Performance of 8 Passive House Envelopes in Cold Climates

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Outline

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

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

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

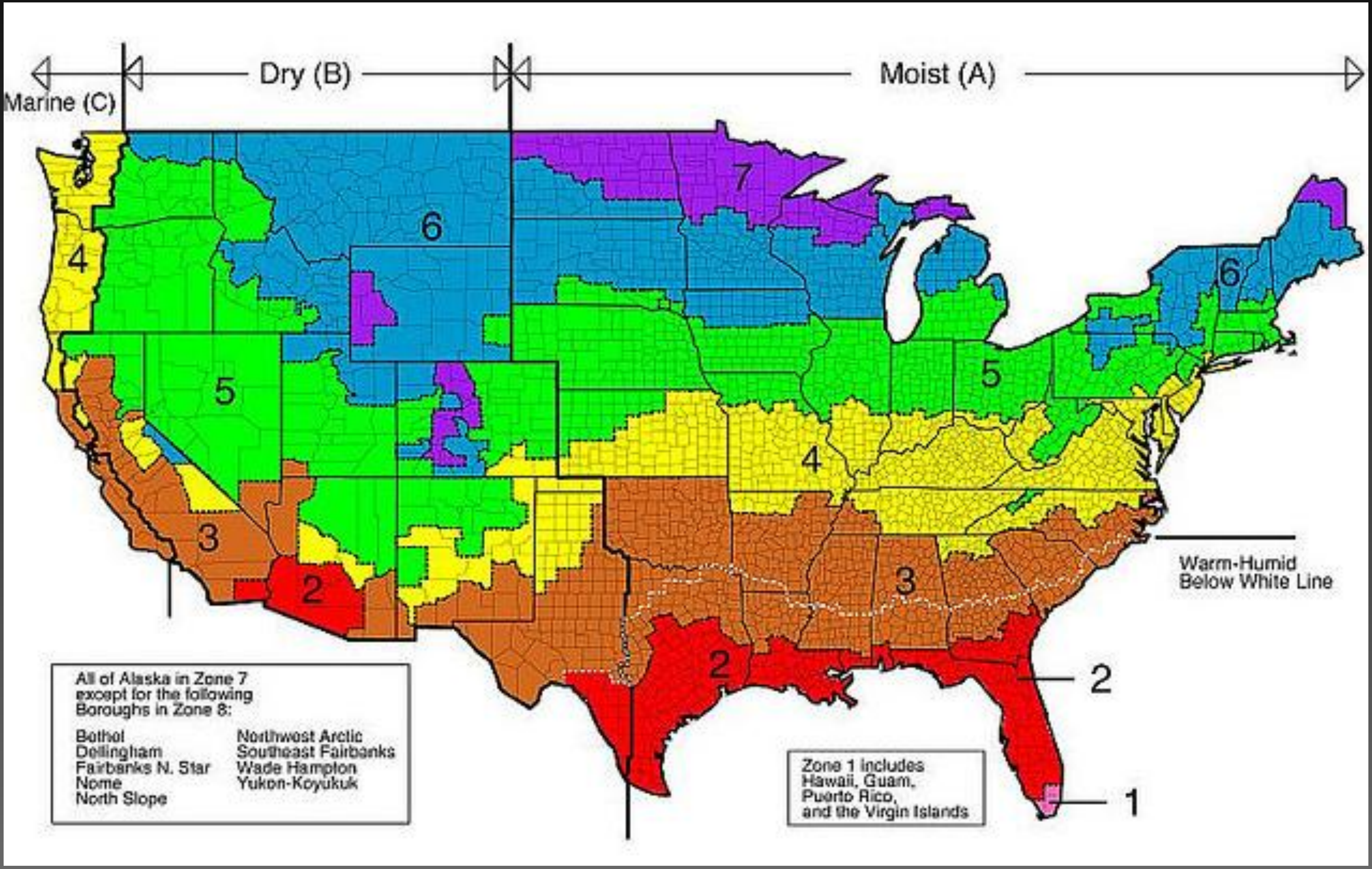
Background

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

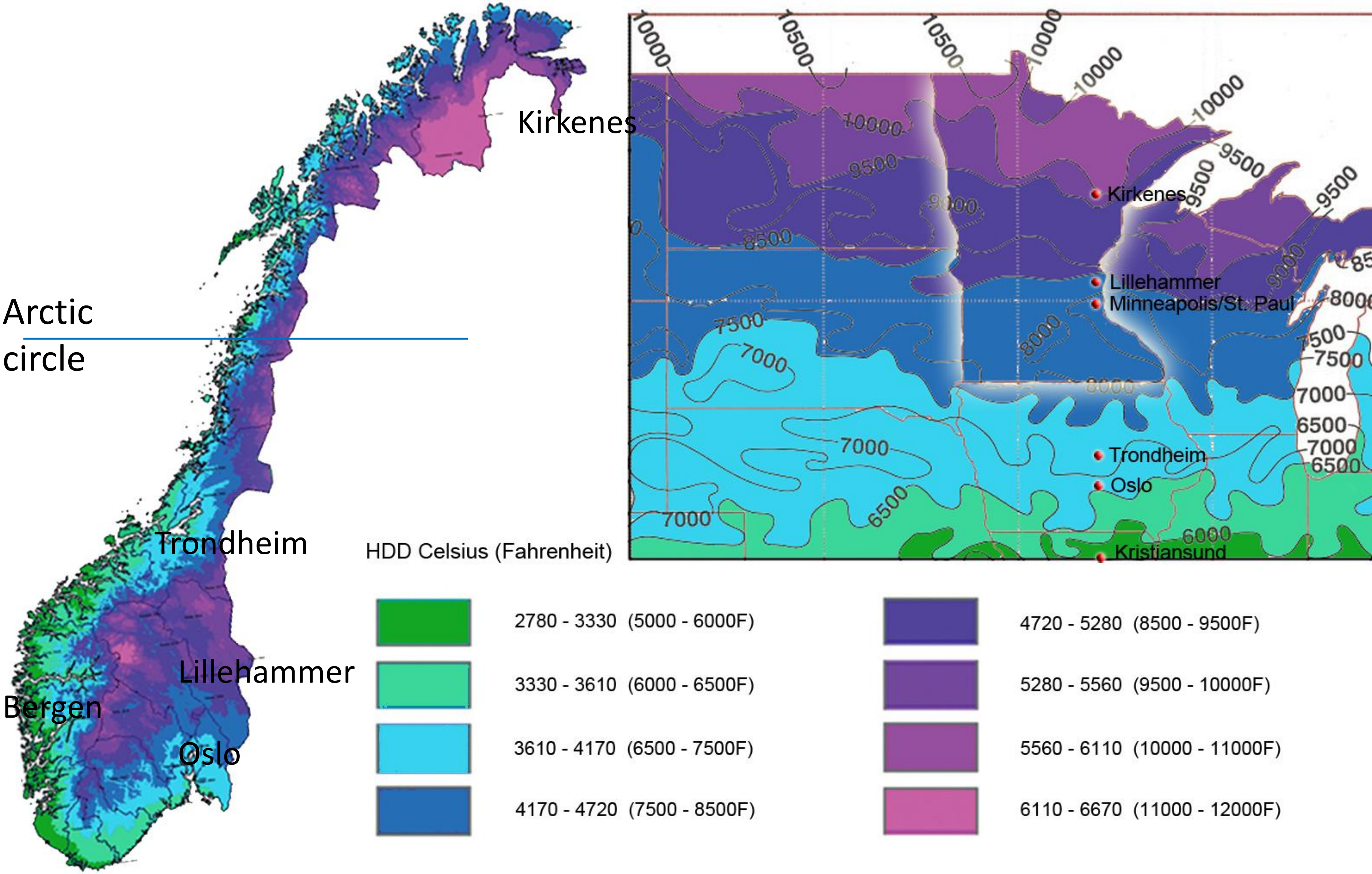
- Housed within the Norwegian technical university, NTNU, in Trondheim

- 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



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?

Case Studies – IECC climate zone 5,6

Project: Smith House Location: Urbana, IL - HDD 6359		Envelope types	R-value
	Wall	12" TJI balloon frame	R-60
		insulated with blown fiberglass + exterior EPS	
	Roof	16" TJI	R-60
		insulated with blown fiberglass	
	Floor slab	concrete	R-56
		insulated with EPS	
	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)	R-70
		5" EPS integral to ICF + exterior EPS	
	Roof	light frame wood truss	R-95
		insulated with exterior polyisocyanurate	
	Floor slab	concrete	R-60
		insulated with XPS	
	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 insulated with open cell SPF + exterior EPS	R-70
		Wall 2	advanced 2x6 stud wall framing insulated with open cell SPF + exterior VIP	R-70
		Roof 1	flat roof, 12" TJI insulated with open cell SPF + exterior VIP	R-100
		Roof 2	flat roof, 12" TJI + 8" perpendicular sleeper trusses 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 insulated with blown cellulose	R-55
		Roof	Light frame wood truss with cold attic insulated with blown cellulose	R-95
		Floor slab	concrete 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 truss	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

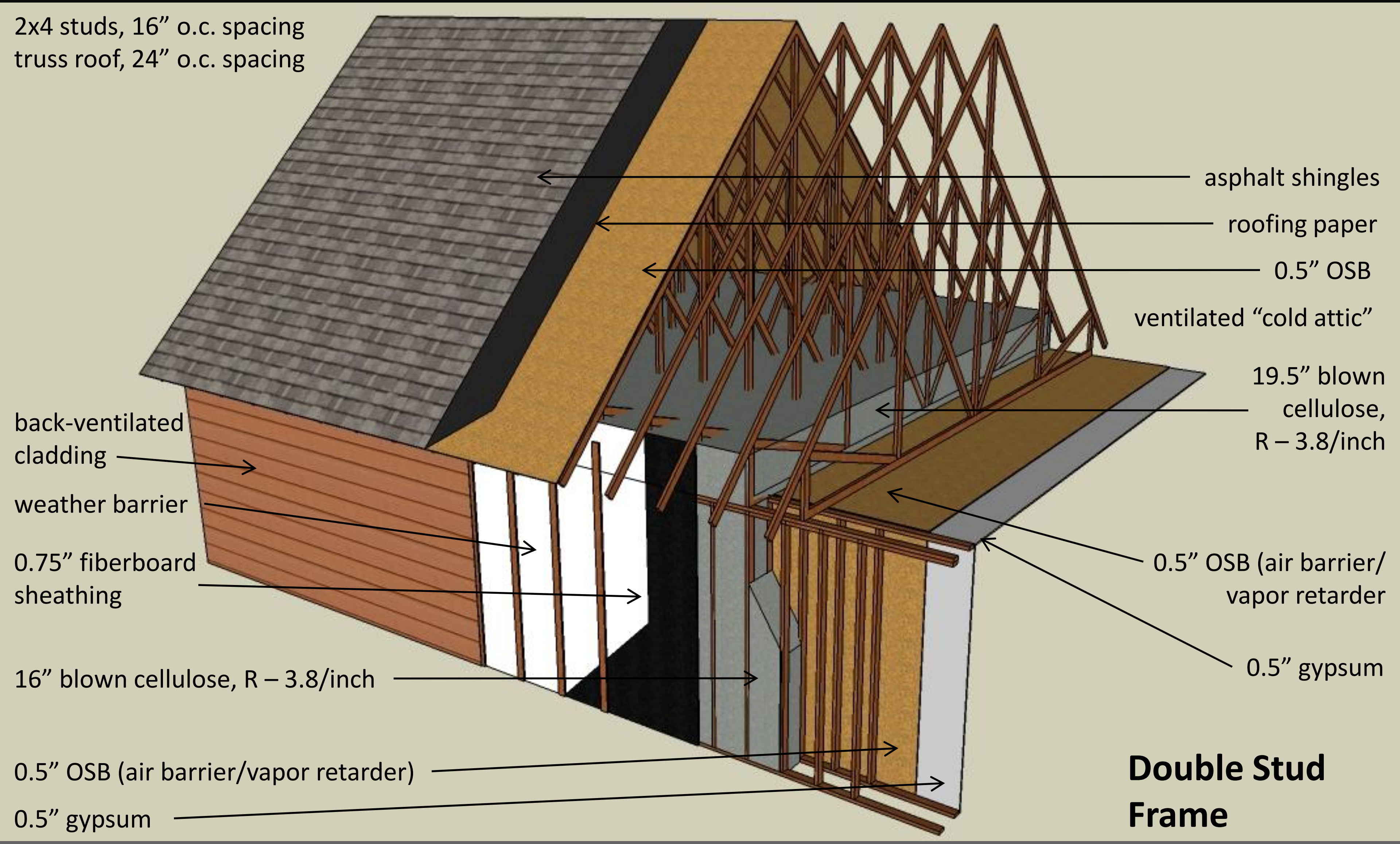
Average R-values of cold-climate Passive House case studies

- 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

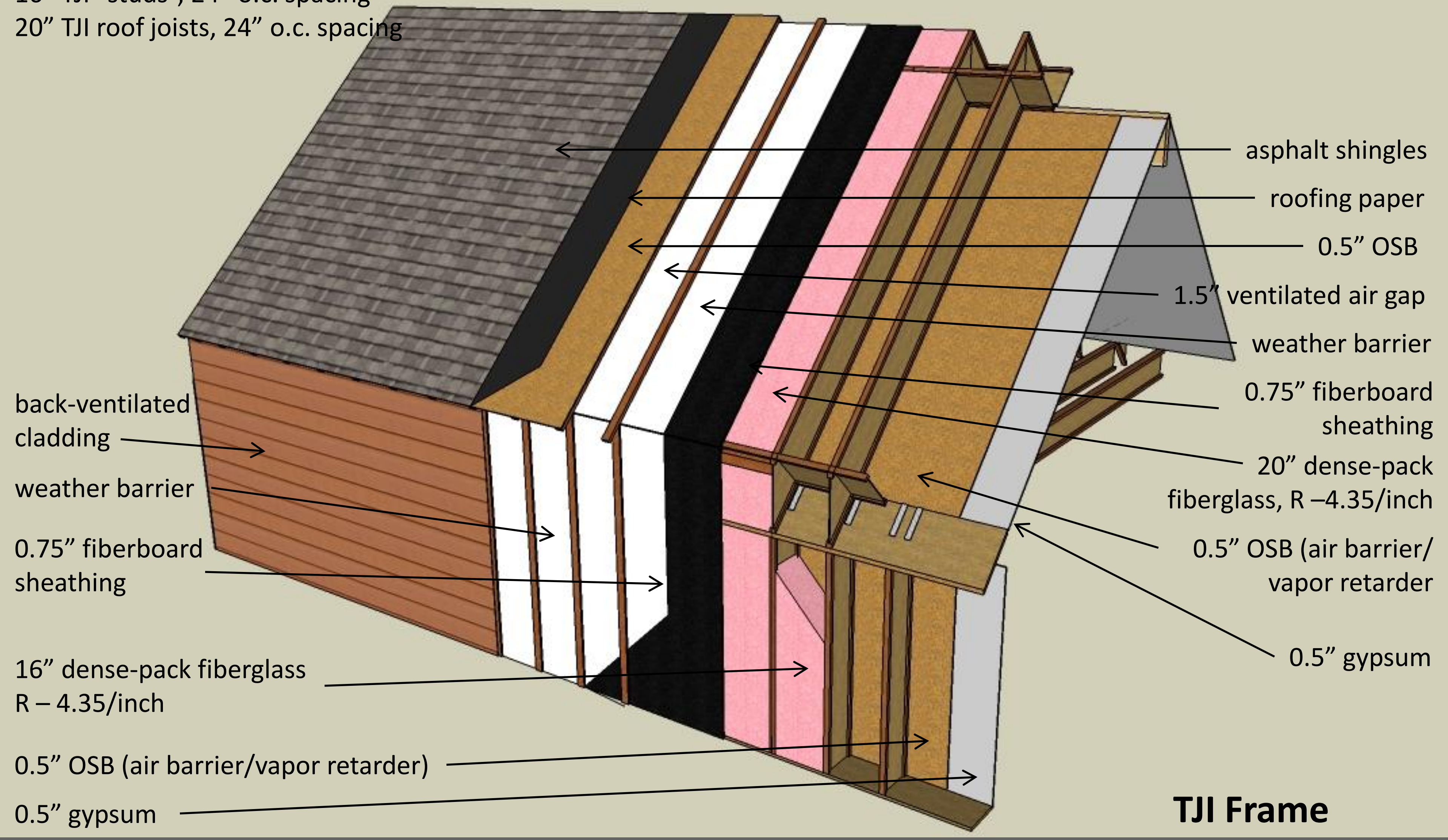
- 0.46 ACH @50Pa Requirement: 0.6

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
0.5” OSB (air barrier/ vapor retarder
16” blown cellulose, R – 3.8/inch
0.5” gypsum
0.5” OSB (air barrier/vapor retarder)
0.5” gypsum
Double Stud Frame

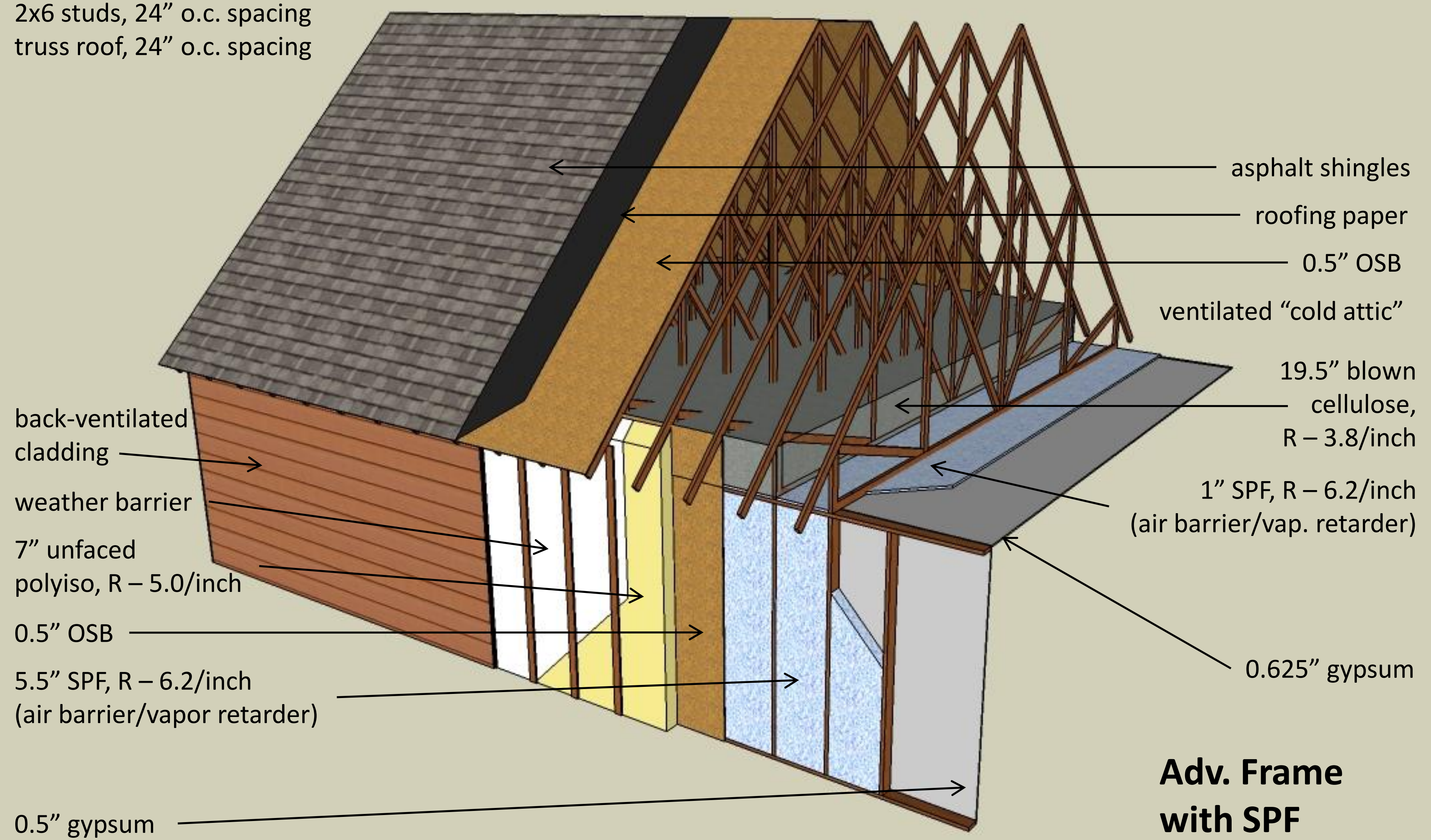
TJI Frame (I-joist)

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



Advanced Frame with SPF

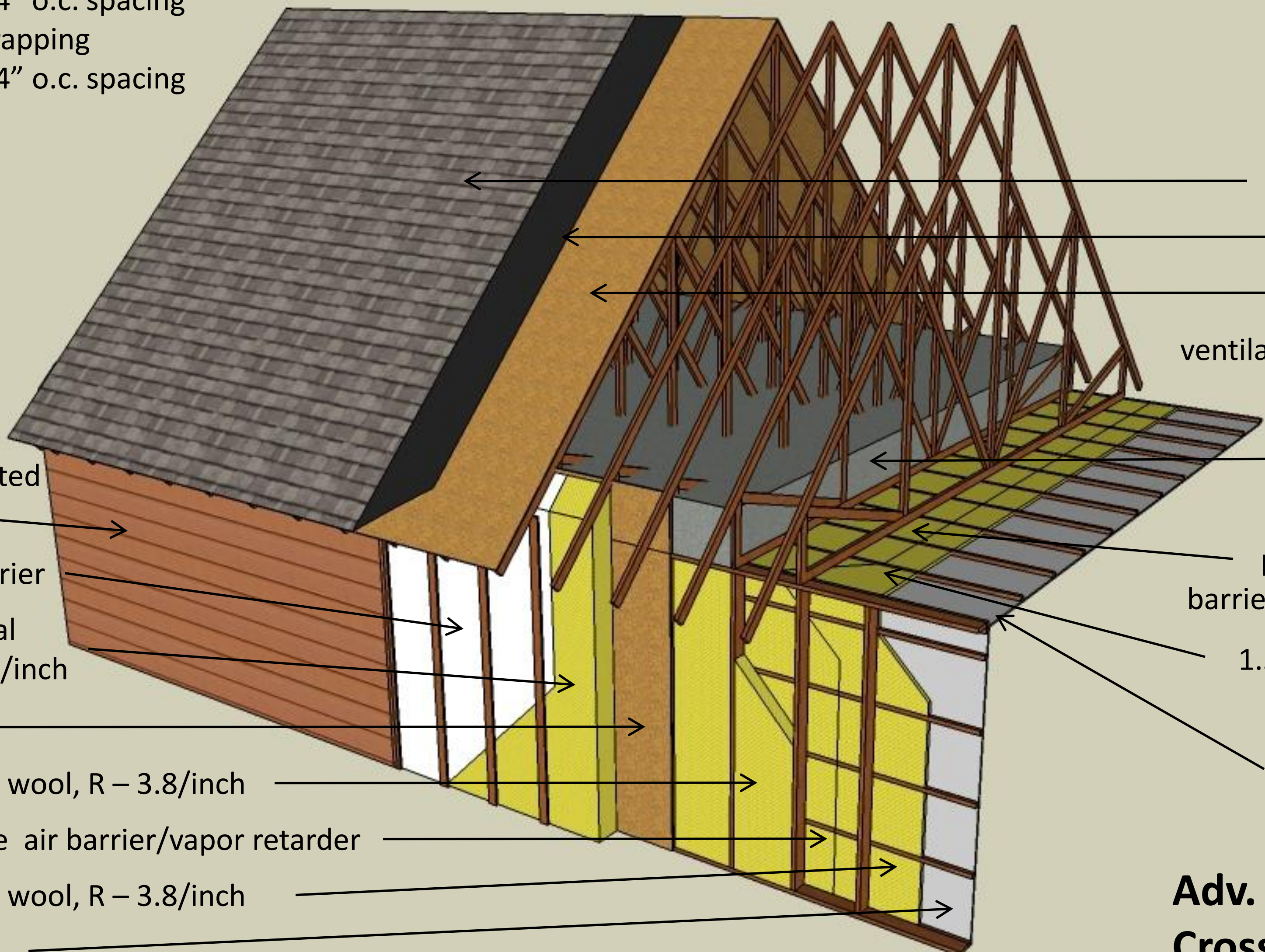
2x6 studs, 24” o.c. spacing
truss roof, 24” o.c. spacing



Adv. Frame with SPF

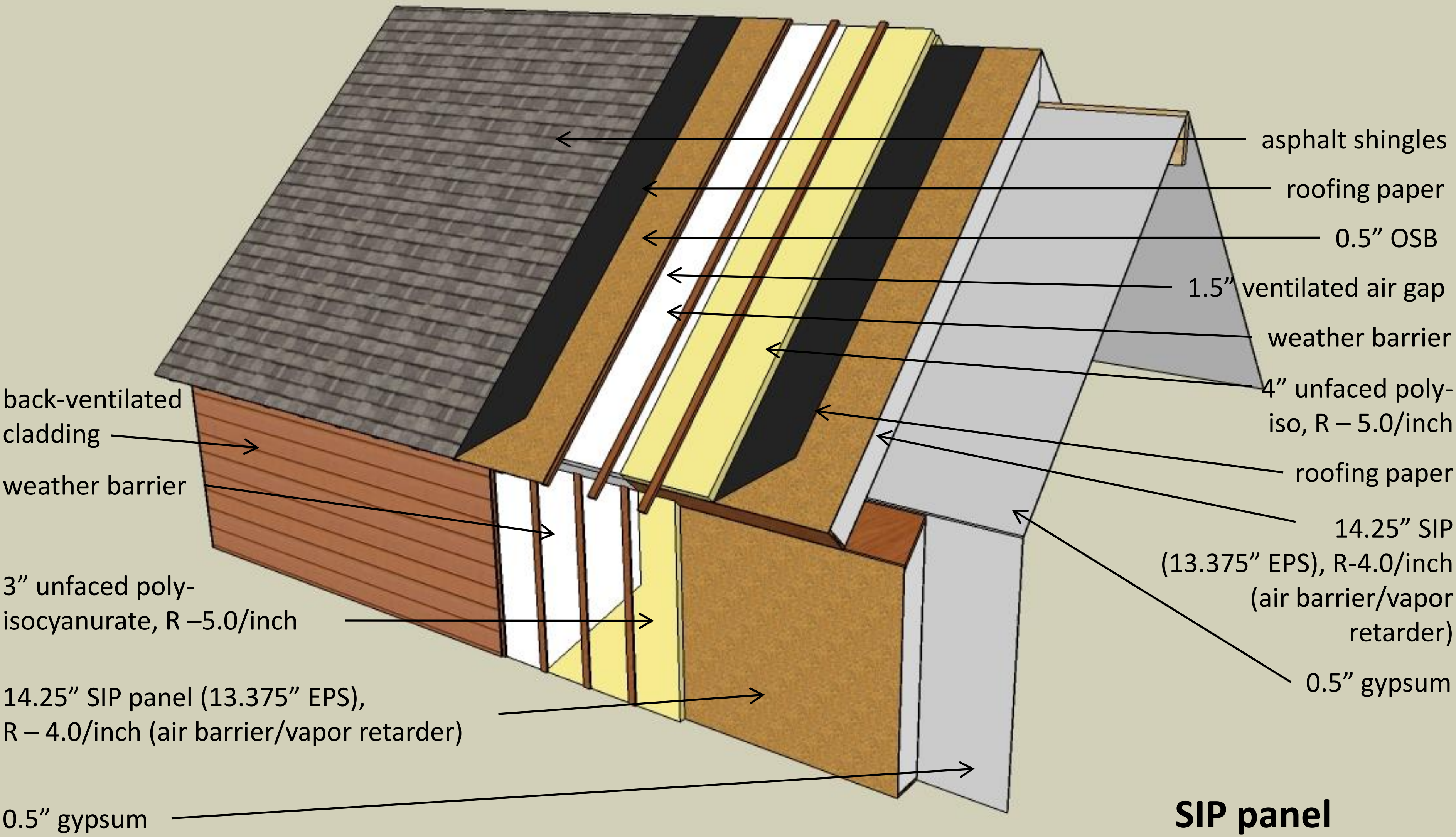
Advanced Frame with cross strapping

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

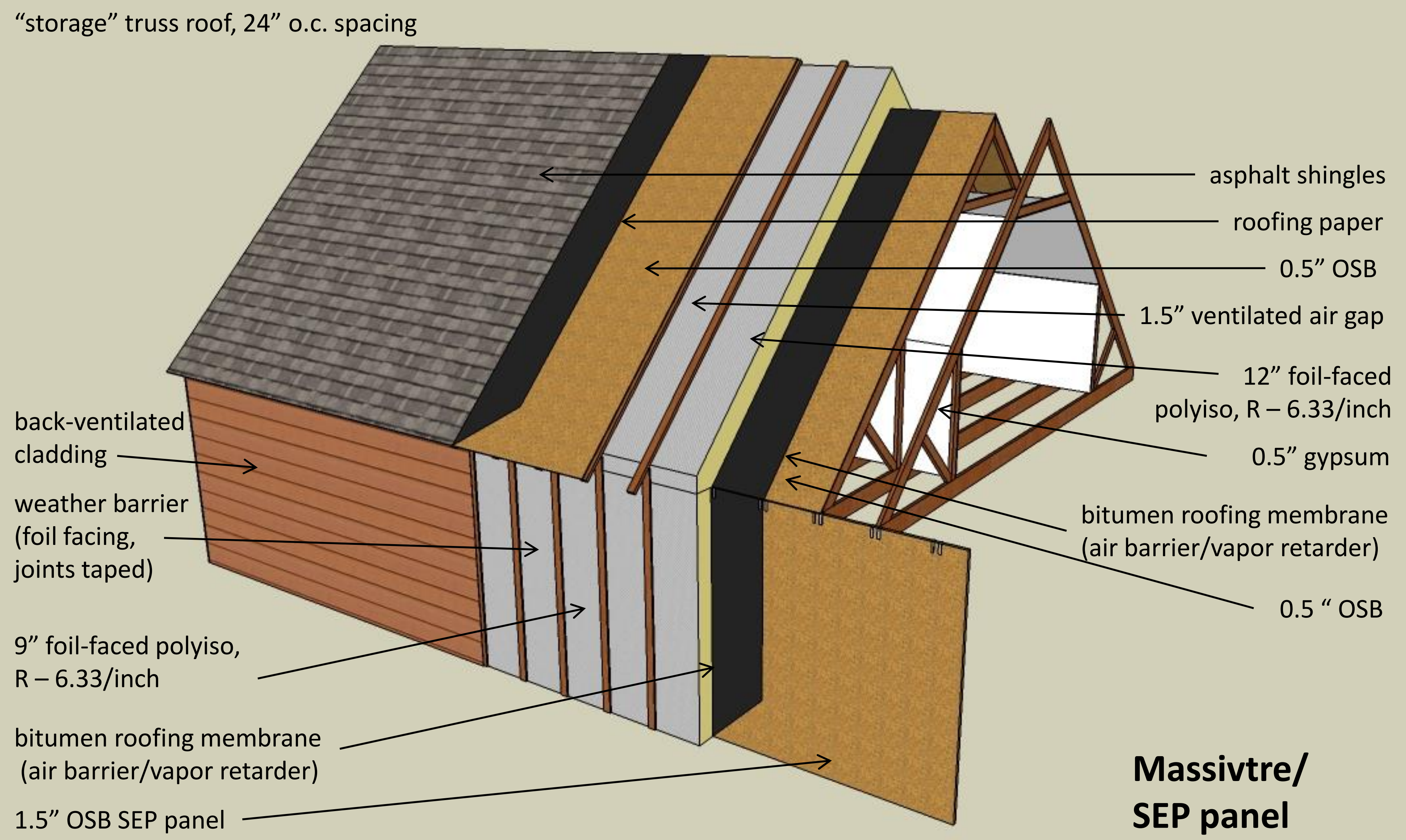


Adv. Frame w. Cross Strapping

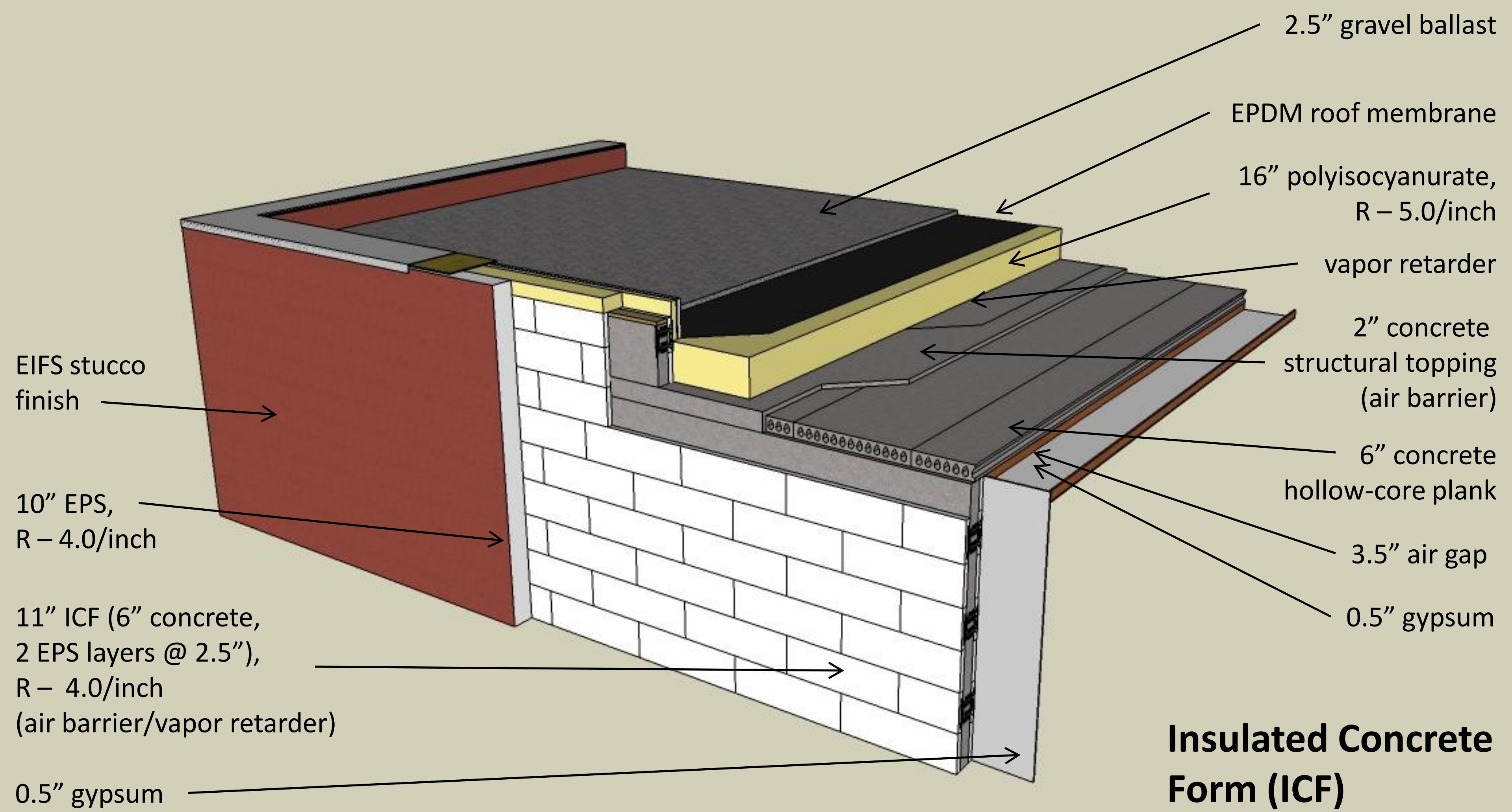
Structural Insulated Panel (SIP)



Massivtre/SEP panel

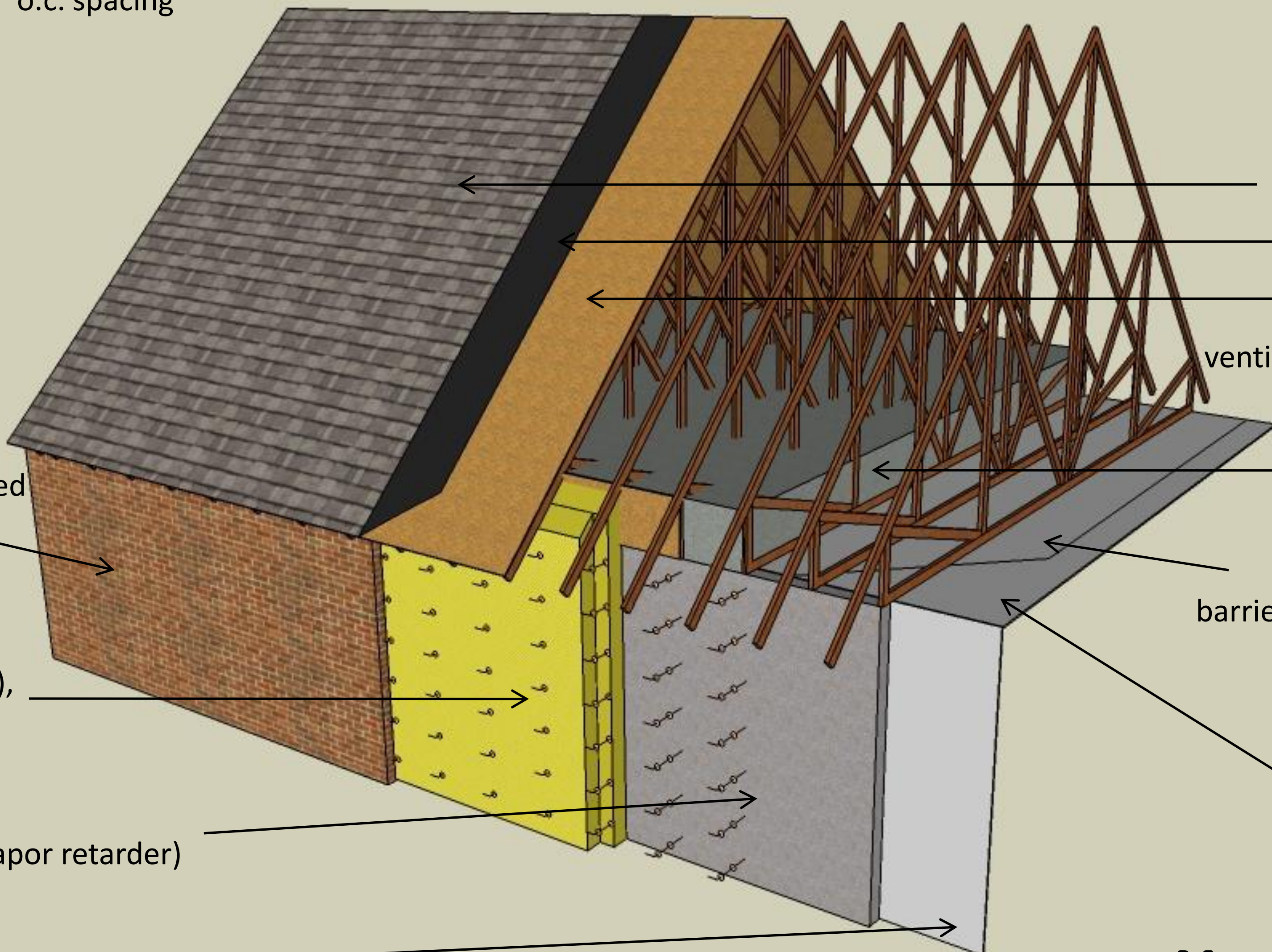


Insulated Concrete Form (ICF)



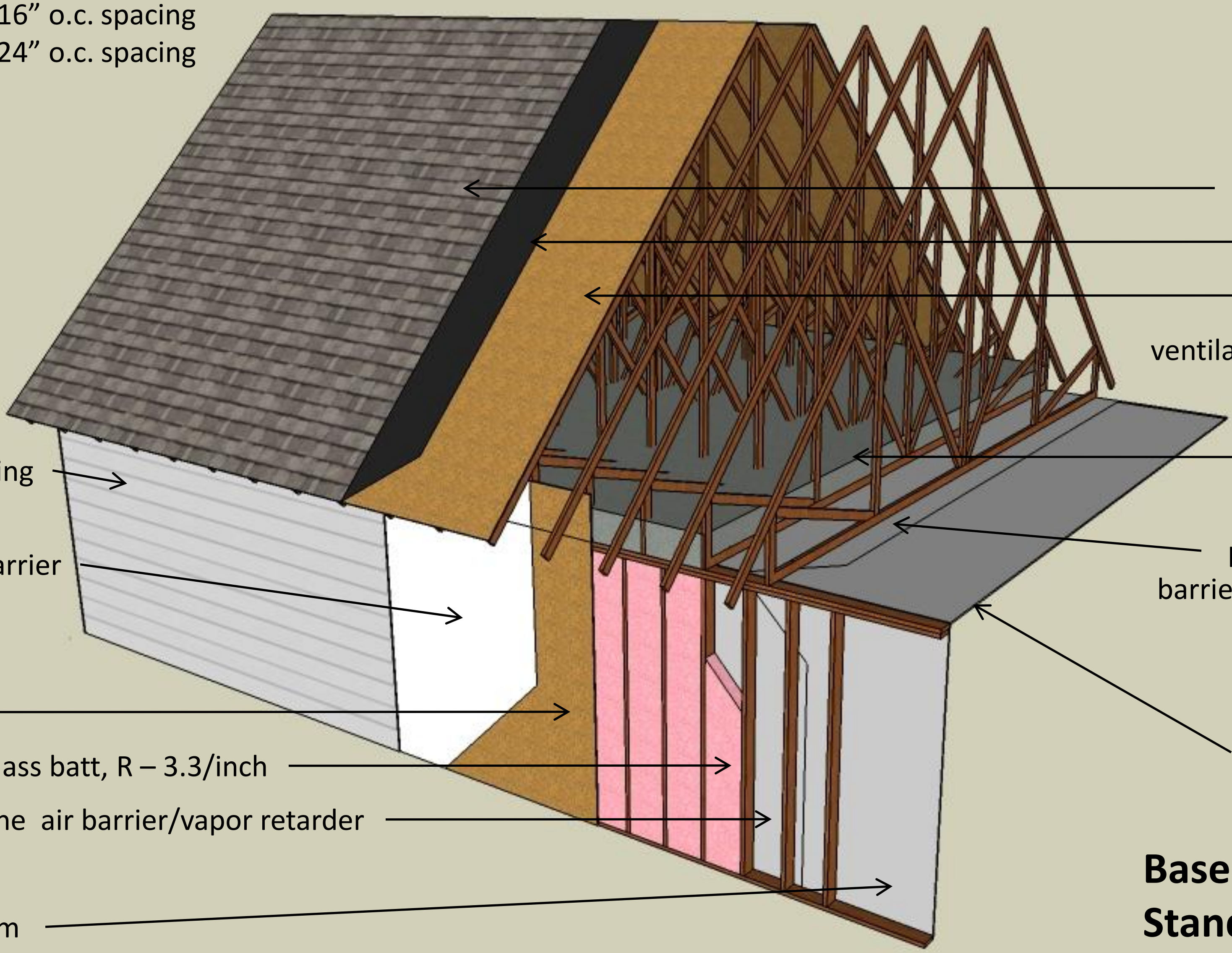
Insulated Concrete Form (ICF)

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

2x6 studs, 16” o.c. spacing
truss roof, 24” o.c. spacing



Base Case Standard Frame

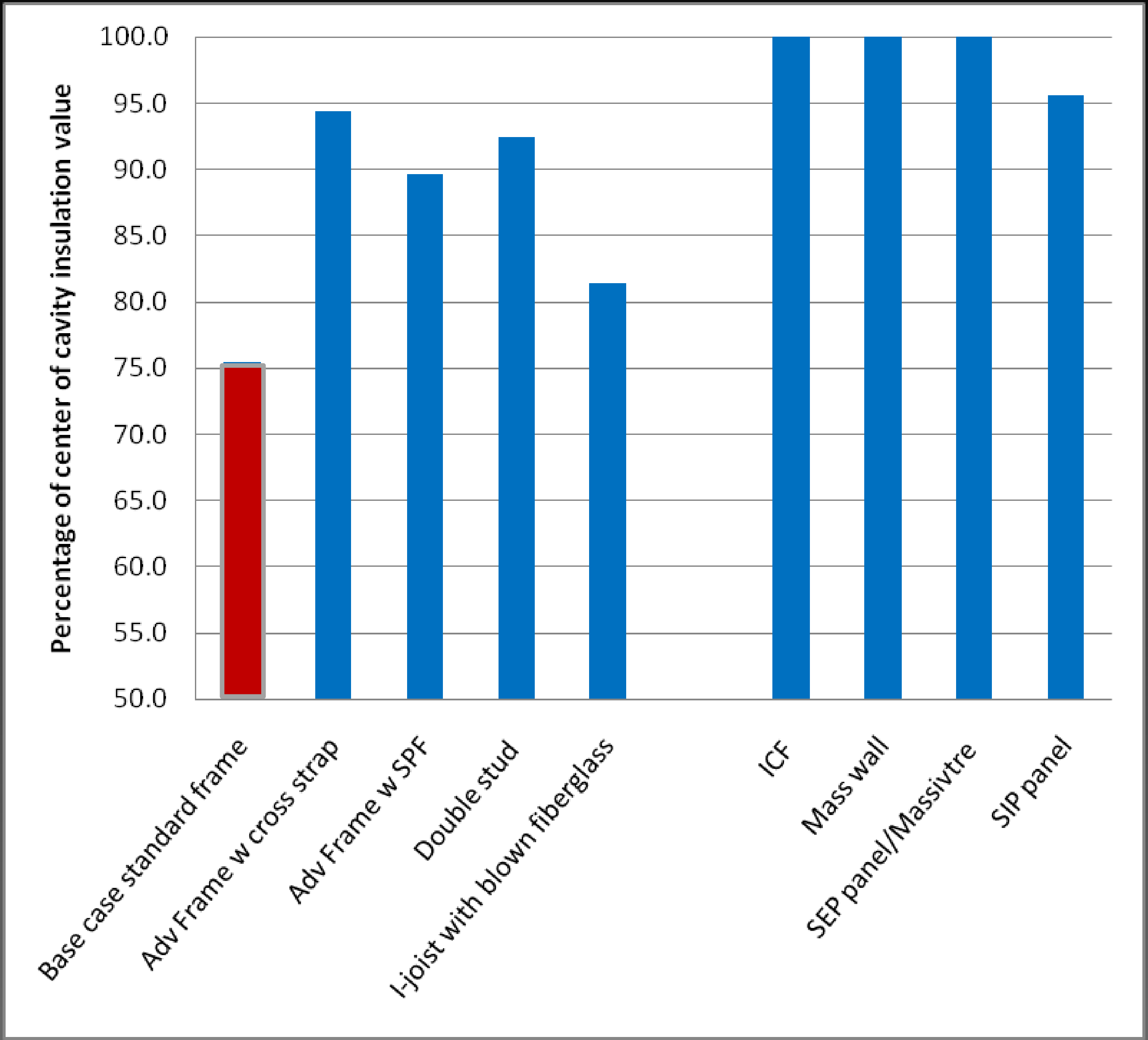
Section 1 – 2-D R-value calculations

- 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

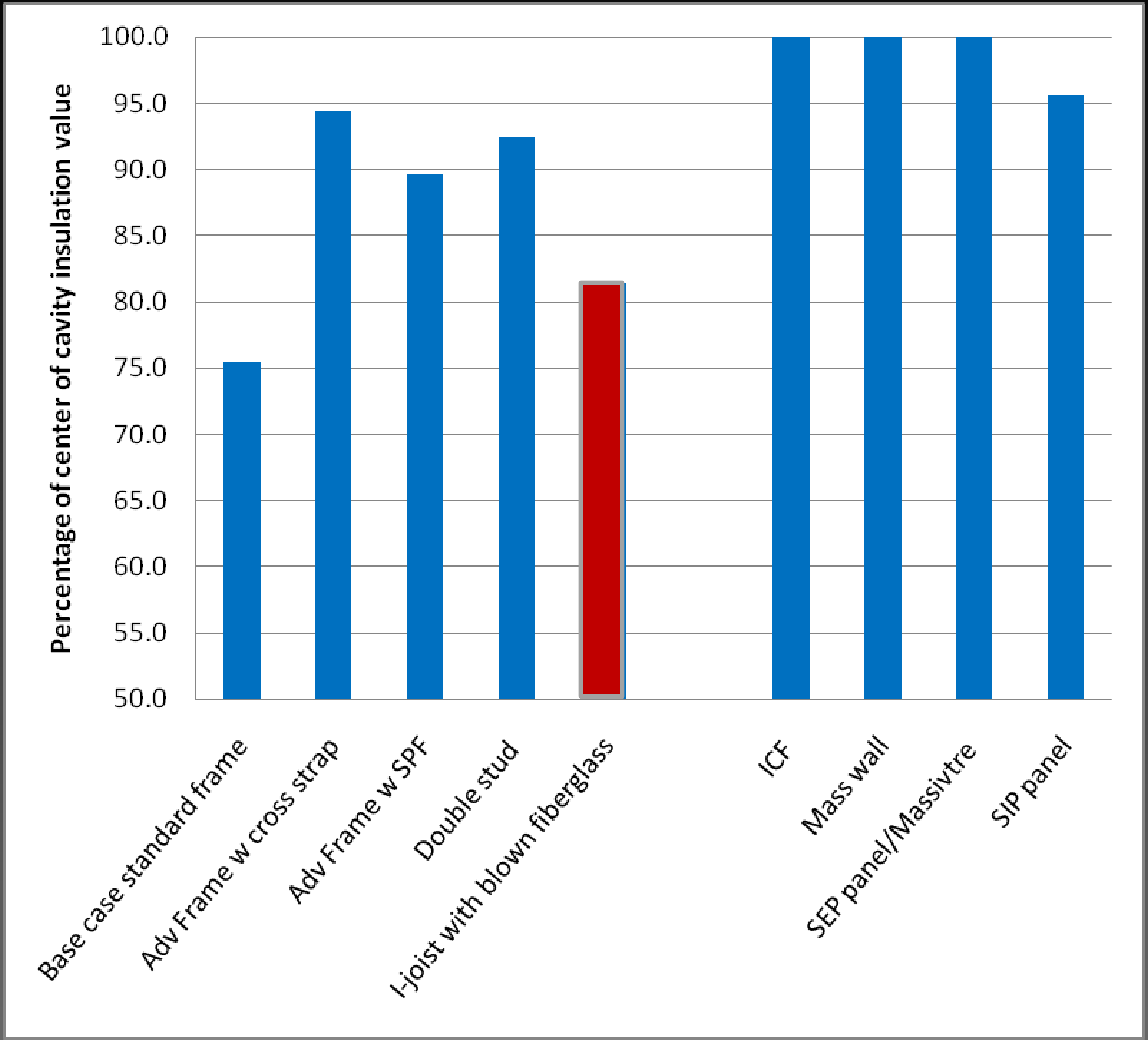


Final 2-D R-value divided by center of cavity R-value.

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

Standard framing loses 25% of the installed R-value.

Section 1 – 2-D R-value calculations

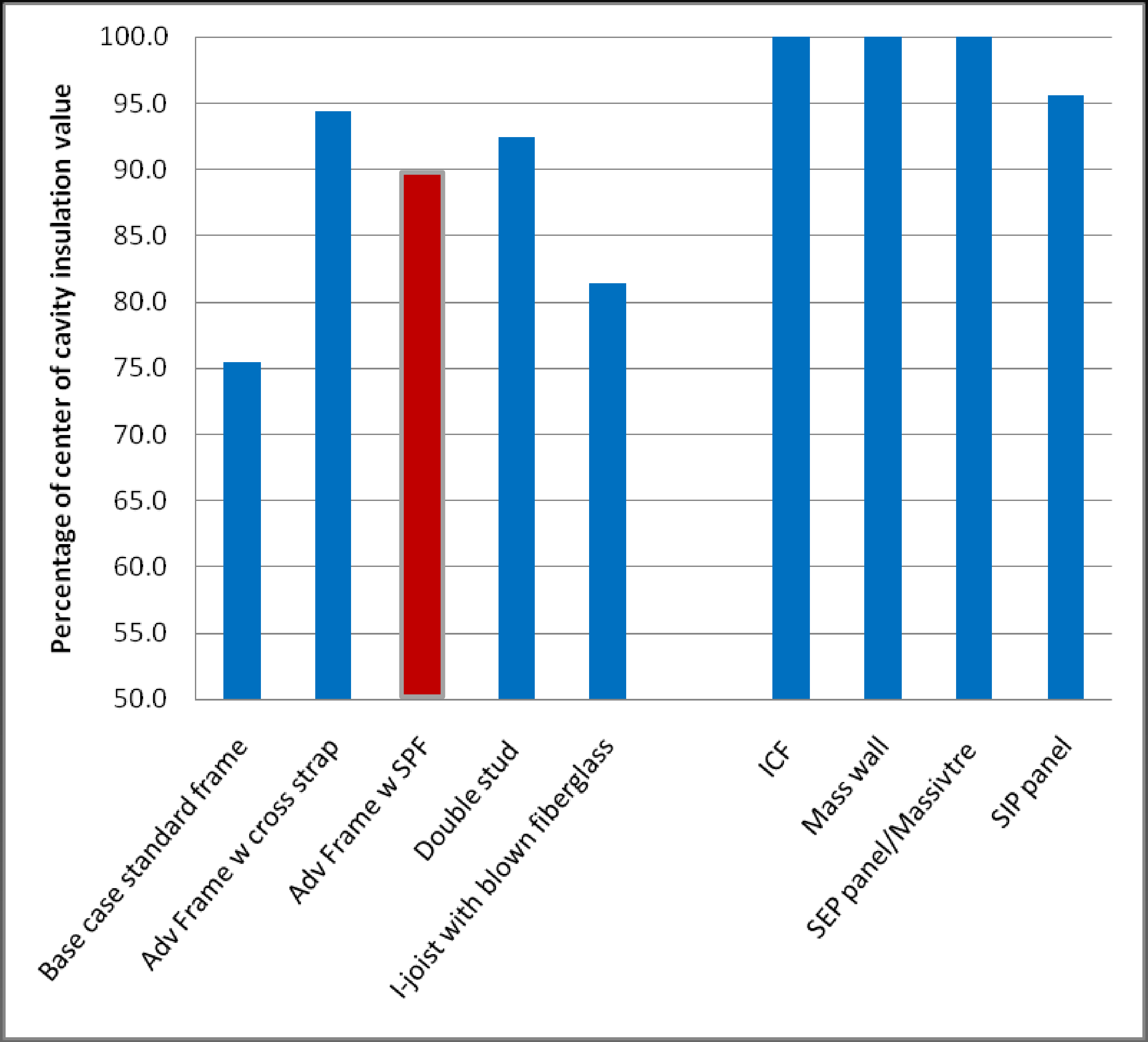


Final 2-D R-value divided by center of cavity R-value.

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

I-joist envelope with thinner stud profile loses about 18% of the installed R-value.

Section 1 – 2-D R-value calculations

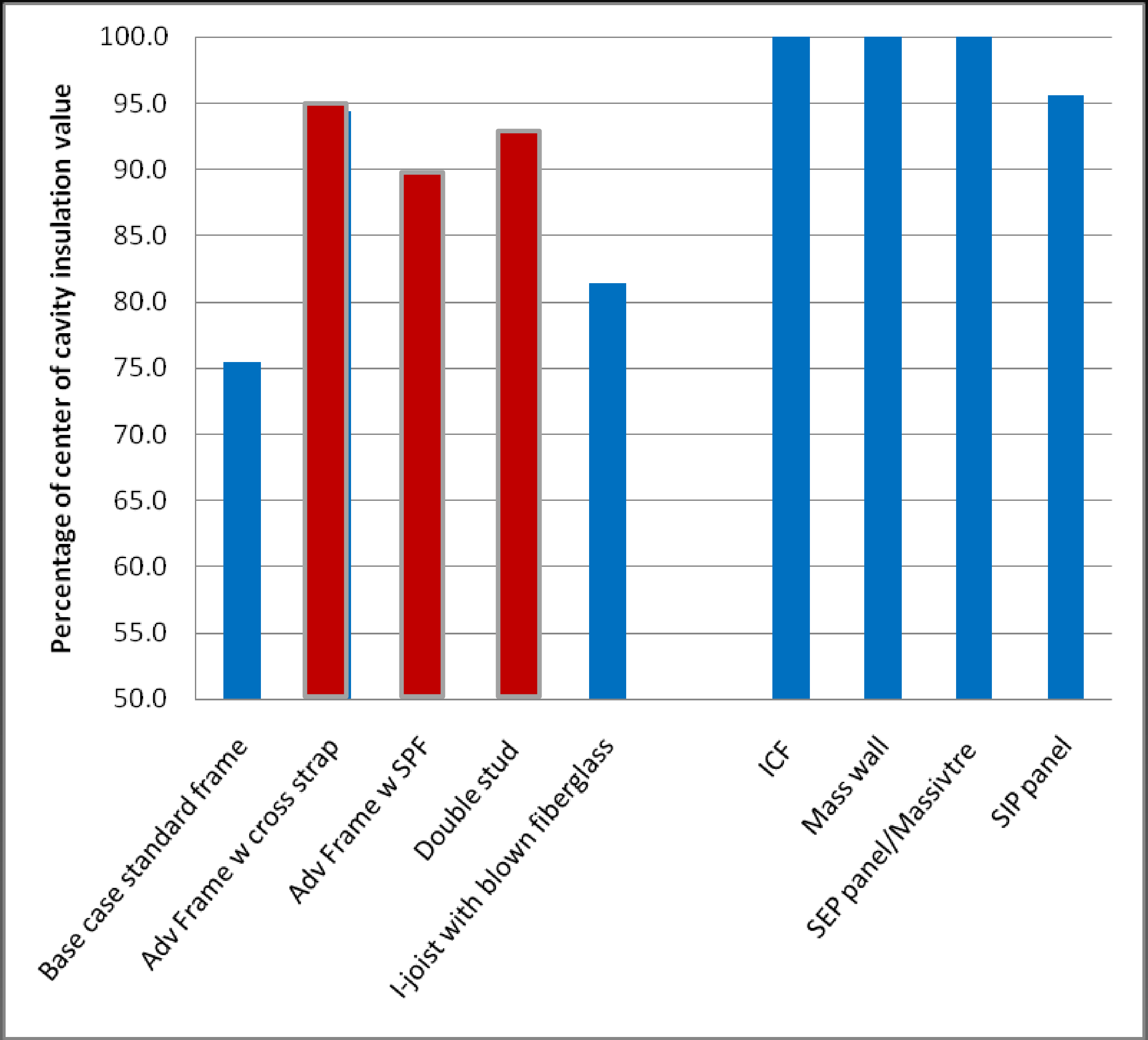


Final 2-D R-value divided by center of cavity R-value.

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

Advanced framing reduces framing factor from 25% to 12% and loses only 10% of installed R-value

Section 1 – 2-D R-value calculations

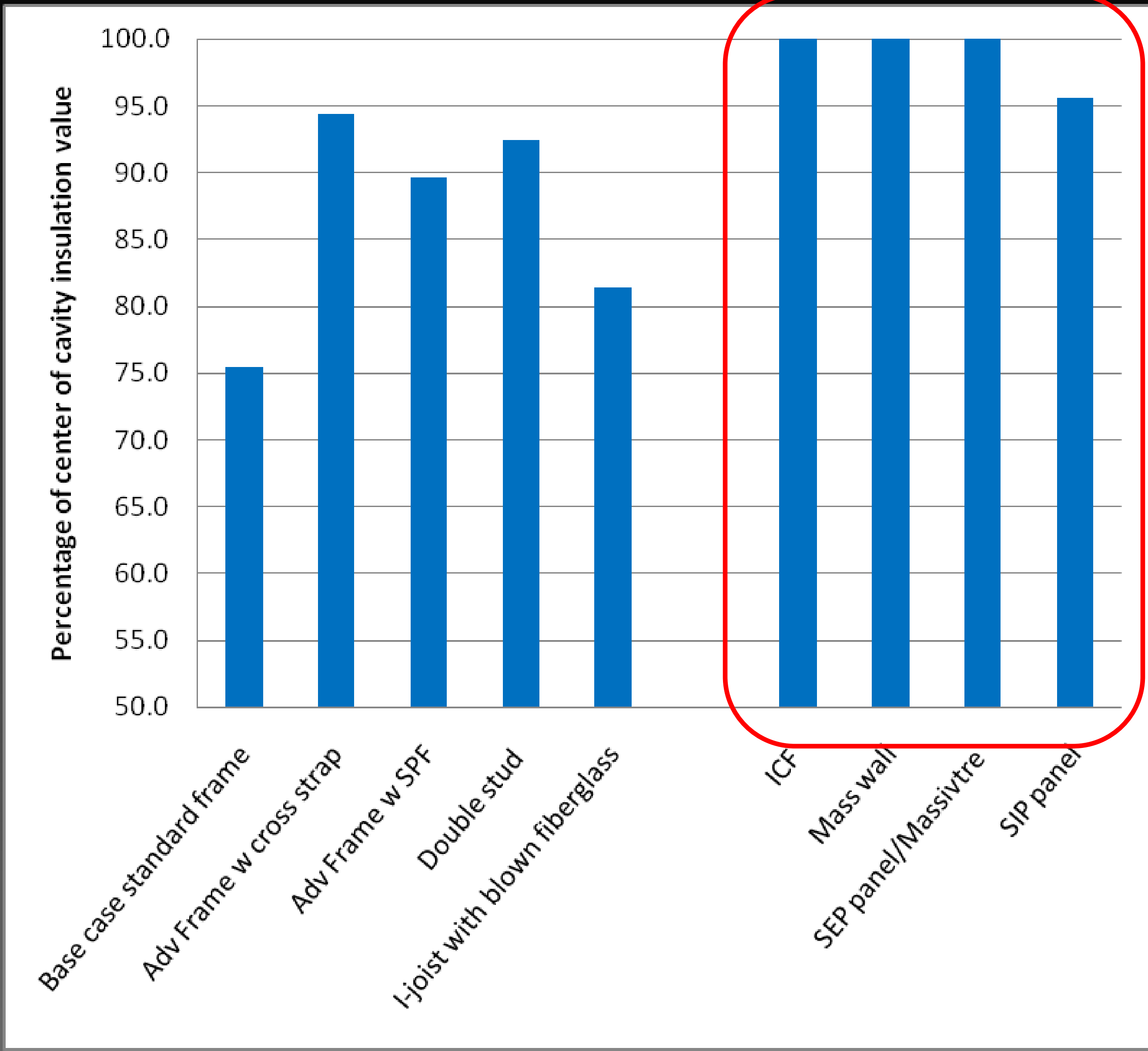


Final 2-D R-value divided by center of cavity R-value.

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

The best three performing wood frame envelopes all incorporate thick layers of continuous insulation.

Section 1 – 2-D R-value calculations

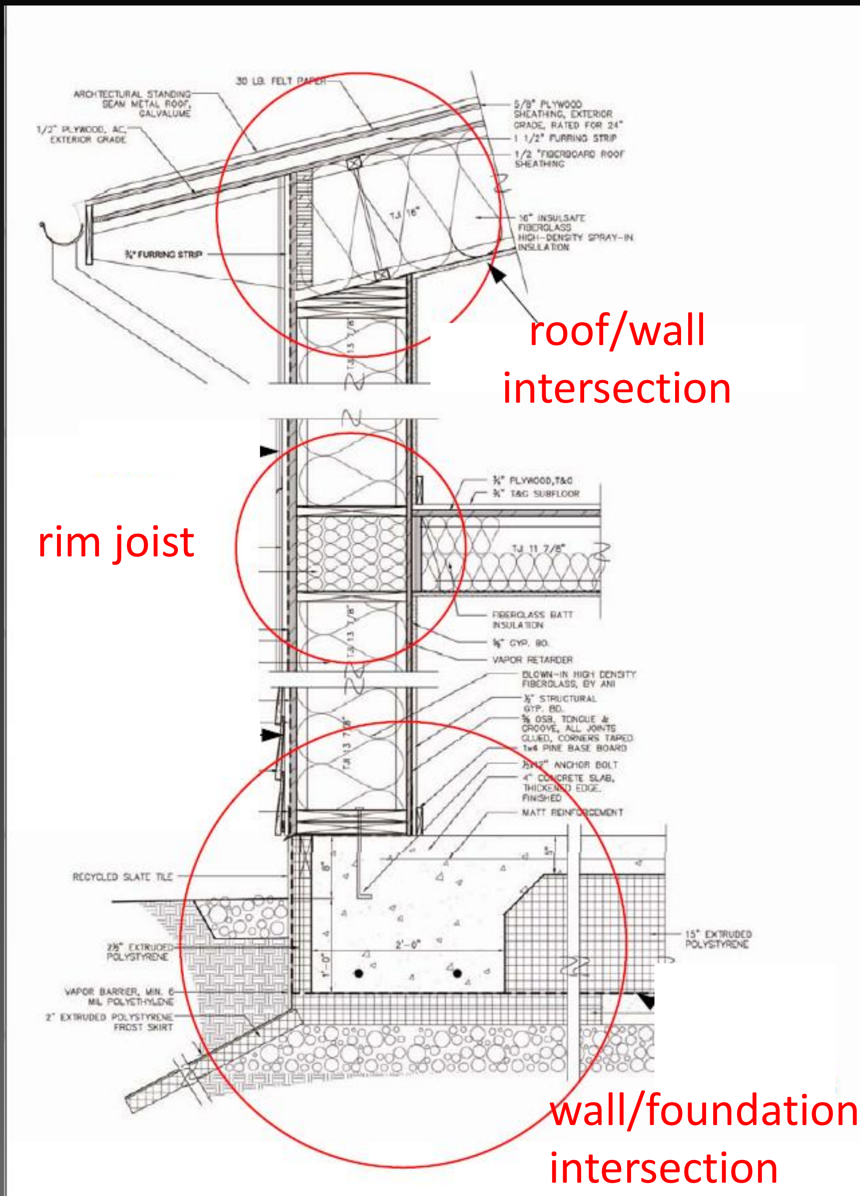


Final 2-D R-value divided by center of cavity R-value.

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

Continuous insulation w/out studs (repetitive thermal bridges) performs the best.

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

- Heat loss through a linear thermal bridge is measured with a Ψ value
- A Ψ value is like a U-value for thermal bridges

  U x A x dT = heat loss from a wall, window, roof, etc…

  Ψ x L x dT = heat loss from a linear thermal bridge
- Ψ values </= 0.01 W/mK qualify as “thermal bridge free” according to Passive House
- To calculate Ψ values, a 2-D heat flow simulation model (such as THERM) is used.

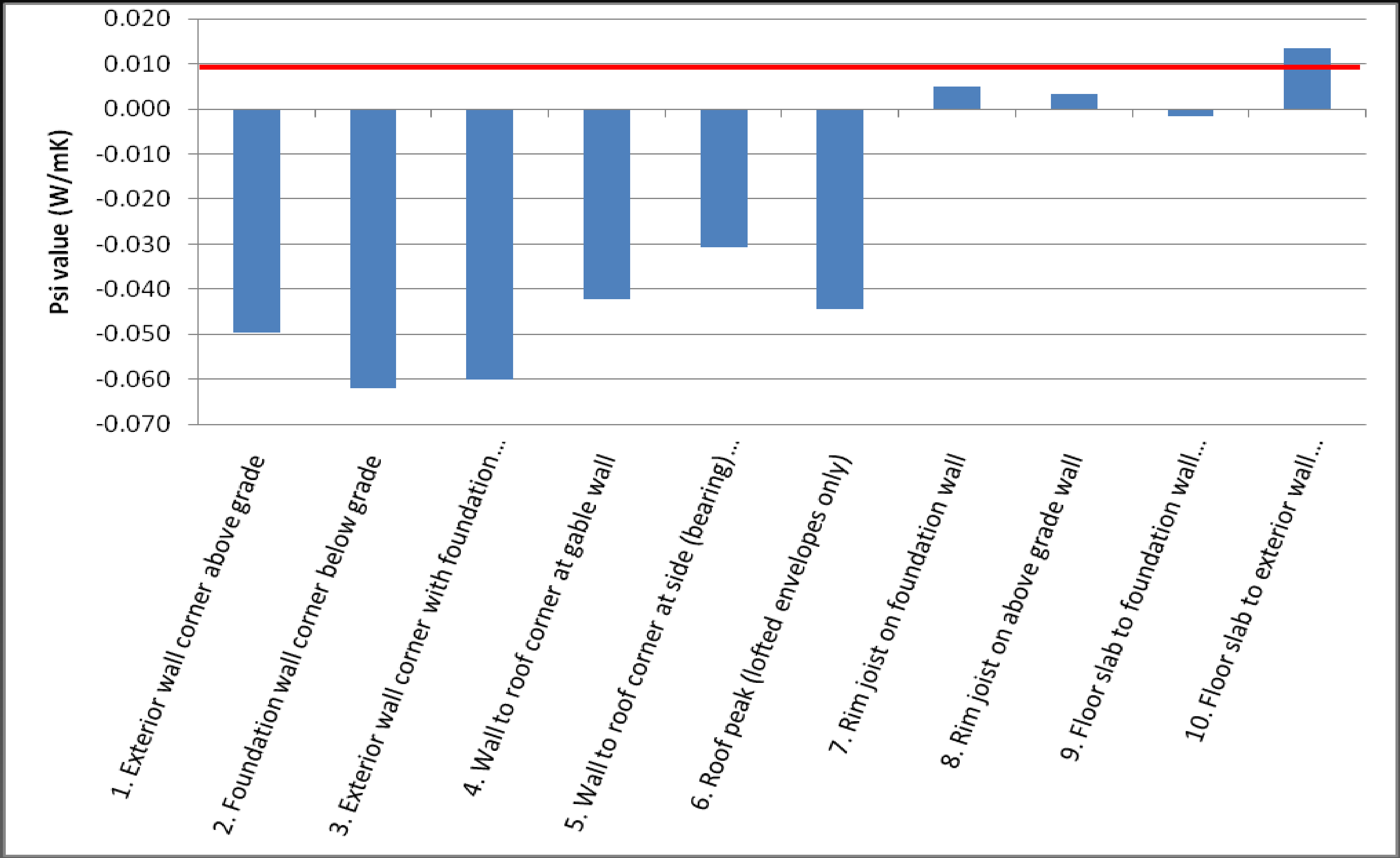
Section 2 – Thermal Bridge Analysis

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	

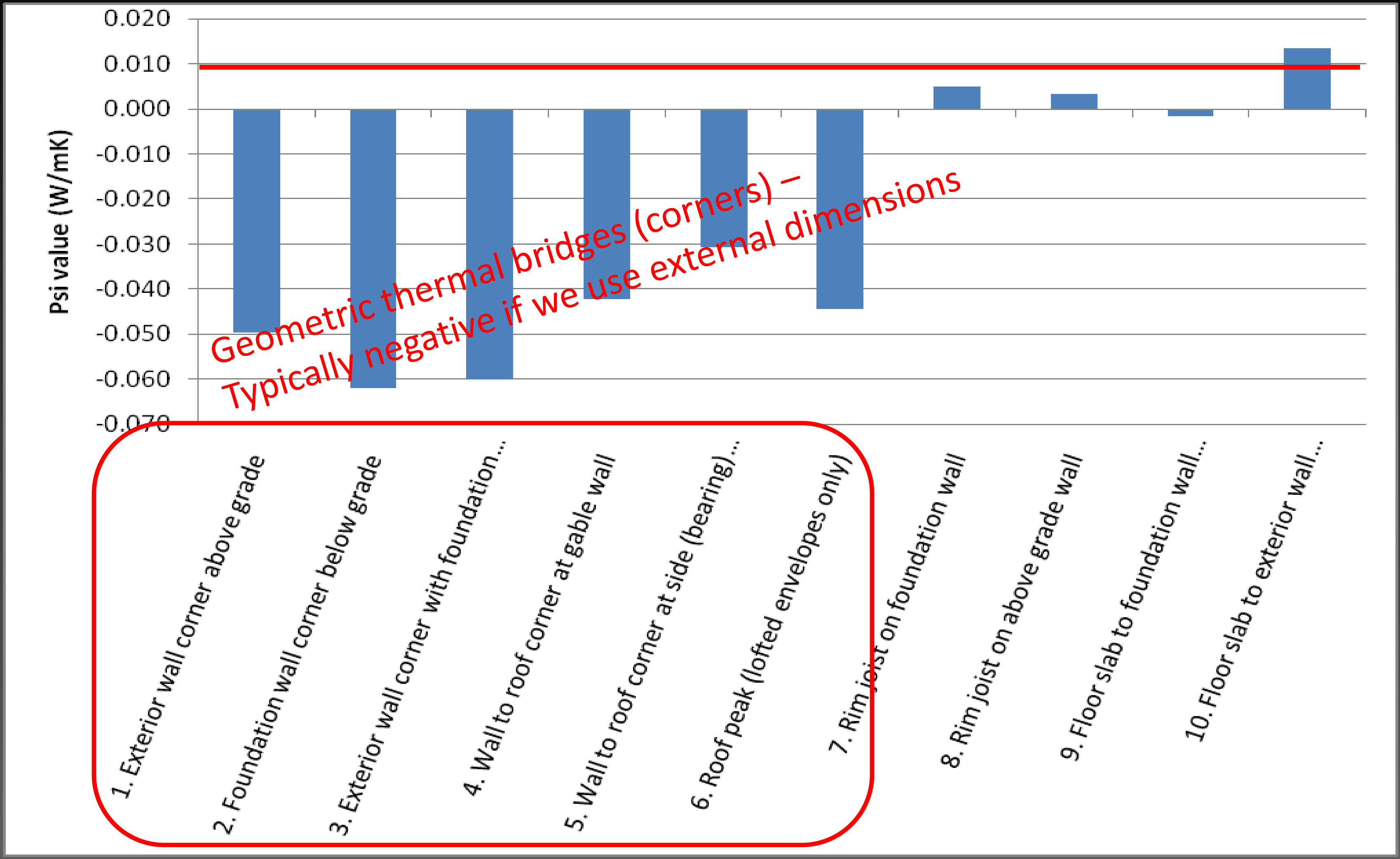
Passive House guideline, Ψ </= 0.01 W/mK

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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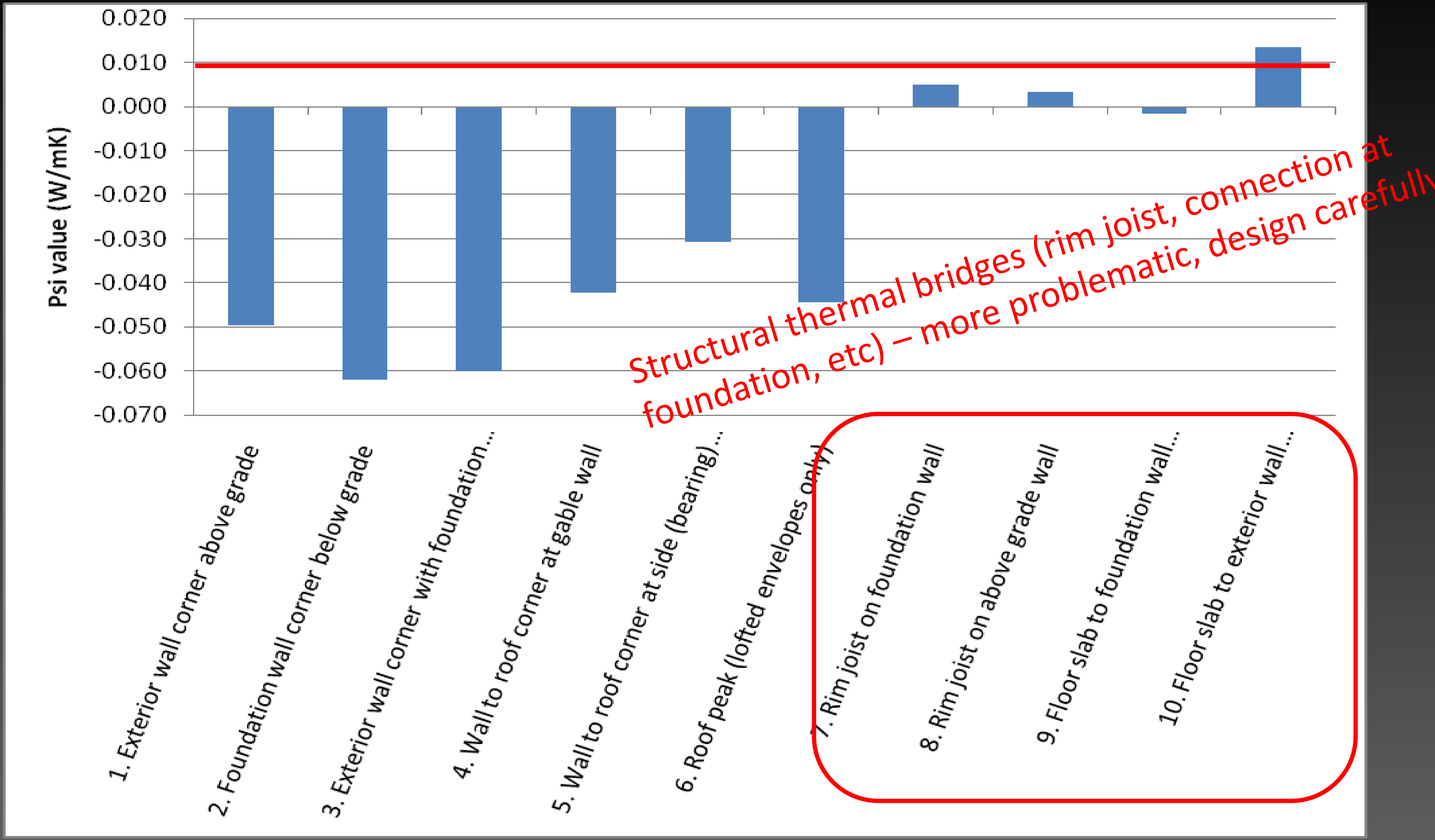
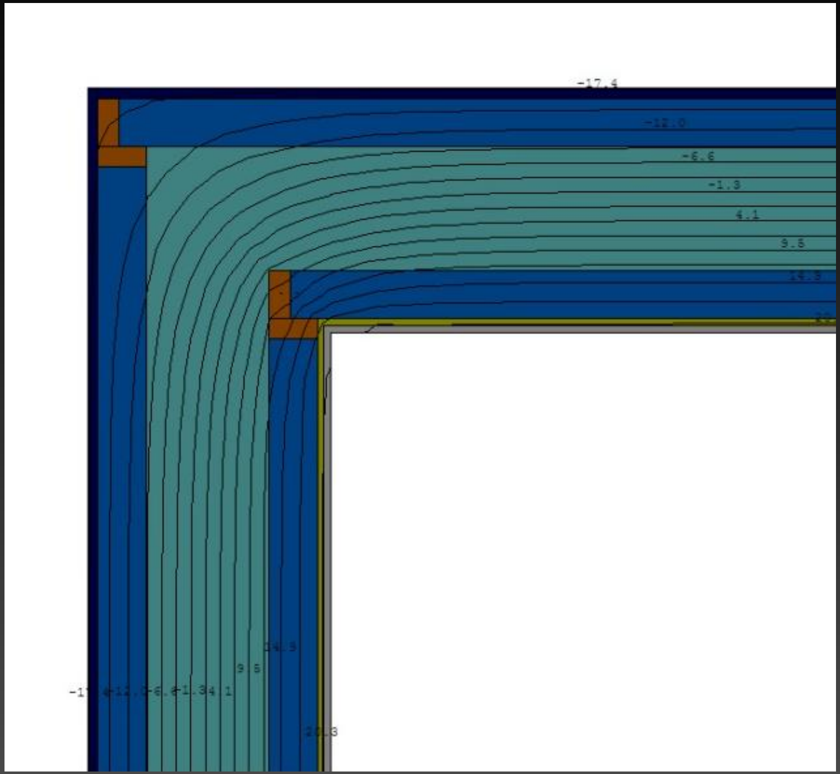
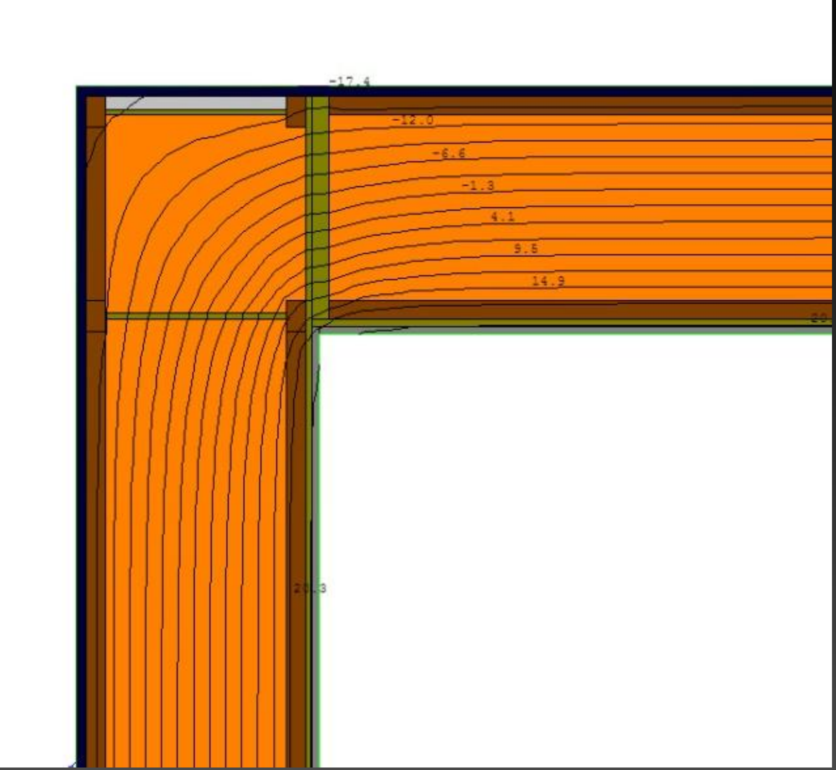


Average Ψ values for each detail location across all envelope types

Section 2 – Thermal Bridge Analysis





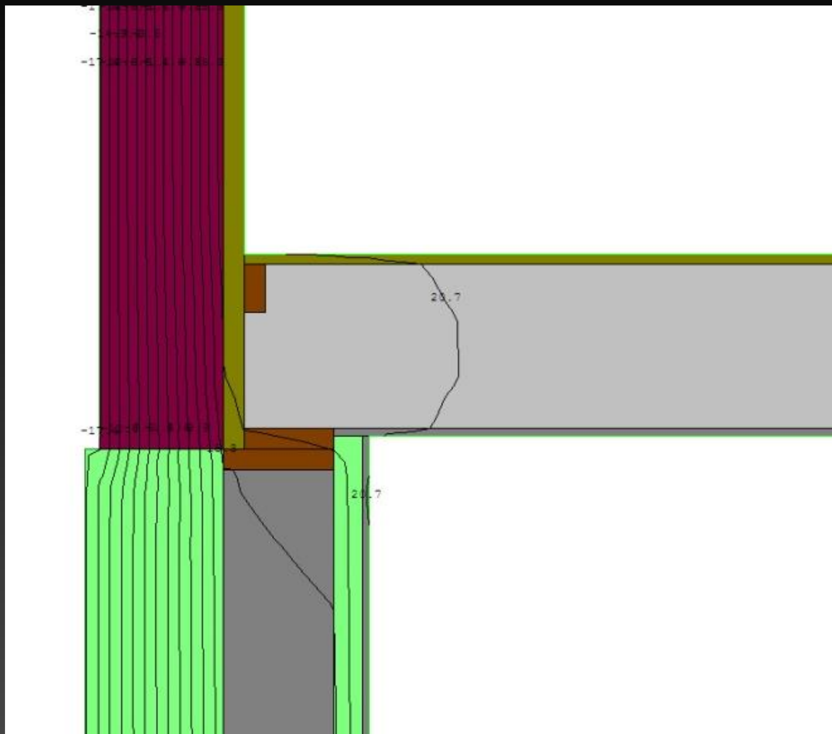
Double stud frame: Ψ = - 0.058 W/mK

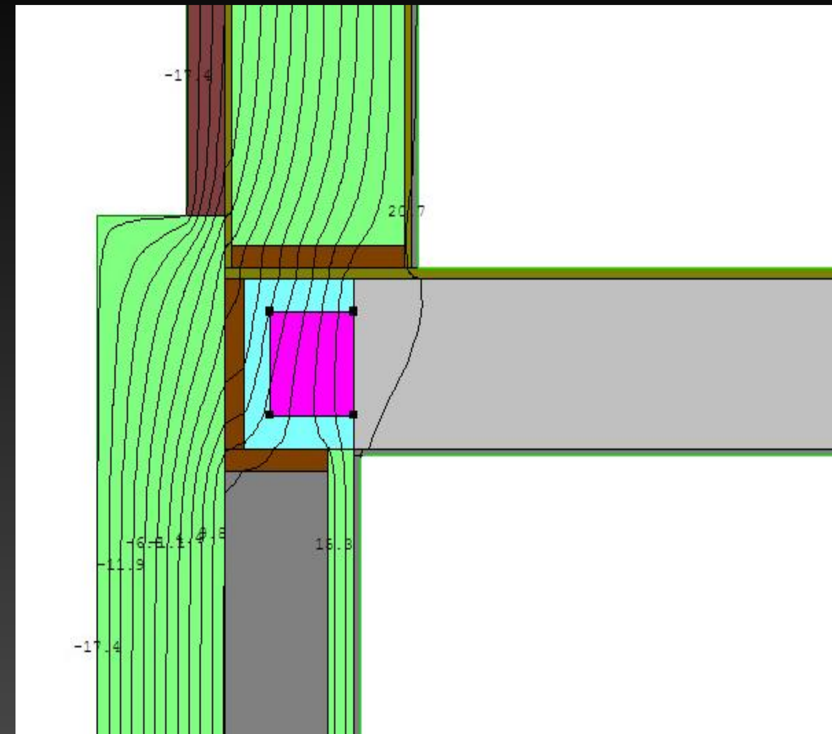
TJI frame: Ψ = - 0.051 W/mK

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





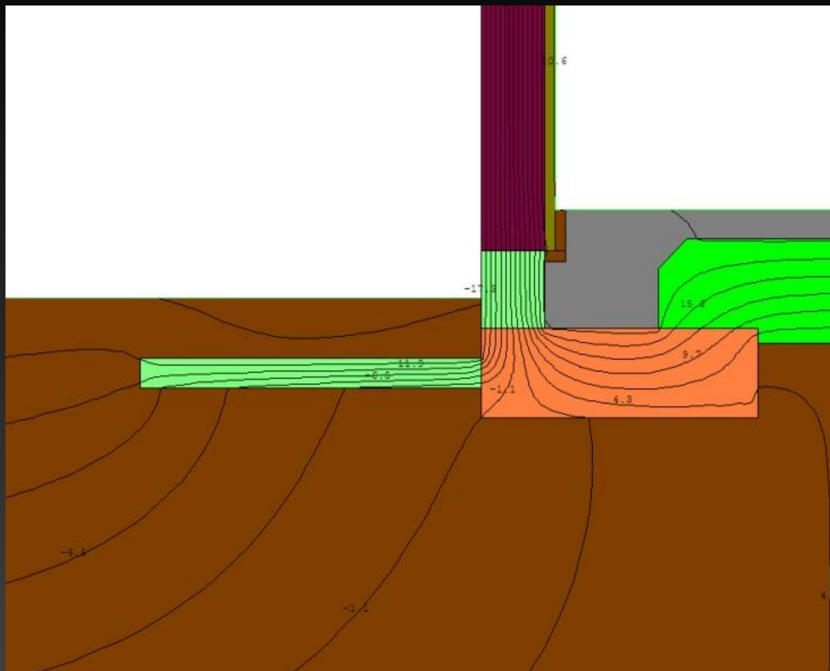
SEP panel rim joist: Ψ = 0.003 W/mK

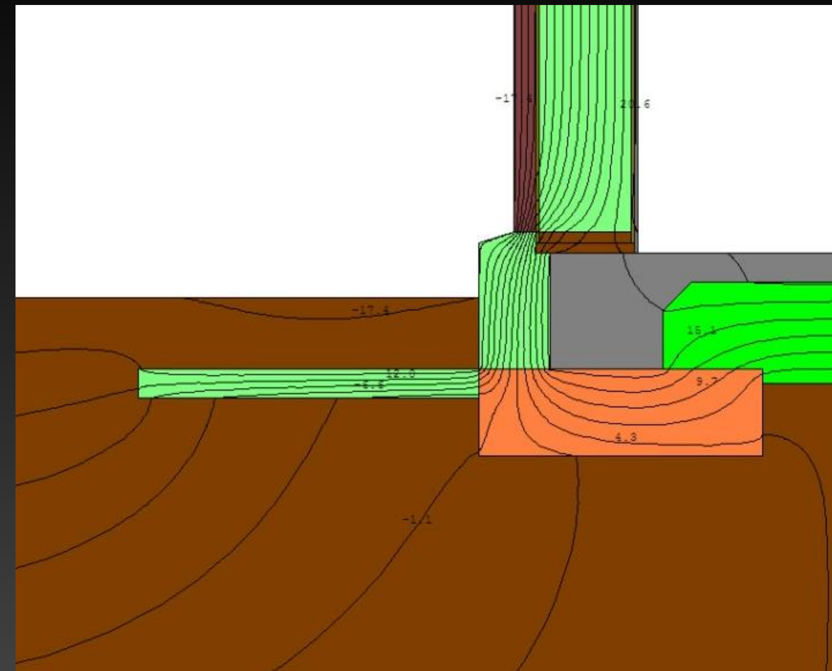
SIP panel rim joist: Ψ = 0.009 W/mK

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





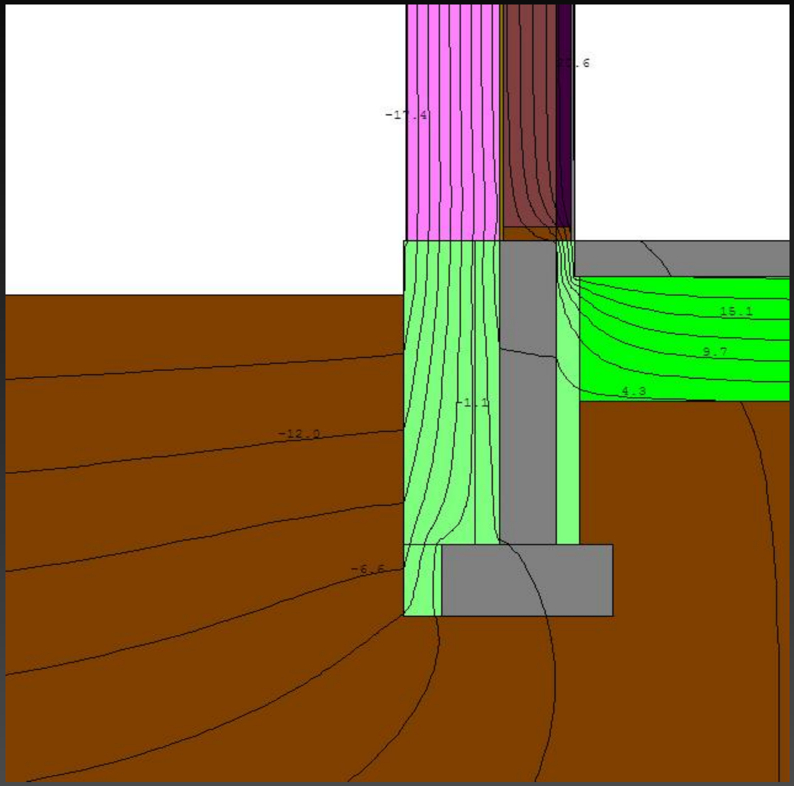
SEP panel FPSF: Ψ = 0.023 W/mK

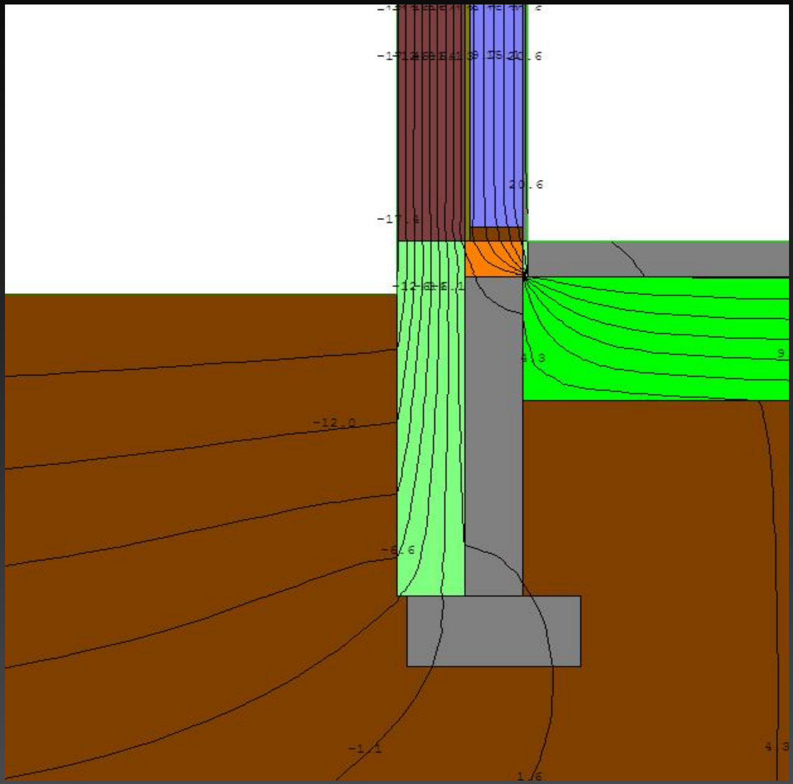
SIP panel FPSF: Ψ = 0.052 W/mK

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 accidental "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

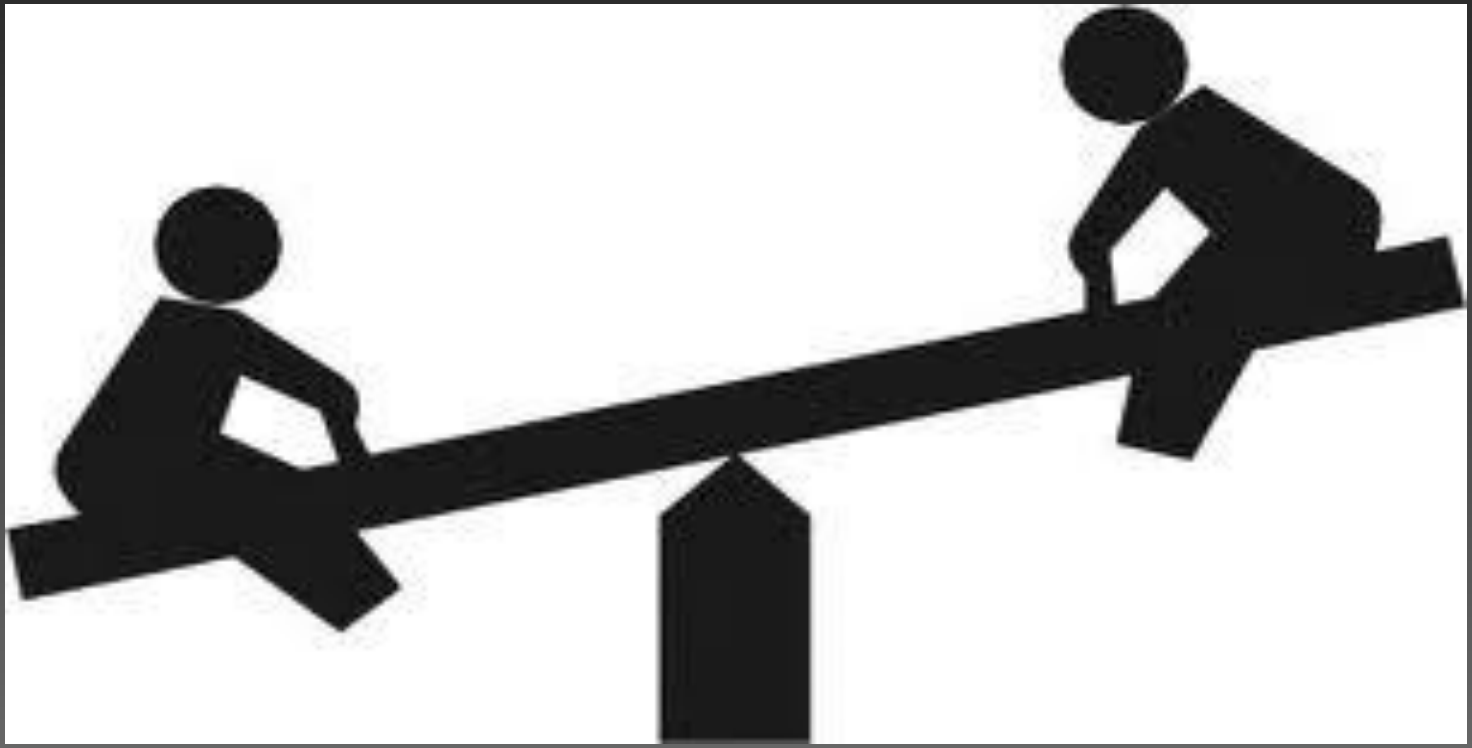
- Mold growth
- Indoor air quality
- Durability of structure

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

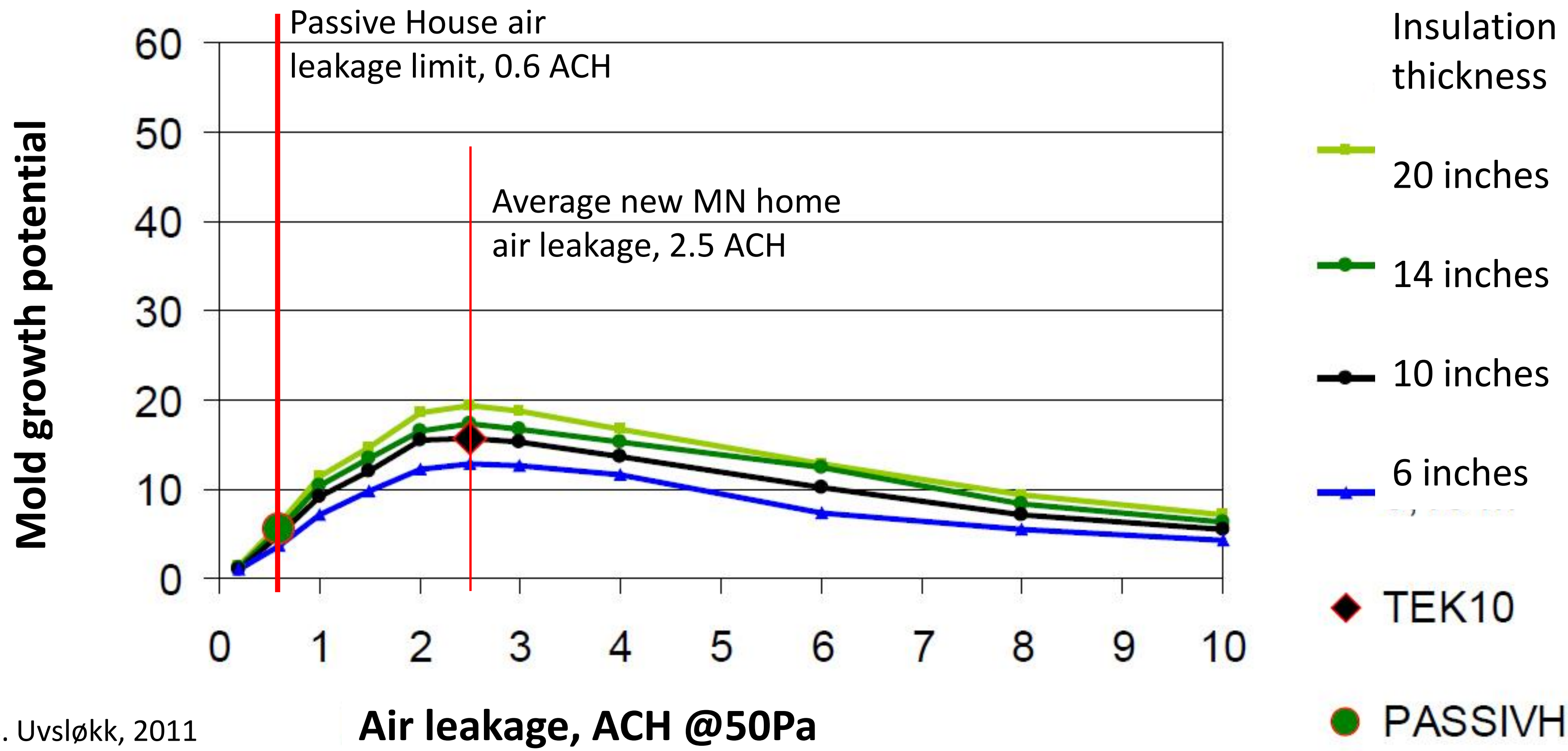
Section 3 – Hygrothermal Analysis

Increased insulation
leads to…
less available heat
leads to…
Slower drying and wetter assemblies

Increased air tightness
leads to…
Less moisture carried into walls and drier assemblies



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.

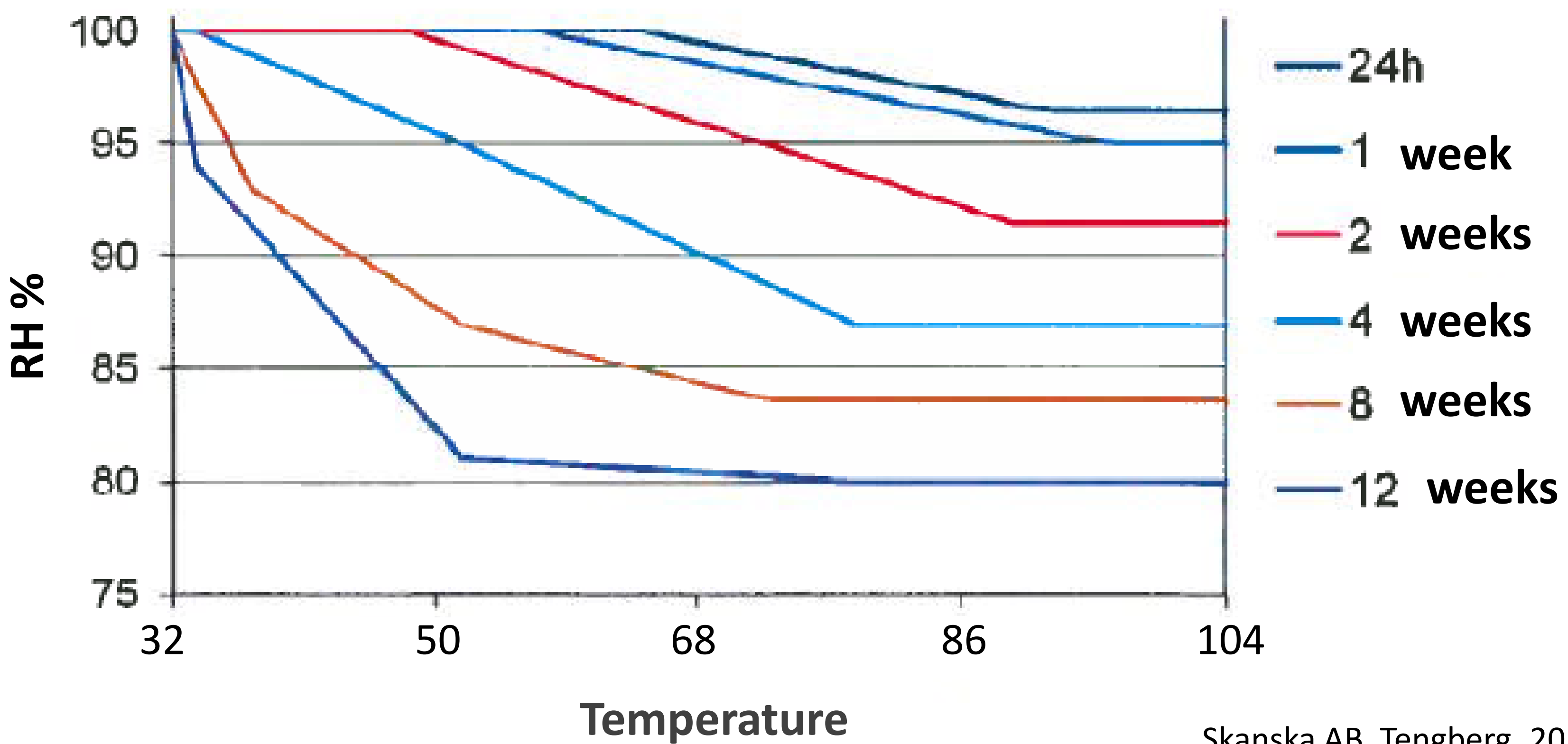
Section 3 – Hygrothermal Analysis

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

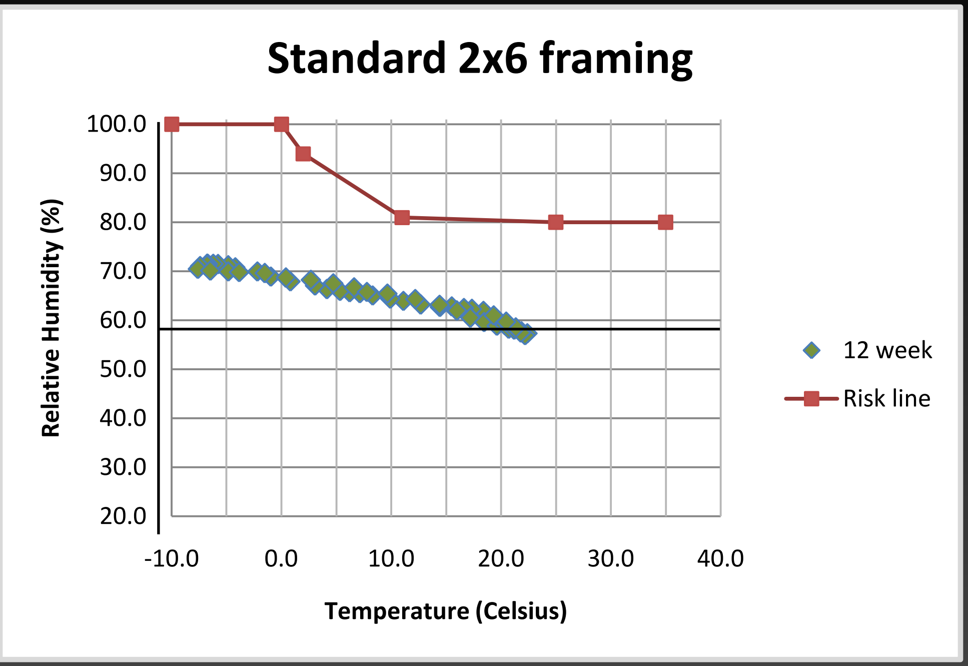
Risk lines for mold growth on wood



Skanska AB, Tengberg, 2010

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.

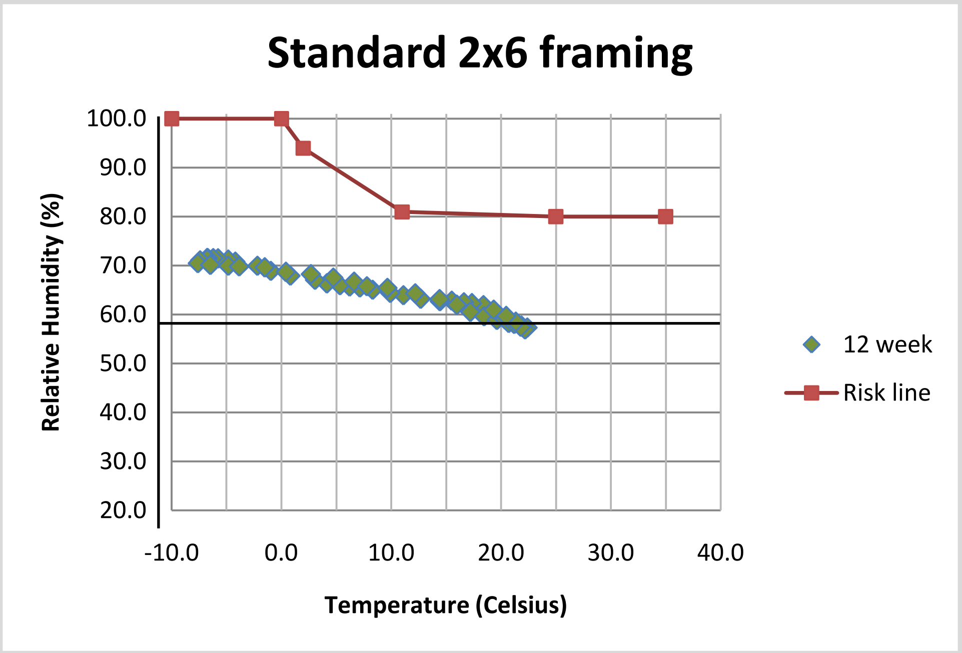
Section 3 – Hygrothermal Analysis

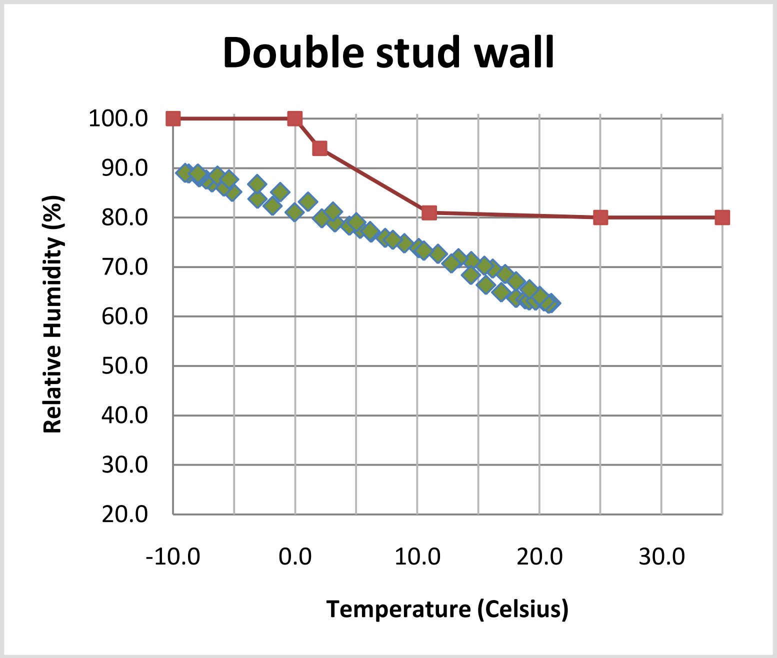


Standard 2x6 framing, 5.5” fiberglass batts,
6mil poly vapor retarder, R-14.75
Critical layer = OSB sheathing

What happens when we take away heat by adding insulation to the stud cavity?

Section 3 – Hygrothermal Analysis



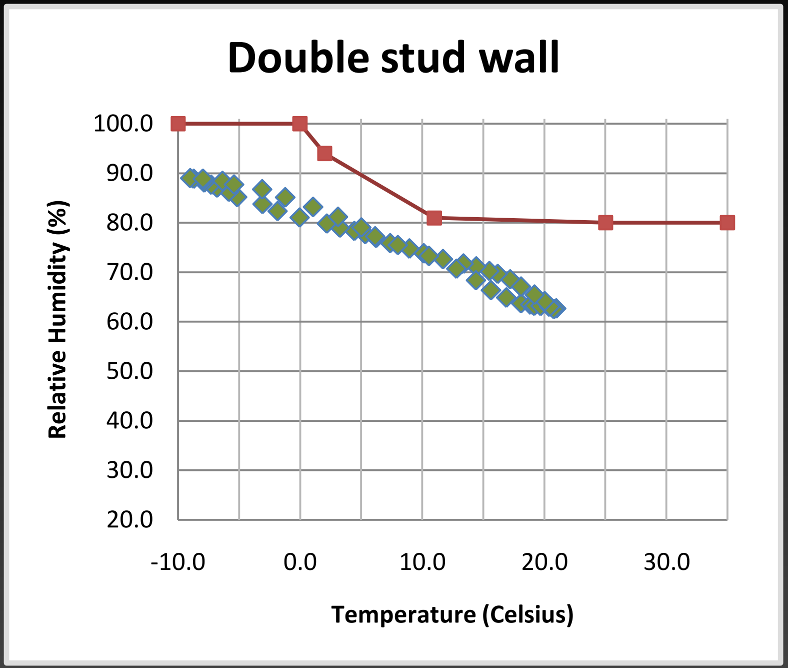


Standard 2x6 framing, 5.5" fiberglass batts,
6mil poly vapor retarder, R-15
Critical layer = OSB sheathing

Double stud 2x4 framing, 16" blown cellulose,
OSB vapor retarder, R-60
Critical layer = fiberboard sheathing

Relative humidity levels in the critical layer rise to 90% in the winter and the ability of the sheathing to dry quickly in the spring becomes imperative.

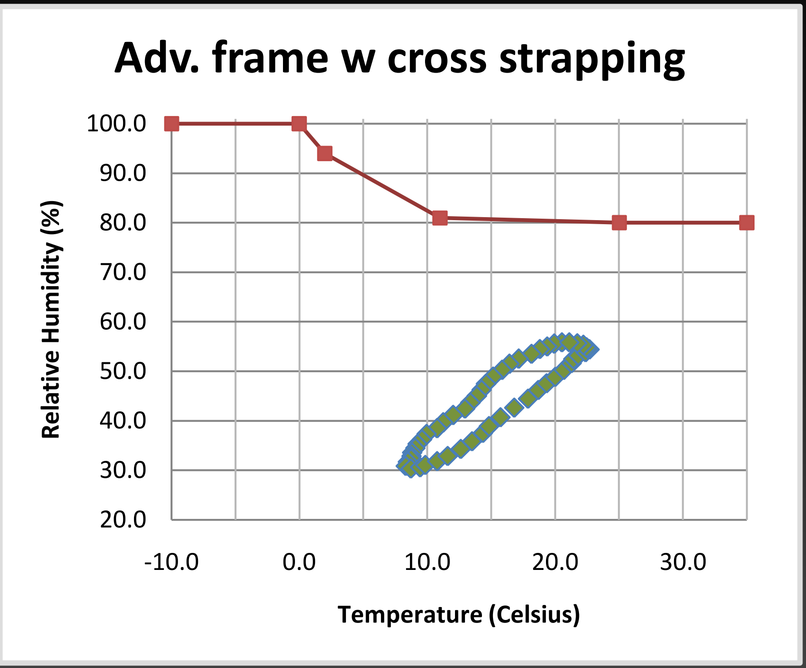
Section 3 – Hygrothermal Analysis

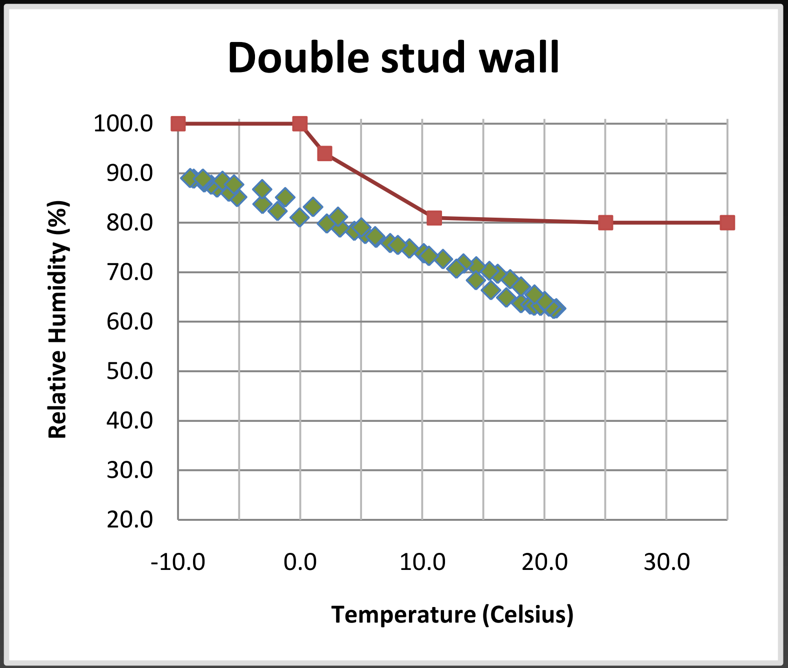


Double stud 2x4 framing, 16" blown cellulose, R-60
OSB vapor retarder
Critical layer = fiberboard sheathing

What happens when we warm the sheathing with permeable exterior insulation?

Section 3 – Hygrothermal Analysis



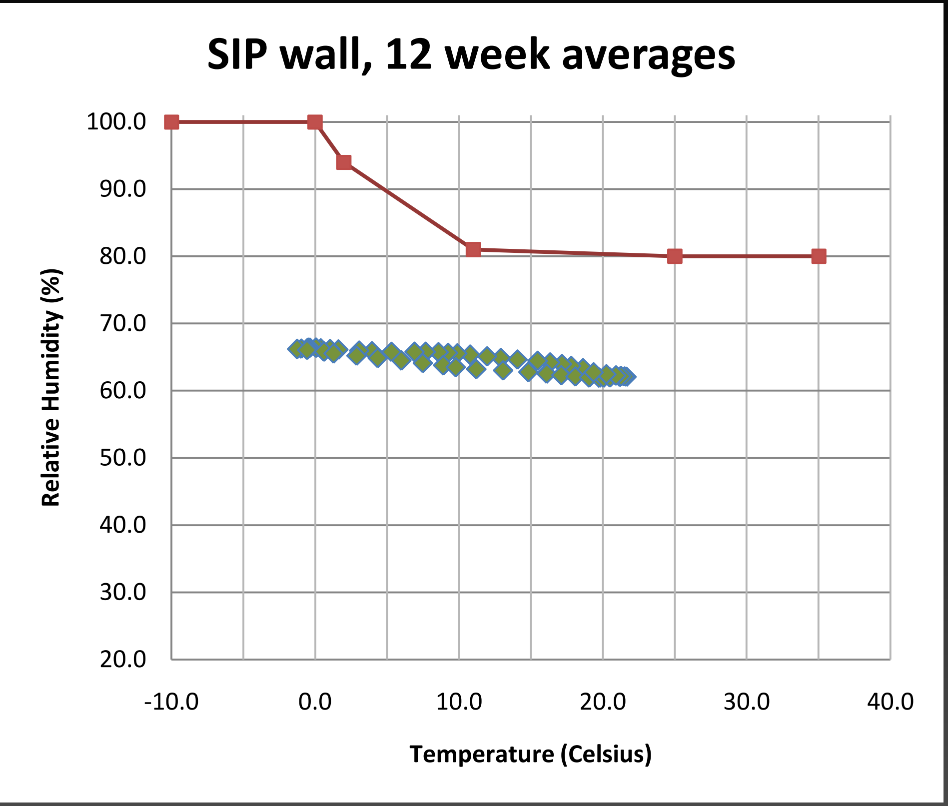


Advanced 2x6 framing, 5.5” mineral wool batts, plus 10” exterior mineral wool, R-60
6mil poly vapor retarder
Critical layer = OSB sheathing

Double stud 2x4 framing, 16” blown cellulose, R-60
OSB vapor retarder
Critical layer = fiberboard sheathing

The sheathing (critical layer) stays above 45 degrees F, and relative humidity levels drop below 60% year-round.

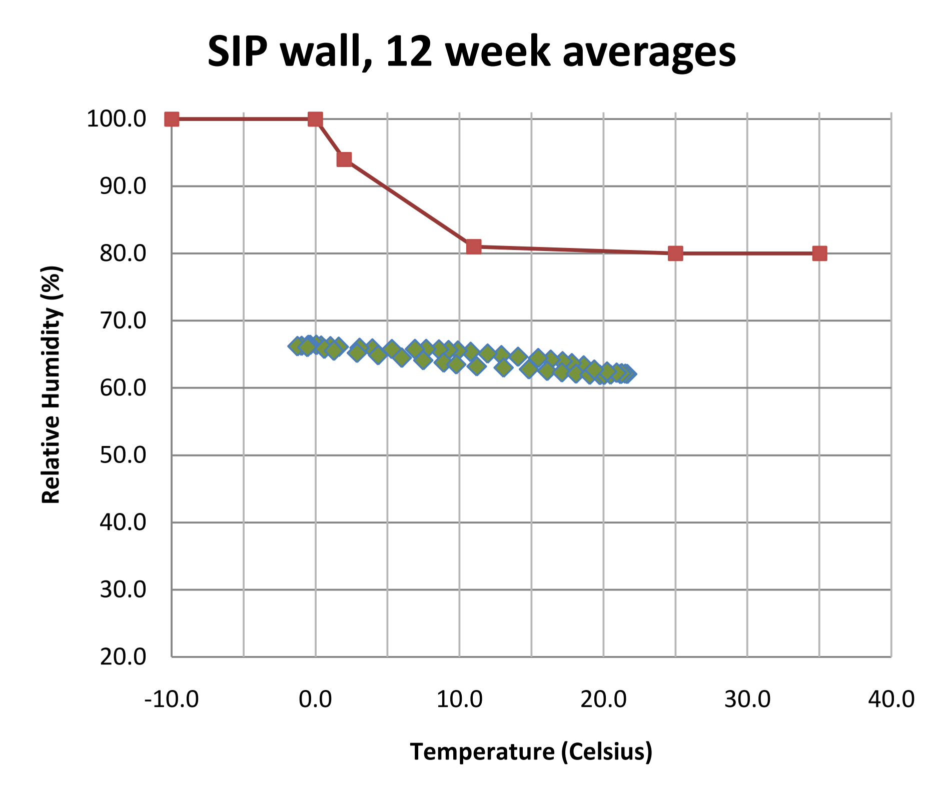
Section 3 – Hygrothermal Analysis



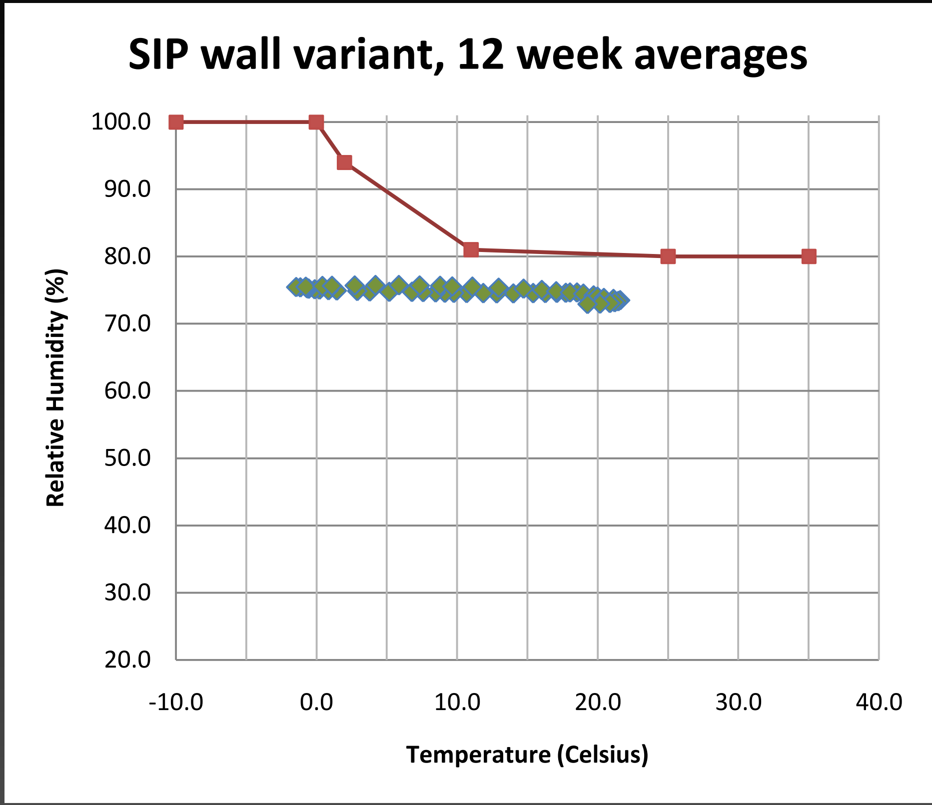
Critical layer = OSB sheathing, beneath 3” unfaced polyiso

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)?

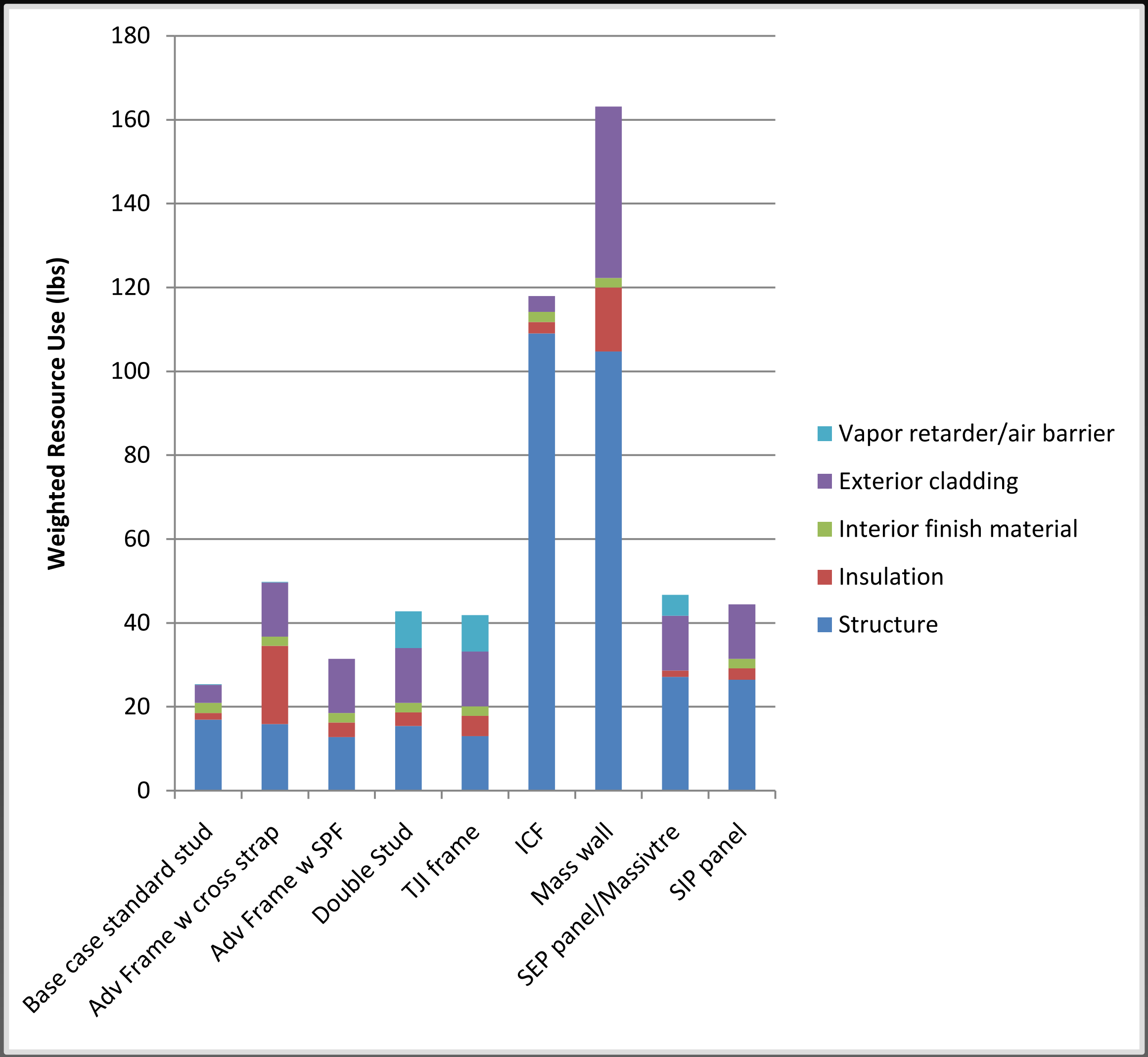
Despite heat, drying is reduced and you may end up with a wetter critical layer!

Section 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

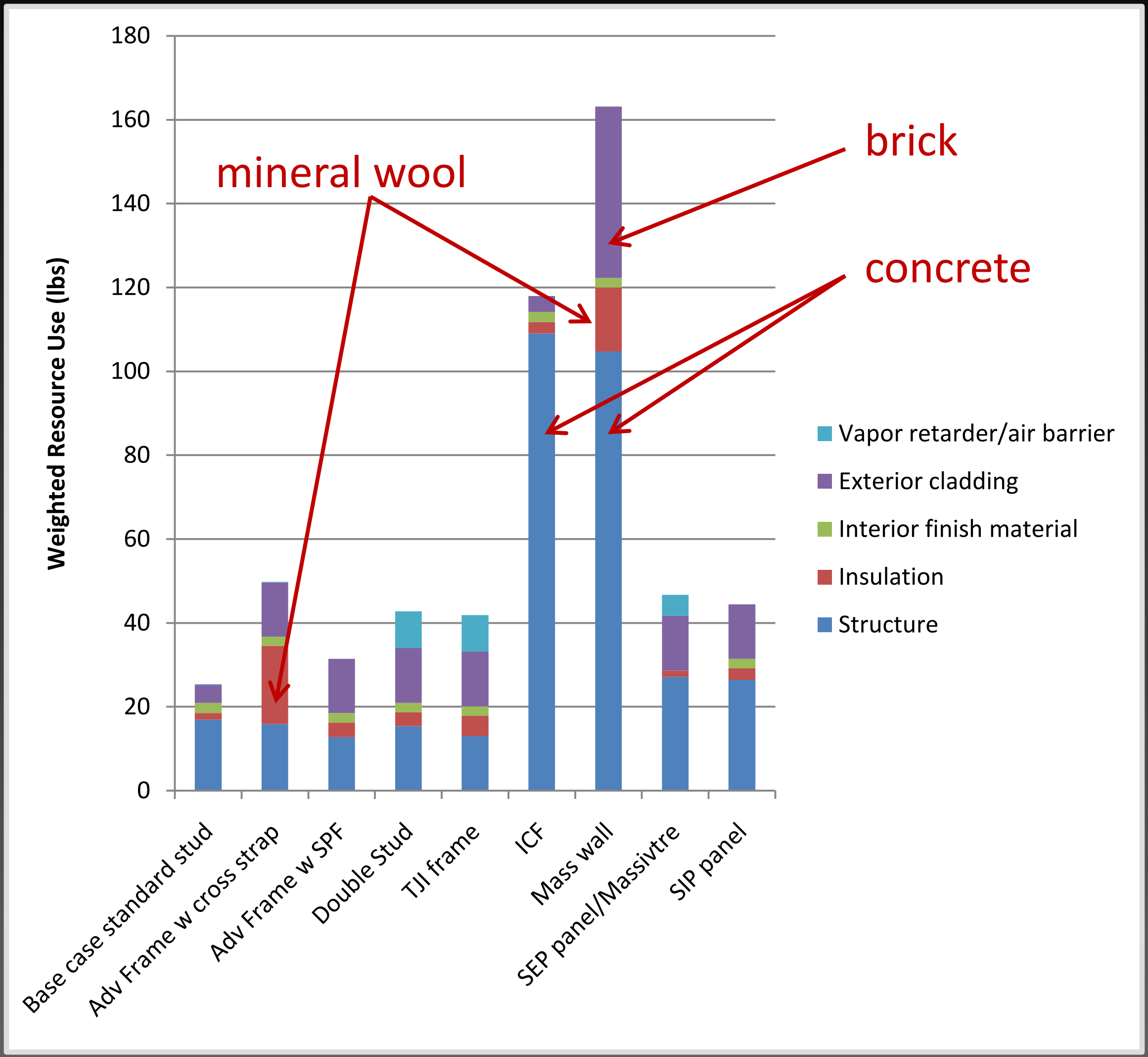
Section 4 – Life Cycle Env. Impacts



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



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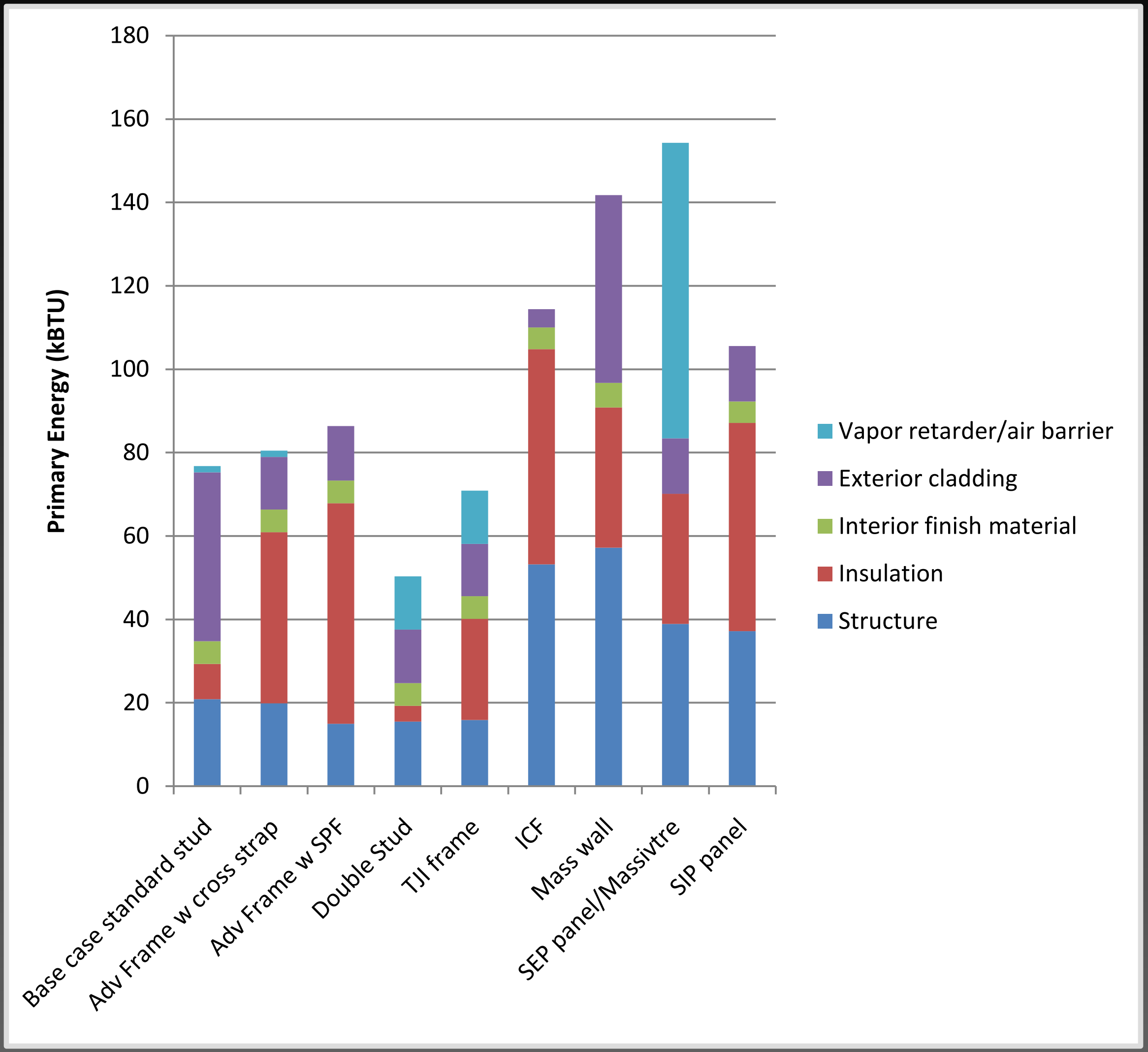
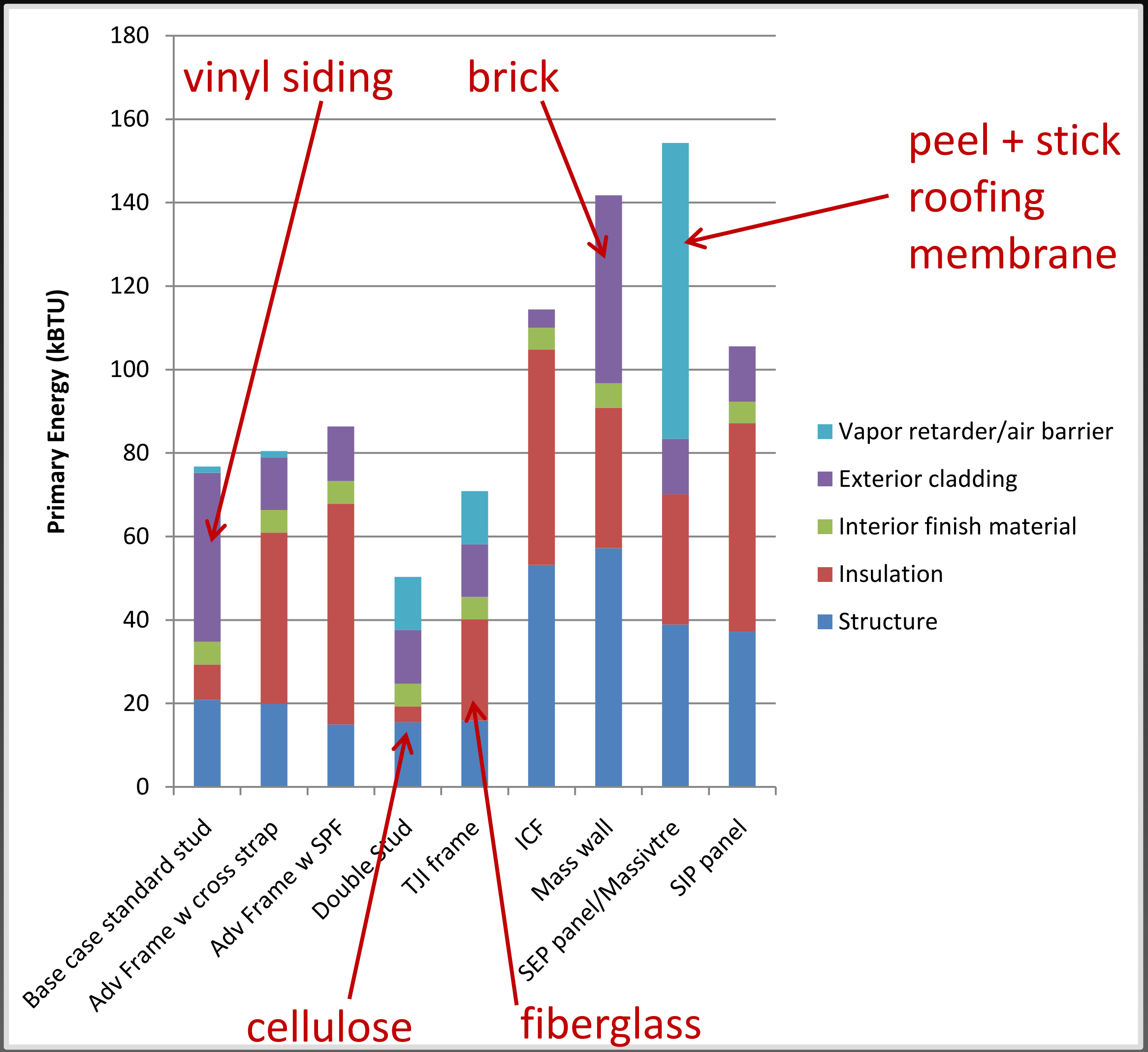


Life cycle embodied energy of above grade walls by building element

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

Section 4 – Life Cycle Env. Impacts



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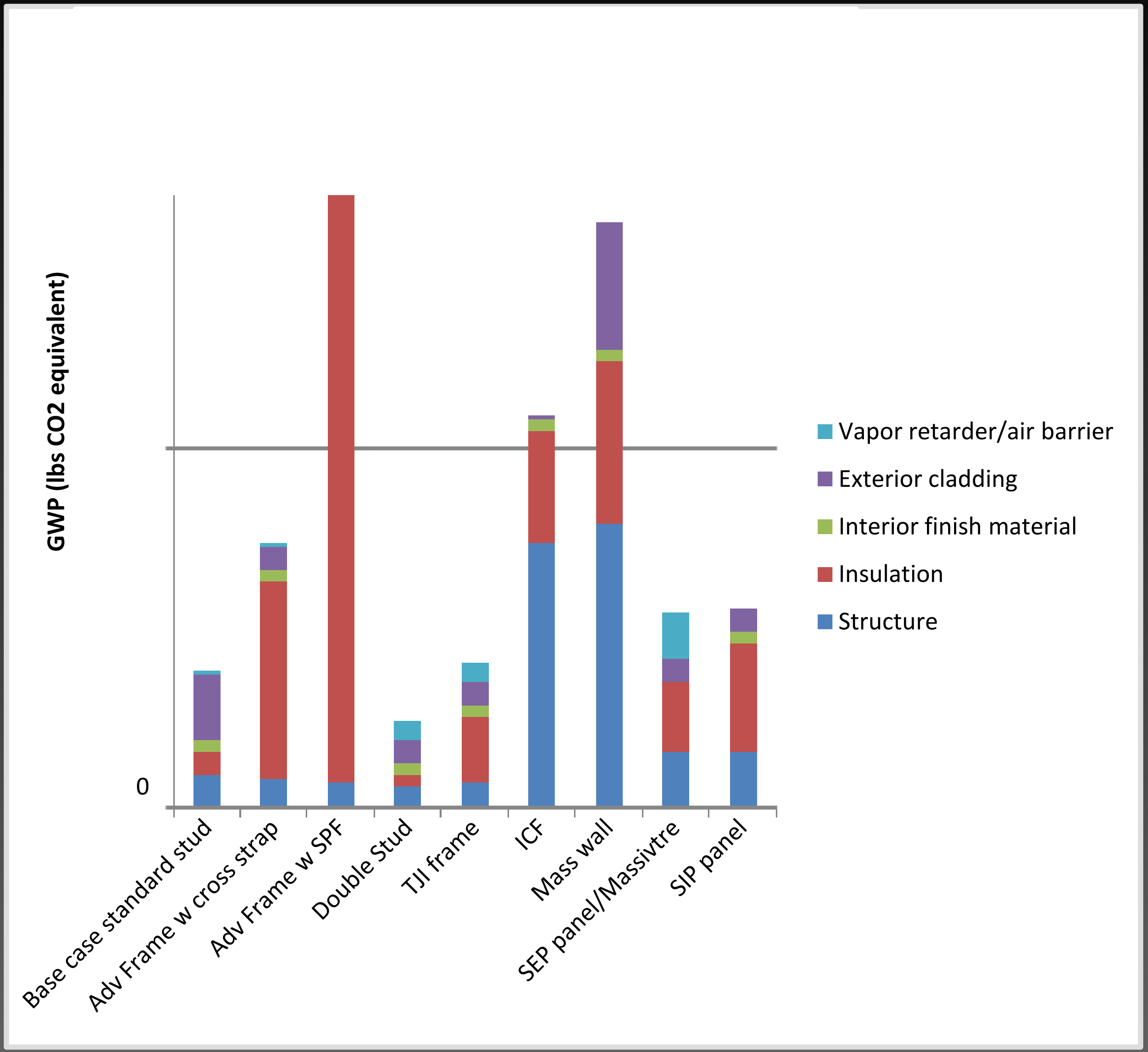
Section 4 – Life Cycle Env. Impacts

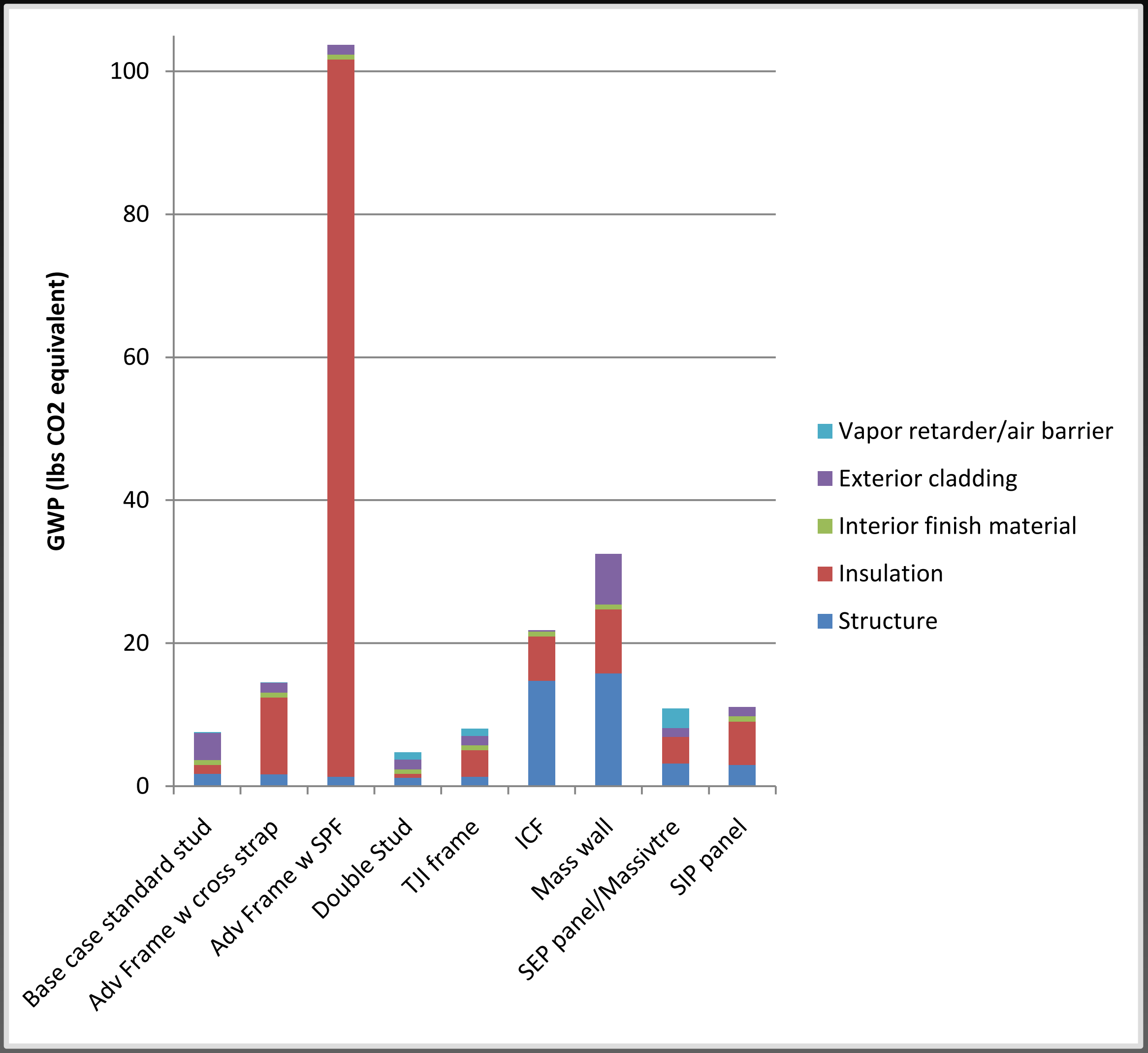


Life cycle global warming potential of the envelope materials:

- 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!

Section 4 – Life Cycle Env. Impacts



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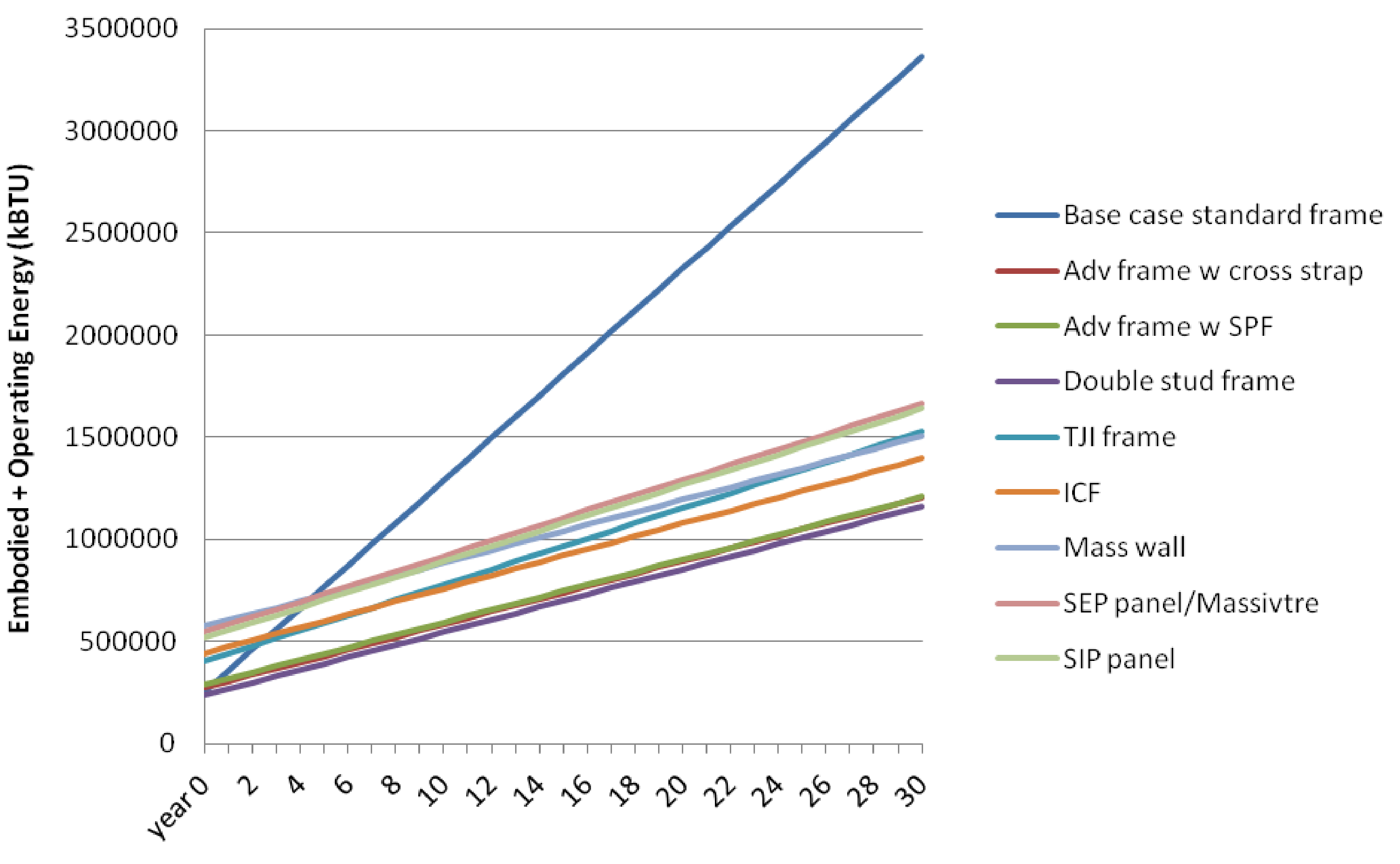
Section 4 – Life Cycle Env. Impacts

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

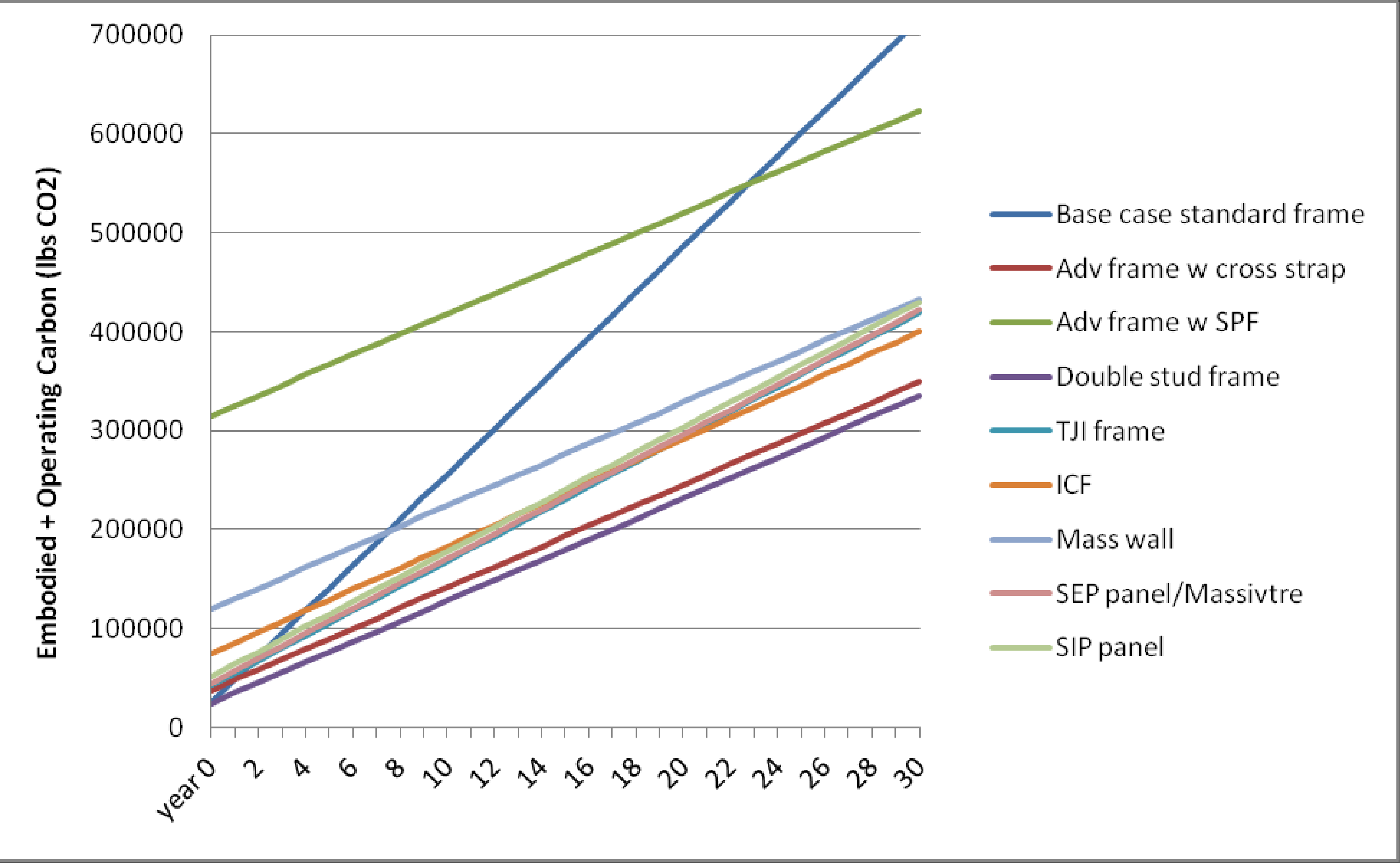
Section 4 – Life Cycle Env. Impacts



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