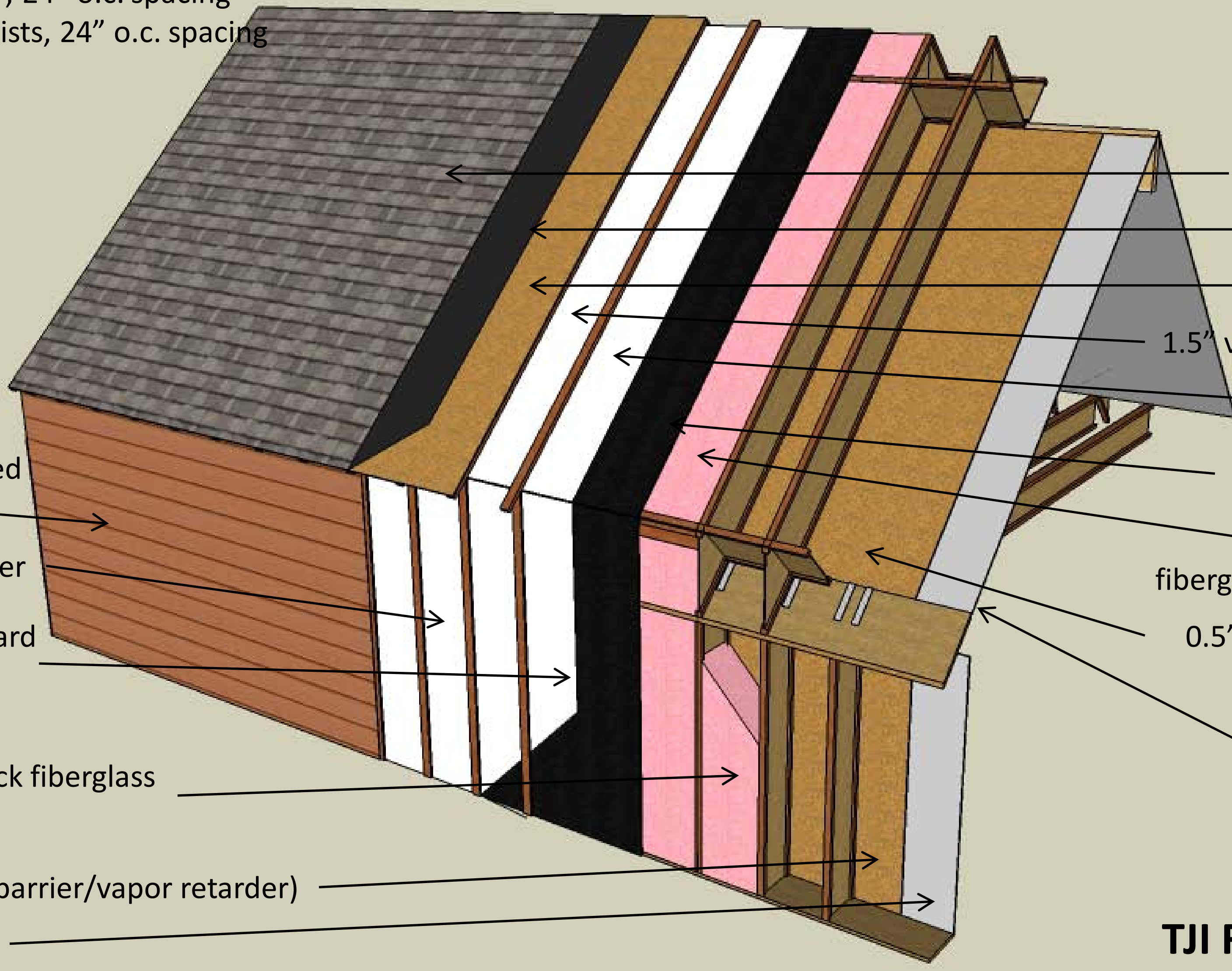
- Will the embodied energy and carbon neutralize the savings?
- With increased insulation and airtightness, is there increased risk of mold and moisture problems? – (hygrothermal performance)
- What is a "thermal bridge-free" detail?
- Unfamiliarity – what R-values are really required in this climate, and how should they be calculated?
- What types of envelopes work best?

# Double stud


2x4 studs, 16” o.c. spacing
truss roof, 24” o.c. spacing
asphalt shingles
roofing paper
0.5” OSB
ventilated “cold attic”
19.5” blown cellulose, R – 3.8/inch
back-ventilated cladding
weather barrier
0.75” fiberboard sheathing
16” blown cellulose, R – 3.8/inch
0.5” OSB (air barrier/ vapor retarder
0.5” gypsum
0.5” OSB (air barrier/vapor retarder)
0.5” gypsum
Double Stud Frame

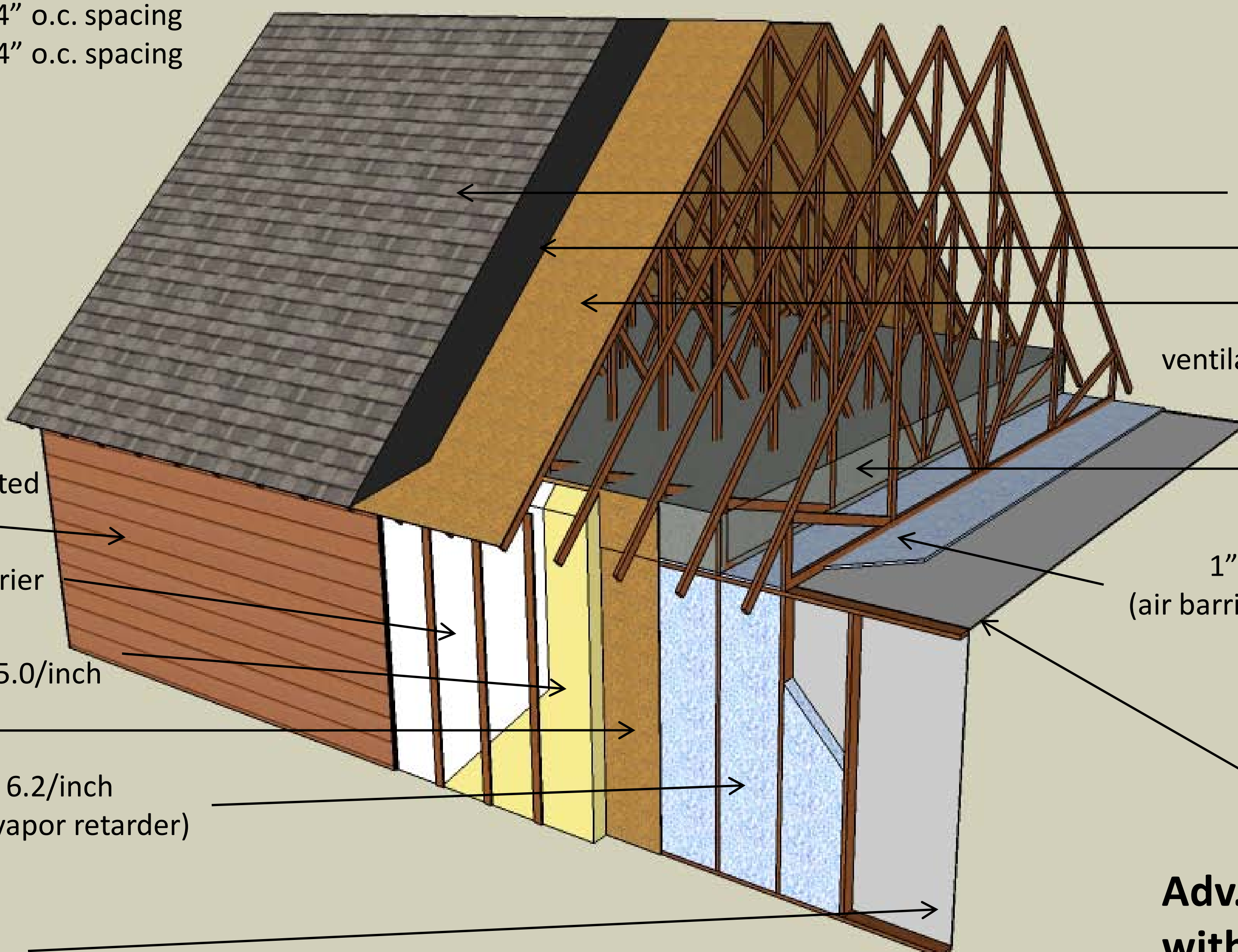
# TJI Frame (I-joist)

16” TJI “studs”, 24” o.c. spacing
20” TJI roof joists, 24” o.c. spacing



# Advanced Frame with SPF

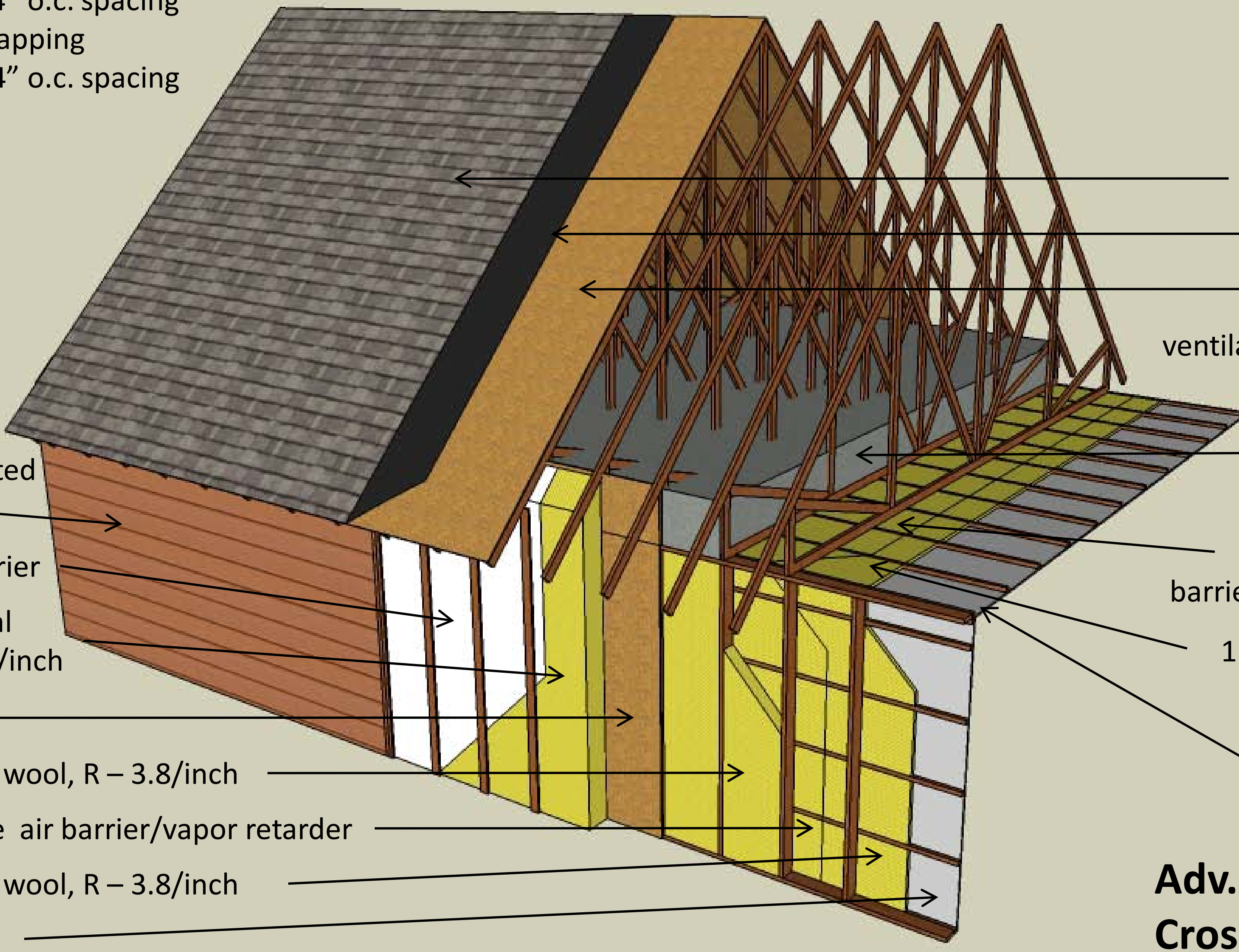
2x6 studs, 24" o.c. spacing
truss roof, 24" o.c. spacing




**Adv. Frame with SPF**

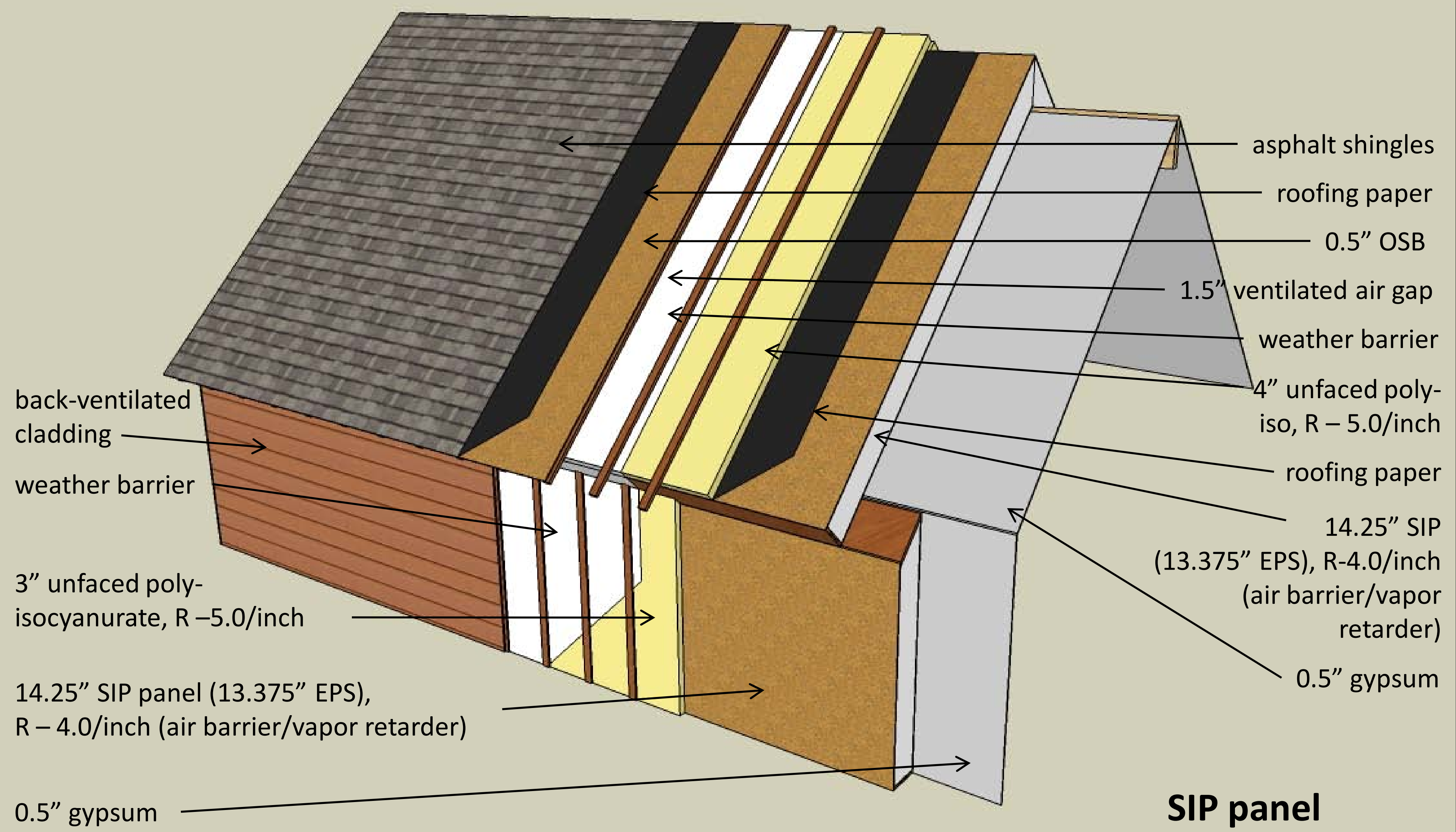
# Advanced Frame with cross strapping

2x6 studs, 24” o.c. spacing
2x2 cross strapping
truss roof, 24” o.c. spacing

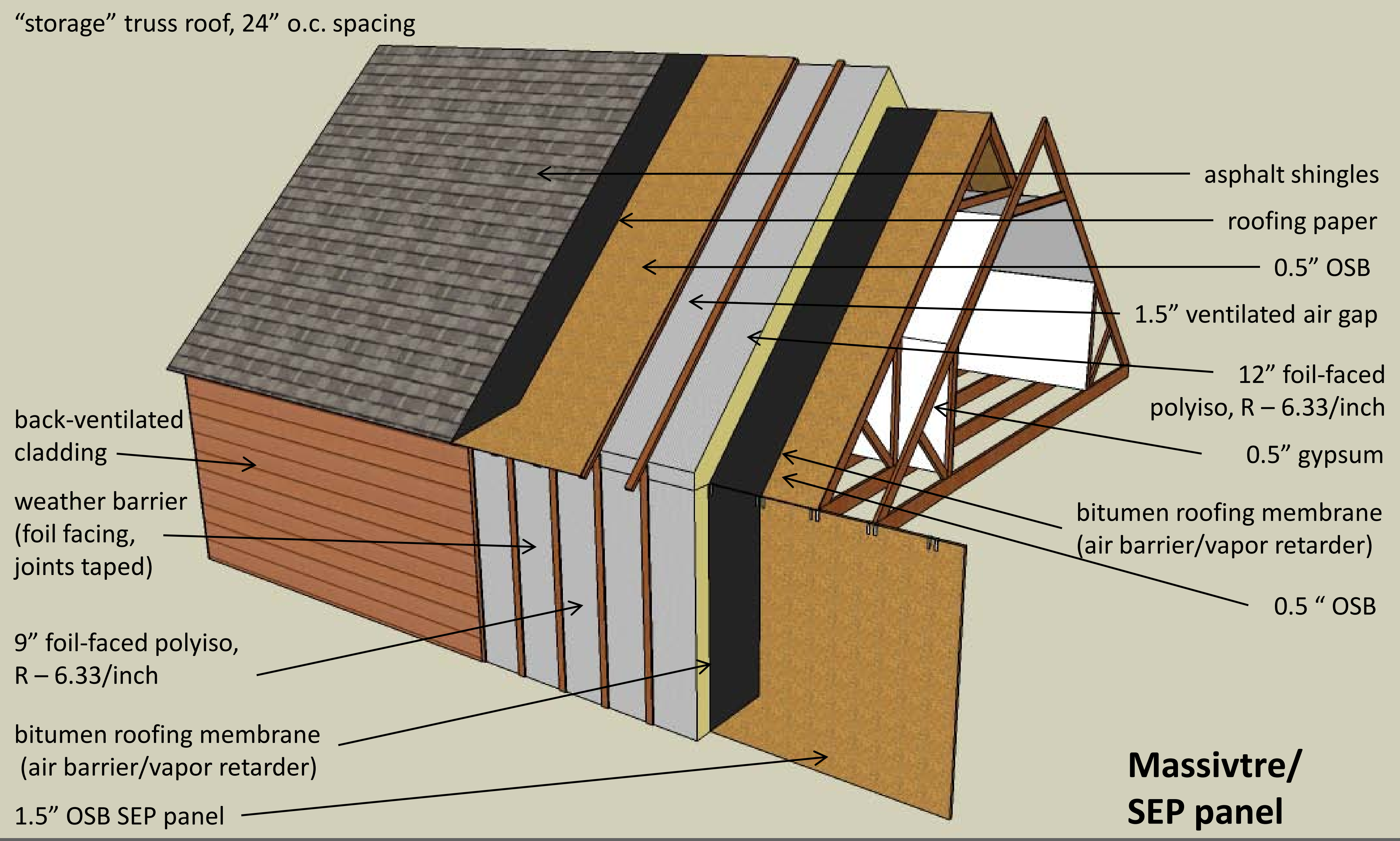



**Adv. Frame w. Cross Strapping**

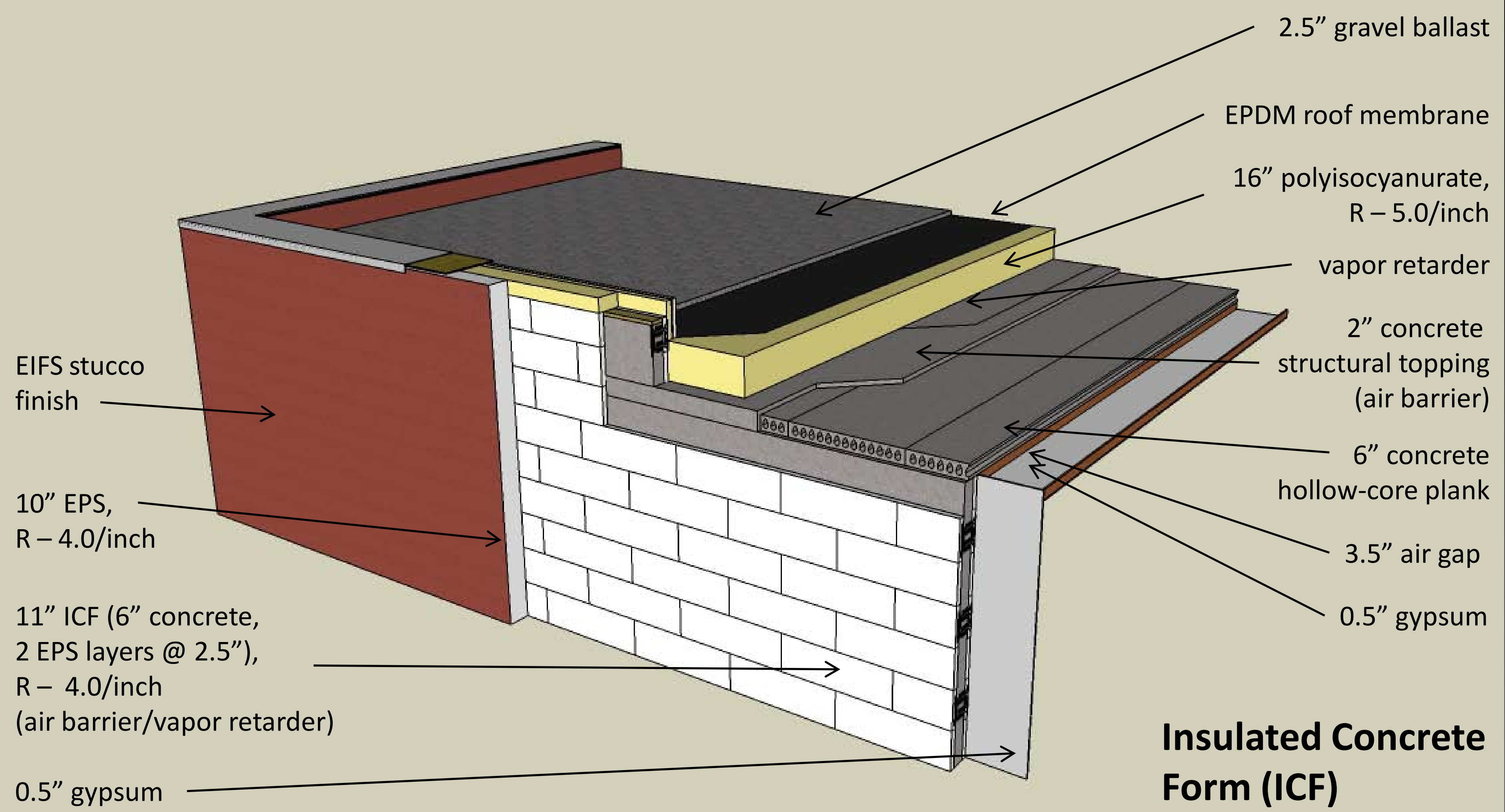
# Structural Insulated Panel (SIP)



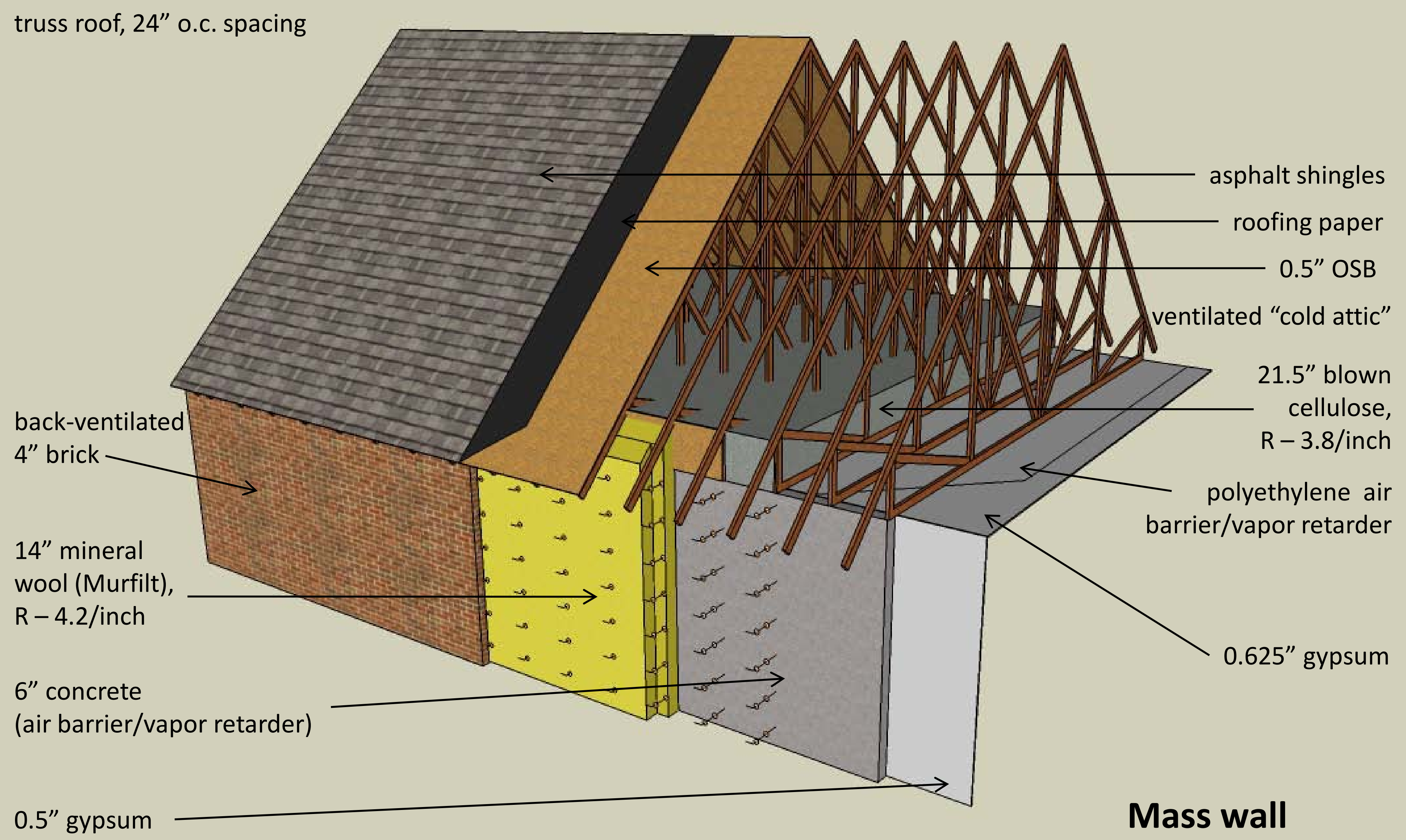
# Massivtre/SEP panel



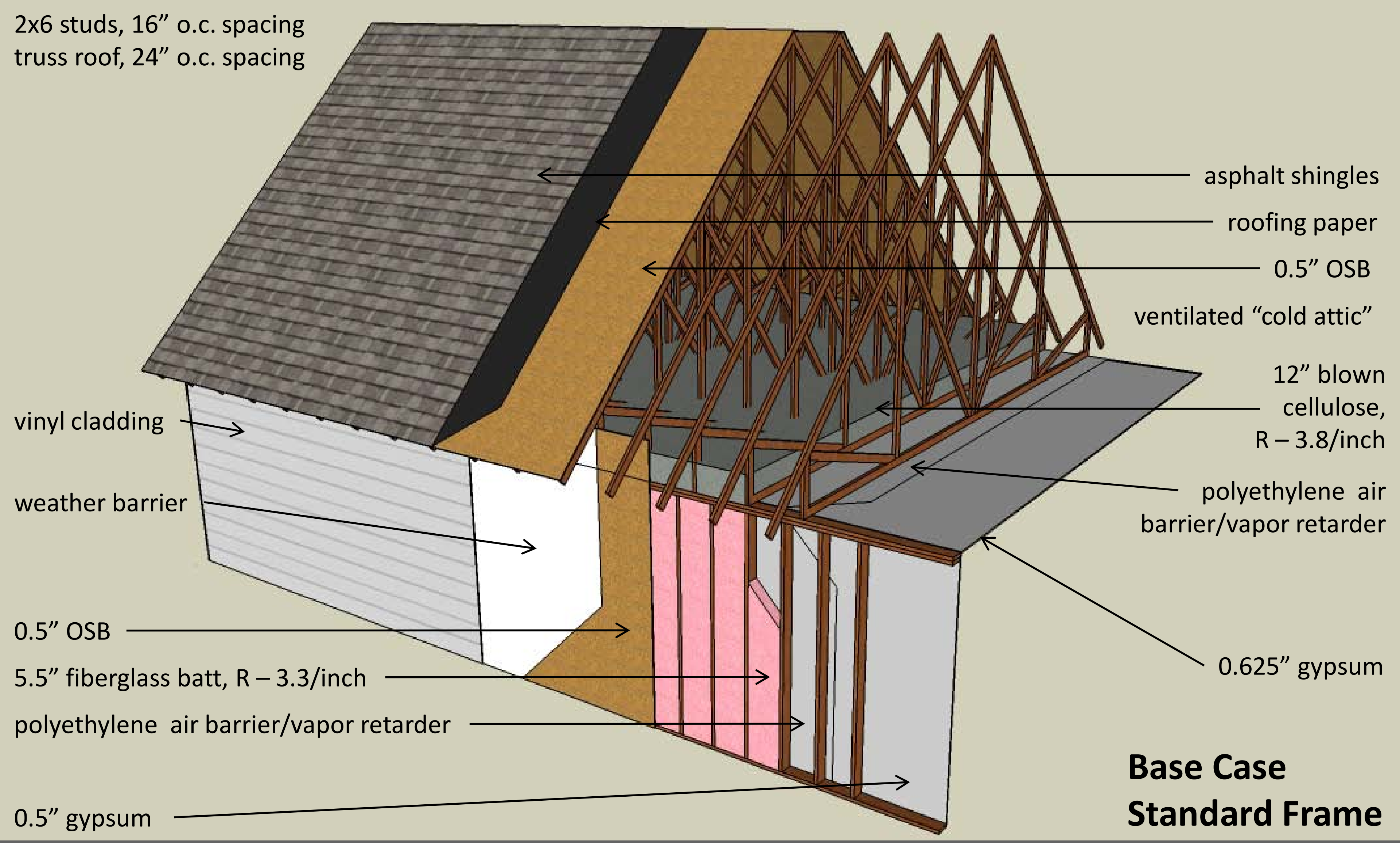
# Insulated Concrete Form (ICF)



# Mass wall


truss roof, 24” o.c. spacing
asphalt shingles
roofing paper
0.5” OSB
ventilated “cold attic”
21.5” blown cellulose, R – 3.8/inch
polyethylene air barrier/vapor retarder
0.625” gypsum
back-ventilated 4” brick
14” mineral wool (Murfilt), R – 4.2/inch
6” concrete (air barrier/vapor retarder)
0.5” gypsum
Mass wall

# Base case standard frame



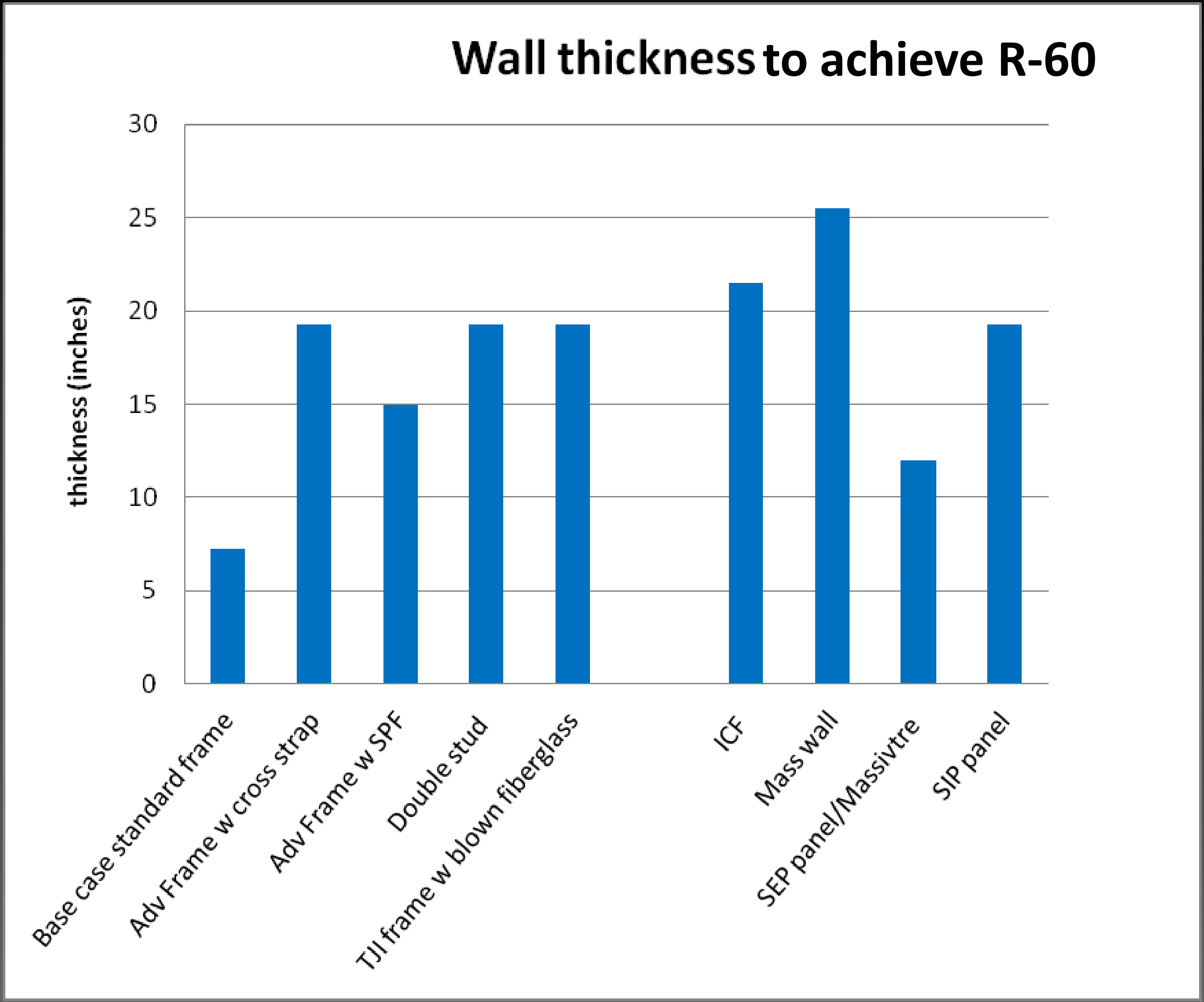
# Section 1 – 2-D R-value calculations

- Center of cavity R-value – the R-value calculated through the center of the wall, with no framing. (R-19) Very inaccurate.

- Clear wall R-value – the R-value calculated for a "clear" section of the wall (no windows, doors, other penetrations), includes framing, which can make up <u>25% of the wall area</u> in typical residential construction. (R-16) This is the typical "parallel paths" or "UA method" used in U.S.

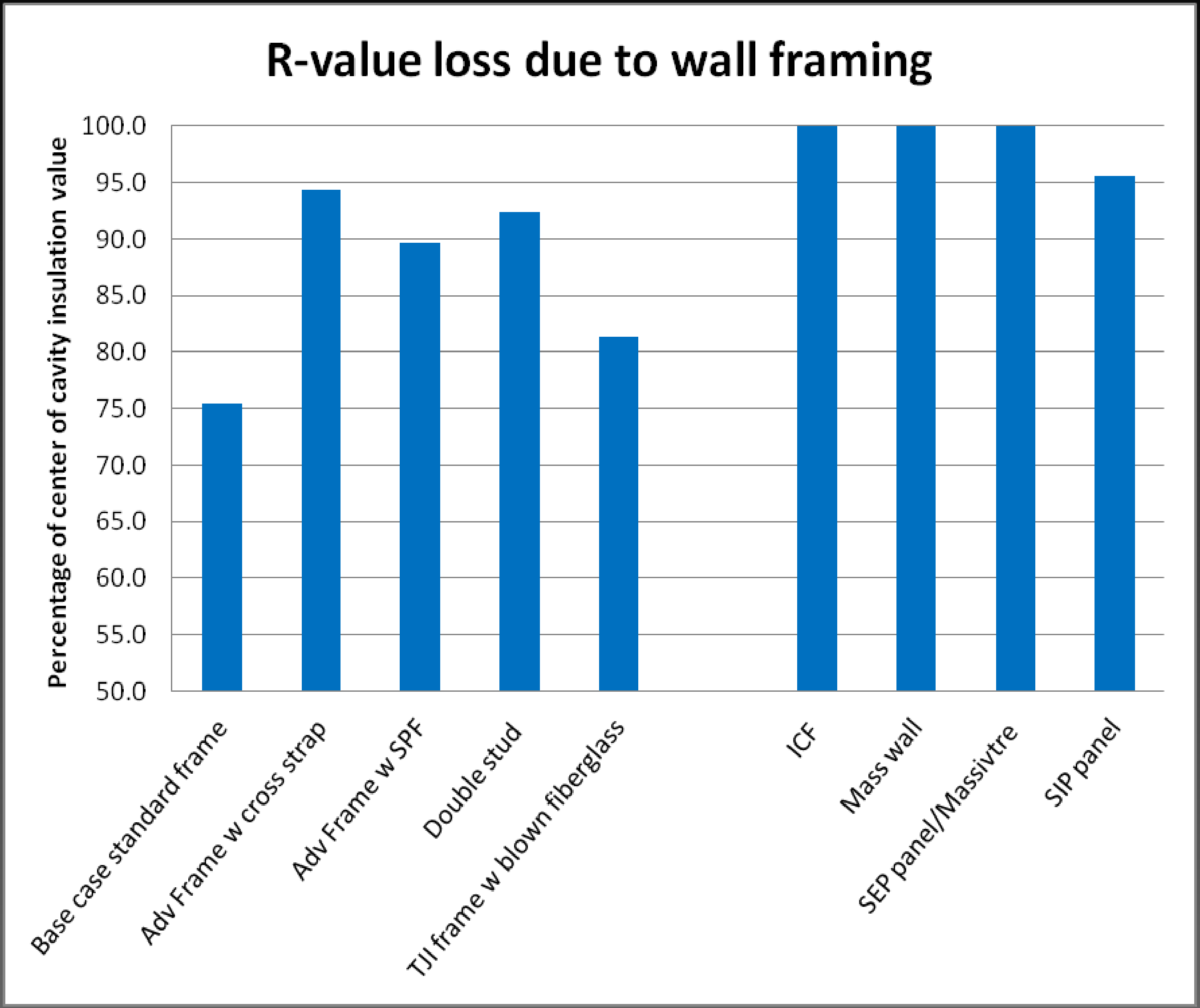
- 2-D R-value – based on the "clear wall" calculation, but adds lateral heat flow in the wall. Takes into account extra heat loss due to 2-dimensional flow of heat through thermal bridges such as studs . (R-15.5) Follows EN ISO 6946

# Section 1 – 2-D R-value calculations




Wall models are assembled using thicknesses of actual construction products and achieve R-60 (with some variation).

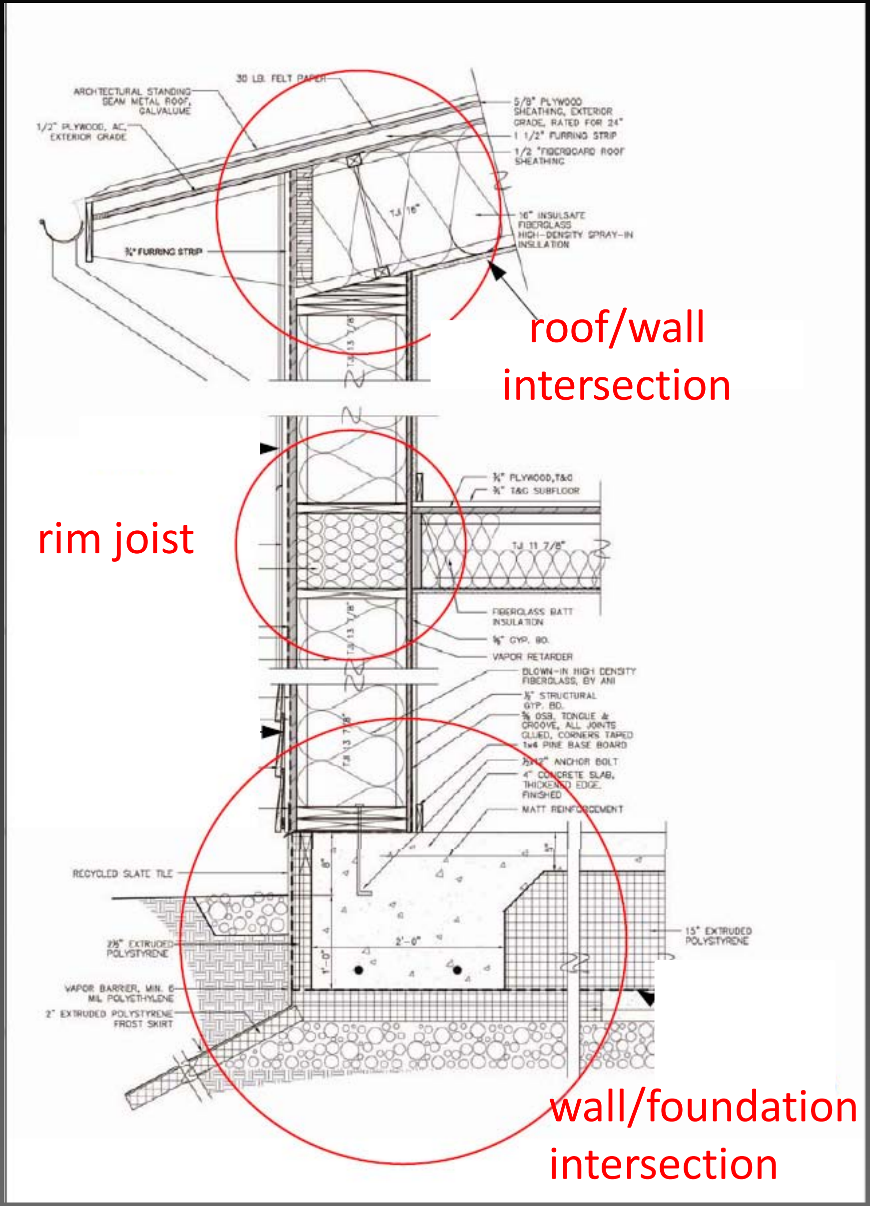
# Section 1 – 2-D R-value calculations




Final 2-D R-value divided by center of cavity R-value.

Shows the percentage reduction in R-value due to repetitive thermal bridges such as studs, plates, splines, etc.

# Section 2 – Thermal Bridge Analysis




## Thermal bridges

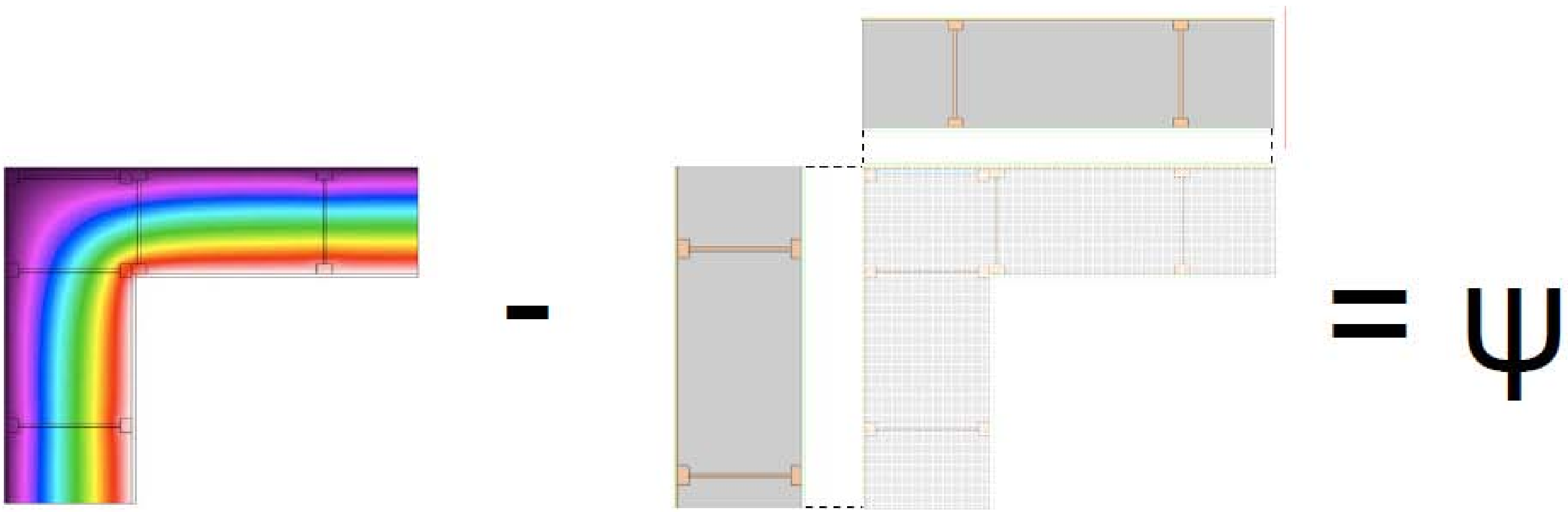
- repetitive bridges – already accounted for!
- point bridges – heat loss too small to consider
- linear bridges – heat loss should be calculated

Circled areas are common linear thermal bridges

Image from David White, Right Environments, 2010

# Section 2 – Thermal Bridge Analysis

Image from David White,
Right Environments, 2010




The thermal bridge heat loss is the difference between the "true" heat loss, calculated using 2-dimensional simulation (THERM), and the heat loss calculated using the typical U·A method.

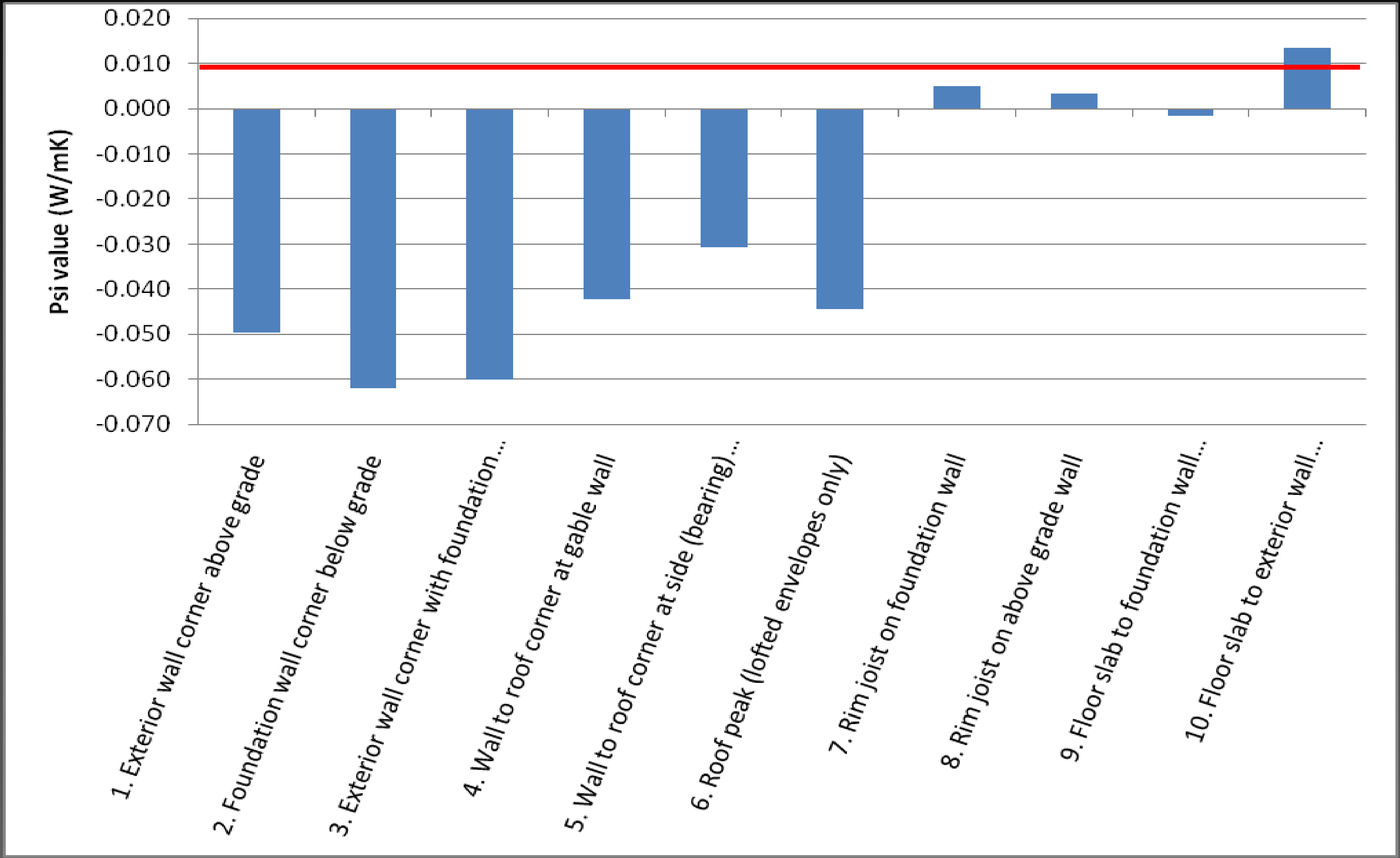
# Section 2 – Thermal Bridge Analysis

## 10 locations (but no window t.bridges), 8 different envelope types

| | Thermal Bridge Location | Adv Frame w cross strap | Adv Frame w SPF | Double Stud | TJI Frame | ICF | Mass wall | SEP panel | SIP panel | Average psi value of TB location |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1. Exterior wall corner above grade | -0.054 | -0.039 | -0.058 | -0.051 | -0.051 | -0.064 | -0.036 | -0.045 | -0.050 |
| 2 | 2. Foundation wall corner below grade | -0.062 | -0.062 | -0.062 | -0.062 | -0.051 | -0.075 | -0.062 | -0.062 | -0.062 |
| 3 | 3. Exterior wall corner with foundation wall | -0.062 | -0.056 | -0.060 | -0.064 | -0.051 | -0.075 | -0.051 | -0.061 | -0.060 |
| 4 | 4. Wall to roof corner at gable wall | -0.054 | -0.069 | -0.059 | -0.051 | 0.042 | -0.061 | -0.037 | -0.049 | -0.042 |
| 5 | 5. Wall to roof corner at side (bearing) wall | -0.054 | -0.069 | -0.059 | -0.018 | 0.042 | -0.058 | -0.014 | -0.017 | -0.031 |
| 6 | 6. Roof peak (lofted envelopes only) | - | - | - | -0.052 | - | - | -0.034 | -0.047 | -0.044 |
| 7 | 7. Rim joist on foundation wall | 0.010 | 0.003 | 0.006 | 0.006 | 0.003 | 0.000 | 0.003 | 0.009 | 0.005 |
| 8 | 8. Rim joist on above grade wall | 0.006 | 0.005 | 0.006 | -0.001 | 0.003 | 0.000 | -0.001 | 0.009 | 0.003 |
| 9 | 9. Floor slab to foundation wall intersection below | -0.021 | -0.021 | -0.021 | -0.021 | -0.005 | 0.008 | 0.034 | 0.034 | -0.002 |
| 10 | 10. Floor slab to exterior wall intersection at grade | 0.005 | 0.008 | -0.001 | 0.009 | 0.006 | 0.006 | 0.023 | 0.052 | 0.014 |
| | **Average psi value of envelope** | -0.032 | -0.033 | -0.034 | -0.030 | -0.007 | -0.036 | -0.017 | -0.018 | |

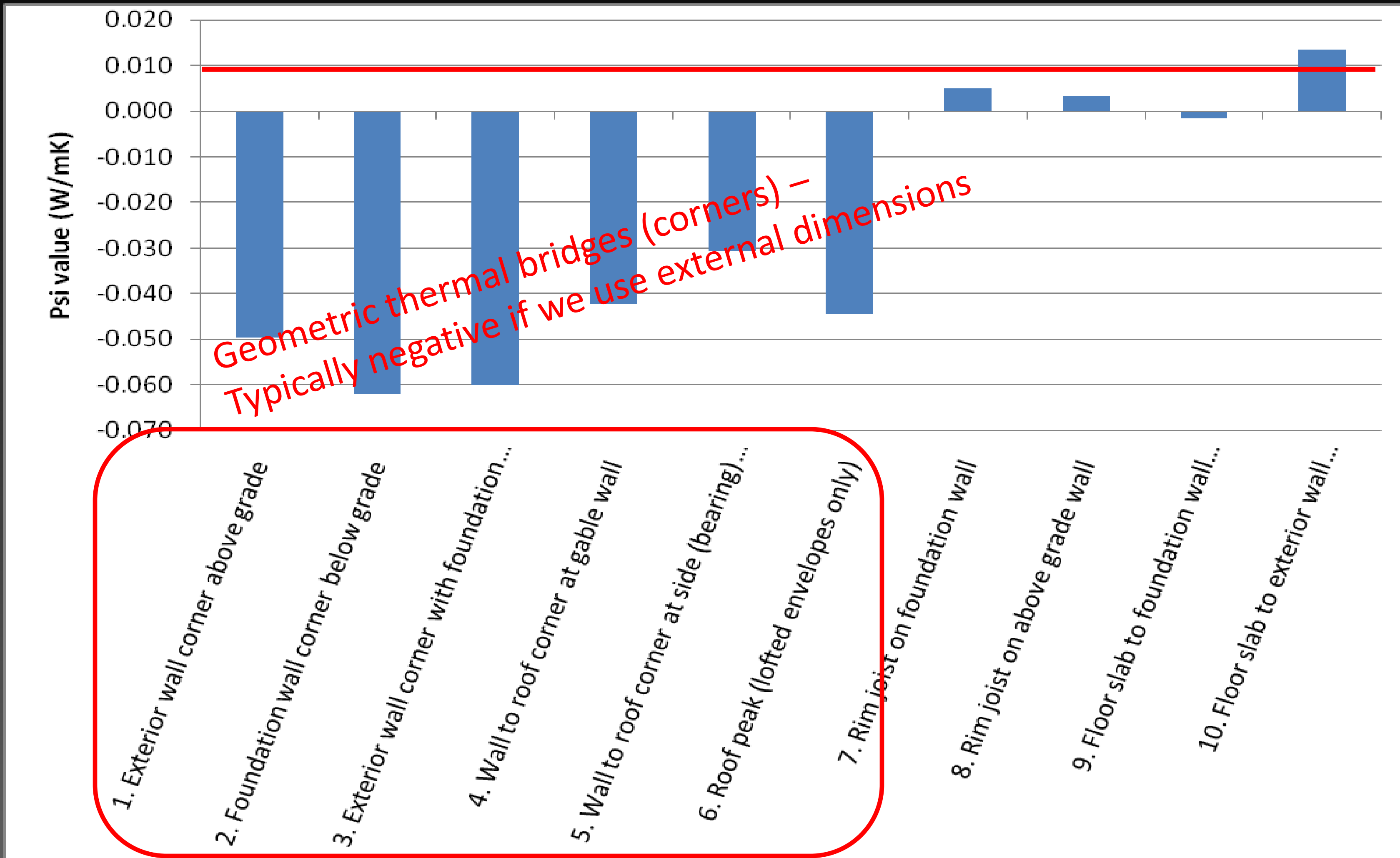
Passive House guideline, Ψ </= 0.01 W/mK

# Section 2 – Thermal Bridge Analysis




Average Ψ values for each detail location across all envelope types

# Section 2 – Thermal Bridge Analysis

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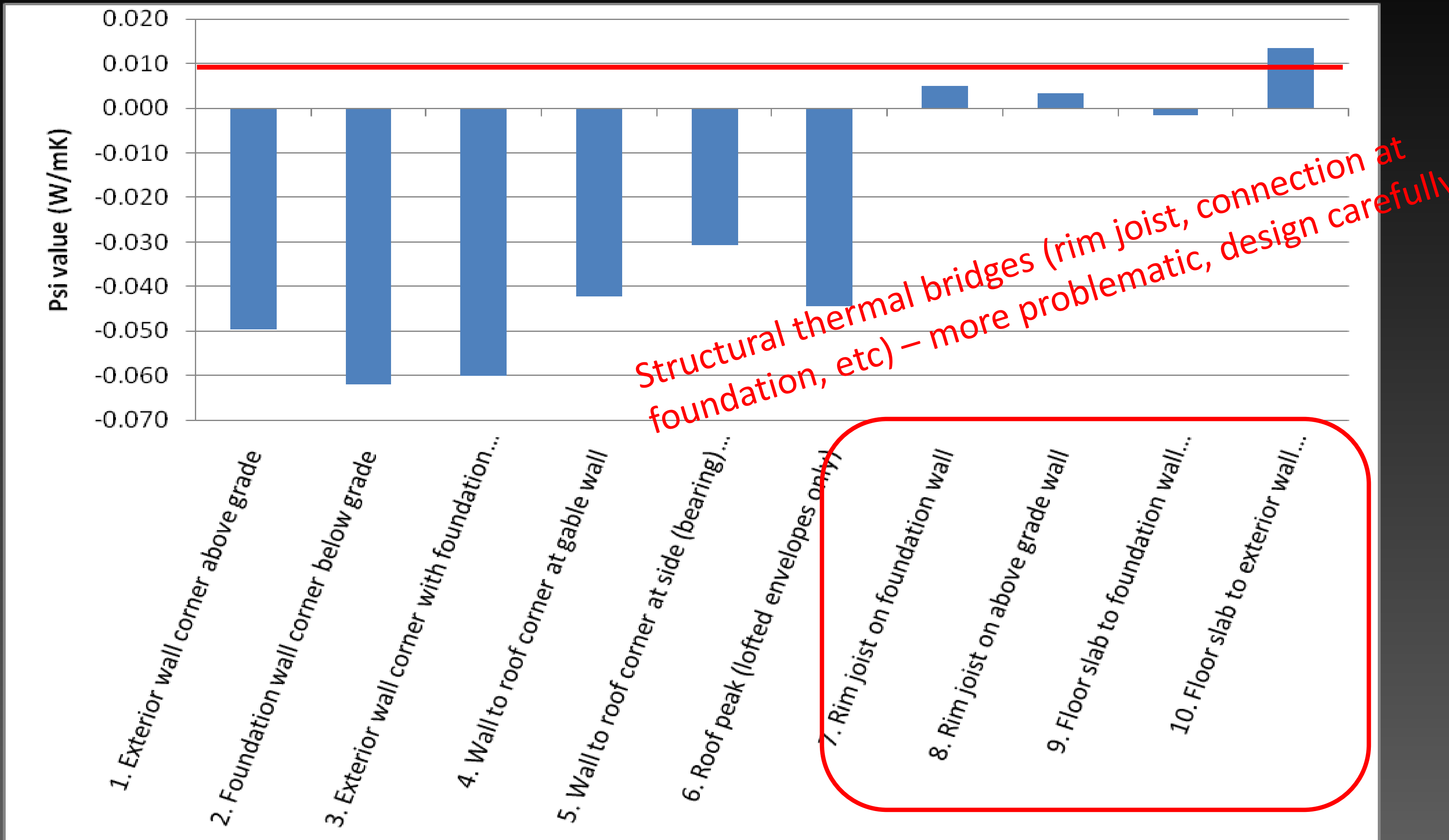
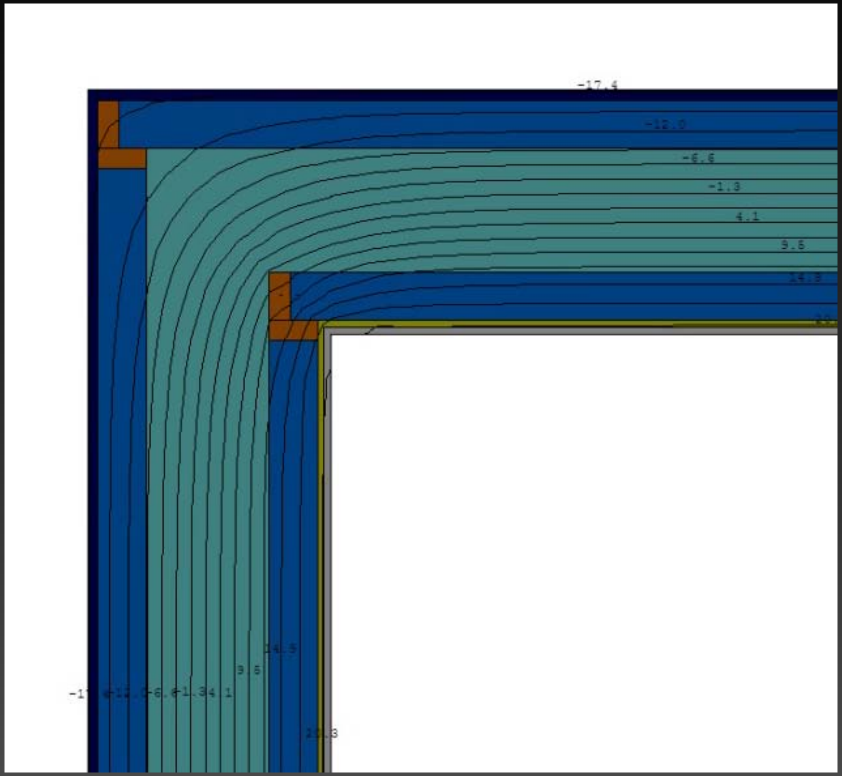
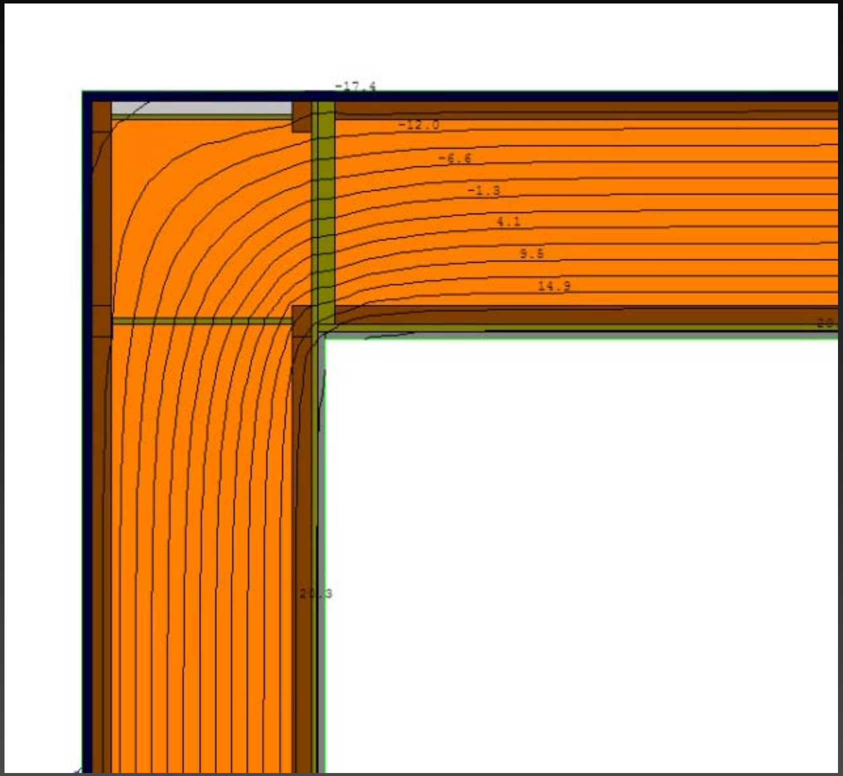



Average Ψ values for each detail location across all envelope types

# Section 2 – Thermal Bridge Analysis



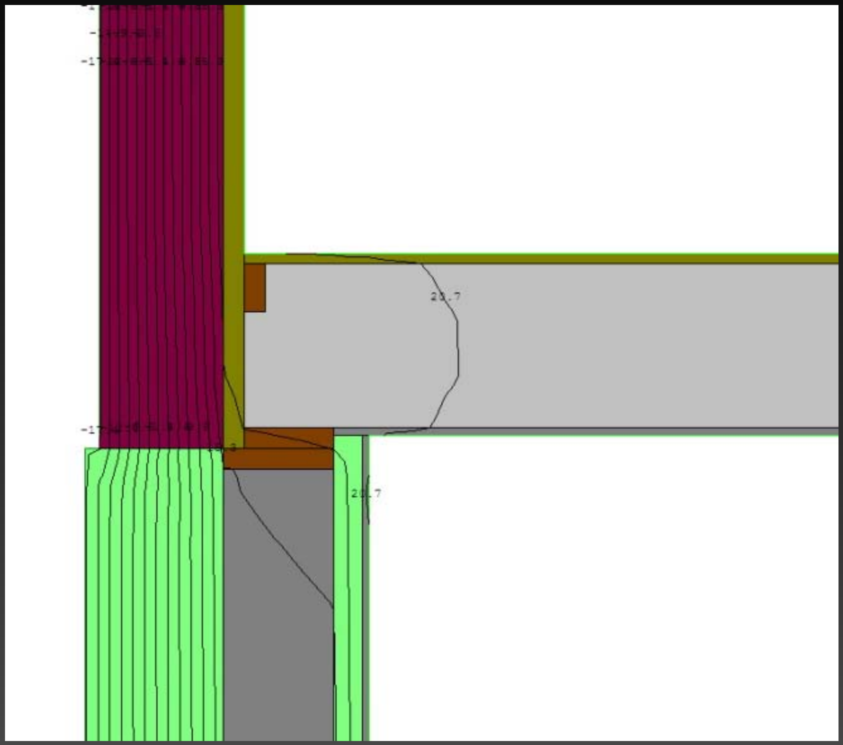

Double stud frame: Ψ = - 0.058 W/mK

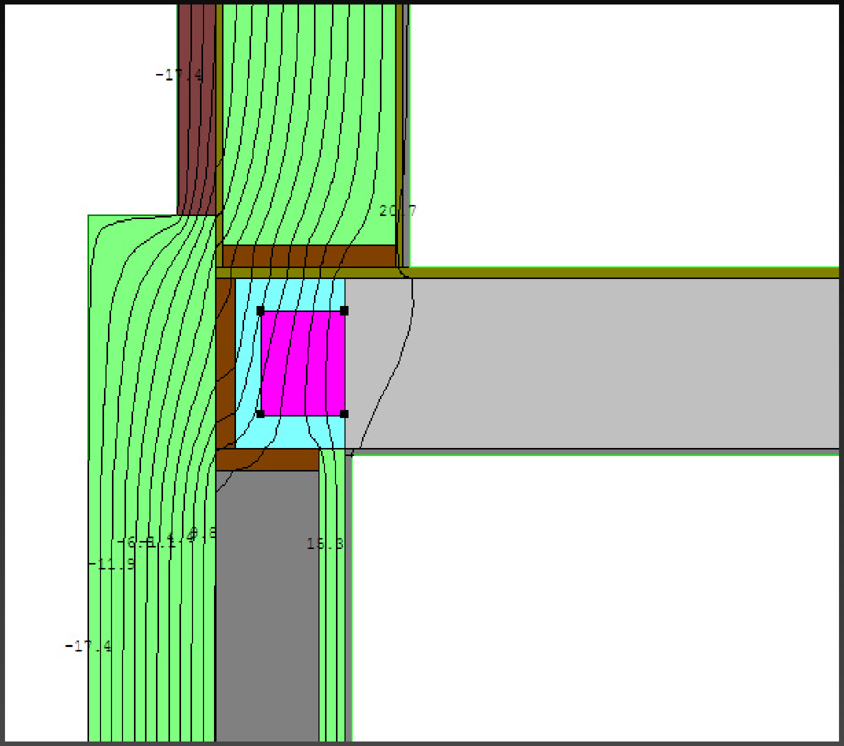
TJI frame: Ψ = - 0.051 W/mK

Both walls are the same thickness and have the same R-value.
Both details easily pass the Ψ </= 0.01 W/mK guideline, but double stud wall slightly better

STEP 1 – Avoid elements that bridge from interior to exterior

# Section 2 – Thermal Bridge Analysis





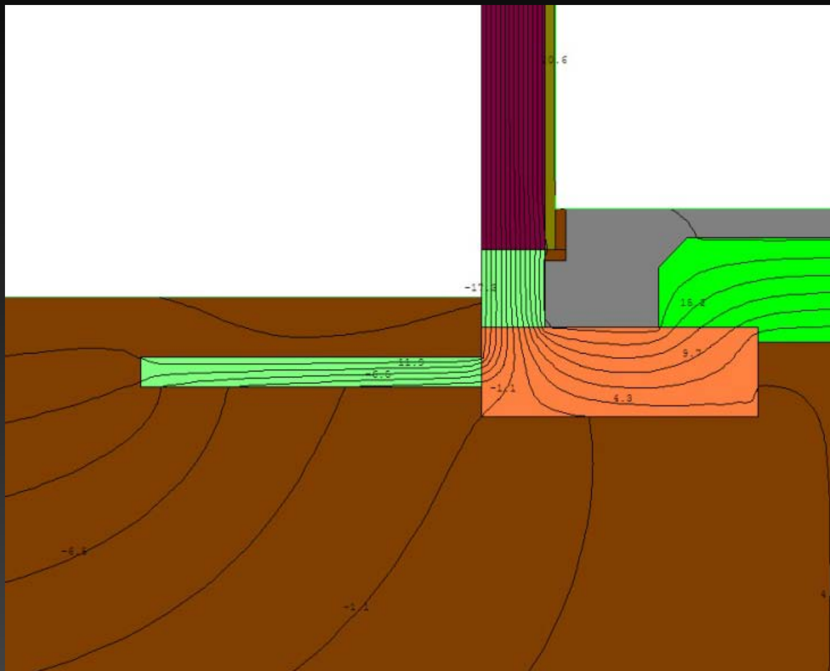
SEP panel rim joist: Ψ = 0.003 W/mK

SIP panel rim joist: Ψ = 0.009 W/mK

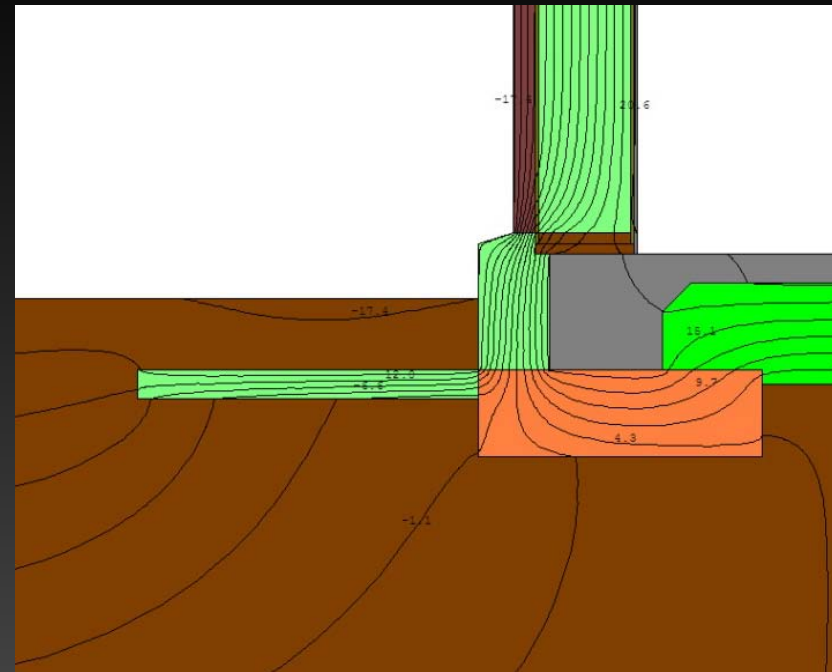
SEP panel wall's external insulation is aligned with basement wall's external insulation
Only SEP detail easily passes the Ψ </= 0.01 W/mK guideline

STEP 2 – Align insulation layers

# Section 2 – Thermal Bridge Analysis



SEP panel FPSF: Ψ = 0.023 W/mK

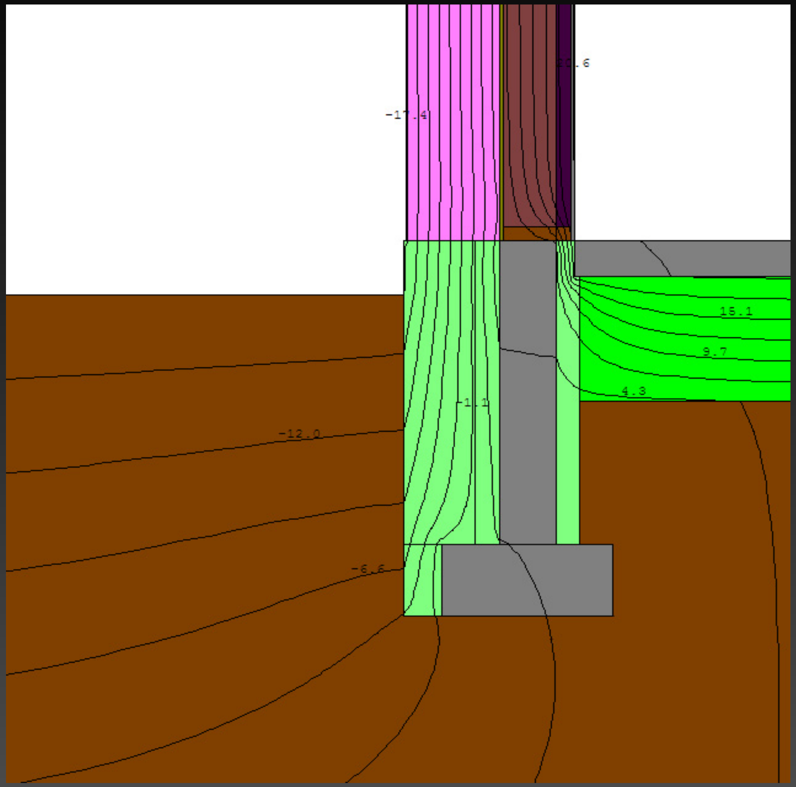


SIP panel FPSF: Ψ = 0.052 W/mK

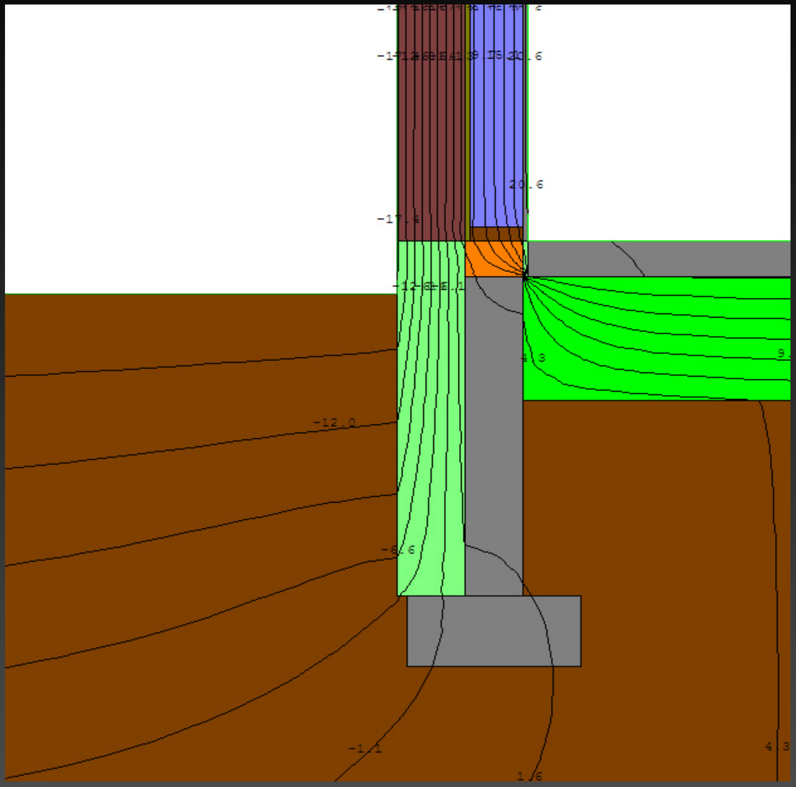
SEP panel wall's external insulation is better aligned, and Ψ value is much better,
But neither detail comes close to passing the Ψ </= 0.01 W/mK guideline

STEP 3 – Avoid "radiation fins", even well-insulated ones.

# Section 2 – Thermal Bridge Analysis




ICF footing: Ψ = 0.005 W/mK




Foamglas block footing: Ψ = 0.006 W/mK

Both ICF footing and Foamglas block footing perform much better than the FPSF
Both details pass the Ψ </= 0.01 W/mK guideline

STEP 4 - An insulated break between the floor slab and exterior wall is necessary!

# Section 3 – Hygrothermal Analysis

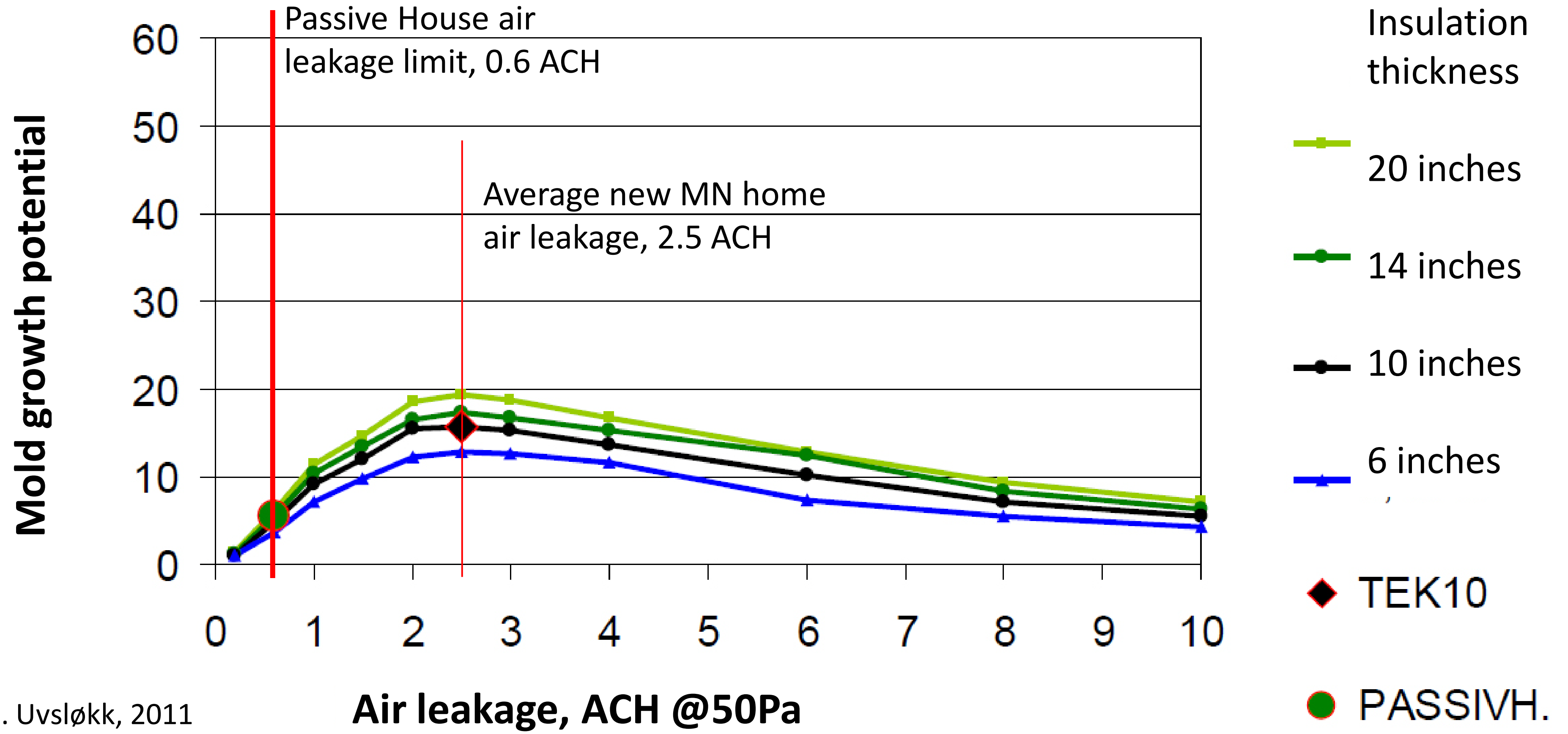
What are we worried about?

Moisture levels in highly insulated envelopes

- Mold growth
- Indoor air quality
- Durability of structure

In general, relative humidity above 80% combined with temperatures above freezing can initiate mold growth on wood/cellulose.

# Section 3 – Hygrothermal Analysis




S. Uvsløkk, 2011

Increasing insulation thickness without improving air tightness increases the risk of mold.

But constructing an airtight 0.6 ACH @ 50Pa passive house envelope with 20 inches of insulation actually reduces the risk of mold growth on wood sheathing.

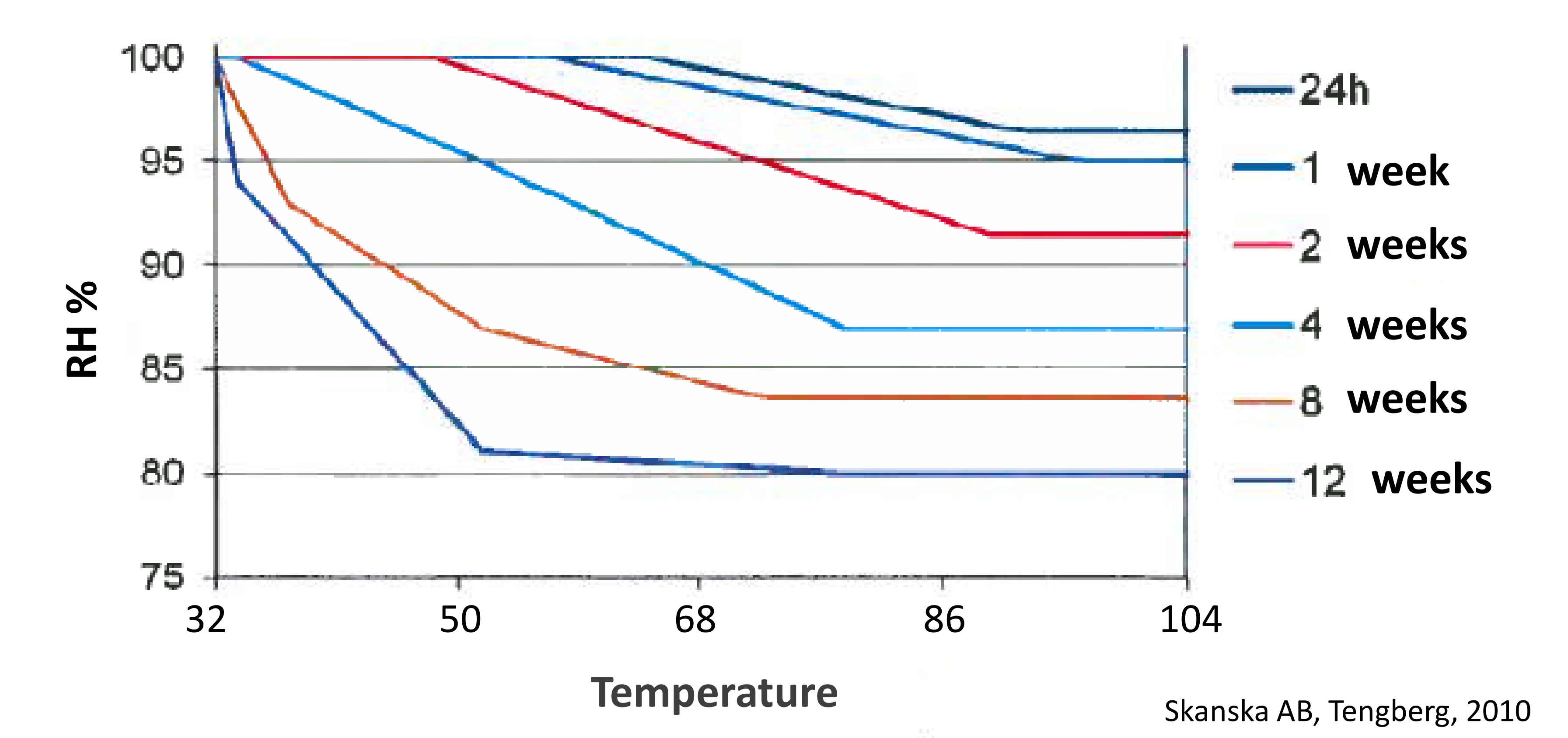
# Section 3 – Hygrothermal Analysis

How do you track potential for mold growth?

- No need to monitor every layer in the envelope for temperature and RH.
- Determine the "critical layer(s)" and monitor temperature and RH levels there
- Generally, the critical layer is the first condensing surface (must be cold, at or below the dewpoint) encountered by outward migrating moisture. Must also contain organic nutrients such as cellulose that support mold growth.
- Wood sheathing is commonly the critical layer in residential assemblies.
- What temperatures and RH levels are required?

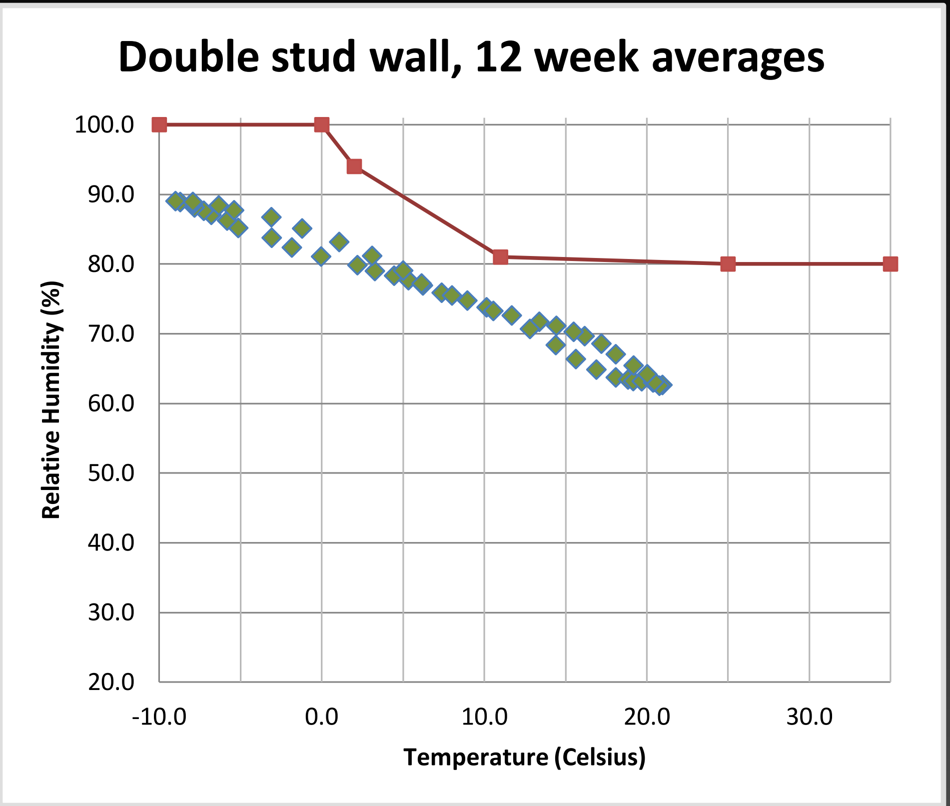
# Section 3 – Hygrothermal Analysis

## Risk lines for mold growth on wood




In the most general terms, it takes temperatures above freezing and RH above 80% to initiate mold growth on wood. Higher RH levels lead to mold growth in shorter time spans. Colder temperatures slow down mold growth.

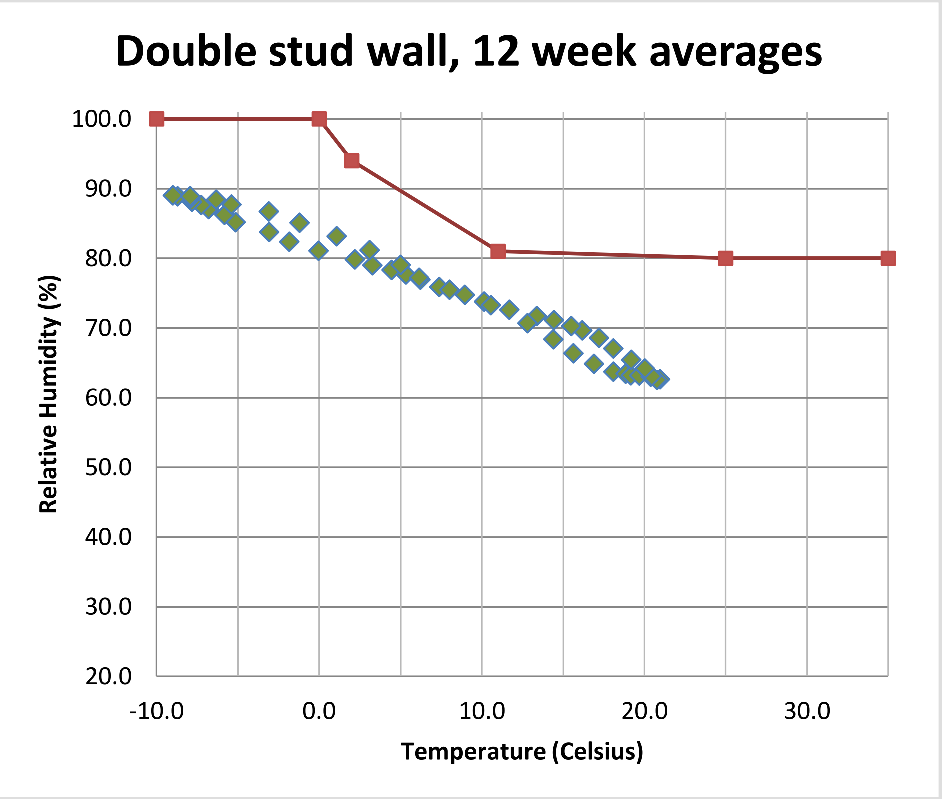
# Section 3 – Hygrothermal Analysis

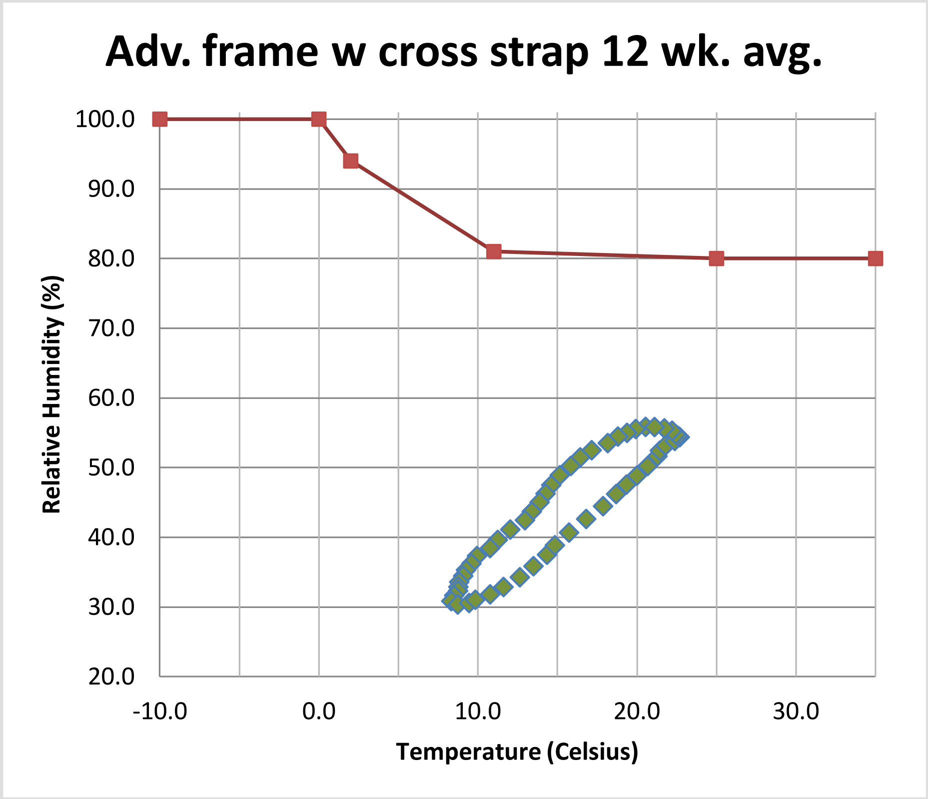



Critical layer = fiberboard sheathing, no exterior insulation

What happens when we add exterior insulation?

# Section 3 – Hygrothermal Analysis



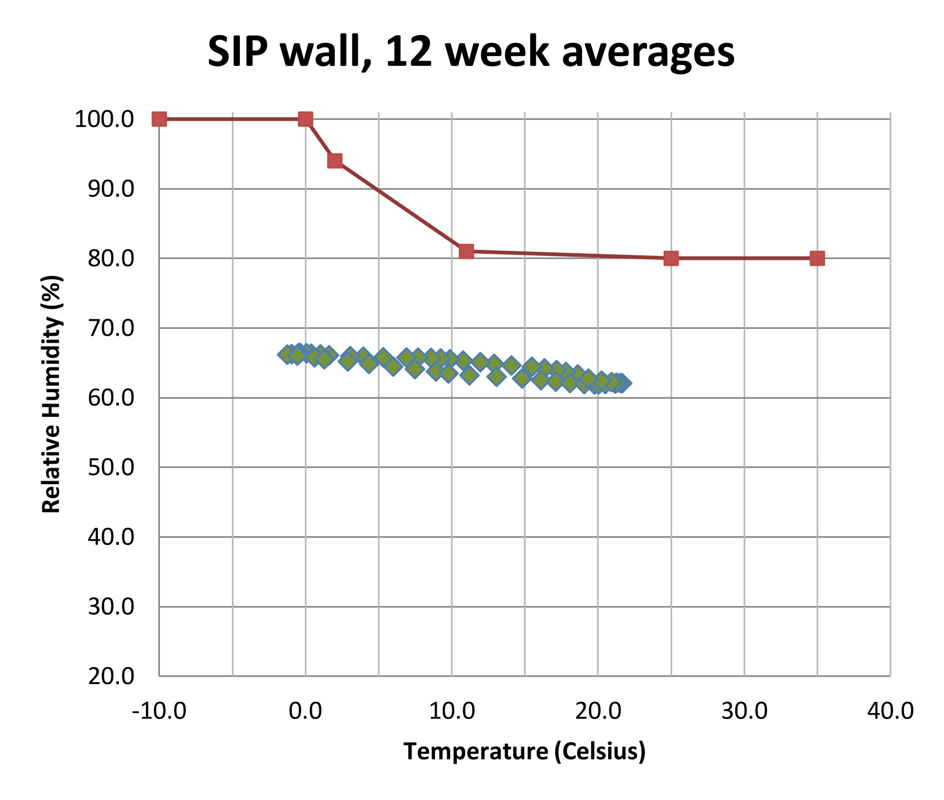

Critical layer = fiberboard sheathing, no exterior insulation

Critical layer = OSB sheathing, beneath 10" of mineral wool

What happens when we add exterior insulation?

Temperatures in the critical layer go up, heat drives off excess moisture.

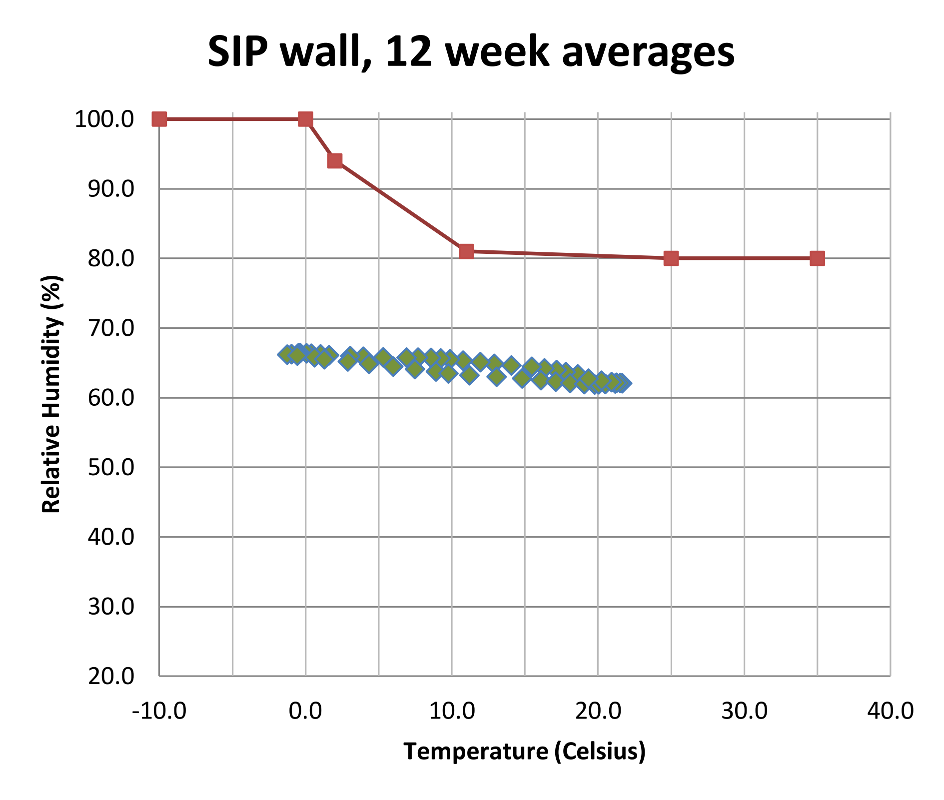
# Section 3 – Hygrothermal Analysis

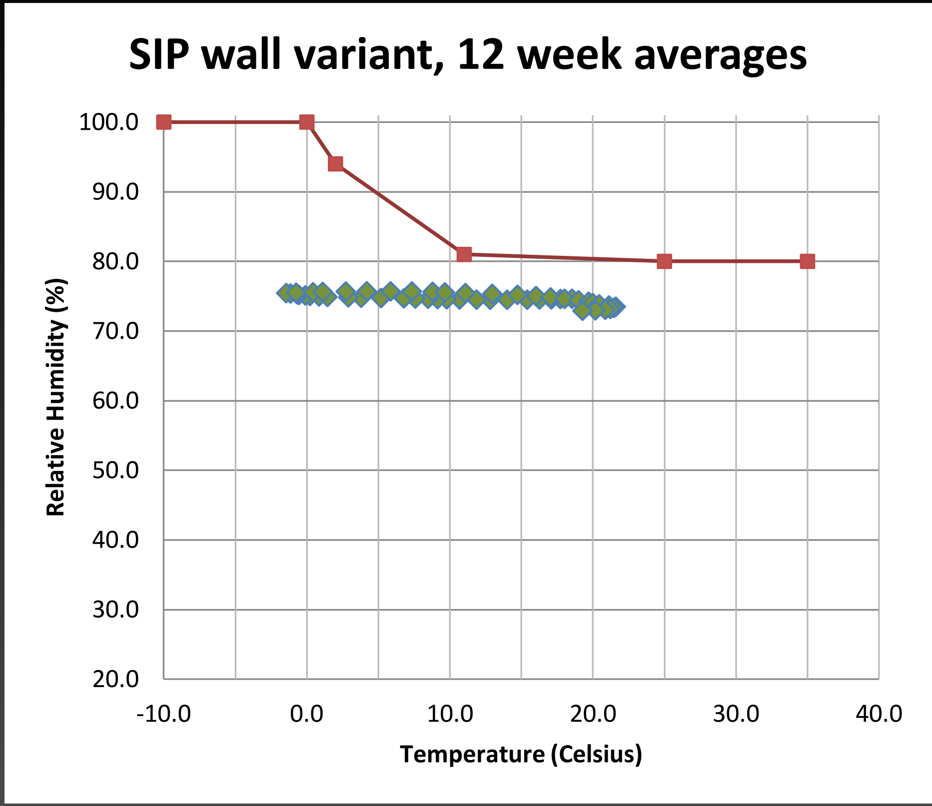



Critical layer = OSB sheathing, beneath 3” unfaced polyiso

What happens if the exterior insulation is not vapor permeable (such as XPS)?

# Section 3 – Hygrothermal Analysis



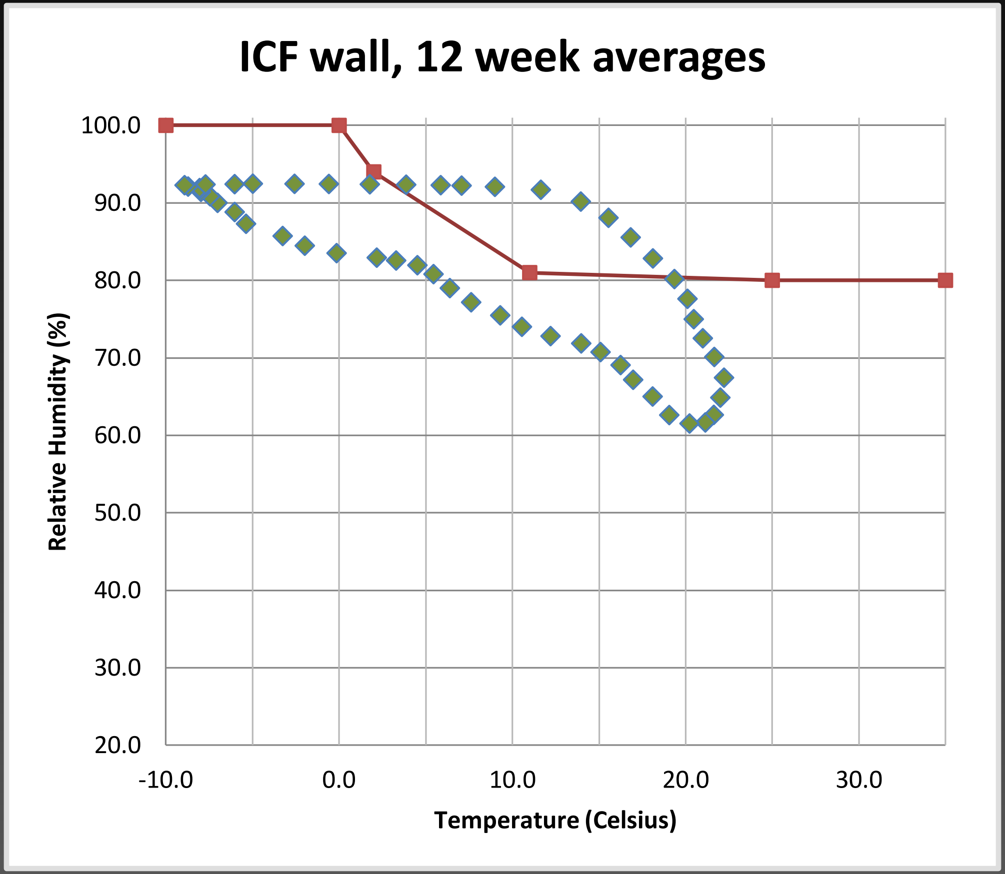

Critical layer = OSB sheathing, beneath 3” unfaced polyiso (perm rating = 4 @ 1 inch thickness)

Critical layer = OSB sheathing, beneath 3” XPS (perm rating = 0.75 @ 1 inch thickness)

What happens if the exterior insulation is not vapor permeable (such as XPS)?

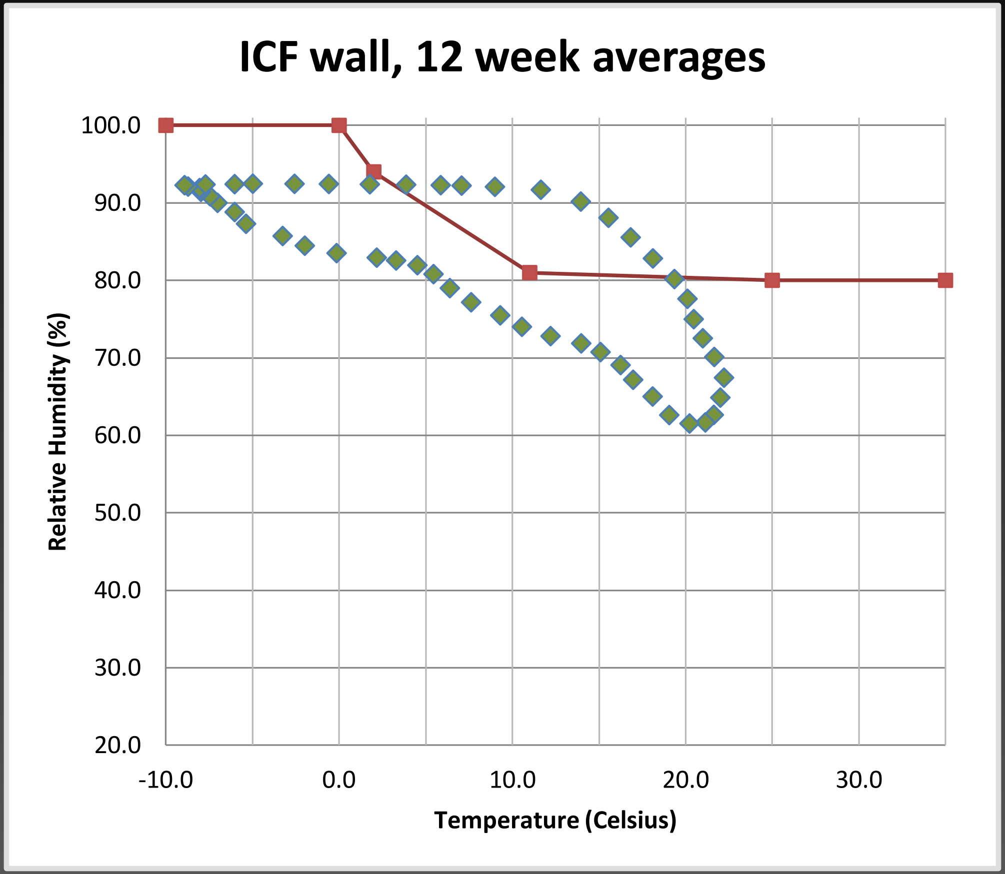
Despite heat, drying is reduced and you may end up with a wetter critical layer!

# Section 3 – Hygrothermal Analysis




Is this assembly moisture safe?

# Section 3 – Hygrothermal Analysis




Is this assembly moisture safe?

- no "critical layer" in an ICF assembly, risk line doesn't apply
- data taken 0.5" from exterior surface
- what about wood materials put into the wall?
- what about R-value performance of the EPS?

# Section 3 – Hygrothermal Analysis

Summary – what are the take-away messages here?

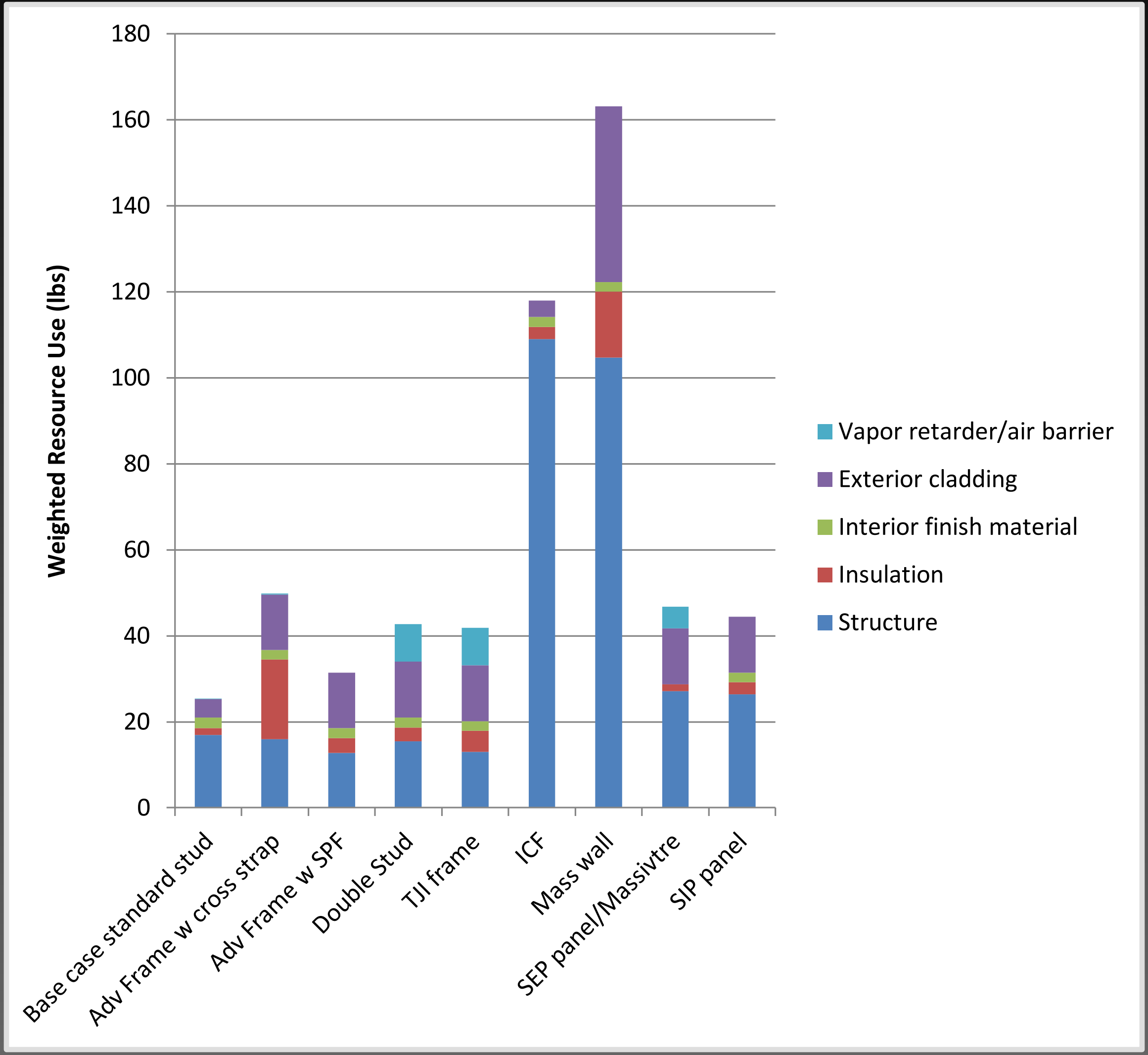
- Know the vapor permeance of the materials in your envelope. The colder the climate, the more important a warm-side vapor retarder becomes.
- Several inches of permeable exterior insulation is a good idea to warm the critical layer and reduce mold growth risks.
- Or eliminate the critical layer with an assembly (such as ICF) that does not support mold growth and is relatively impervious to moisture.
- Hit the air tightness target (0.6 ACH @50Pa)!

# Section 4 – Life Cycle Env. Impacts

Life cycle environmental impacts of the envelope materials:

- Measured using Athena Environmental Impact Estimator
- Athena's "life cycle" includes raw material extraction/mining, transportation, processing, product fabrication, distribution, maintenance, and disposal
- Entire envelopes were modeled, ensuring "functional equivalence"
- Results measured in terms of 8 environmental indicators such as embodied energy, global warming potential, weighted resource use, eutrophication, etc. These indicators represent a comprehensive view of the impact on the environment

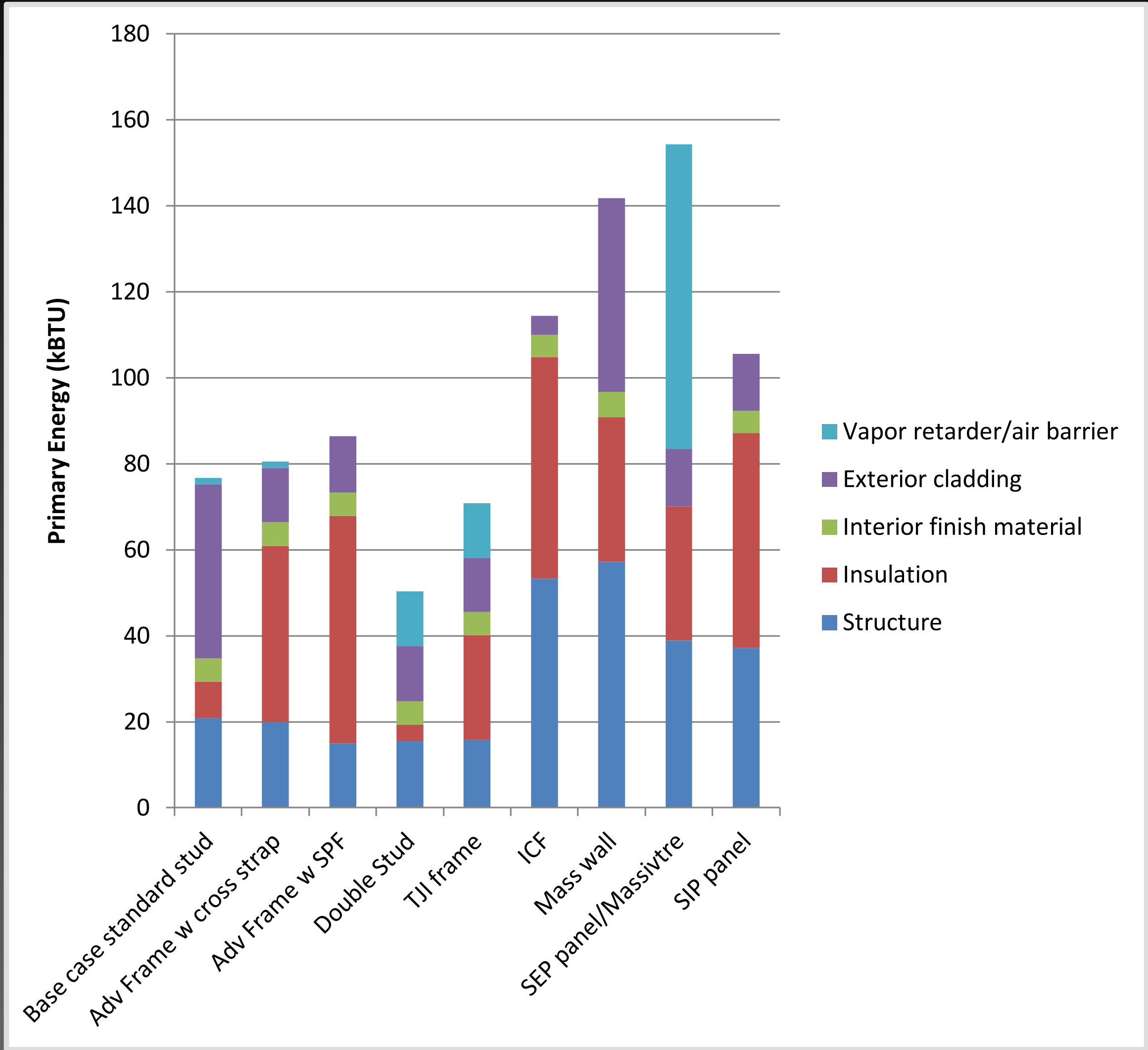
# Section 4 – Life Cycle Env. Impacts




Life cycle weighted resource use of above grade walls by building element

- concrete, brick and mineral wool have large impacts
- insulation in general has the smallest impact (it's mostly air)

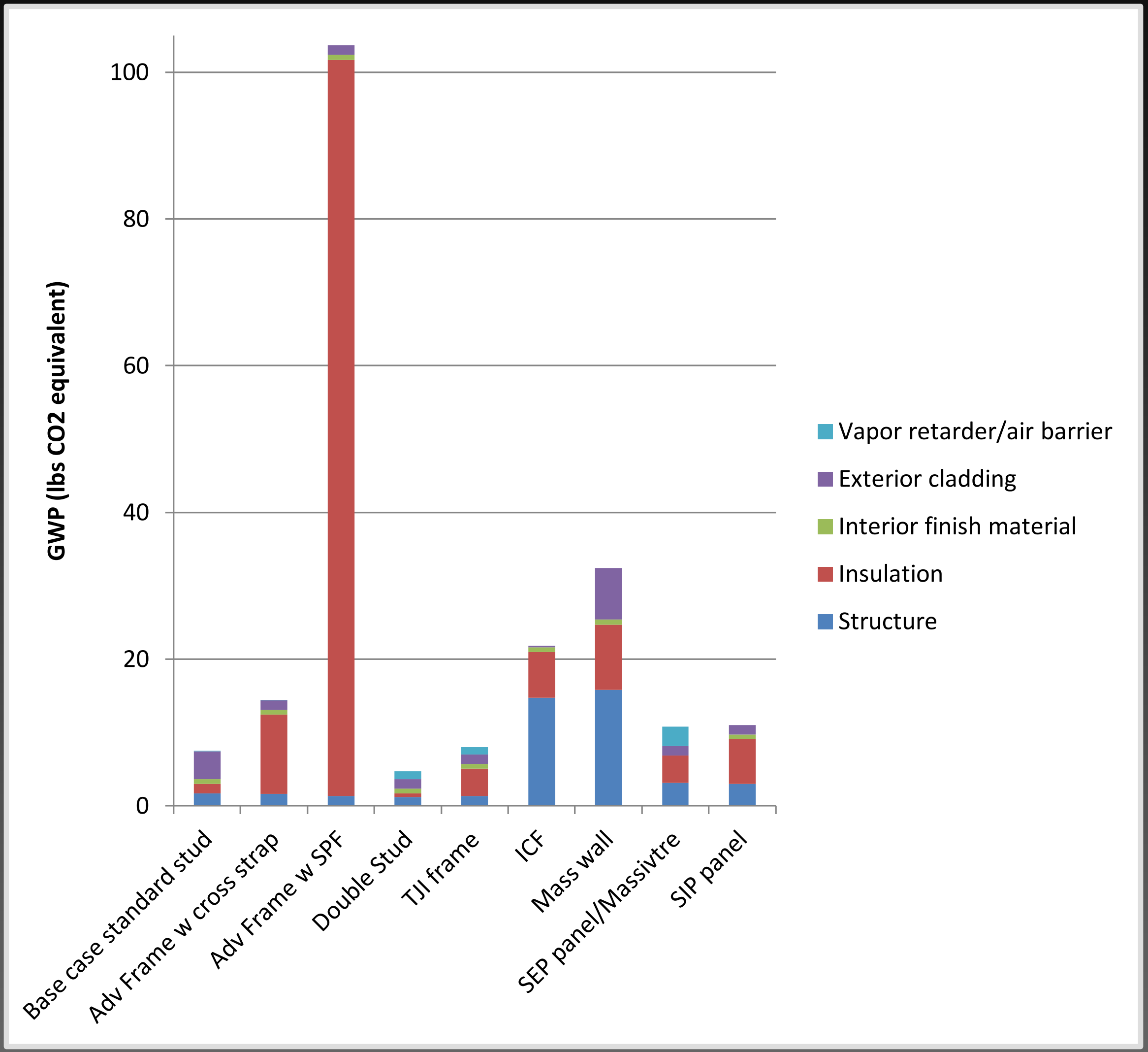
# Section 4 – Life Cycle Env. Impacts




Life cycle embodied energy of above grade walls by building element

- mineral wool and foam insulation have quite a bit of embodied energy
- fiberglass is better, but cellulose is best
- Concrete, brick, vinyl siding and bitumen roofing membrane also have large embodied energy

# Section 4 – Life Cycle Env. Impacts

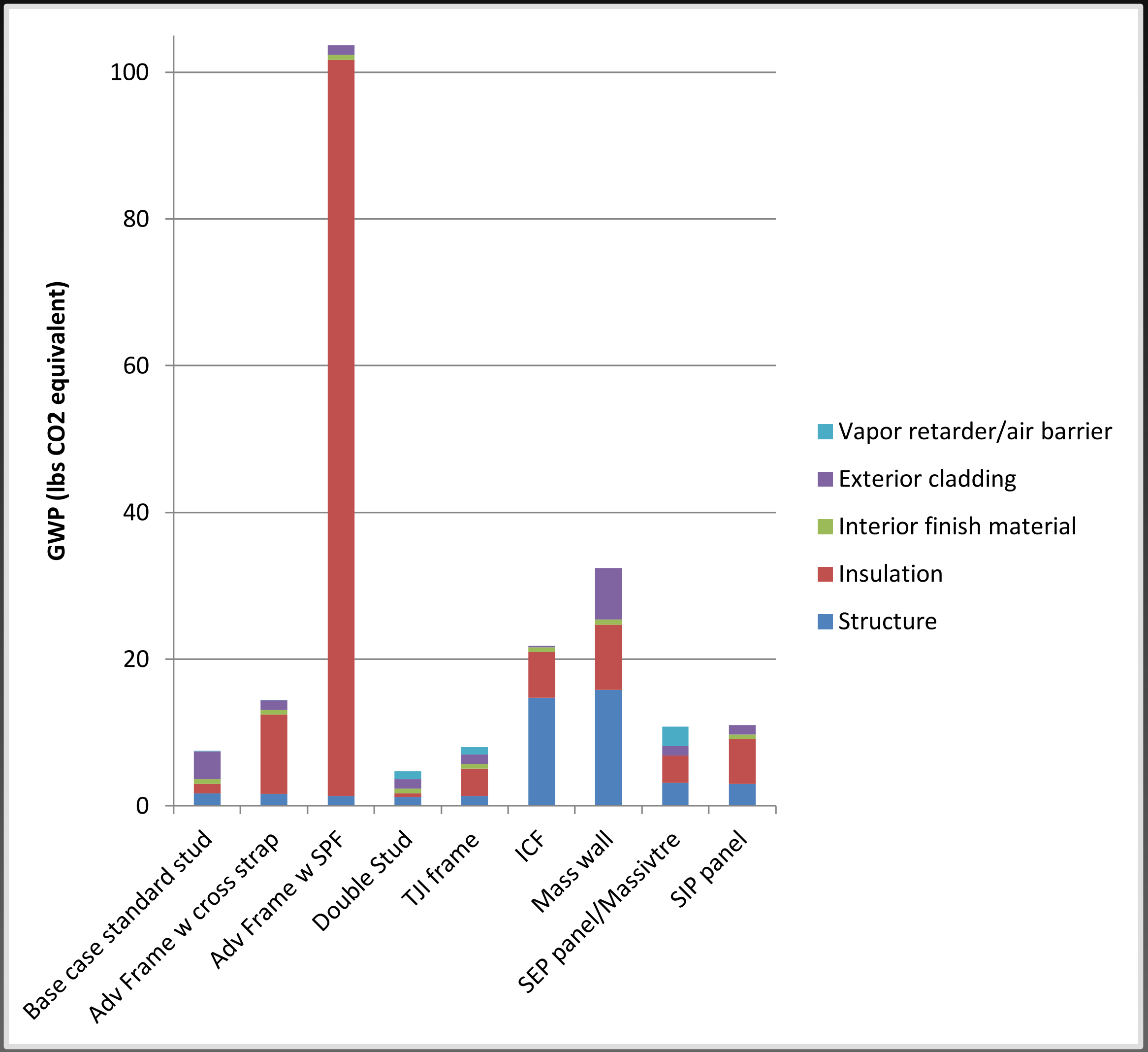



Life cycle global warming potential of the envelope materials:

- concrete, EPS, brick, and mineral wool have high GWP, but…
- spray polyurethane foam blown with HFC blowing agents has almost 100x greater GWP than fiberglass per unit area per R-value

Similar effects are seen with XPS! – all XPS removed from envelopes.

# Section 4 – Life Cycle Env. Impacts




Incredibly high GWP of closed cell SPF and XPS are reported in Environmental Building News article by Alex Wilson in 2010.

XPS can be replaced by EPS or foamglass below grade. Above grade, a good replacement might be non-foil-faced polyiso.

Closed cell SPF can be replaced with spray foam that does not use HFC blowing agents (icynene, for example).

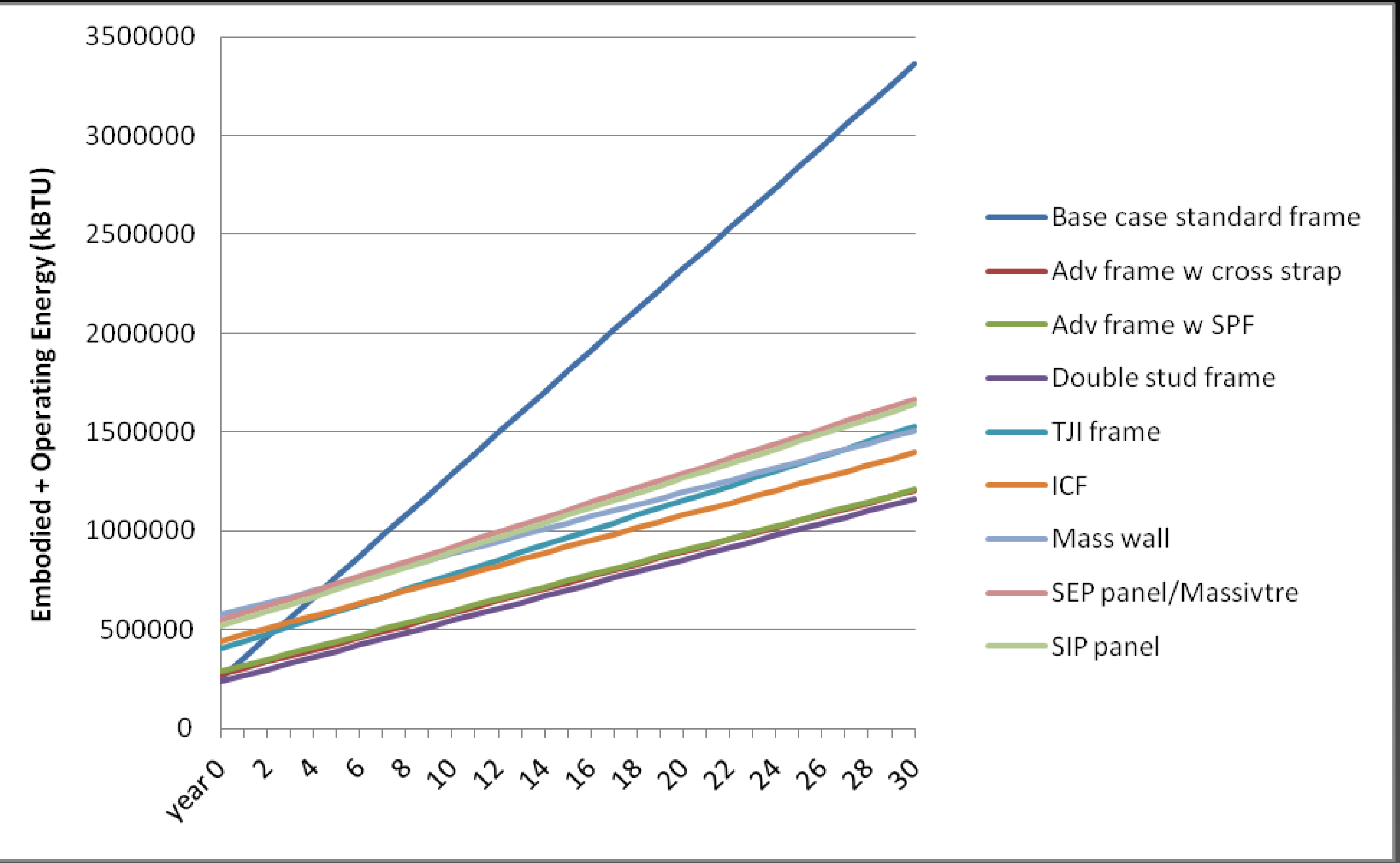
New blowing agent formulations for both closed cell SPF and XPS are expected starting in late 2013.

# Section 4 – Life Cycle Env. Impacts

The big question – do Passive House envelopes save energy and carbon emissions in the long run?

- We know the embodied energy and carbon of passive house envelopes are often several times higher than a standard envelope.
- Add the yearly operating impacts (energy use and carbon emissions) of a standardized Passive House to the embodied energy and GWP of the envelopes.
- Compare to a base case house with a standard envelope to see if there are any paybacks

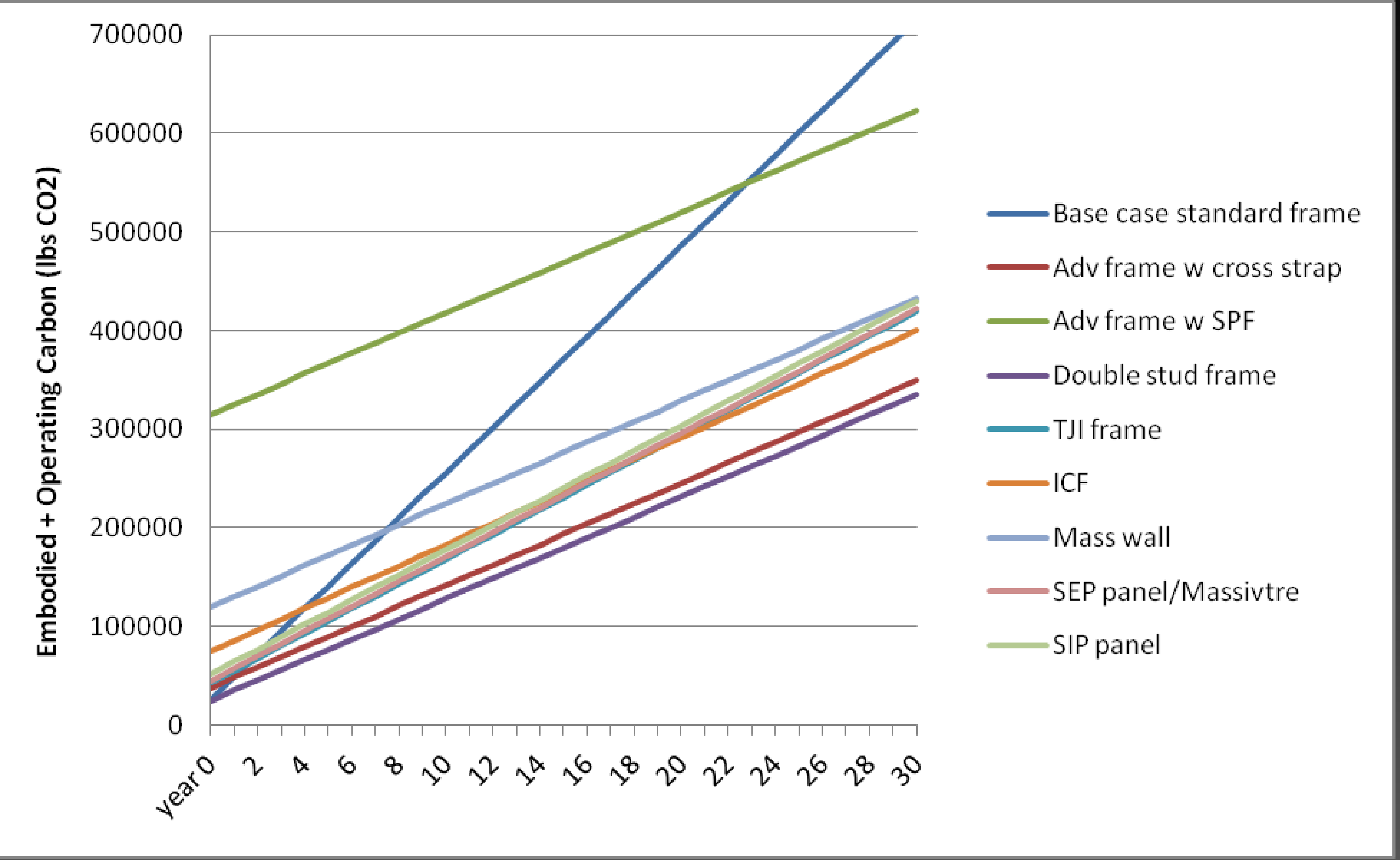
# Section 4 – Life Cycle Env. Impacts




Life cycle embodied energy plus site operating energy.

Energy payback: Mass wall envelope = 4.4 years
ICF envelope = 2.7 years
Double stud envelope = immediate

# Section 4 – Life Cycle Env. Impacts




Life cycle embodied carbon plus carbon emissions from operating energy. (Carbon emissions based on Minnesota emissions factors for electricity and natural gas.)

Carbon payback: Advanced frame with SPF envelope = 23 years
Mass wall envelope = 7.5 years
Double stud envelope = immediate

# Conclusion

- No great differences between envelope types for linear thermal bridges (specific location matters more!)

- There are substantial differences in terms of…
  1) hygrothermal performance
  2) life-cycle performance
  3) R-value performance (i.e. R-value/inch, repetitive thermal bridges)