An Update on Project Overcoat: Wall Insulation Upgrade Testing at CRRF

Garrett Mosiman
Senior Research Fellow
Center for Sustainable Building Research, University of Minnesota
mosi0019@umn.edu

Pacific Northwest National Laboratory

Oak Ridge National Laboratory

University of Minnesota
Driven to Discover℠

Study Team

Pacific Northwest
NATIONAL LABORATORY

Building AMERICA℠
U.S. Department of Energy

Dr. Jian Zhang

Cheryn Metzger

Chrissi Antonopoulos

Dr. Sumitrra Ganguli

Harshil Nagda

Travis Ashley

Philip Jensen

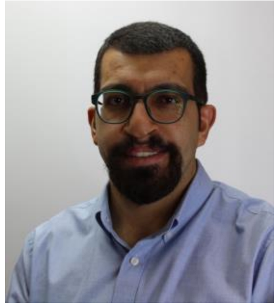
UNIVERSITY OF MINNESOTA
Driven to Discover℠

OAK RIDGE
National Laboratory

Pat Huelman

Garrett Mosiman

Rolf Jacobson



Faith Evren

Andre Desjarlais

Dr. Antonio Aldykiewicz

Jerry Atchley

Background and Scope

Project Goals

Original (Proposed)

- Analyze the performance of a variety of exterior wall retrofit systems for the cold climate based on the following criteria:

  - Low-cost relative to the energy-efficient benefit

    or

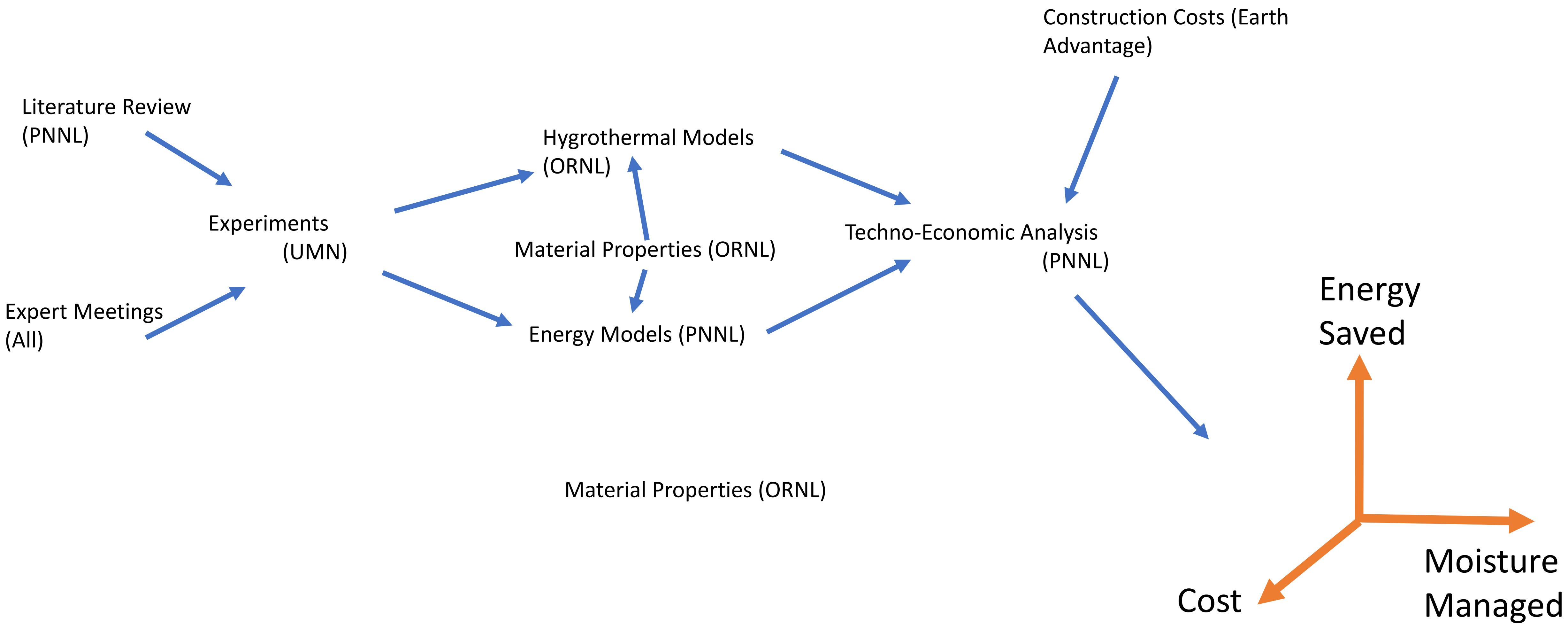
  - Potential for future cost compression

  - Moisture-durable
  - Deep energy retrofits only
  - Leaving cladding on only

Advisory Group and Evolution of Project Goals

- Nearly 30 experts from all sectors of residential construction
- Five meetings over the course of the project
- First Meeting: Most Important Selection Criteria for Test Walls
  - air infiltration
  - constructability
  - cost/potential for cost compression
  - ease of control layer installation
  - time to install
- Updated Project Goals
  - Most impactful (most homes, most energy savings)
  - Removing OR leaving cladding in place
  - Does not necessarily need to be “deep”

Major Project Components



Guiding Research Questions

- Which systems are easier or harder to install correctly (based on lab team experience)?
- Which walls perform better than others in terms of moisture performance in the cold climate?
- Which walls perform better than others in terms of thermal performance in the cold climate?
- How do these walls compare in terms of
  - Cost?
  - Future/predicted cost?

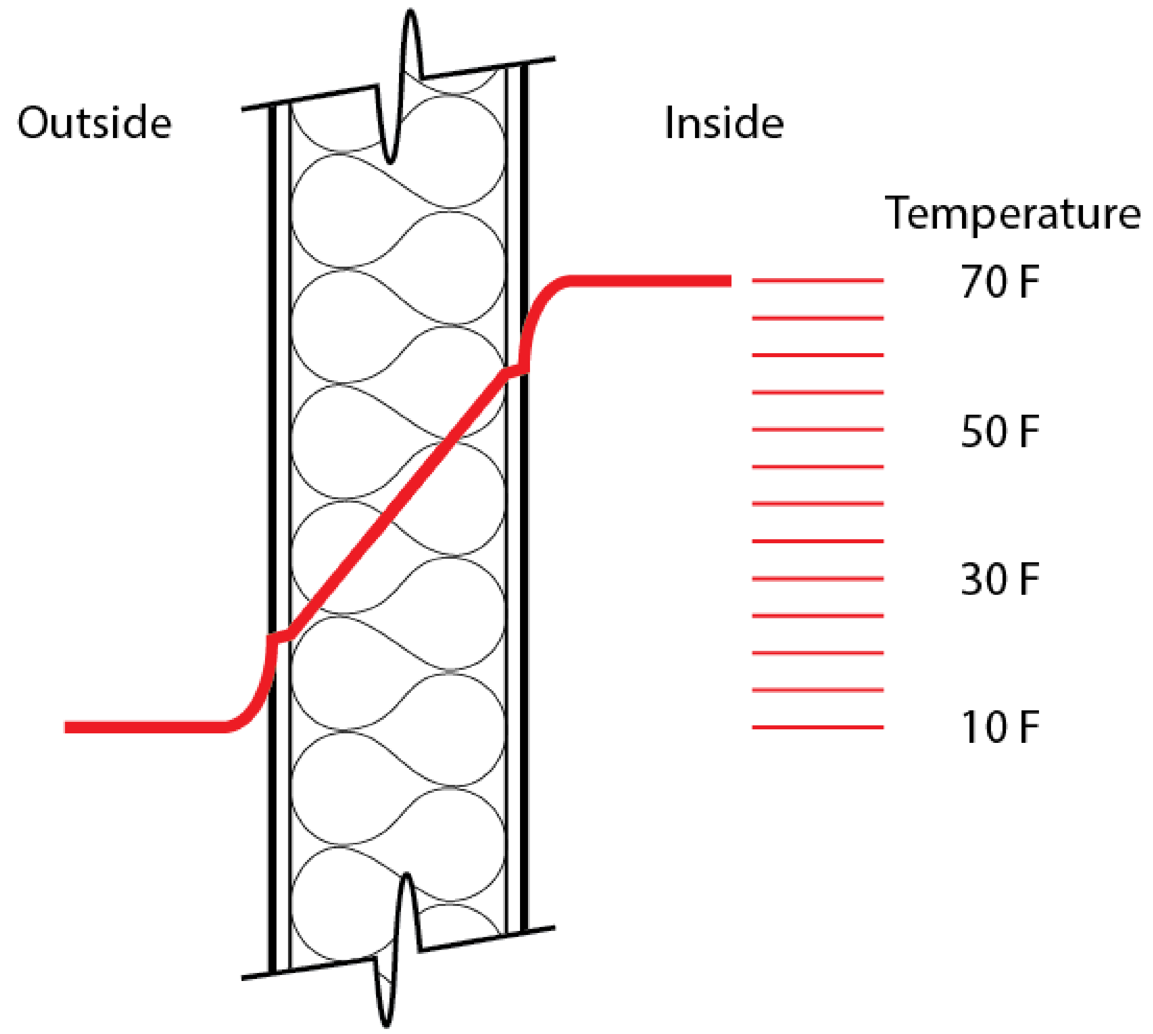
Relationship to Advanced Building Construction (ABC) Initiative

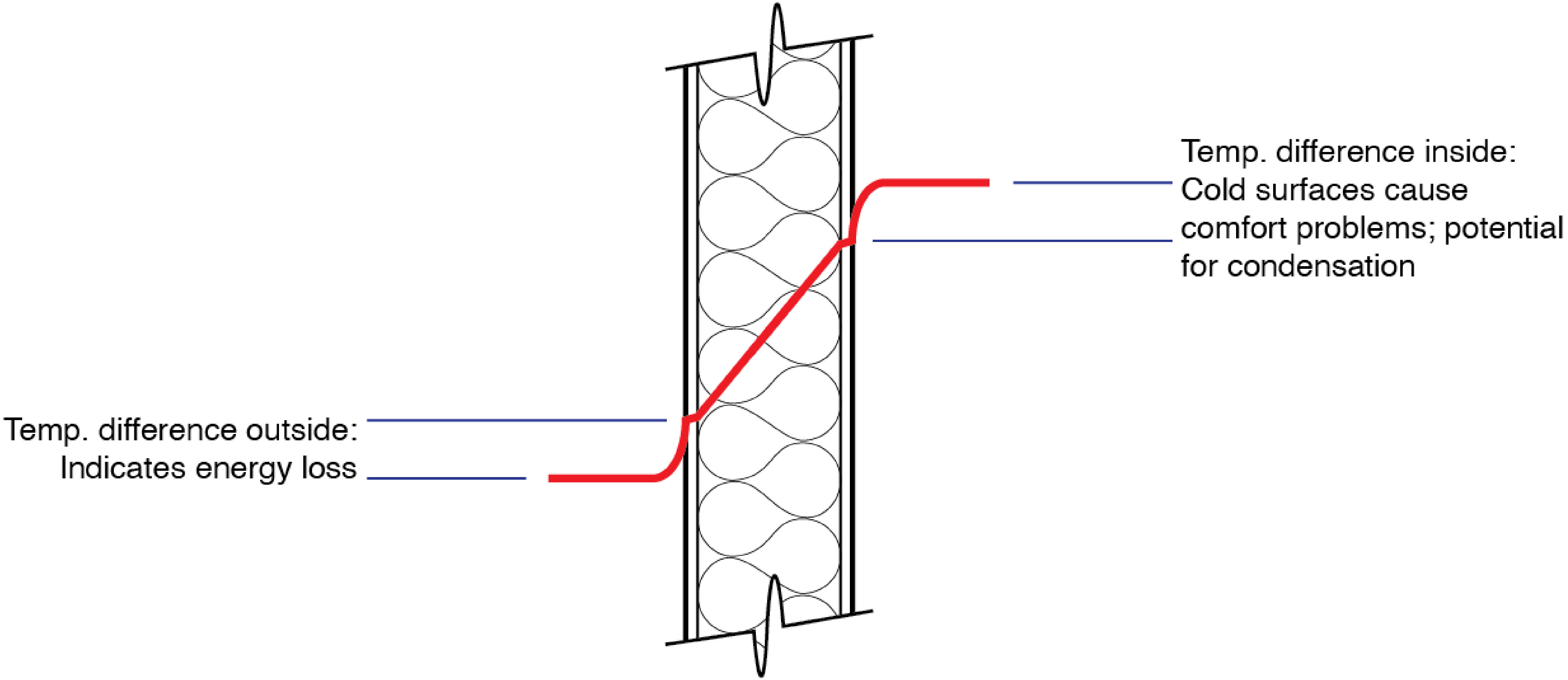
- Most walls are exterior retrofits –
  can be installed without disruption to occupants
  - *Bonus: Pandemic friendly*
- Walls from DOE's Advanced Building Construction (ABC) program that were "ready" for testing were added to Phase 2 of this project

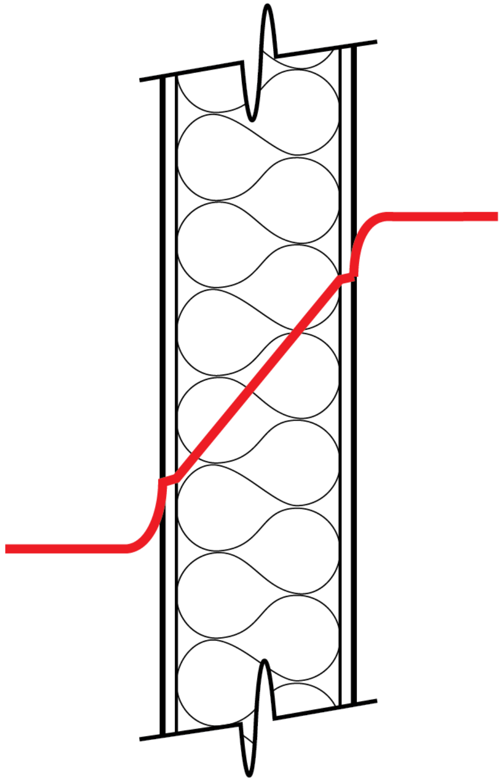
Project Goal

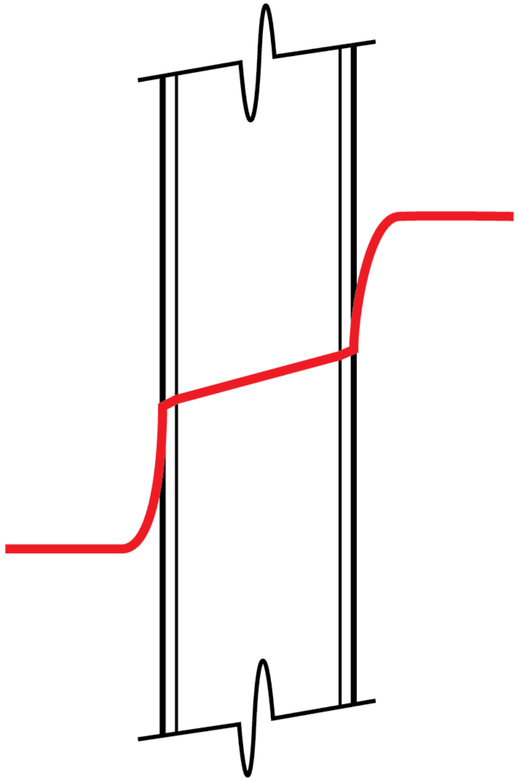
- Determine “the best” exterior wall retrofit system for the cold climate based on the walls studied and according to the following criteria:
  - low cost relative to the energy-efficient benefit –High R-value, airtight construction
  - Moisture-durable –Location of thermal control layer, airtight construction, vapor control strategy
  - can be applied to a large portion of existing walls
  - “Fool Proof” construction

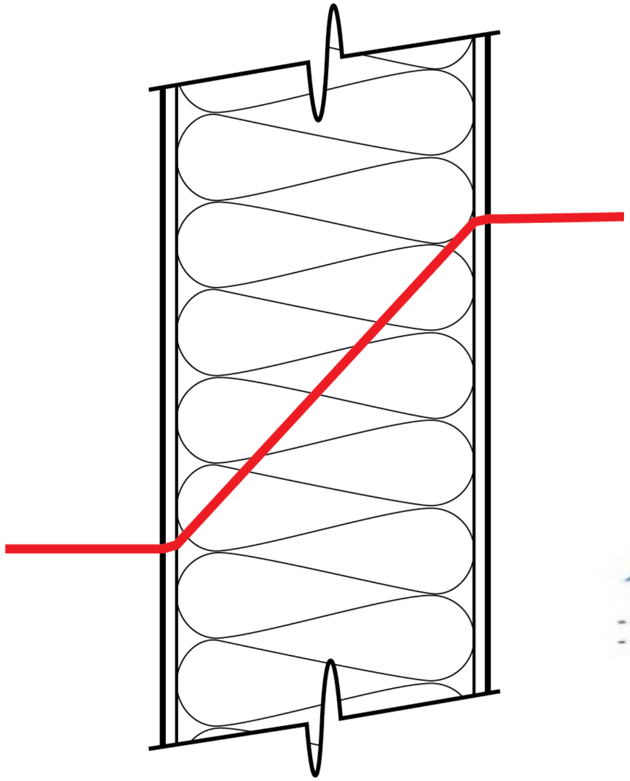
Building Science Issues: Thermal Control



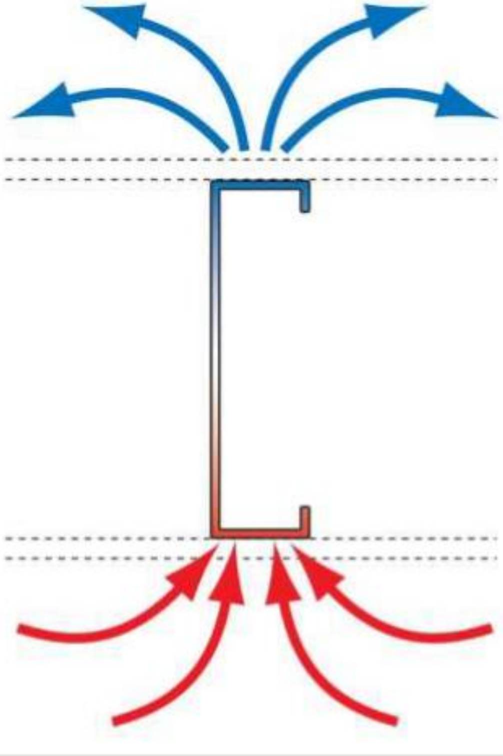

Temp. difference inside:
Cold surfaces cause
comfort problems; potential
for condensation
Temp. difference outside:
Indicates energy loss





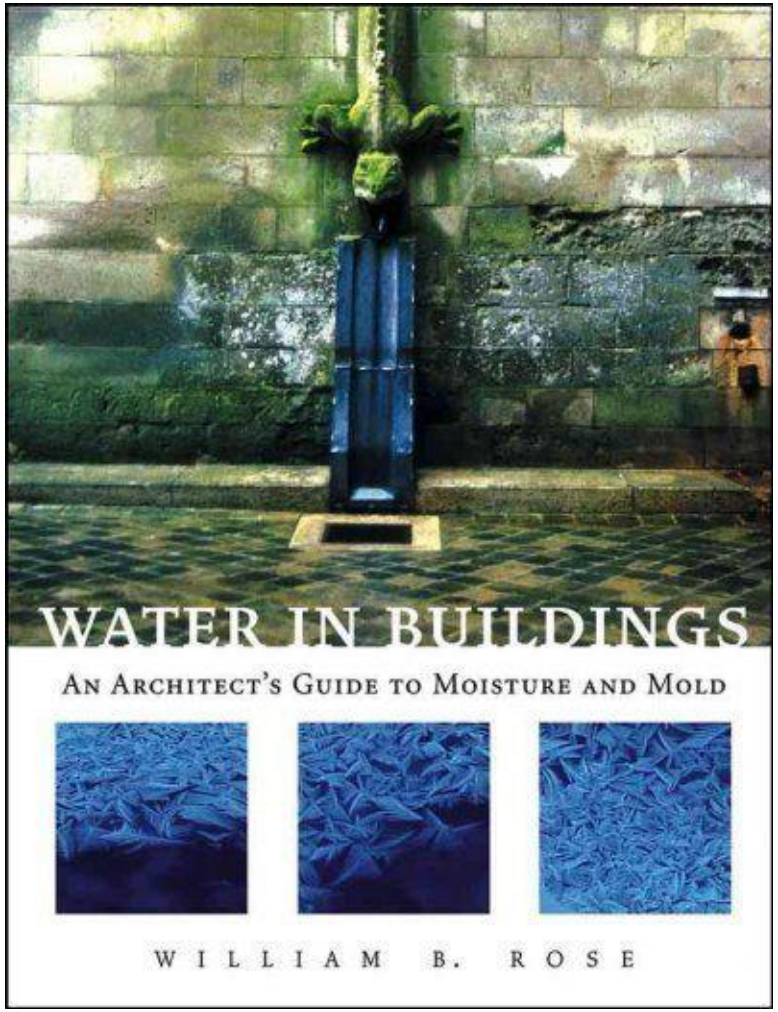



58.0F



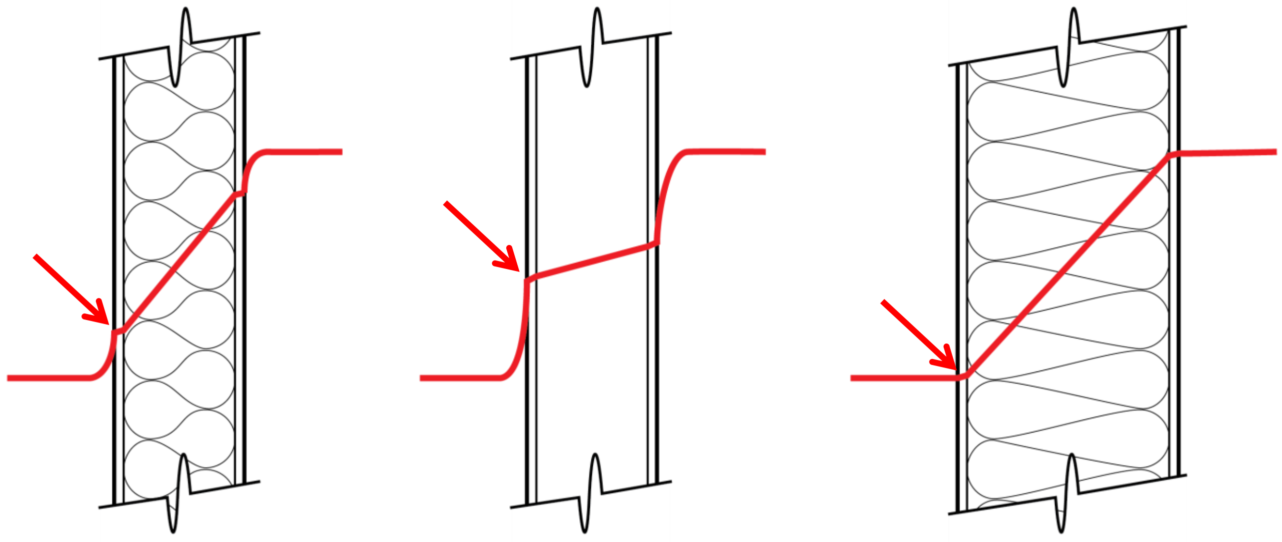
The relationship between insulation and moisture

As insulation levels increase, moisture risks are inherently magnified. This is due to what William Rose calls this the **Fundamental Rule of Material Wetness**: *Cold materials tend to be wet and warm materials tend to be dry.*



Or, from Pat Huelman, renowned U of M Building Scientist:

"It's not a moisture problem, it's an energy problem!"



Building Science Issues: Air Control

A premium retrofit would include a dedicated air barrier which is:

-Continuous
-Structural (must not move under load)
-Impermeable (to air)
-Durable

However we are attempting to represent the real world, so some upgrades have one, some don't.

Air control integrity and air leakage calibration:

- Sheathing boards were not set tight, building paper was lapped and stapled but not sealed
- The entire panel perimeter was sealed before installation
- Used TEC Minneapolis Micro Leakage Meter @ 50 Pa across the wall panel
- Used a sealed electrical box with small hole to calibrate and equilibrate
- Final base wall measurements varied between 0.37 – 0.42 cfm @ 50Pa
- Post-treatment: cavity treatments were TLM (< 0.2 cfm); exterior treatments remained similar

Building Science Issues: Vapor Control

As we all know, the vapor retarder goes on the warm side…

But our basecase wall already has two: one on the interior, one on the exterior.

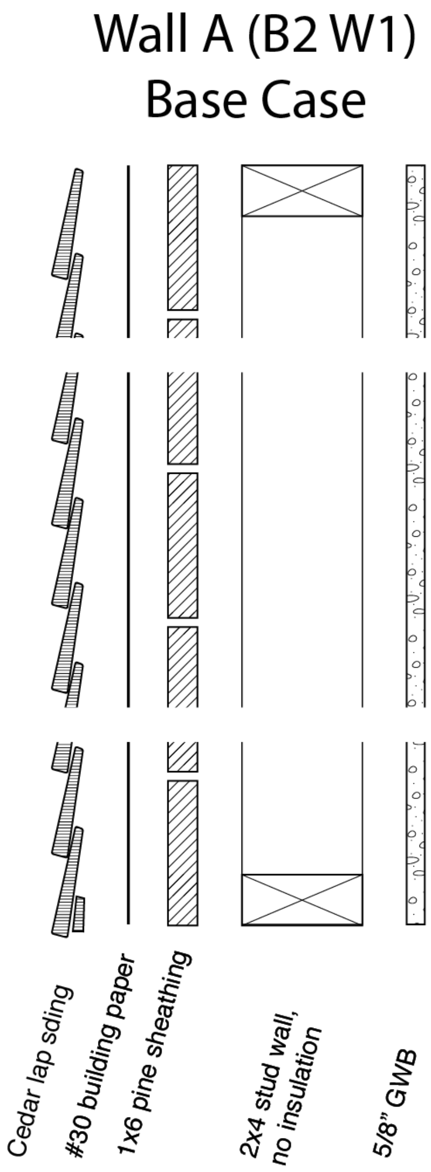
Treatments are designed so some ignore this fact, and some explicitly aim to accommodate this potential risk.

Building Science Issues: Water Control

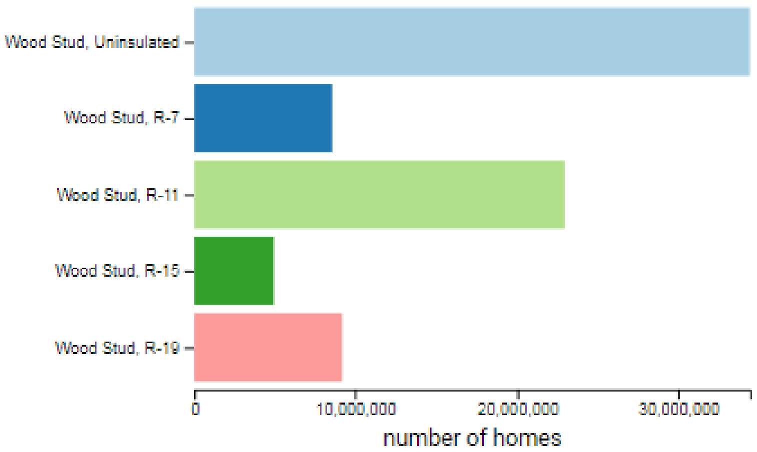
The base case wall has an existing water control layer: #30 building paper.

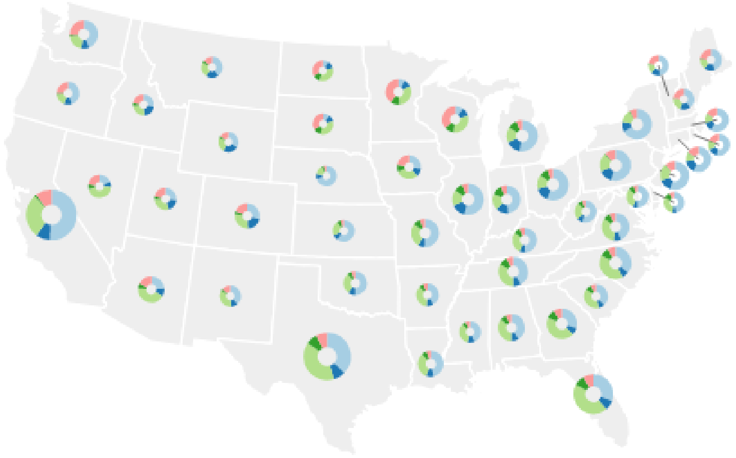
Some treatments rely on this existing layer, while others add supplemental water control layers, or remove the siding and paper to add a new water control layer.

- **Oil primer**
- **Vapor retarder primer (0.6 perm)**
- **Latex paint**



Vapor retarder primer (0.6 perm)



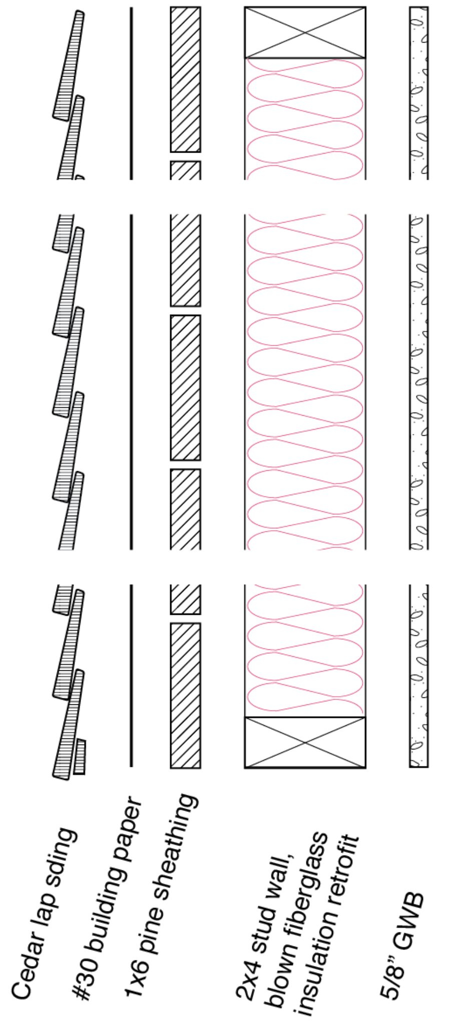


Preparation of Base Case Walls:

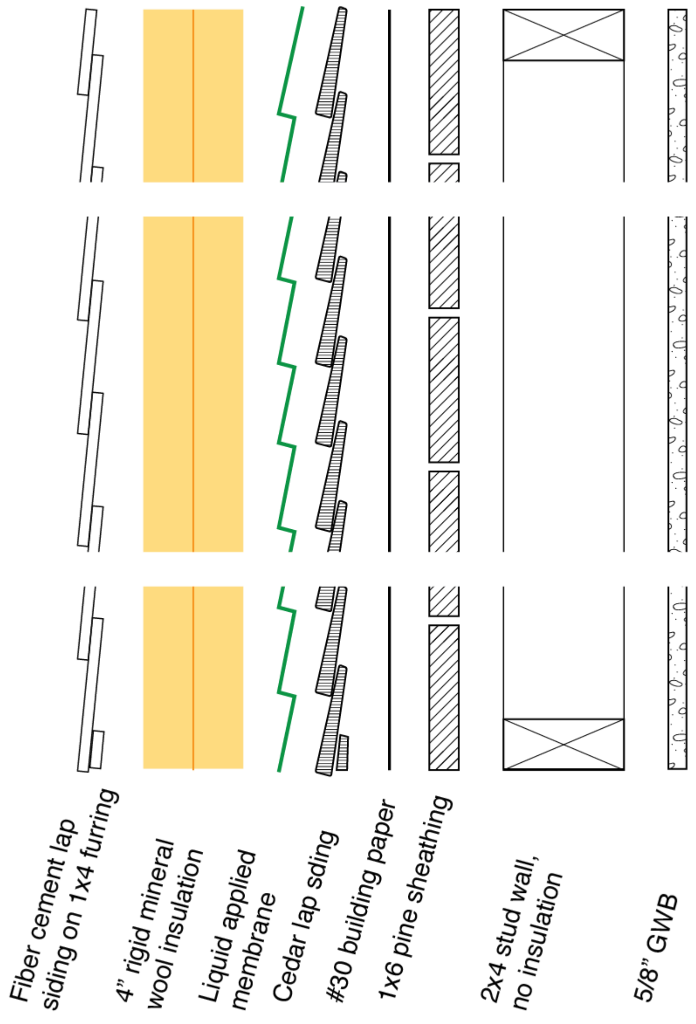
Interior Finish:	5/8” Drywall (with vapor retarder primer)
Framing:	2x4 SPF at 16” o.c.
Sheathing:	1x6 Pine
Water Control:	#30 Building paper
Cladding:	7 ¼”” Cedar Lap Siding (with oil primer, vapor retarder primer, and latex topcoat)

Potential insulation location strategies

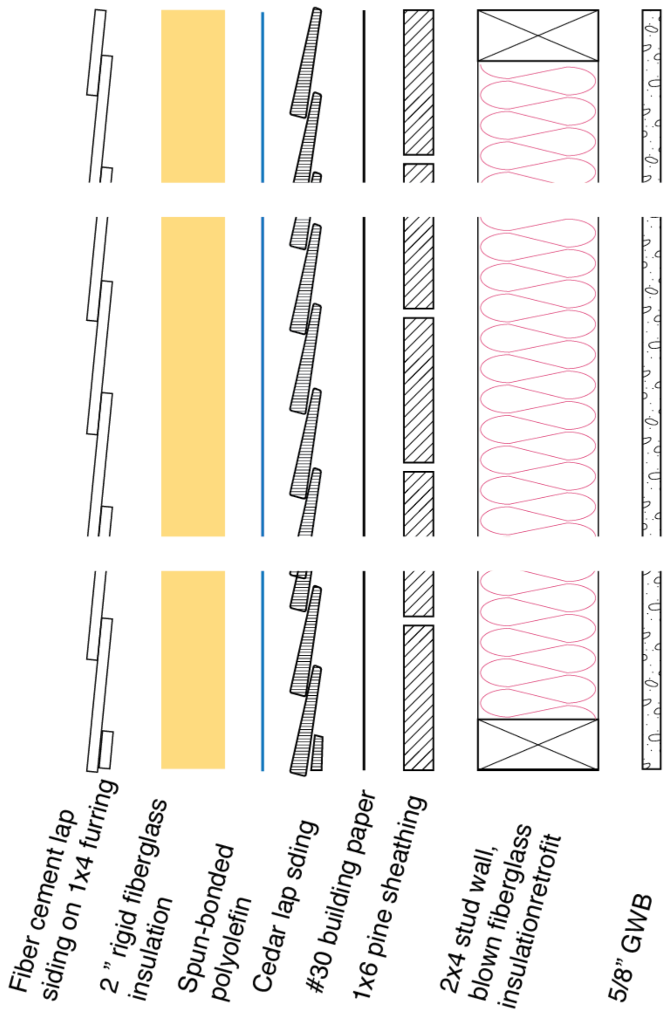
Cavity only

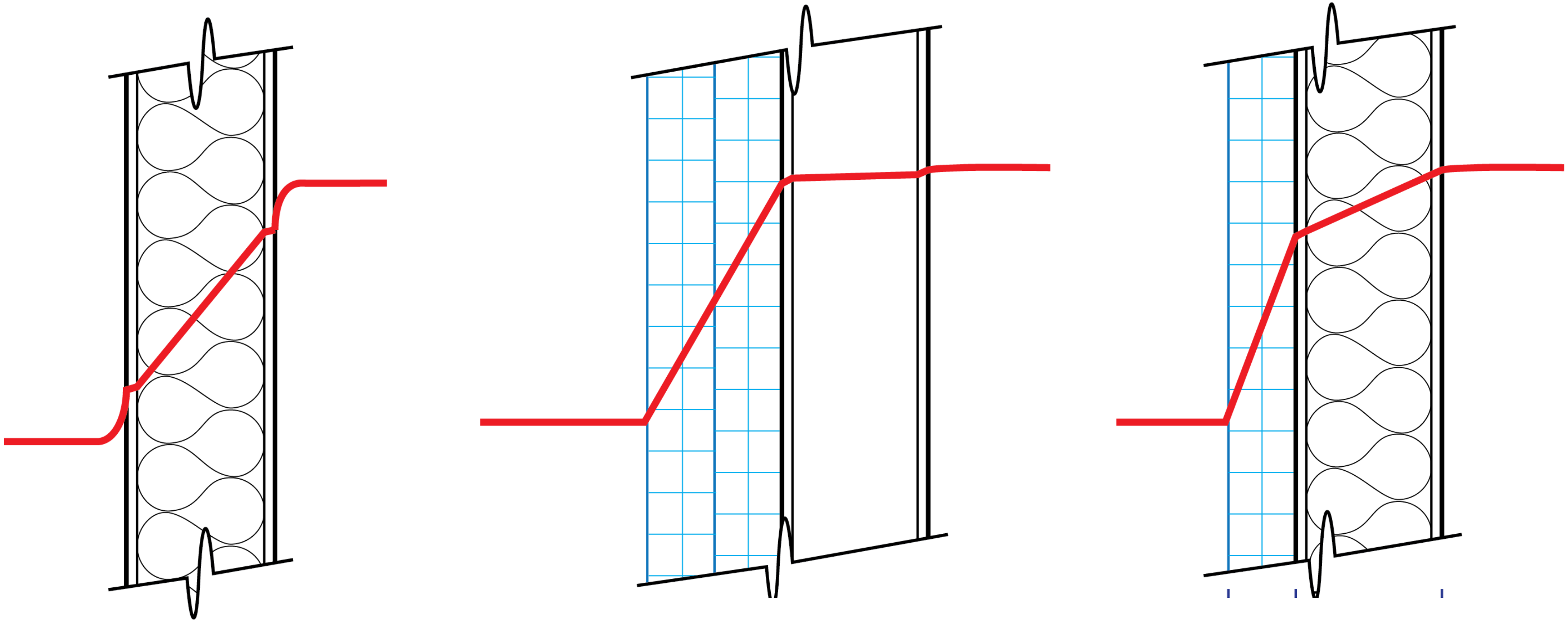


Exterior only



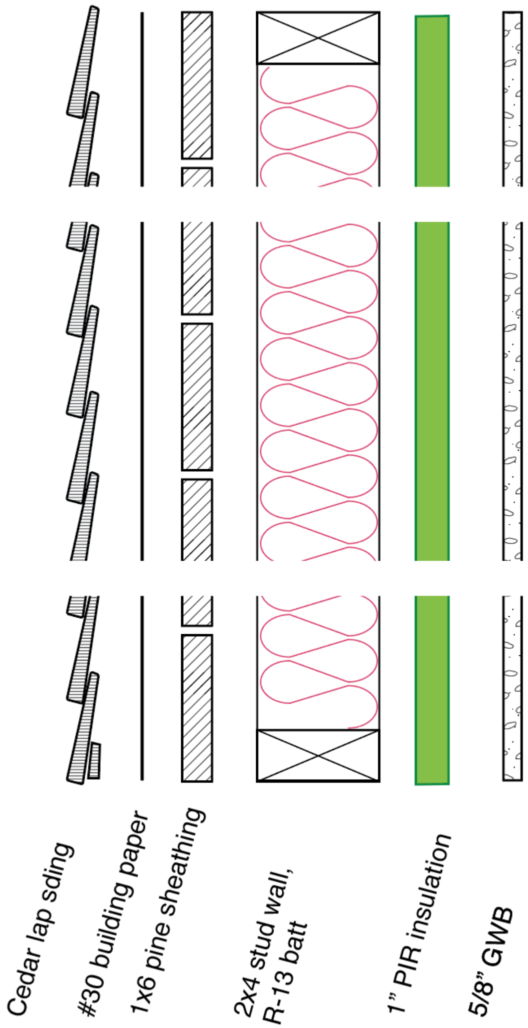
Hybrid (cavity + exterior)

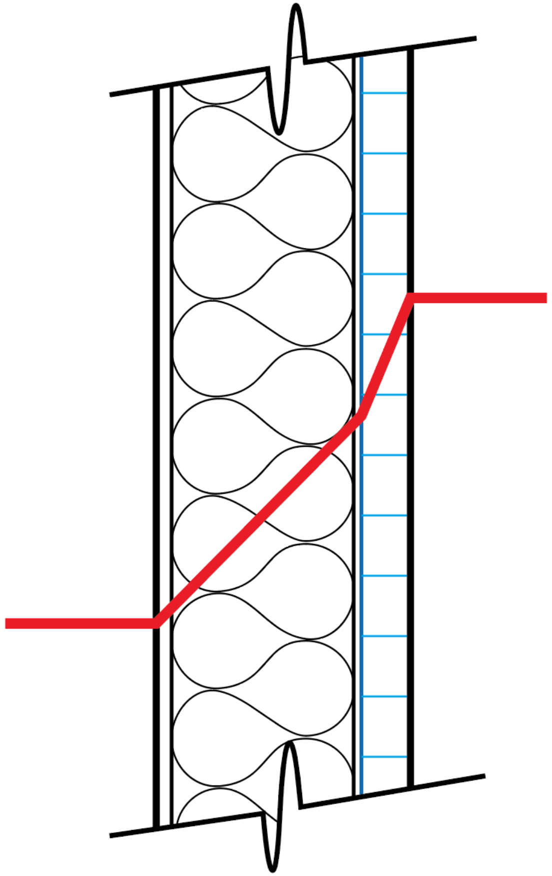




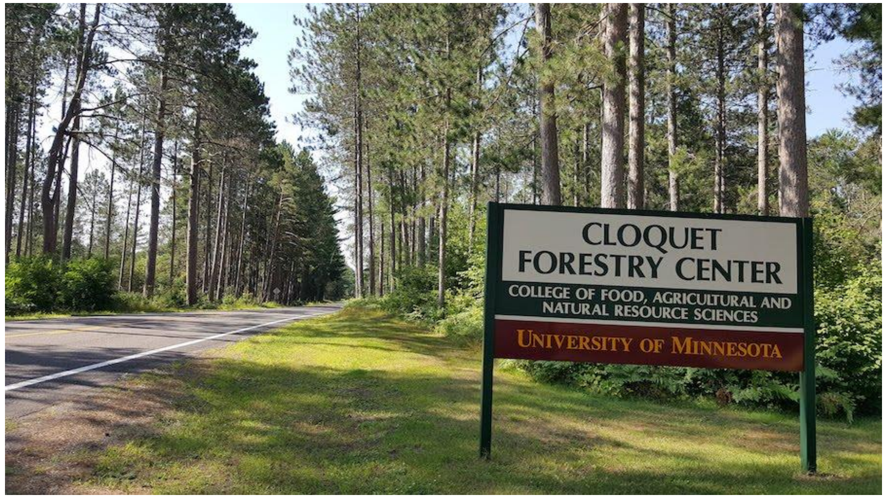
Potential insulation location strategies

Hybrid Cavity + Interior





Cloquet Residential Research Facility



PNNL – Wall Upgrades for Residential Deep Energy Renovation

In-situ Experimental Research

Cloquet Residential Research Facility
University of Minnesota

Research Team

Pat Huelman, Principal Investigator
Garrett Mosiman, CRRF Manager
Rolf Jacobson, Field Support
Fatih Evren, Graduate Assistant

Cloquet Residential Research Facility

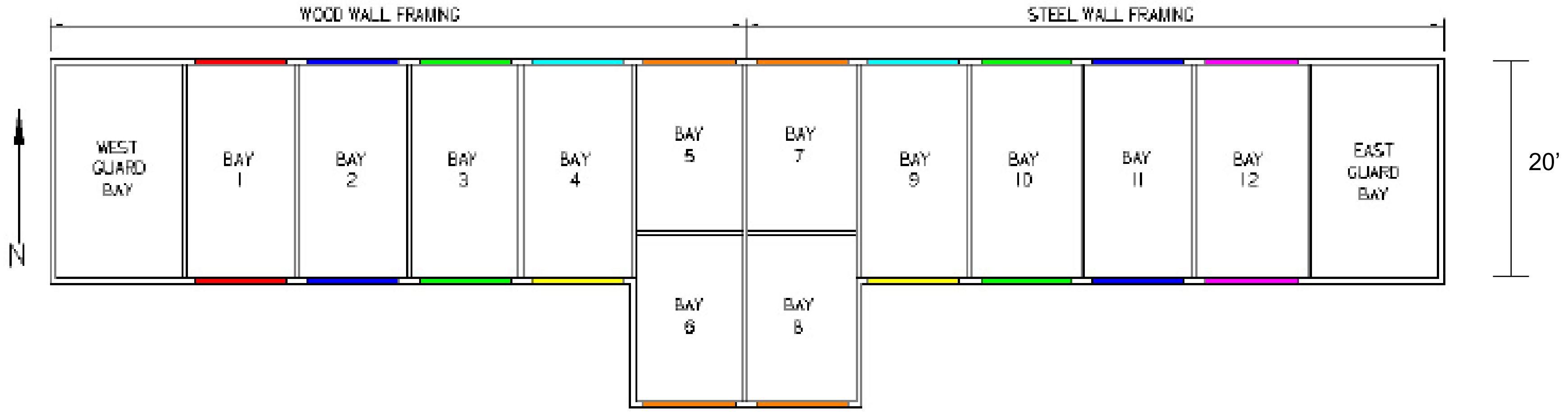
- Located at the University of Minnesota's Cloquet Forestry Center near Cloquet, MN
- Completed in 1997
  - original funding provided by CertainTeed Corp.
- Designed as a test bed to:

  evaluate long-term,

  cold-climate performance

  of full-scale building envelope components including:
  - foundations,
  - walls,
  - wall/window interface, and
  - roofing systems.

CRRF Building Design



Single-story building on a full basement

- West basement has hollow masonry block walls and I-joist floor trusses
- East basement has poured concrete walls with open web floor trusses

Divided into 10’ test bays along east/west axis

- 12 bays on main level with end guard bays
  - bays 1 to 6 framed in wood
  - bays 7 to 12 framed in metal
- 2 basement bays with end guard bays

Wall Selection

Results From 2019 Expert Meeting

- Most important wall selection criteria
  - air infiltration
  - constructability
  - cost
  - ease of control layer installation
  - time to install

Additional DOE Guidance

- After reviewing expert meeting results with DOE, additional guidance included:
  - Most impactful (most homes, most energy savings)
  - Removing OR leaving cladding in place
  - Does not necessarily need to be “deep”

Treatment Summary

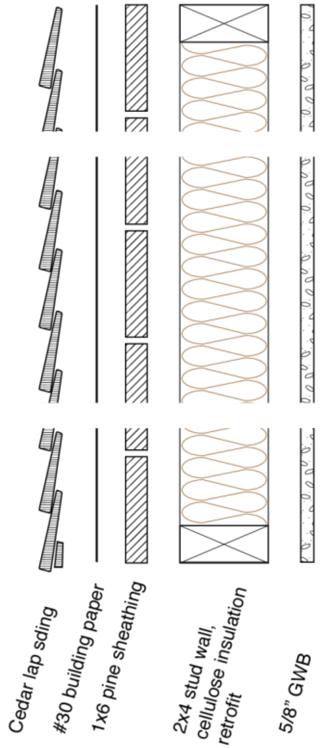
- 8 types of insulation; fiberglass, cellulose, mineral fiber, EPS, XPS, Polyiso, PU, VIP
- 5 forms of insulation; batt, blown-in, panels, blocks, pourable/injected
- 12 combos of insulation type and form (more than one insulation is used in some treatments)
- 3 types of added water and/or air control layers (housewrap, peel and stick, LAM)

We ended up with:
- 9 wall treatments built on-site with existing building materials
- 1 wall treatments used prefabricated components
- 3 wall treatments used off-site produced systems
- 4 wall treatments of novel/emerging materials or systems

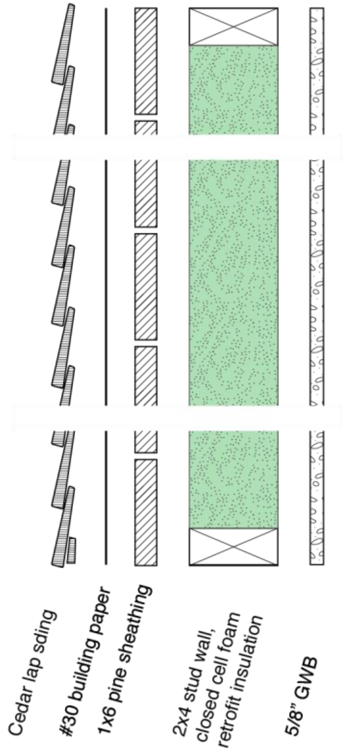
Wall Treatment Summary	Phase 1	Phase 2	Total
- Interior w/ cavity	0	1	1
- Cavity only	2	1	3
- Exterior w/ cavity	2	3	5
- Exterior only	3	2	5

Test walls, Phase 1

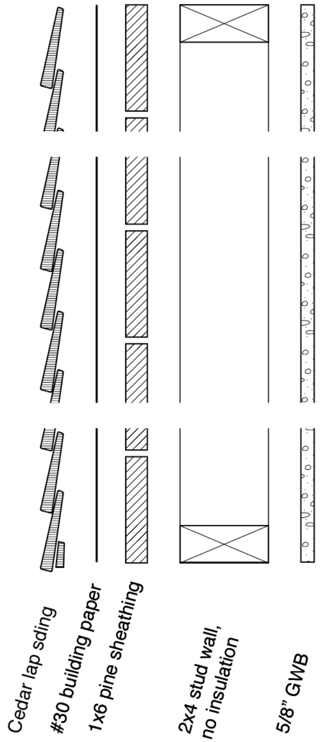
Wall B (B1 W1)
Cellulose



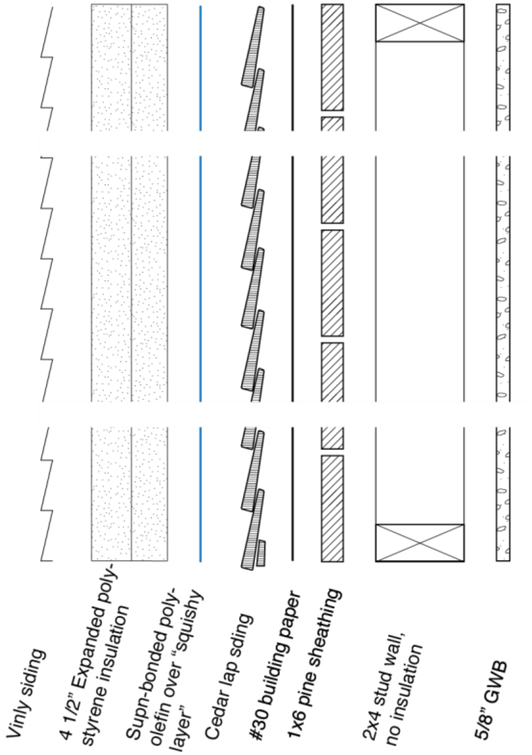
Wall C (B1 W2)
Injected Foam



Wall A (B2 W1)
Base Case

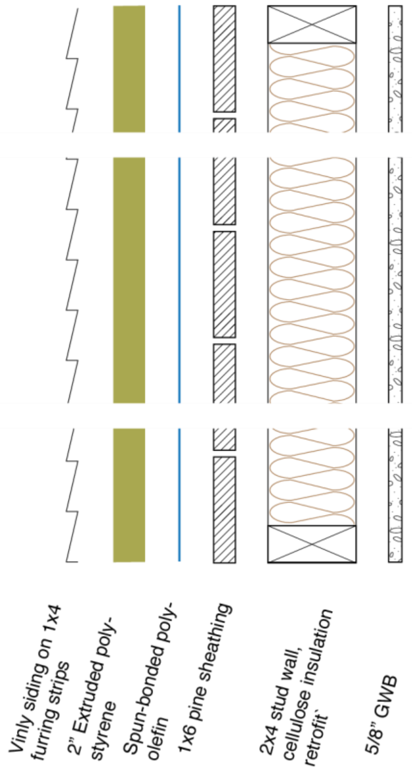


Wall D (B2 W2)
Exterior EPS

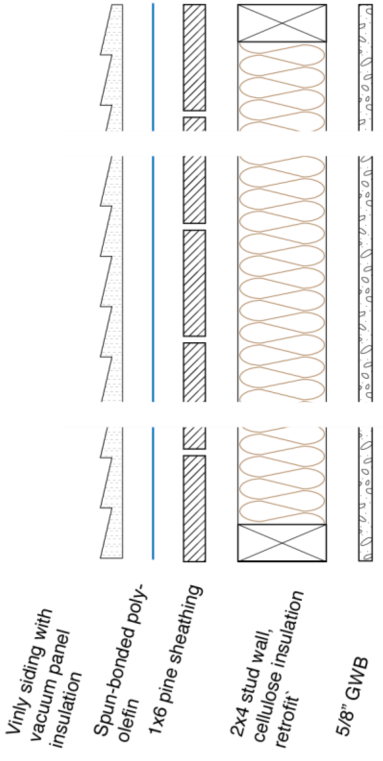


Test walls, Phase 1

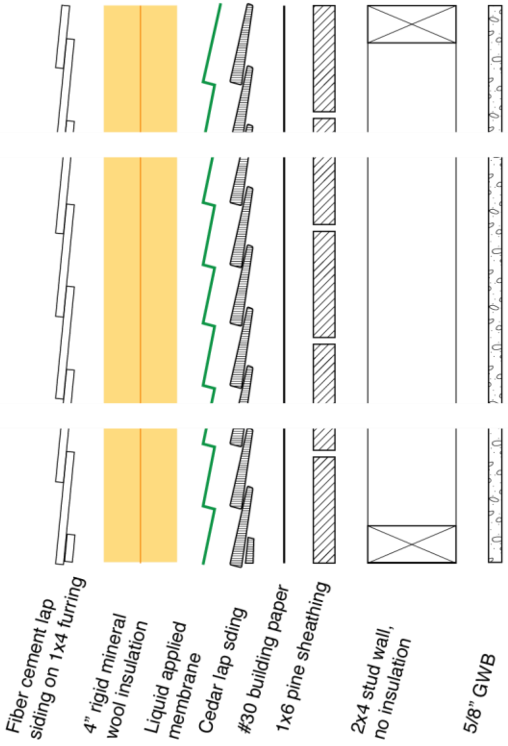
Wall E (B3 W1)
Cellulose + XPS



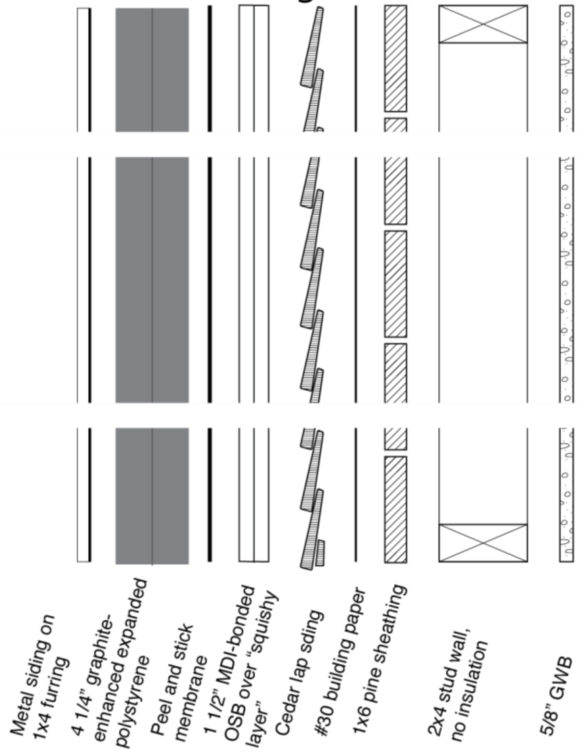
Wall F (B3 W2)
Cellulose + VIP



Wall G (B4 W1)
Ext. Mineral Wool

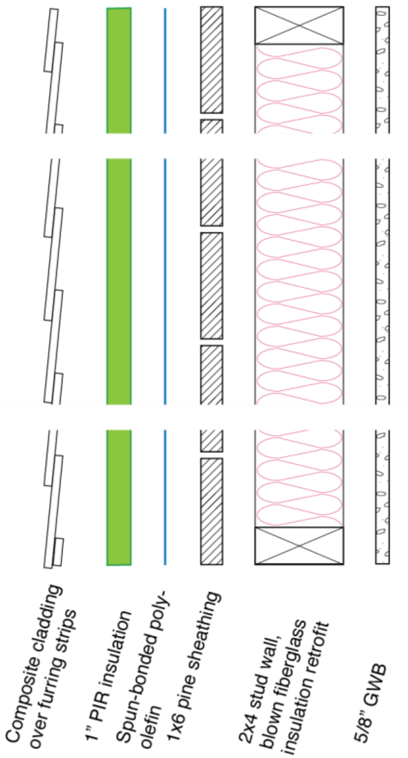


Wall H (B4 W2)
Ext. g-EPS

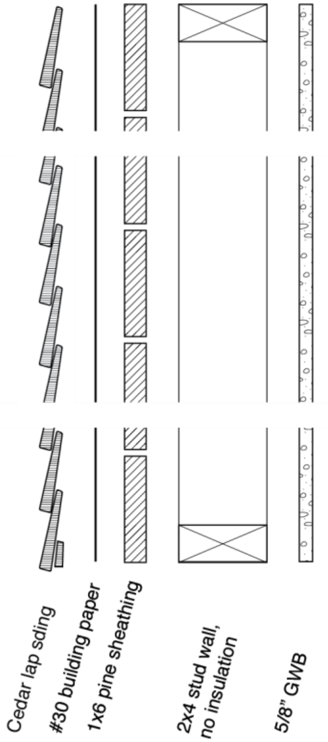


Test walls, Phase 2

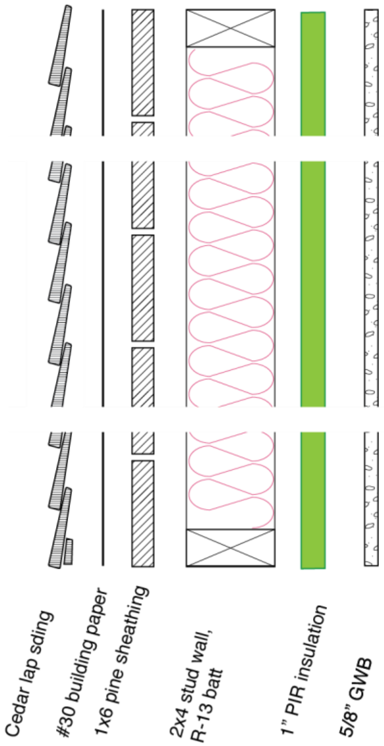
Wall L (B11 W1)
Exterior PIR



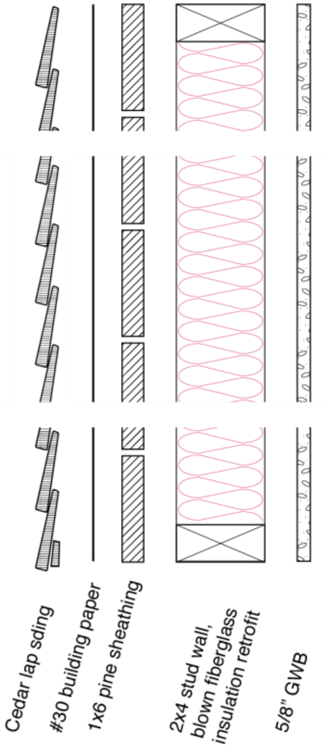
Wall I (B11 W2)
Base Case 2



Wall K (B12 W1)
Interior PIR

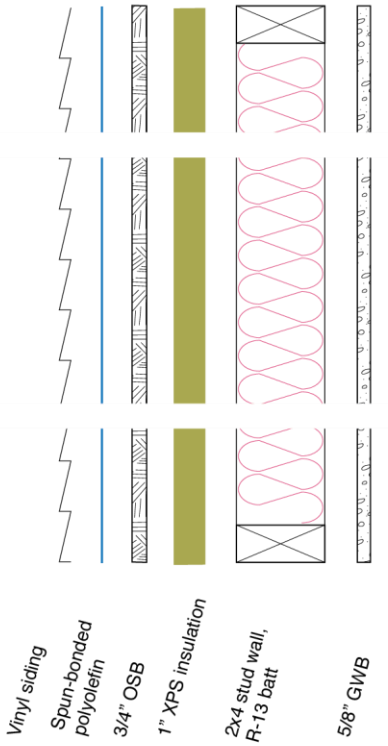


Wall J (B12 W2)
Fiberglass

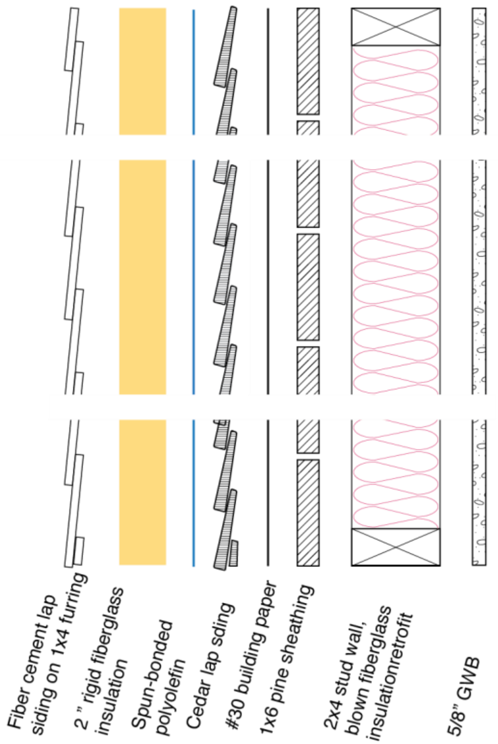


Test walls, Phase 2

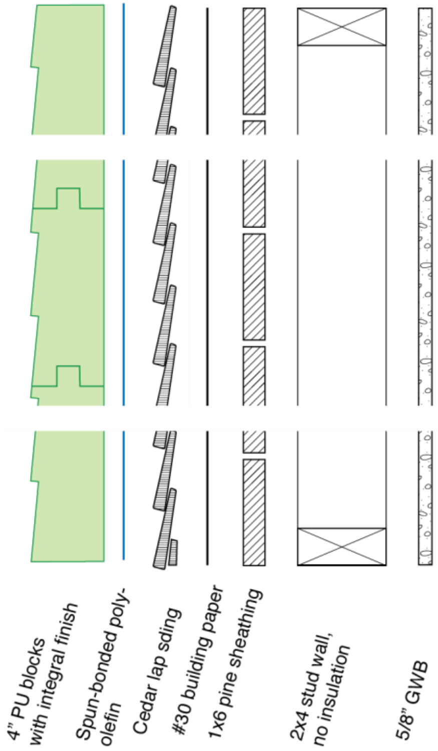
Wall P (B9 W1)
Thermal Break Shear



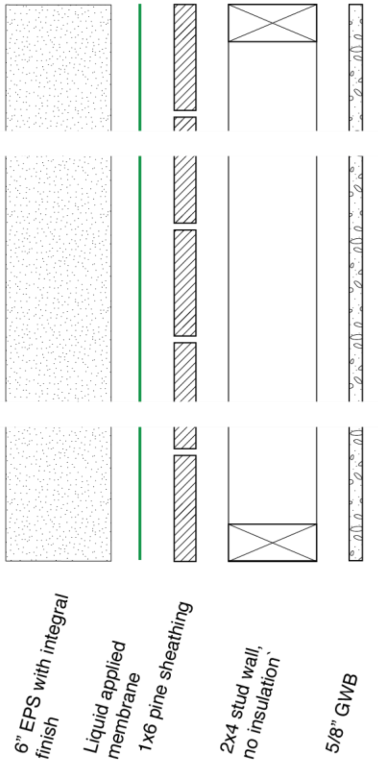
Wall O (B9 W2)
Exterior Fiberglass



Wall N (B10 W1)
ABC-Fraunhofer



Wall M (B10 W2)
REALIZE-EIFS



Measuring constructability

ID	Description	Material Acquisition	Installation Ease	Installation Speed	# of Operations	Added Thickness
B	Drill-&-Fill Cellulose (dense-pack)	readily available to contractor	very easy; straightforward	very fast	2	0
C	Injected Cavity Foam (proprietary oc-spu)	not currently available	moderately easy	very fast	2	0
D	Pre-fab Ext EPS (panel w/struts)	available at some BMS*	very easy; straightforward	somewhat fast	3	5.25”+
E	Drill-&-fill Cellulose + Ext XPS	readily available to contractor	several layers or steps	somewhat slow	5	2.5”
F	Drill-&-fill Cellulose + VIP/Vinyl Siding	not currently available	several layers or steps	somewhat fast	4	0.5
G	Exterior Mineral Fiber Board	available at some BMS*	moderately easy	somewhat slow	3	5.25”+
H	Ext. gEPS Structural Panel System	available at some BMS*	several layers or steps	somewhat fast	4	7”
J	Drill-&-Fill Fiberglass (proprietary, high-dens)	available at most BMS*	very easy; straightforward	very fast	2	0
K	Fiberglass Batt + Int Polyiso	readily available to contractor	moderately easy	somewhat slow	4	1”
L	Drill-&-Fill FG + Ext Polyiso	readily available to contractor	several layers or steps	somewhat slow	5	1.5”
M	Pre-fab Ext EPS/EIFs Panel System	available from manufacturer	moderately easy	somewhat fast	3	5.75”
N	Pre-fab Ext PU/Vinyl Block System	not currently available	very easy; straightforward	somewhat fast	2	4”
O	Drill-&-Fill FG + Ext FG Board	available at some BMS*	moderately easy	somewhat slow	4	3.25”
P	FG Batt + XPS + OSB (thermal break shear)	readily available to contractor	moderately difficult	quite slow	6	0.75”

* BMS refers to Building Materials Supply outlets such as big-box DIY chains and larger local or national lumberyards

+ Two layers of continuous exterior insulation for colder climates; a single layer may be adequate for warmer climates

Instrumentation

Sensor Array
+/- 700 sensors

- TC-Thermocouple temperature sensor
- RH-Relative humidity sensor
- MP-Pin-type moisture content sensor
- HF-Heat flux plate
- Sensor position number

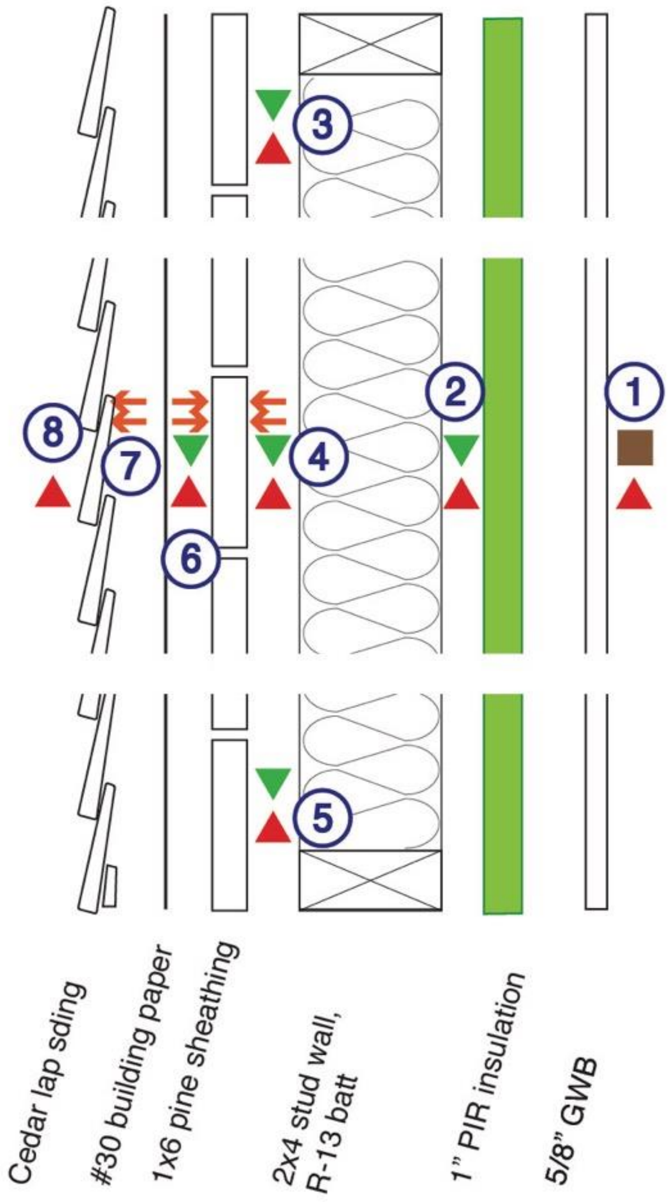
Omega Type-T Thermocouple
Honeywell HIH-4000 Series
Brass nails + Enamel Paint
FluxTeq PHFS-09e

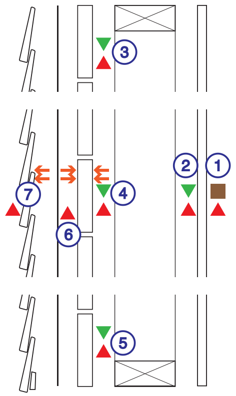
Pyronometers

- 6 Campbell Scientific CS320
- Vertical mount (4 south, 2 north)

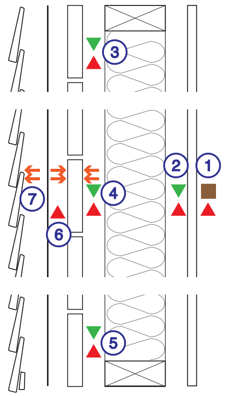
Weather Station

- Wind speed / direction
- Temp / RH
- Horizontal pyronometer
- Rain gauge

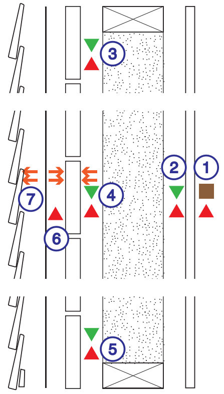




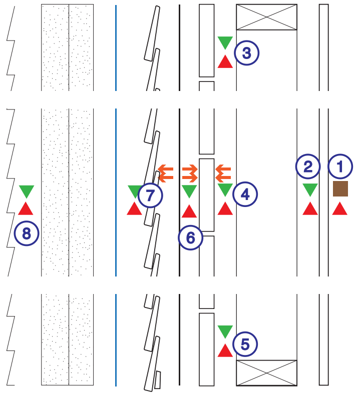
Wall A



Wall B



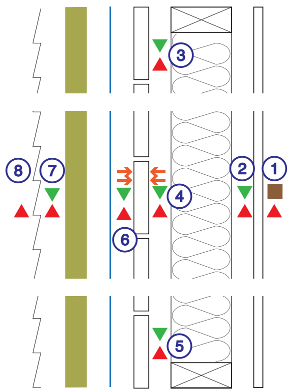
Wall C



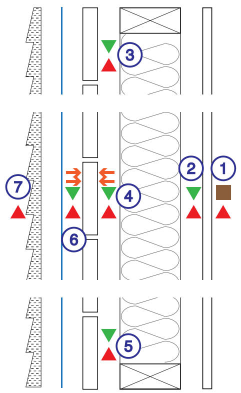
Wall D

Sensor Array

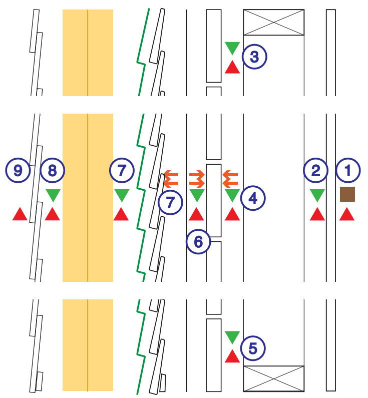
- TC-Thermocouple temperature sensor
- RH-Relative humidity sensor
- MP-Pin-type moisture content sensor
- HF-Heat flux plate
- Sensor position number



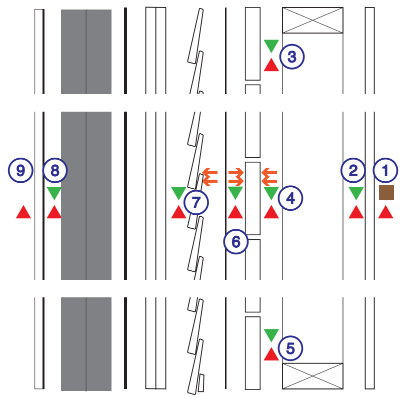
Wall E



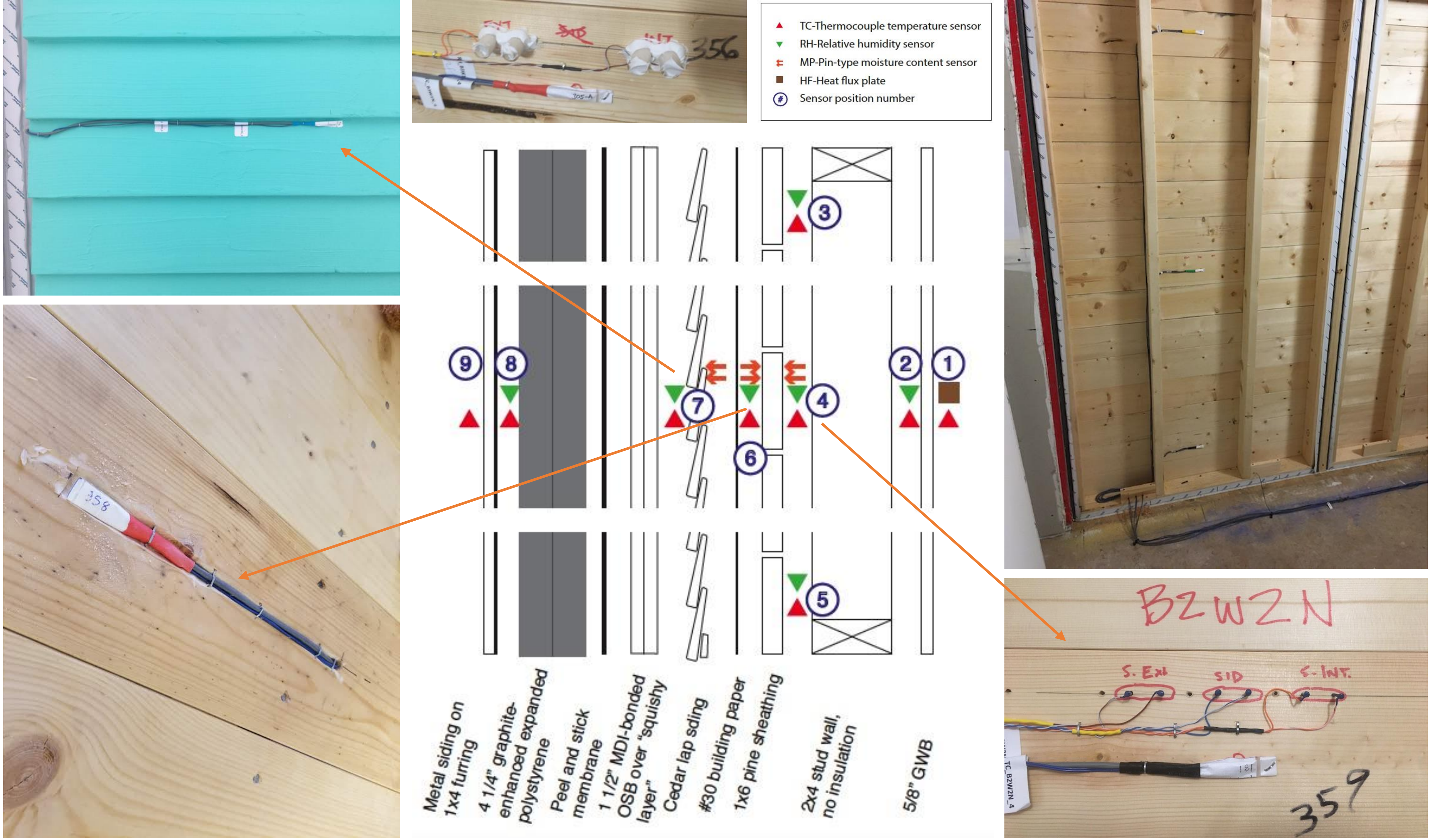
Wall F

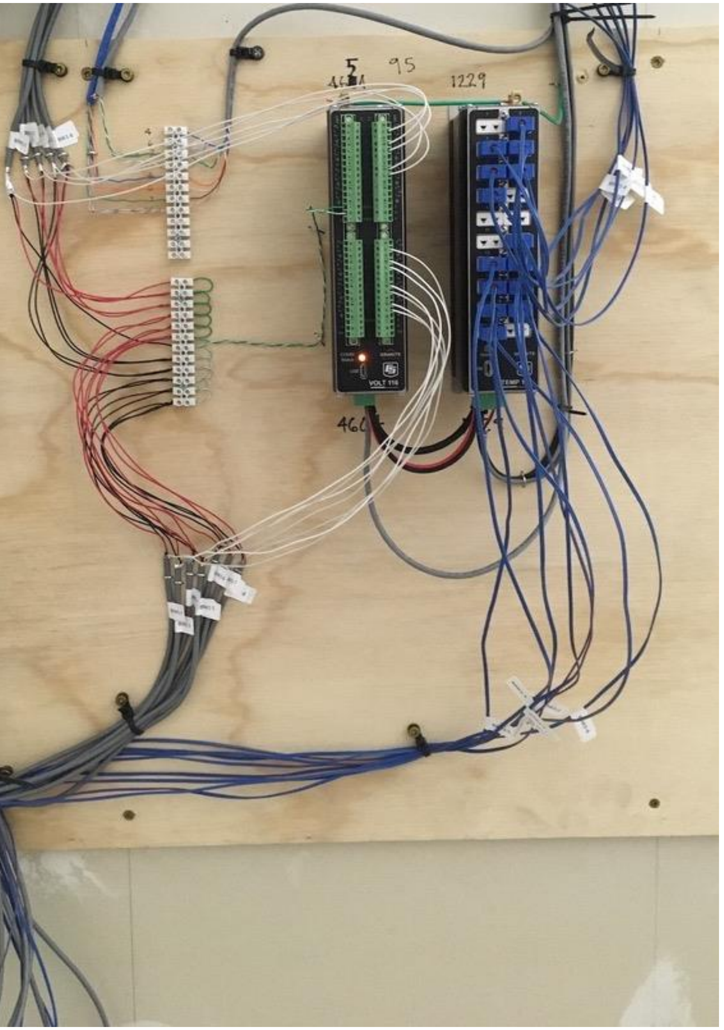


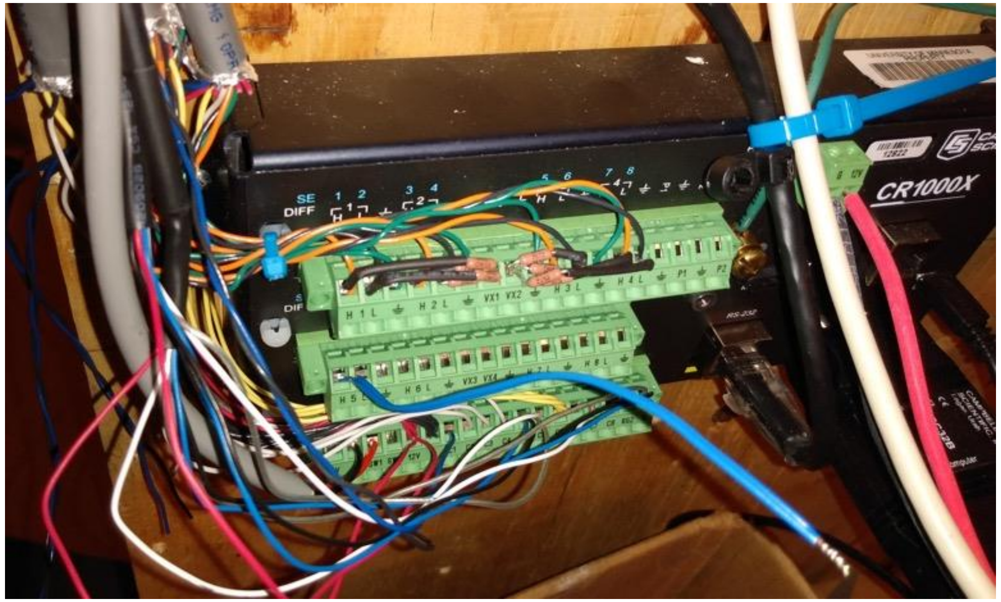
Wall G

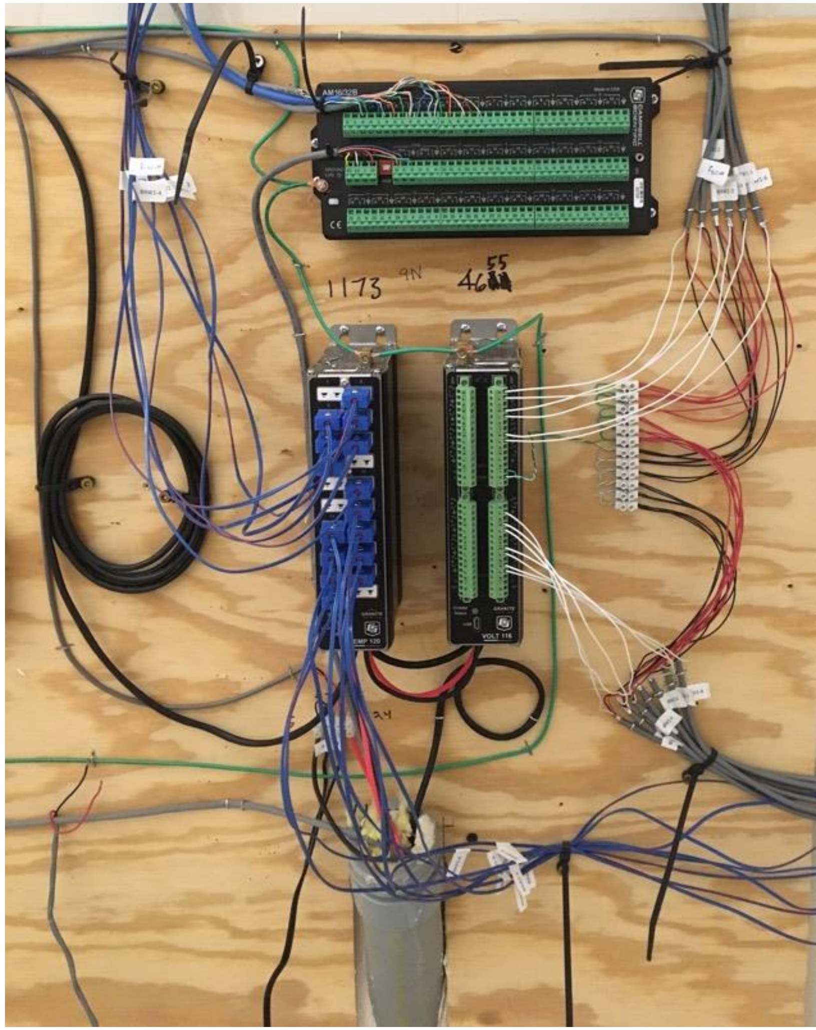


Wall H


TC-Thermocouple temperature sensor
RH-Relative humidity sensor
MP-Pin-type moisture content sensor
HF-Heat flux plate
Sensor position number
1
2
3
4
5
6
7
8
9
Metal siding on 1x4 furring
4 1/4" graphite-enhanced expanded polystyrene
Peel and stick membrane
1 1/2" MDI-bonded OSB over "squishy layer"
Cedar lap sding
#30 building paper
1x6 pine sheathing
2x4 stud wall, no insulation
5/8" GWB
356
358
B2W2N
359





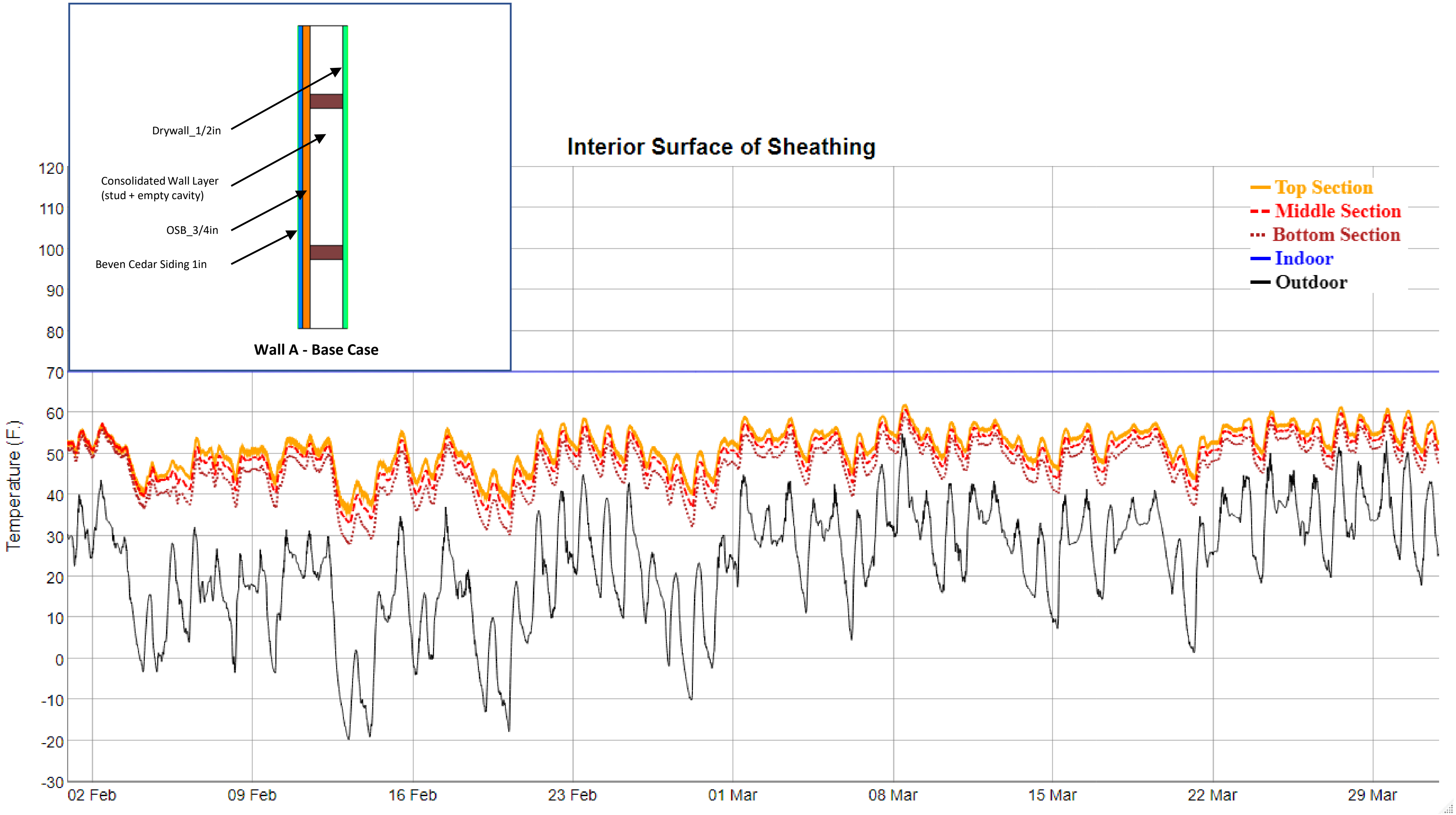


DAS Equipment by Campbell Scientific:

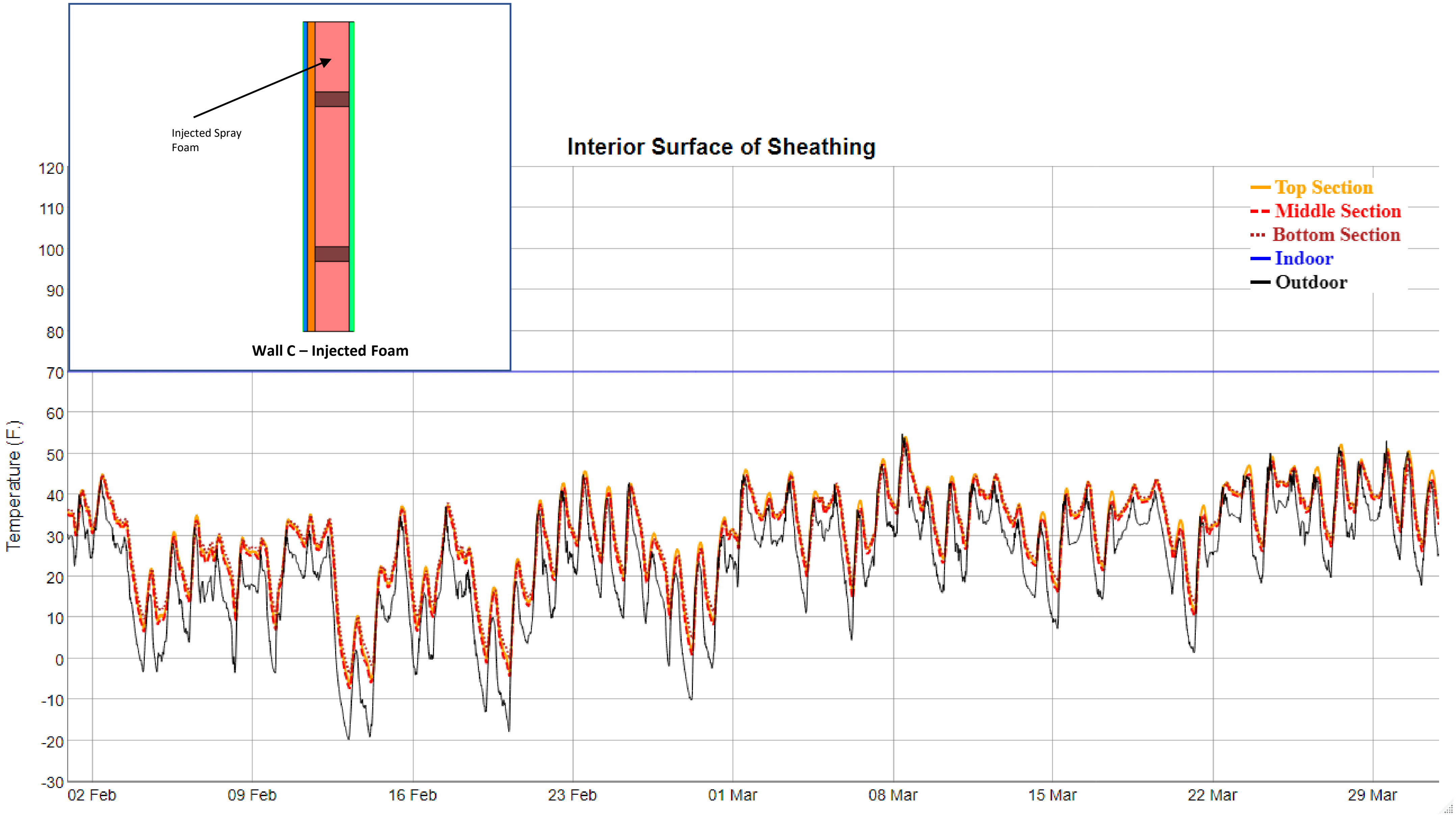
Datalogger	CR1000X (2)
Thermocouple Module	Temp 120 (16)
RH and Heat Flux	Volt 116 (16)
Moisture Content	AM 16/32 (8)
Communication	Sierra RV50X cellular modem

Initial Monitoring Results

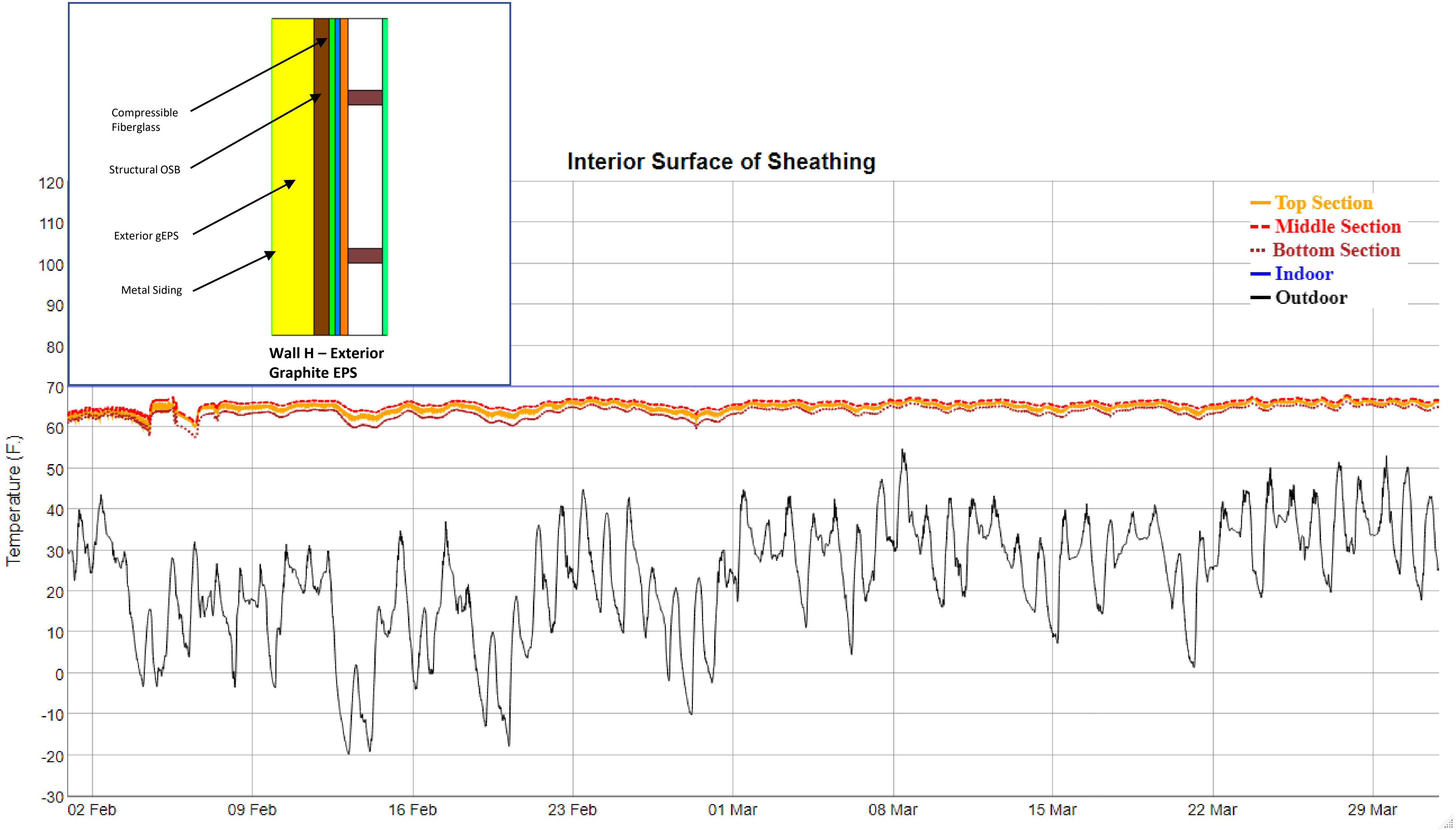
Baseline Wall Temperature



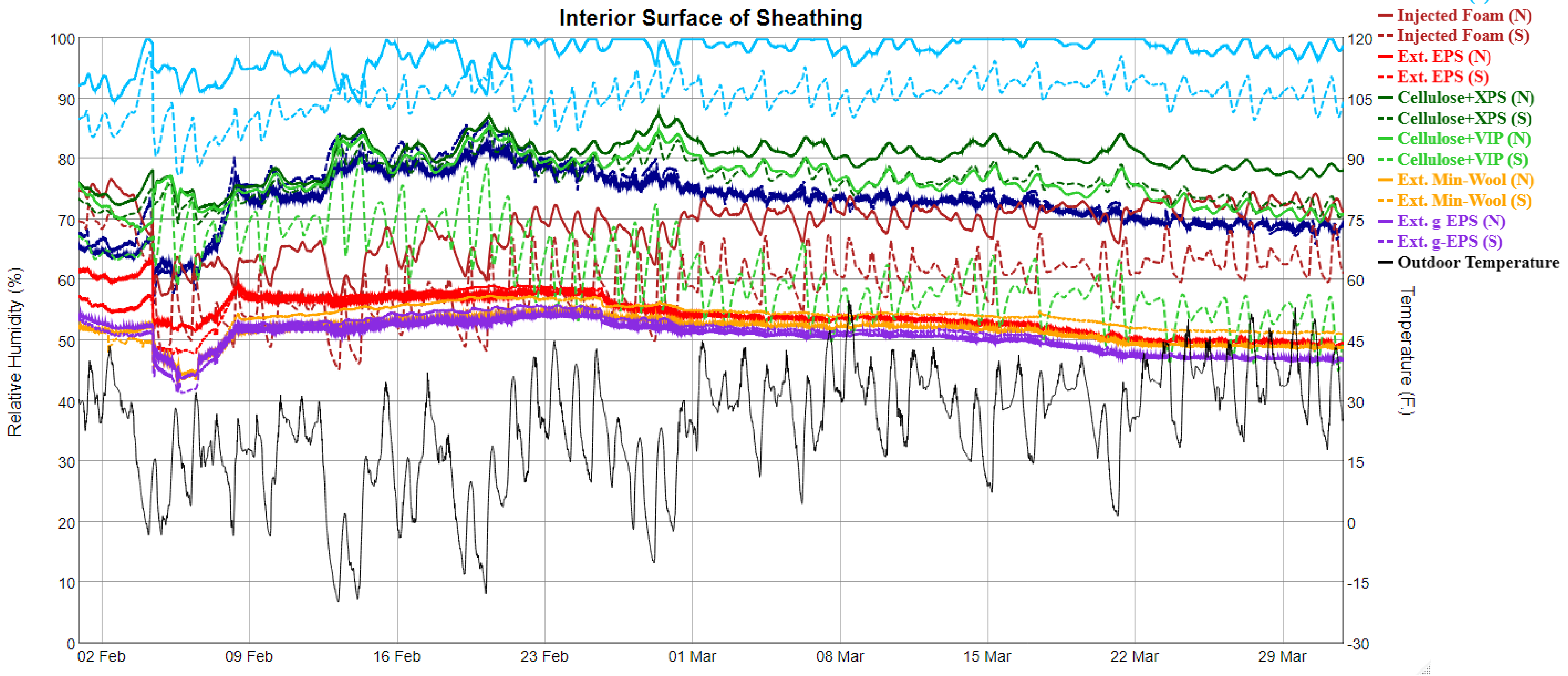
Injected Foam Wall Temperature



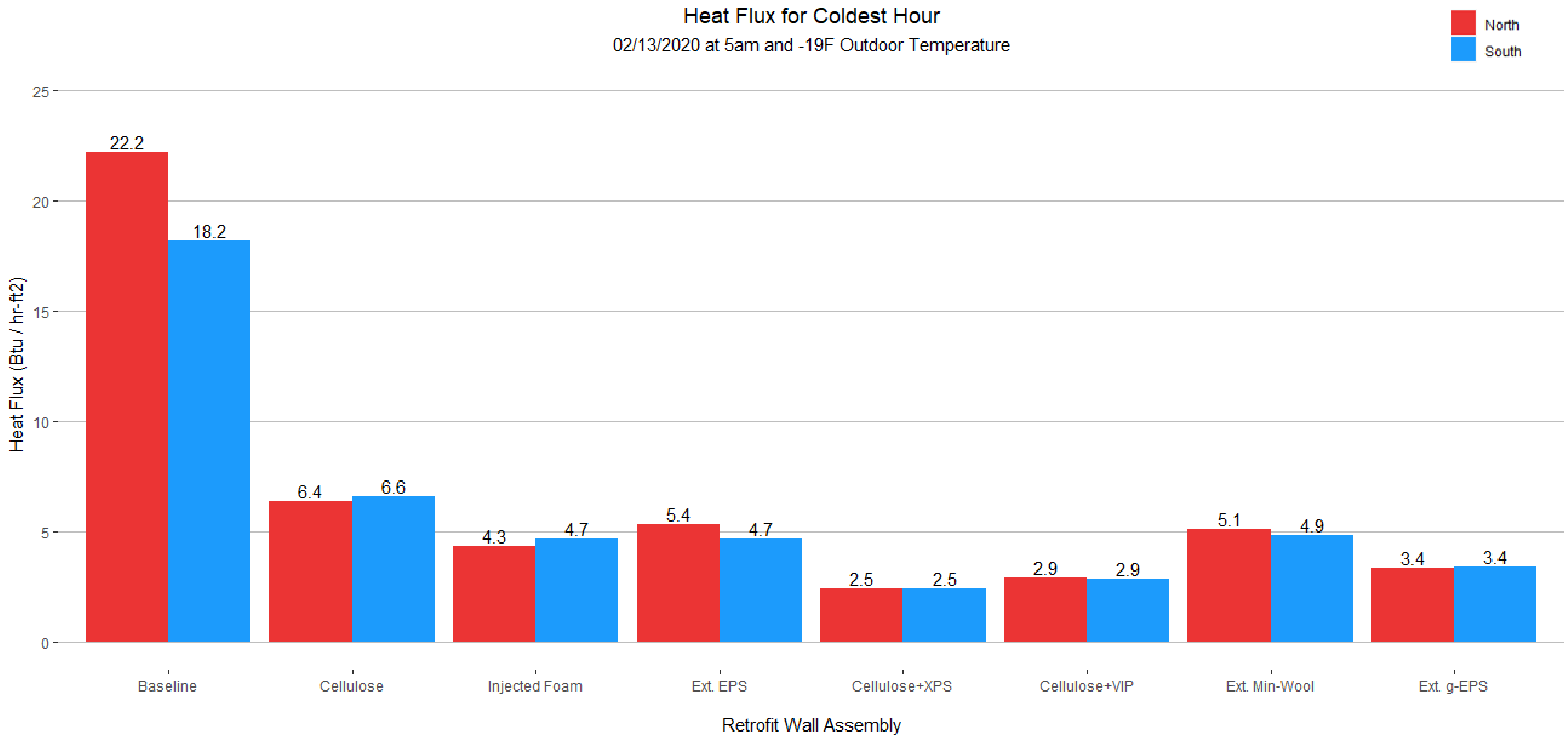
Exterior Graphite EPS Wall Temperature



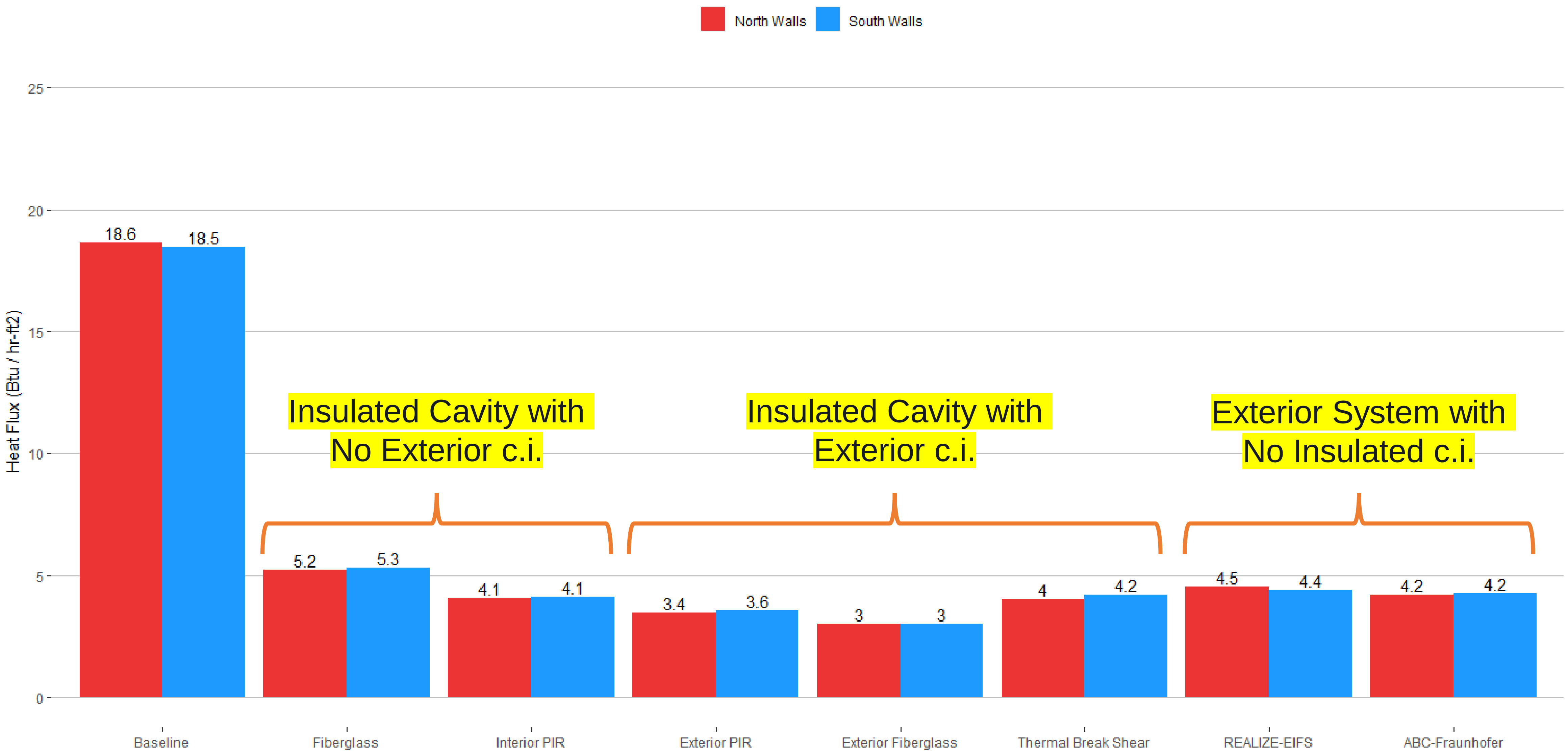
Relative Humidity For All Walls Over Time



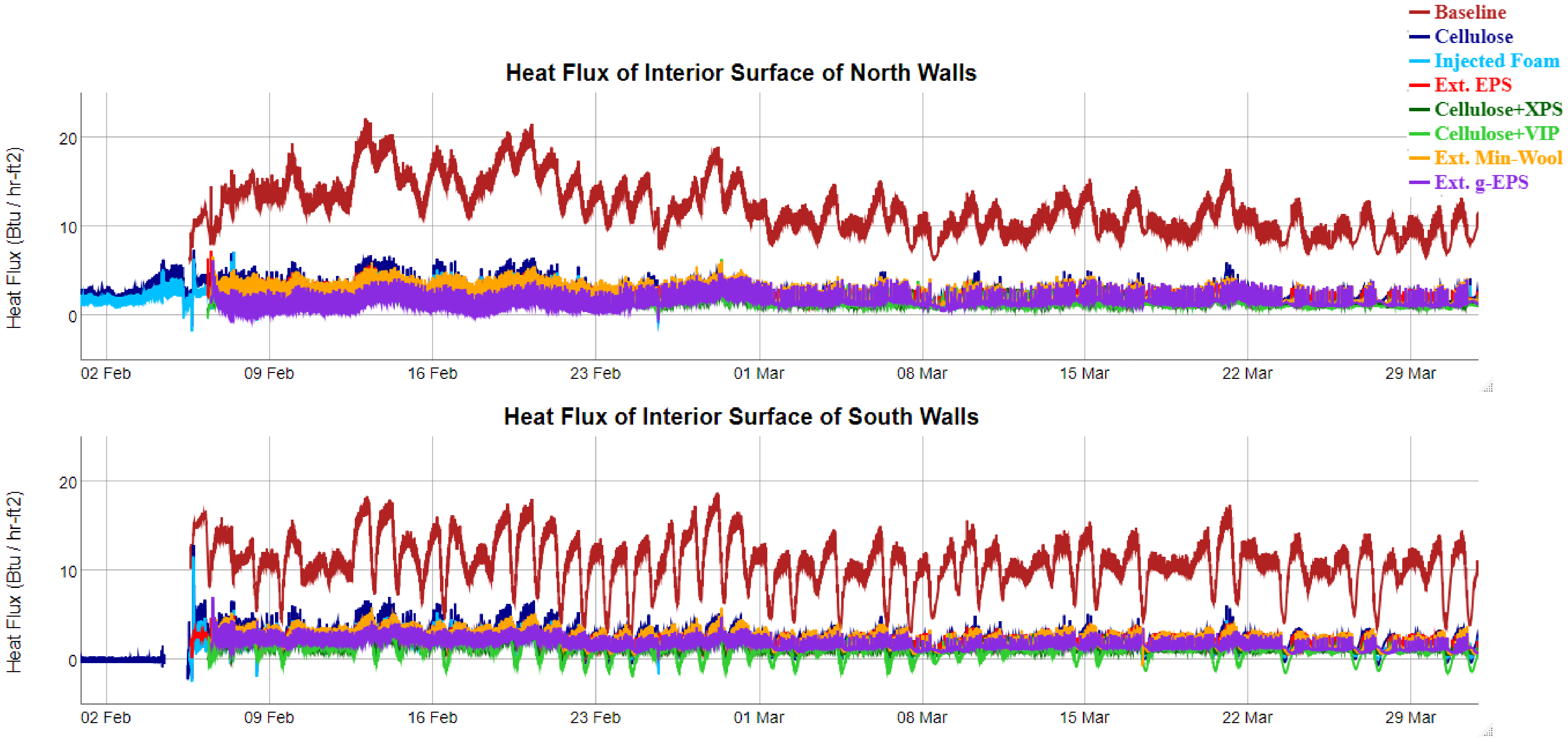
Heat Flux For All Walls on Coldest Day



Heat Flux For Phase 2 Walls on Coldest Day 2021/02/13 7am <-30F

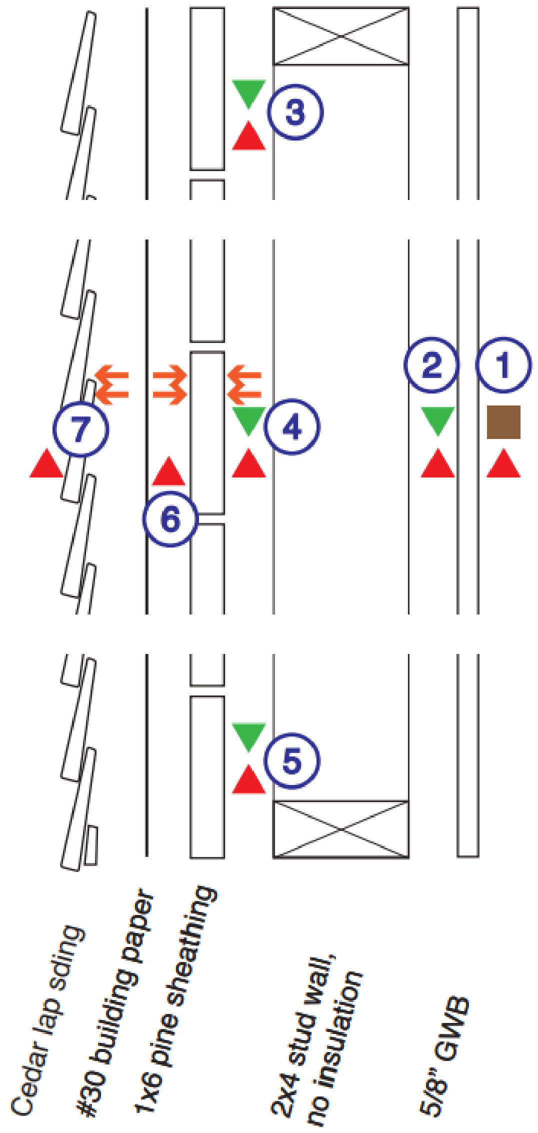


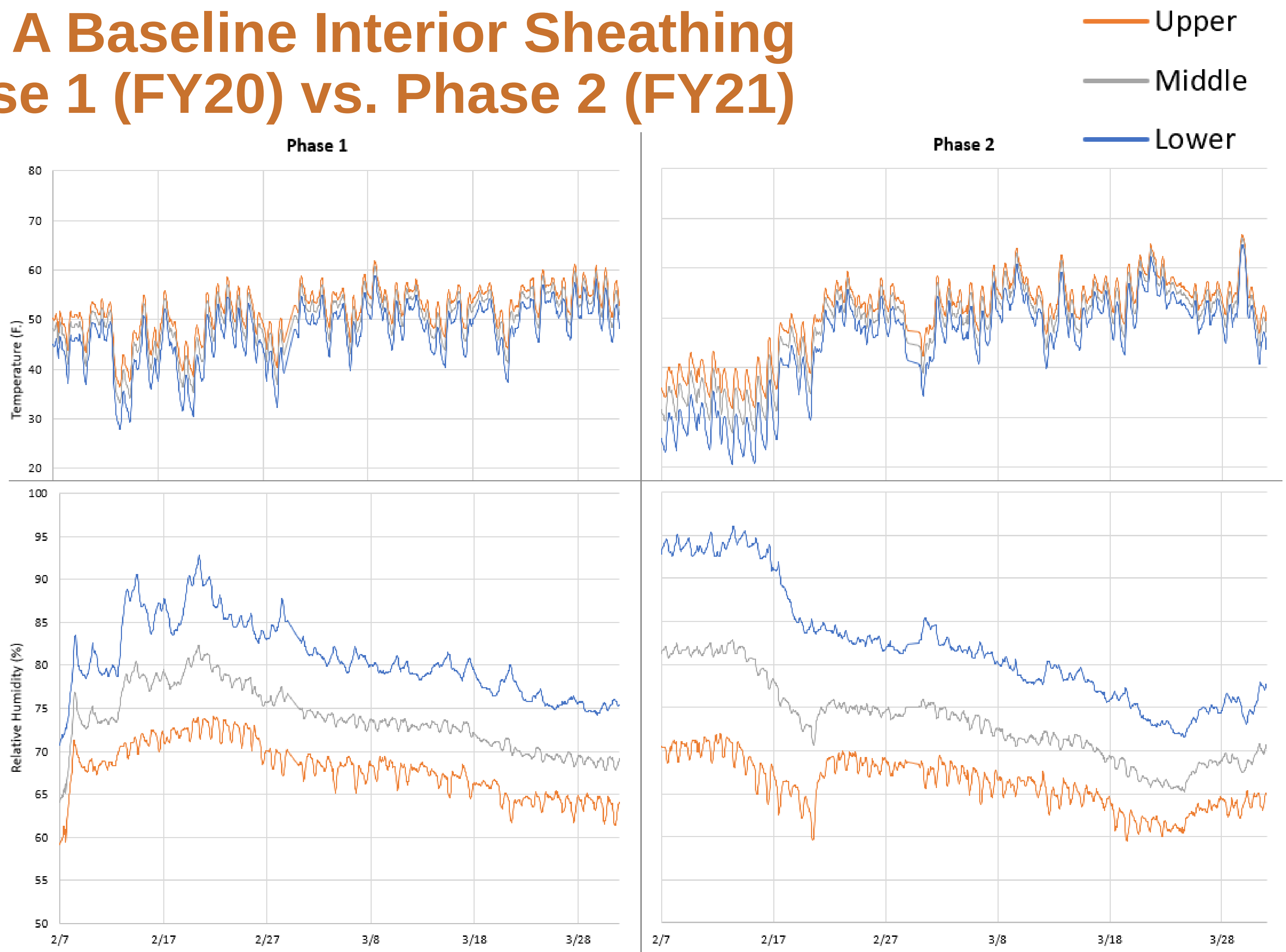
Heat Flux Over Time For All Walls



Heat Flux For Phase 2 Walls Over Time

Wall A Baseline Interior Sheathing Phase 1 (FY20) vs. Phase 2 (FY21)





Hygrothermal testing and Modeling

Material property testing

Thermal properties

- ASTM C518, Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus

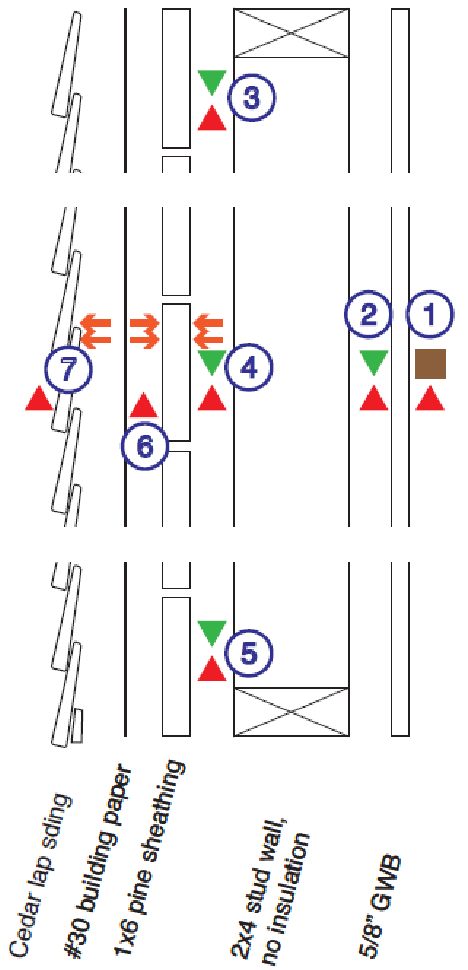
Insulation	Thickness, in	Density, pcf	k, Btu-in/hr ft^2 F	R, hr ft^2 F/Btu-in
2-in. EPS	1.54	1.40	0.241	4.16
2.5-in. EPS	2.03	1.21	0.252	3.97
2-in. graphite-impregnated EPS	2.15	1.95	0.217	4.60
2-in. XPS	2.01	1.50	0.199	5.02
2-in. mineral wool	1.88	9.20	0.239	4.18
Dense-packed cellulose	3.50	3.50	0.286	3.50
Spray foam	2.01	1.58	0.174	5.76
1 by 6-in. wood siding	0.77	27.1	0.652	1.53
5/8-in. gypsum	0.62	43.7	0.513	2.81
3/4-in. OSB	0.71	40.5	0.407	2.46
Wood siding	0.80	26.0	0.588	1.79
Fiber cement siding	0.32	79.5	0.538	1.86
Fiberglass compression layer	0.50	3.83	0.221	4.52

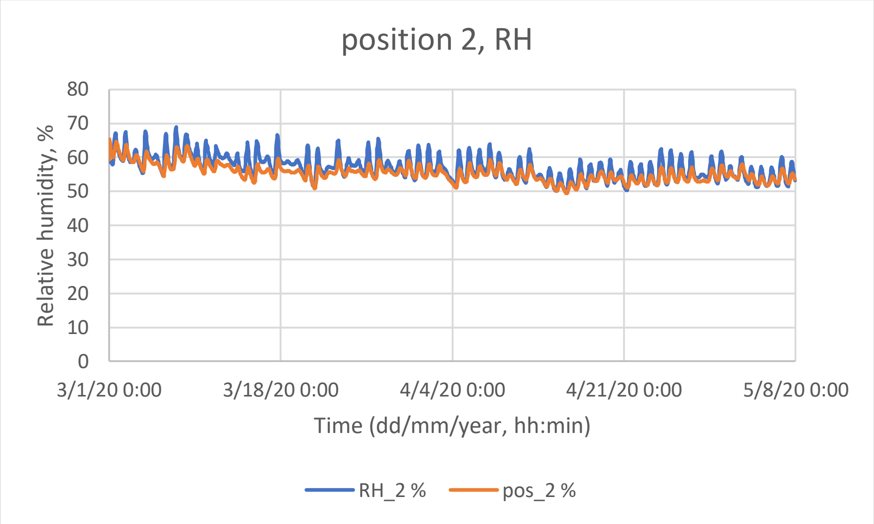
Vapor permeance

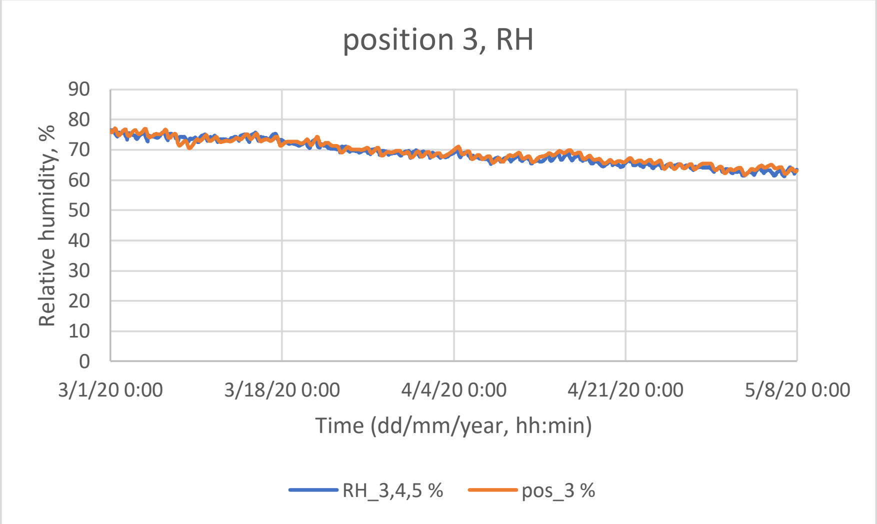
- ASTM E96, Standard Test Methods for Water Vapor Transmission of Materials

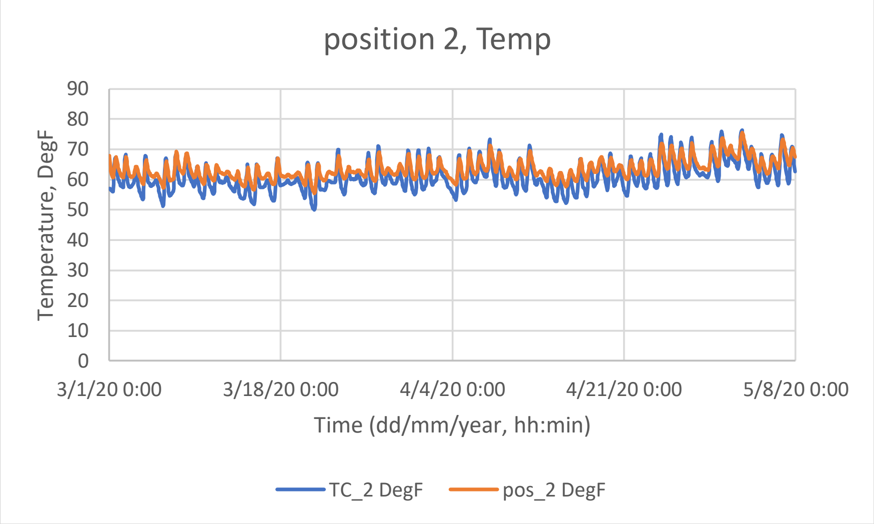
Materials	Water vapor transmission		Permeance		Permeability	
	g/h*m^2	grains/h*ft^2	g/s*Pa*m^2	perm	g/s*Pa*m	perm-in
1x6 wood siding	2.356	3.369	4.200×10^{-7}	7.735	8.411×10^{-9}	5.787
Gypsum board	10.659	15.243	2.000×10^{-6}	34.999	3.110×10^{-8}	21.394
Gyp board + paint	2.457	3.514	4.616×10^{-7}	8.068	7.120×10^{-9}	4.962
15# Felt	4.979	7.120	9.342×10^{-7}	16.348	6.202×10^{-10}	0.427
WRB	7.065	10.103	1.326×10^{-6}	23.199	1.189×10^{-10}	0.082
WRB + liquid AVB coating	3.227	4.615	6.056×10^{-7}	10.597	5.628×10^{-10}	0.387
AVB membrane	0.006	0.008	1.069×10^{-9}	0.019	8.380×10^{-13}	0.001

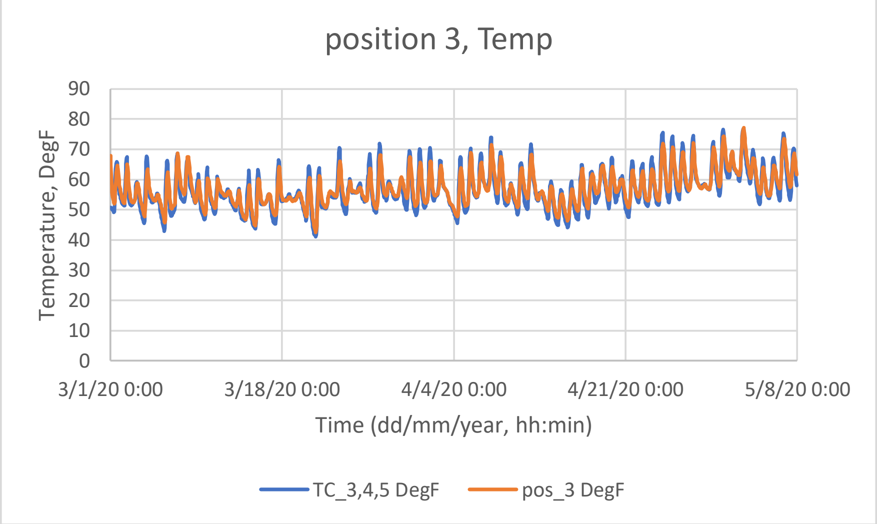
Wall A, base case, simulated & measured temp & RH, south facing orientation











WUFI (pos_#) vs measured RH (RH_#) and Temperature (TC_#)

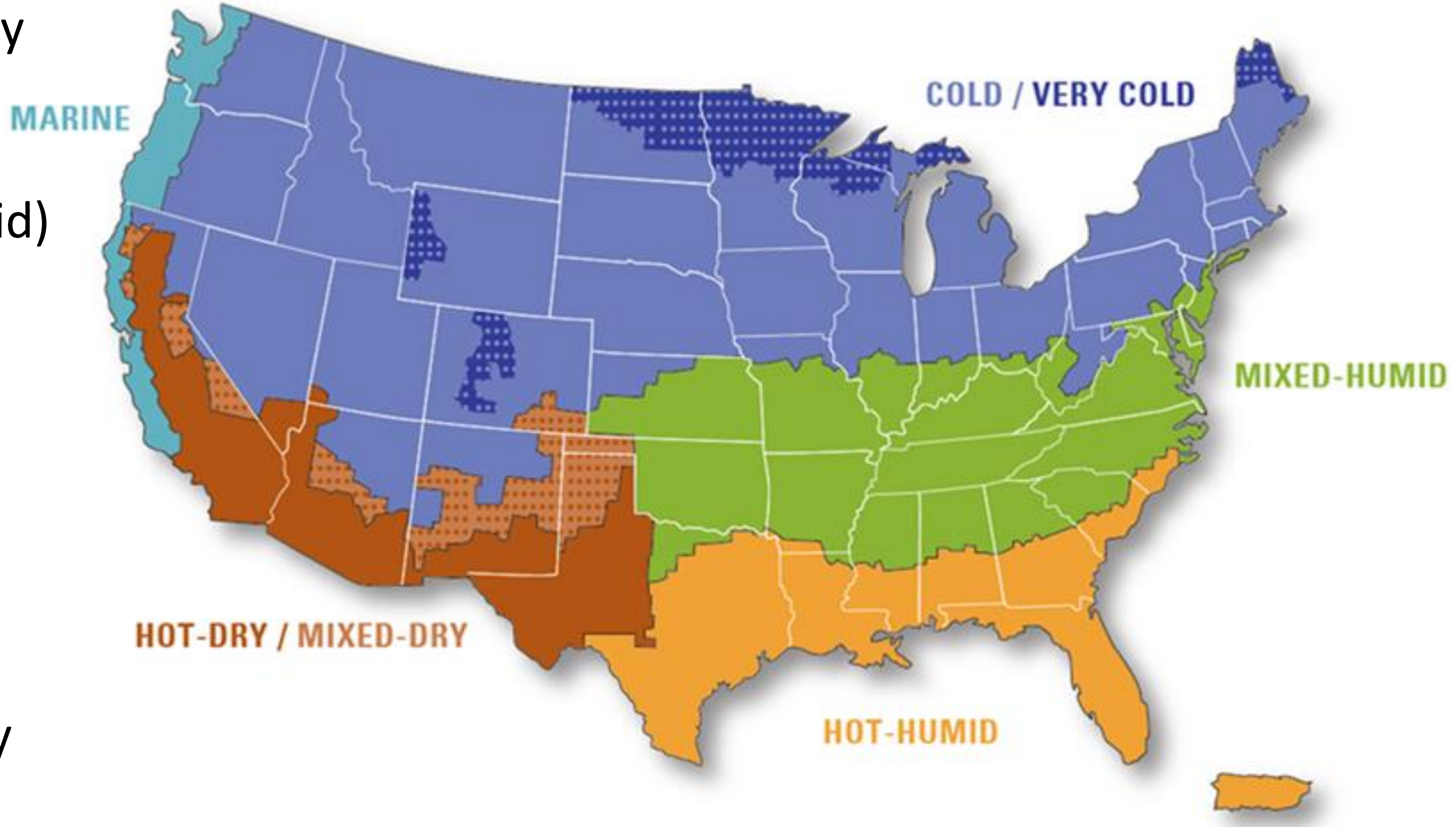
Simulations

Cities & Climate Zones

- Fairbanks, AK (subarctic)
- International Falls, MN (very cold)
- Boston, MA (cold)
- Charleston, SC (mixed humid)
- Amarillo, TX (mixed dry)
- Miami, FL (hot humid)
- Tucson, AZ (hot dry)
- Seattle, WA (marine)

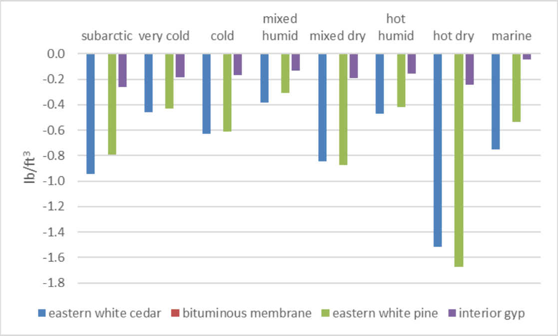
ASHRAE 160

- Simulations run for 3 years
- Interior conditions, htg only

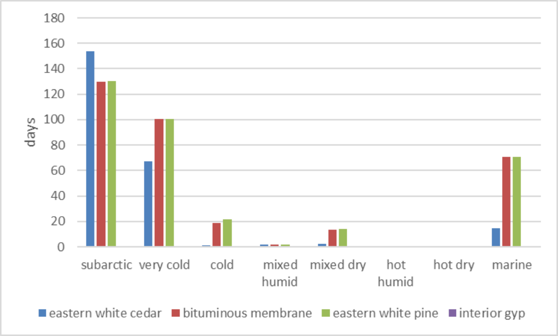


Simulations

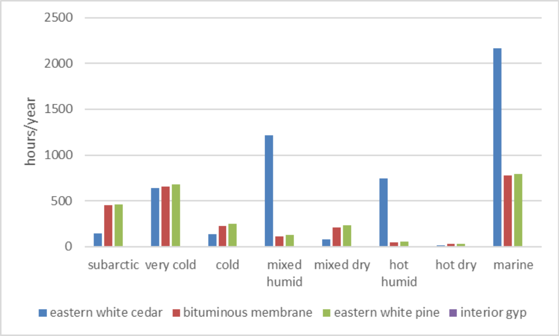
Total moisture accumulation



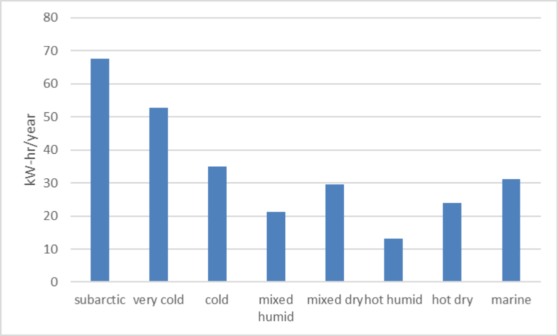
Consecutive days RH > 80%



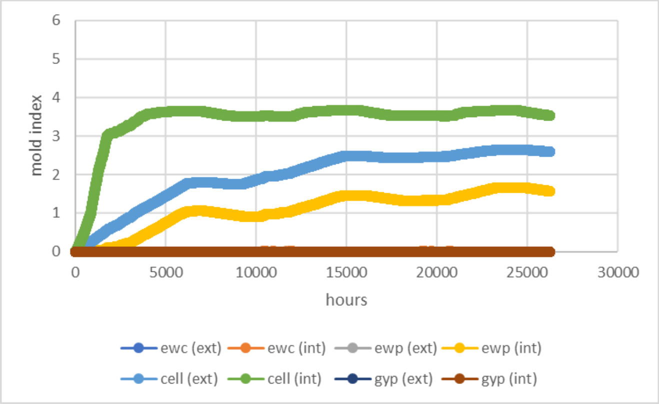
Time of wetness



Energy consumption



Mold index

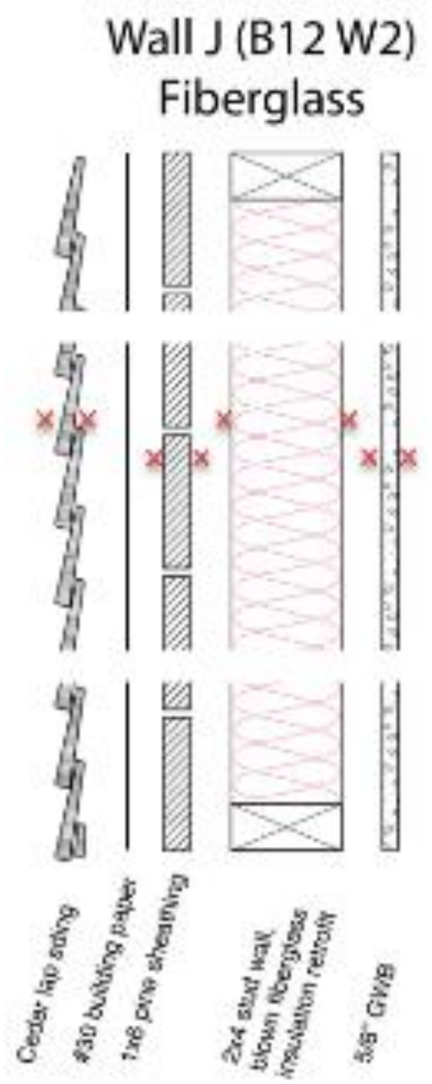


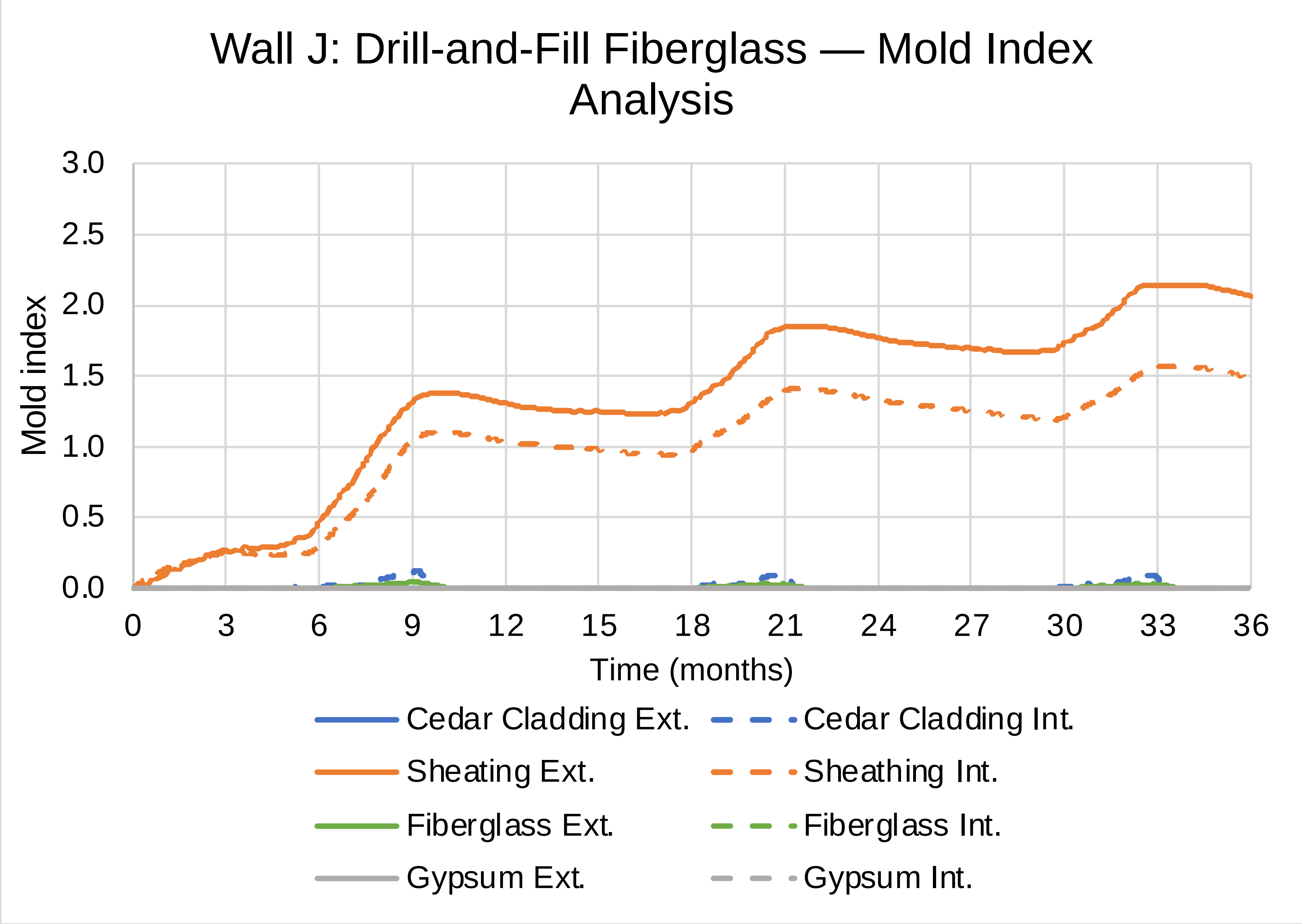
Note: The hygrothermal properties are used to calculate a mold index based on the VTT model for all surfaces, excluding WRBs, and then classified in accordance with ASHRAE 160. Mold index is used to compare different wall retrofits.

Simulations

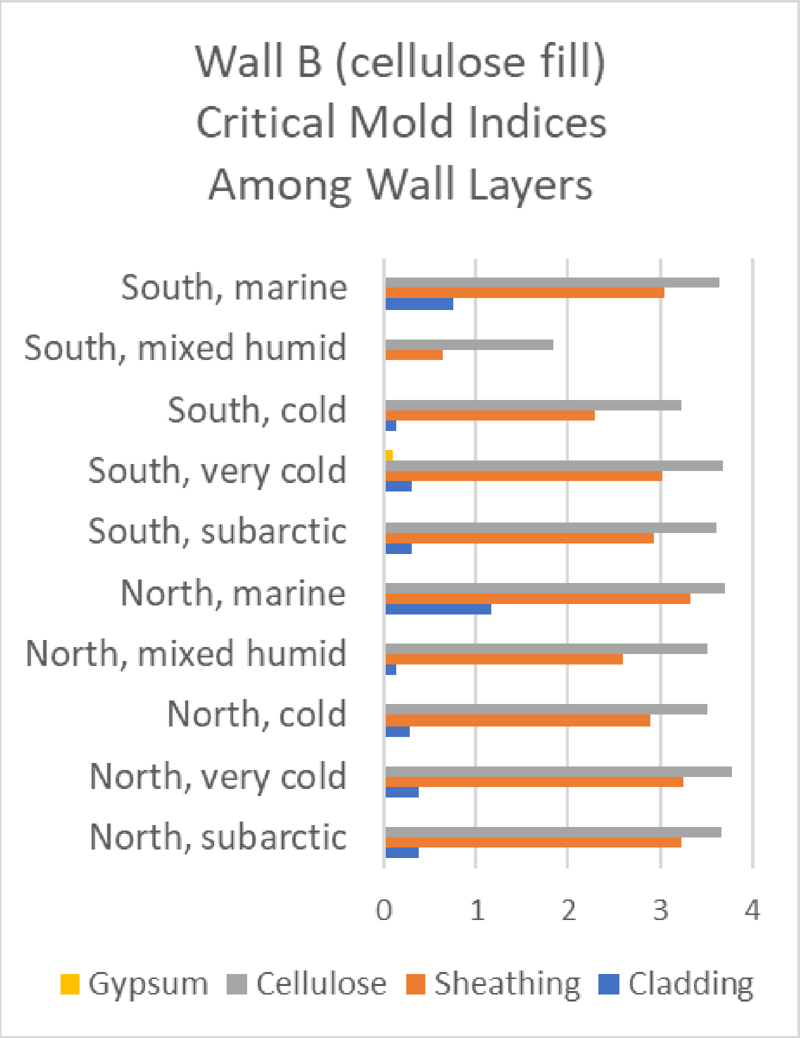
ID	Highlighted indicates mold index ≥ 3	Subarctic	Very Cold	Cold	Mixed humid	Mixed dry	Hot humid	Hot dry	Marine	Subarctic	Very Cold	Cold	Mixed humid	Mixed dry	Hot humid	Hot dry	Marine
ID	Wall Name/ Description	Southern Wall Exposures								Northern Wall Exposures							
A	Base Case 1	0.5	0.8	0.5	0.1	0.2	0.0	0.0	1.5	0.5	1.3	0.8	0.7	0.6	0.3	0.0	2.4
B	Drill-&-Fill Cellulose (dense-pack)	3.6	3.7	3.2	1.8	2.4	0.3	0.1	3.6	3.7	3.8	3.5	3.5	2.7	2.4	0.6	3.7
C	Injected Cavity Foam (cc-spu)	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.3	0.3	0.1	0.4	0.0	0.3	0.0	0.3
D	Pre-fab Ext EPS (panel w/struts)	0.0	0.1	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.1	0.1	0.6	0.0	0.0	0.0	0.1
E	Drill-&-fill Cellulose + Ext XPS	0.3	0.5	0.4	0.3	0.4	0.2	0.1	1.1	0.3	0.5	0.5	0.7	0.5	0.3	0.1	1.3
F	Drill-&-fill Cellulose + VIP/Vinyl Siding	0.3	0.3	0.2	0.1	0.2	0.1	0.0	0.7	0.3	0.3	0.3	0.3	0.3	0.1	0.1	0.6
G	Exterior Mineral Fiber Board	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.1
H	Exterior gEPS Structural Panel System	1.4	1.3	1.1	0.7	0.9	0.4	0.6	1.0	1.5	1.3	1.1	0.8	1.0	0.5	0.7	1.0
I	Base Case 2	0.5	0.8	0.5	0.1	0.2	0.0	0.0	1.5	0.5	1.2	0.8	0.7	0.6	0.3	0.1	2.4
J	Drill-&-Fill FG (proprietary FG, high-dens)	2.9	3.0	2.2	0.4	0.4	0.1	0.0	3.0	3.2	3.2	2.8	2.6	1.3	1.2	0.0	3.3
K	Fiberglass Batt + Int Polyiso	1.3	1.8	0.6	0.1	0.1	0.1	0.0	2.5	2.4	2.7	1.6	1.6	0.5	0.7	0.0	2.8
L	Drill & Fill FG + Ext Polyiso	0.5	0.6	0.1	0.1	0.1	0.1	0.0	1.3	1.2	1.4	0.4	0.6	0.2	0.3	0.0	2.1
M	Pre-fab Ext EPS/EIFs Panel System	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0
N	Pre-fab Ext PU/Vinyl Block System	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.1
O	Drill-&-Fill FG + Ext FG Board	0.3	0.4	0.2	0.1	0.1	0.1	0.0	0.9	0.4	0.5	0.3	0.4	0.2	0.1	0.0	1.1
P	FG Batt + XPS + OSB (Thermal Break Shear Wall)	0.3	0.5	0.0	0.7	0.1	0.1	0.0	1.2	0.6	1.1	0.3	1.1	0.1	1.1	0.0	1.2

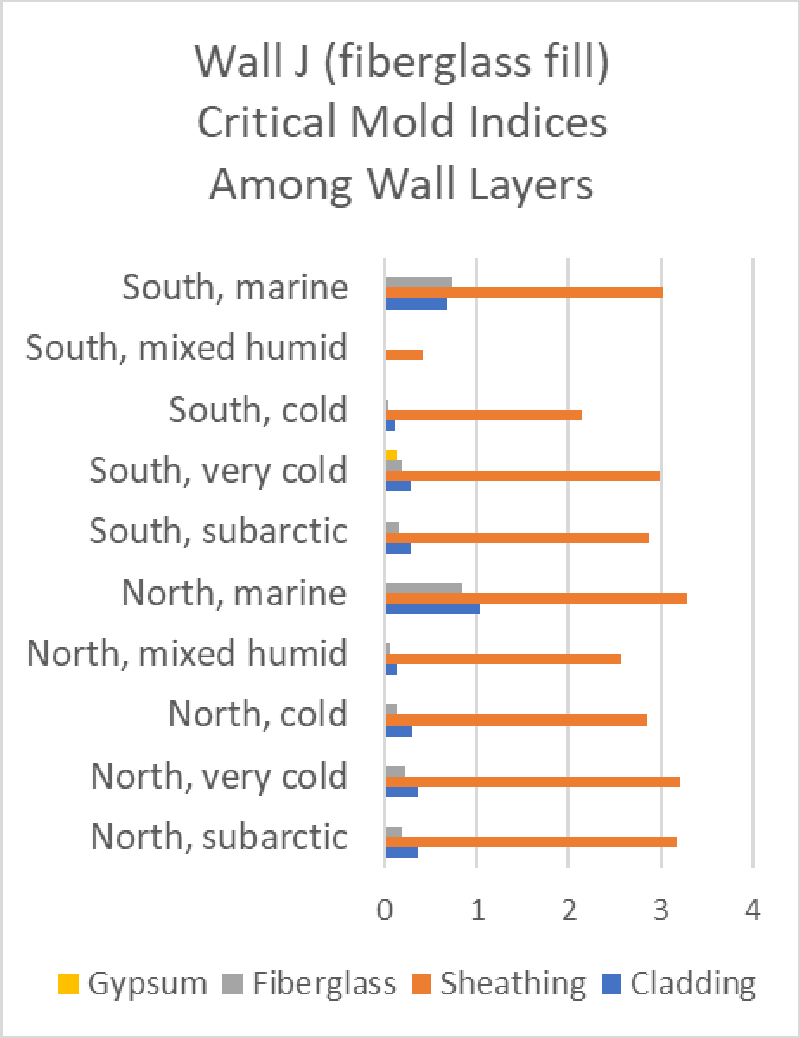
Simulations: sample layer-by-layer results





Simulations: comparing layers and exposures



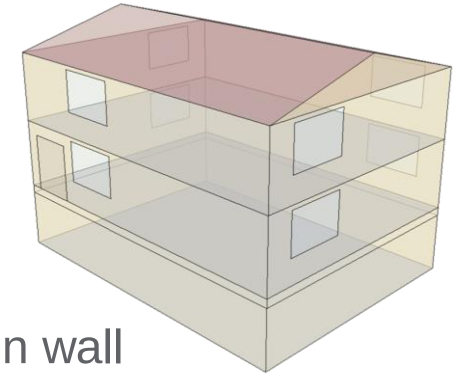


Building Energy Modeling

Energy Modeling

- Objectives
  - Evaluate the performance of wall retrofits
  - Support the selection of the candidate walls
  - Estimate the energy and energy cost savings of the retrofits
- Methodology
  - Adopt the DOE Single-family Prototype Model to represent existing homes based on ResStock and other data sources
  - Collect material properties and use THERM to calculate performance of the composite wall layers
  - Develop EnergyPlus models for different wall configurations and climates to estimate energy and energy cost savings
  - Feed the energy savings data to techno-economic analysis

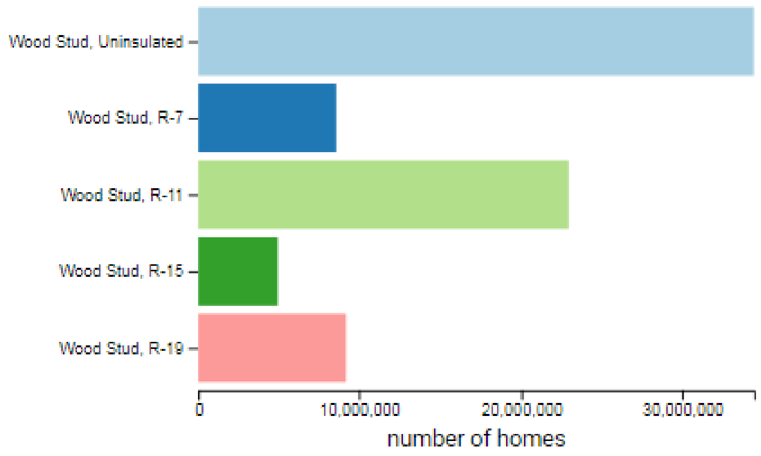
DOE Prototype Single-Family Building Model

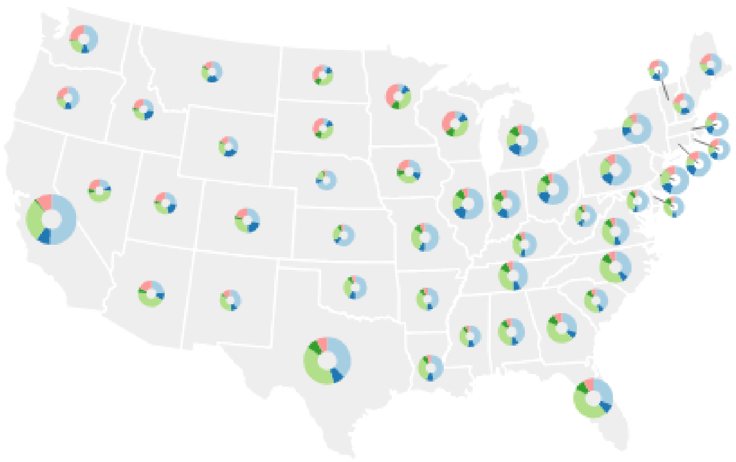


Item	Description	Data source
Total Floor Area (sq. feet)	3,600 (30' x 40' x 3 stories) including conditioned basement	DOE prototype
Aspect Ratio	1.33	DOE prototype
Window-to-Floor Ratio	15%	DOE prototype
Thermal Zoning	Single zone with living space, attic, and heated basement	DOE prototype
Attic	vented	DOE prototype
Basement	Conditioned and uninsulated	DOE prototype
Floor to ceiling height	8.5'	DOE prototype
Windows	Double pane U-factor of 0.55 Btu/h-ft2-F and SHGC of 0.76	ResStock
Roof insulation	Insulated at attic floor R30	ResStock
Wall insulation	Wood framed without insulation (or R0)	ResStock
Air infiltration	ACH50 of 15	ResStock
Heating	Gas furnace 80% AFUE	ResStock
Cooling	SEER 10	ResStock
Duct	In conditioned space	ResStock
Water heater	Gas storage water heater	DOE prototype

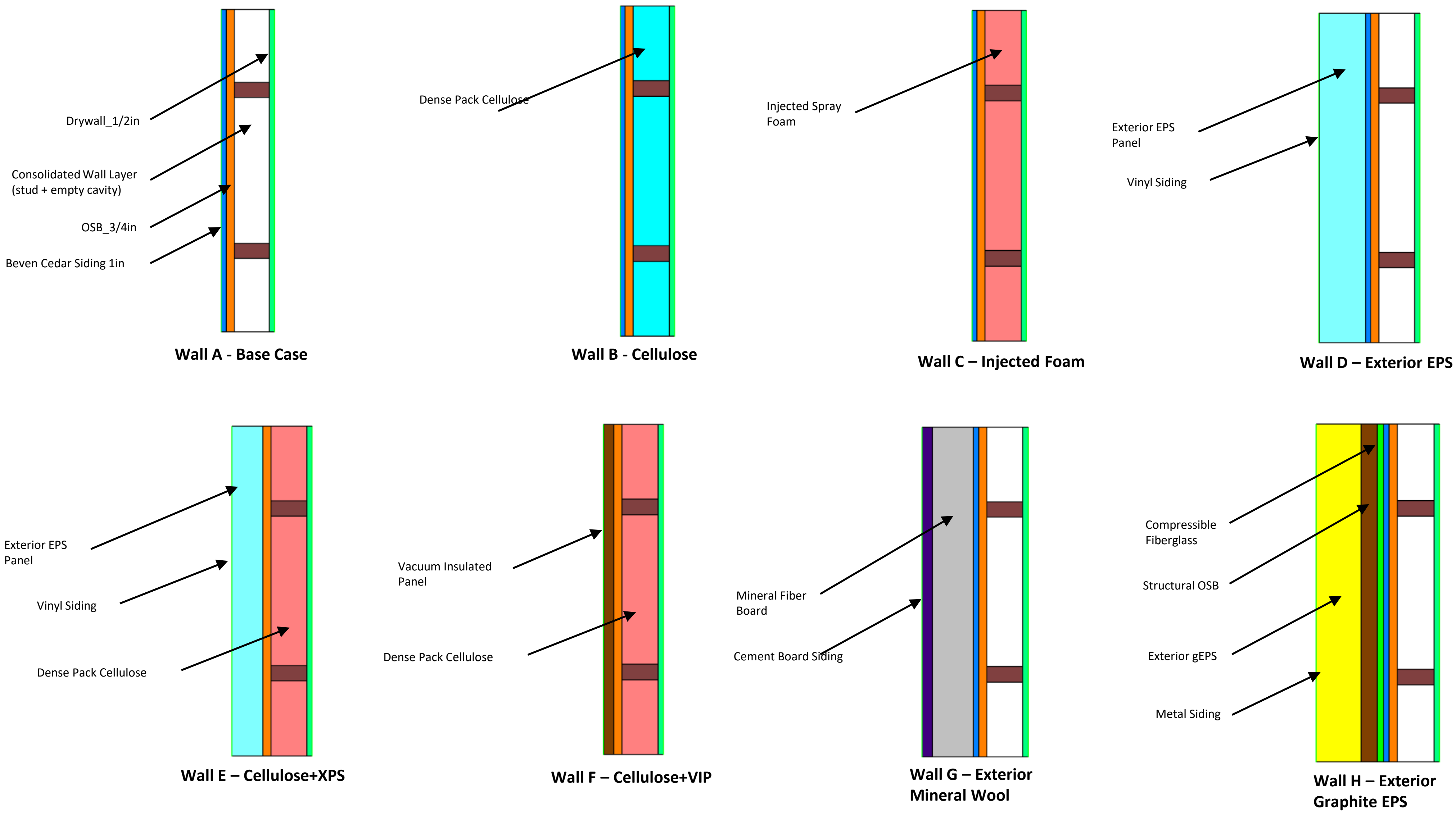
https://www.energycodes.gov/development/residential/iecc_models
https://www.nrel.gov/buildings/resstock.html

Baseline – Insulation wall



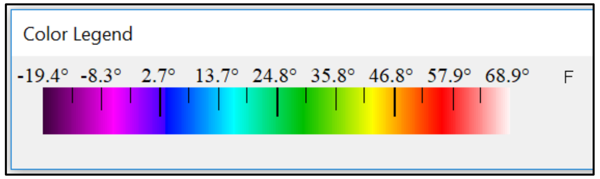


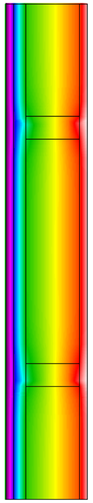
THERM Model of Baseline and Retrofit



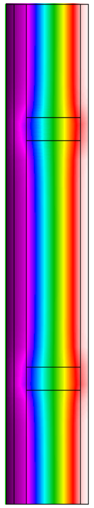
THERM Results of Walls in Isothermal View

Winter design day
Outdoor air T: -20 deg F
Indoor air T: 70 deg F

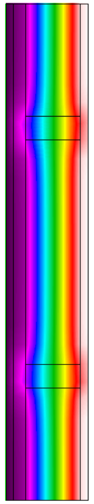




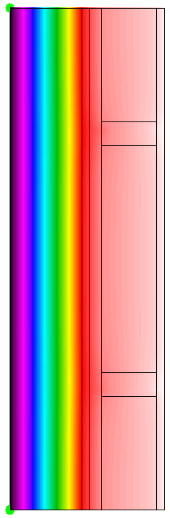
Wall A - Base Case



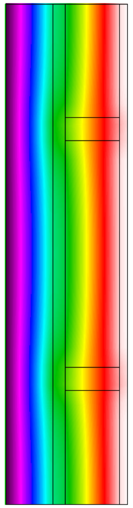
Wall B - Cellulose



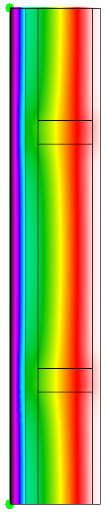
Wall C – Injected Foam



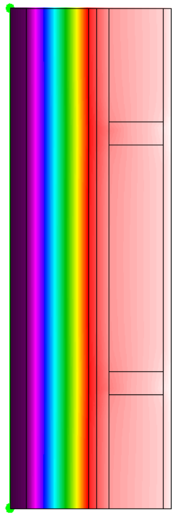
Wall D – Exterior EPS



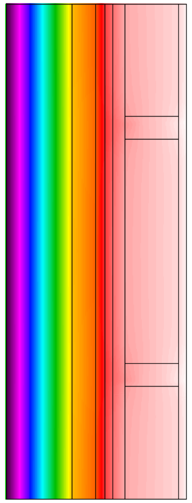
Wall E – Cellulose+XPS



Wall F – Cellulose+VIP

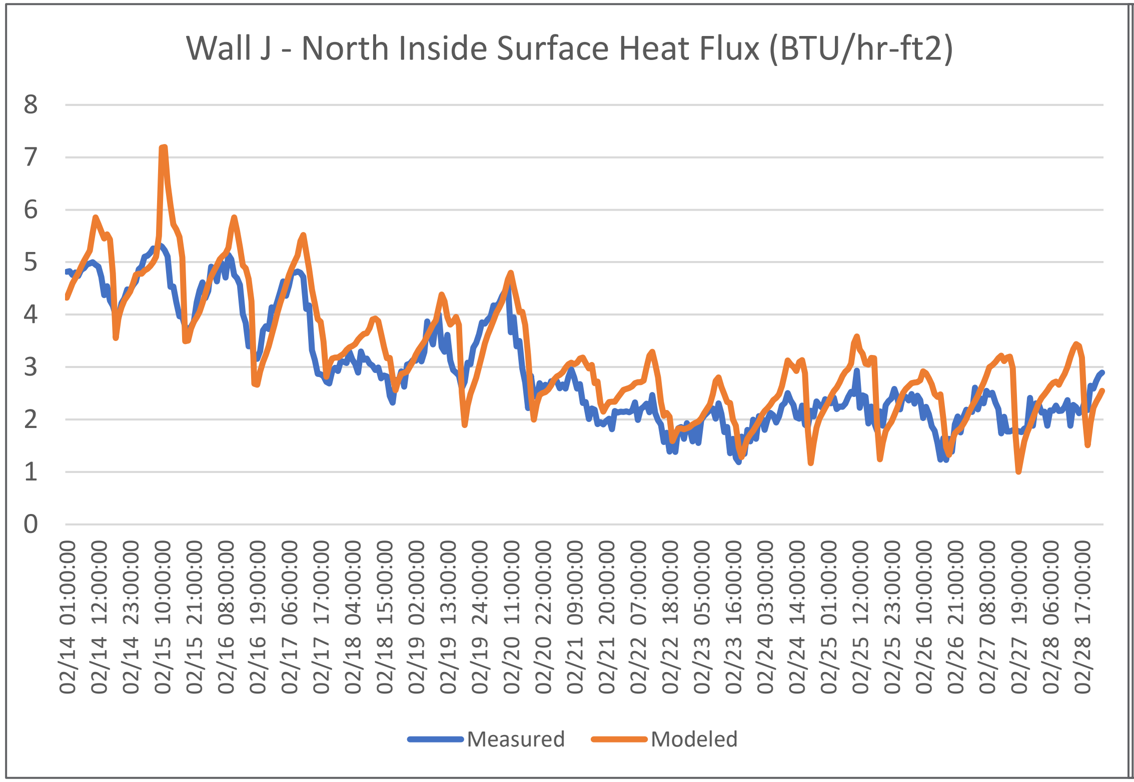


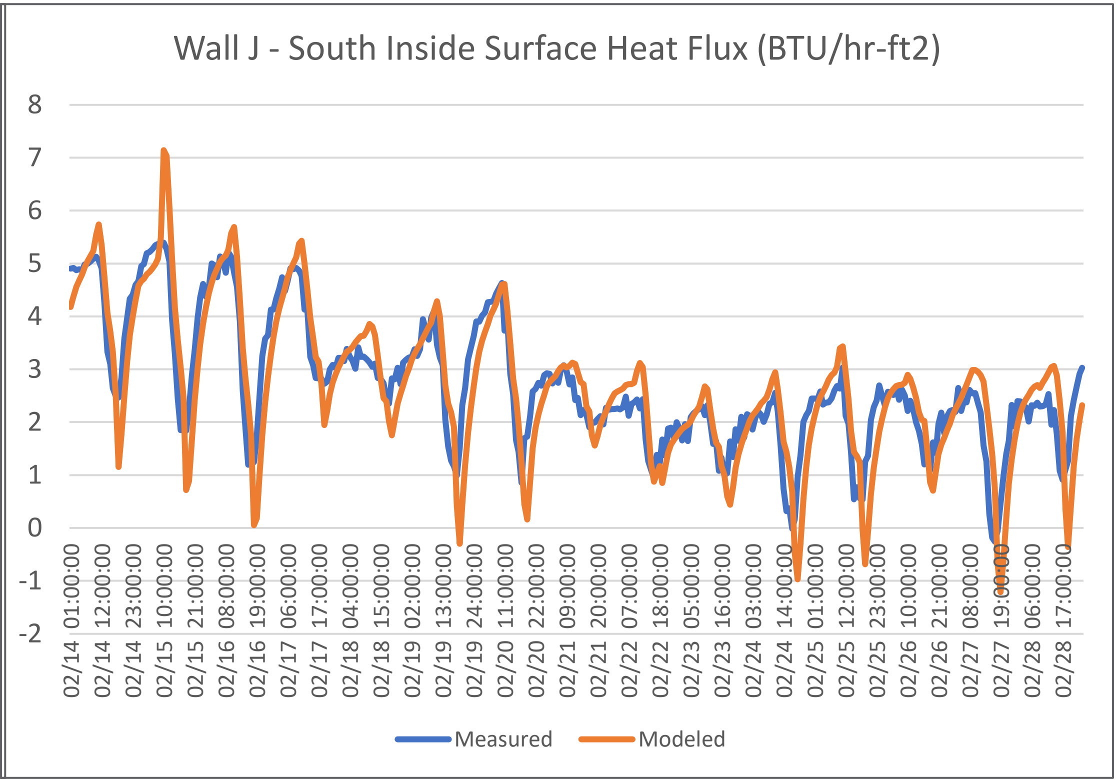
Wall G – Exterior Mineral Wool



Wall H – Exterior Graphite EPS

Benchmark of Modeled Results with Measurement for Wall J – Drill-and-Fill (Fiberglass)





Wall Name	Energy Savings due to Insulation Improvement (kBTU/sqft)	Overall Assembly Thermal Resistance (hr-sqft-deg F/Btu)	Savings to R-Value Ratio
Wall B: Drill-and-Fill (Cellulose)	34.29	14.2	2.42
Wall J: Drill-and-Fill (Fiberglass)	36.26	16.5	2.20
Wall P: Thermal Break Shear	38.46	18.9	2.03
Wall C: Minimally Invasive Cavity Spray Foam	38.24	19.5	1.96
Wall K: Interior Polyiso Insulation	38.84	20.6	1.89
Wall G: Exterior Mineral Fiber Board Insulation	40.62	22.9	1.77
Wall L: Exterior Polyiso Insulation	40.1	22.8	1.76
Wall O: Exterior Fiberglass Board Insulation	41.24	25.2	1.64
Wall D: Exterior EPS Insulation	40.44	24.8	1.63
Wall F: Drill-and-Fill with Exterior VIP Siding	41.29	25.5	1.62
Wall M: Realize EIFS Panel	42.38	27.2	1.56
Wall N: ABC Fraunhofer Blocks	42.21	27.6	1.53
Wall H: Exterior Structural gEPS Panel (Inspired by EnergieSprong)	42.54	28.5	1.49
Wall E: Drill-and-Fill with Exterior XPS Insulation	42.24	28.4	1.49

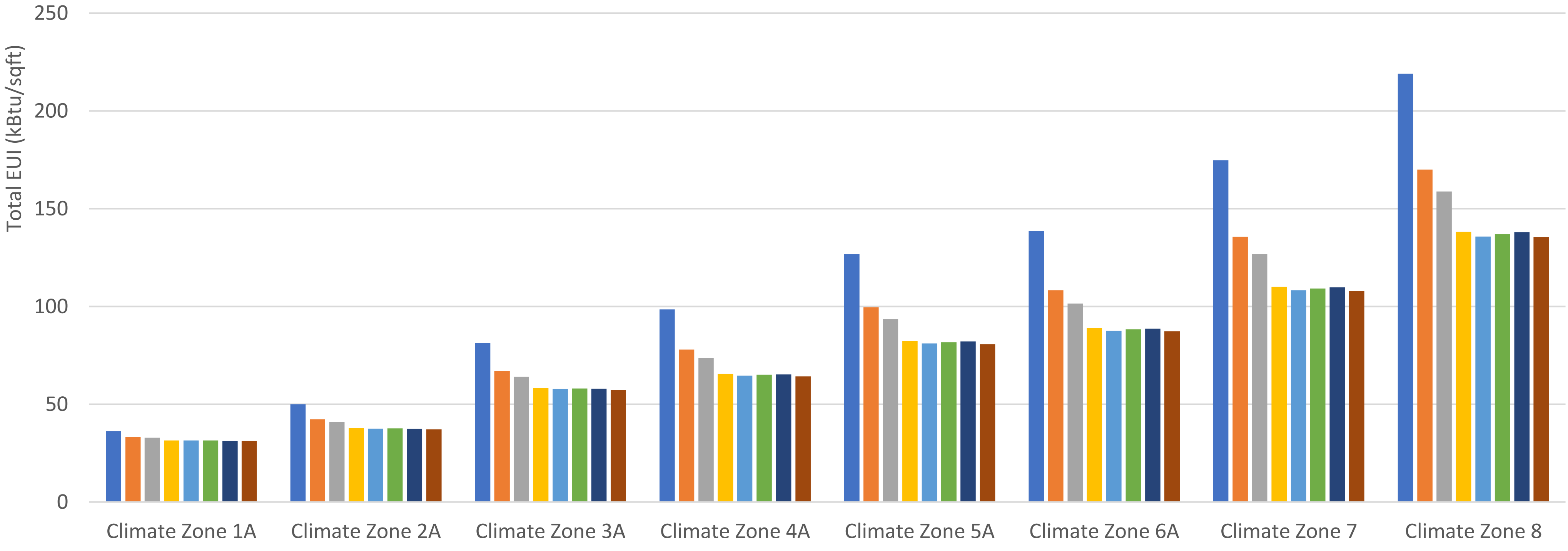
Annual Site Energy Use Savings Phase-1

Annual Energy Use Intensity for DOE Prototype Single-family Home

- Wall A: Baseline
- Wall B: Drill-and-Fill (Cellulose)
- Wall C: Minimally Invasive Cavity Spray Foam
- Wall D: Exterior EPS Insulation
- Wall E: Drill-and-Fill w/ Exterior XPS Insulation (Siding Removed)
- Wall F: Drill-and-Fill w/ Exterior VIP Siding (Siding Removed)

Percent Energy Savings compared to Wall-A Base Case

Wall-B	7.9%	15.3%	17.6%	20.8%	21.5%	21.9%	22.4%	22.4%
Wall-C	9.4%	18.1%	21.2%	25.2%	26.2%	26.7%	27.4%	27.5%
Wall-D	13.3%	24.4%	28.3%	33.5%	35.1%	35.9%	37.0%	36.9%
Wall-E	13.3%	24.8%	28.9%	34.4%	36.0%	36.9%	38.1%	38.0%
Wall-F	13.2%	24.5%	28.5%	33.9%	35.5%	36.3%	37.5%	37.5%
Wall-G	13.7%	25.0%	28.7%	33.7%	35.2%	36.0%	37.2%	37.0%
Wall-H	14.0%	25.7%	29.4%	34.7%	36.3%	37.1%	38.2%	38.1%



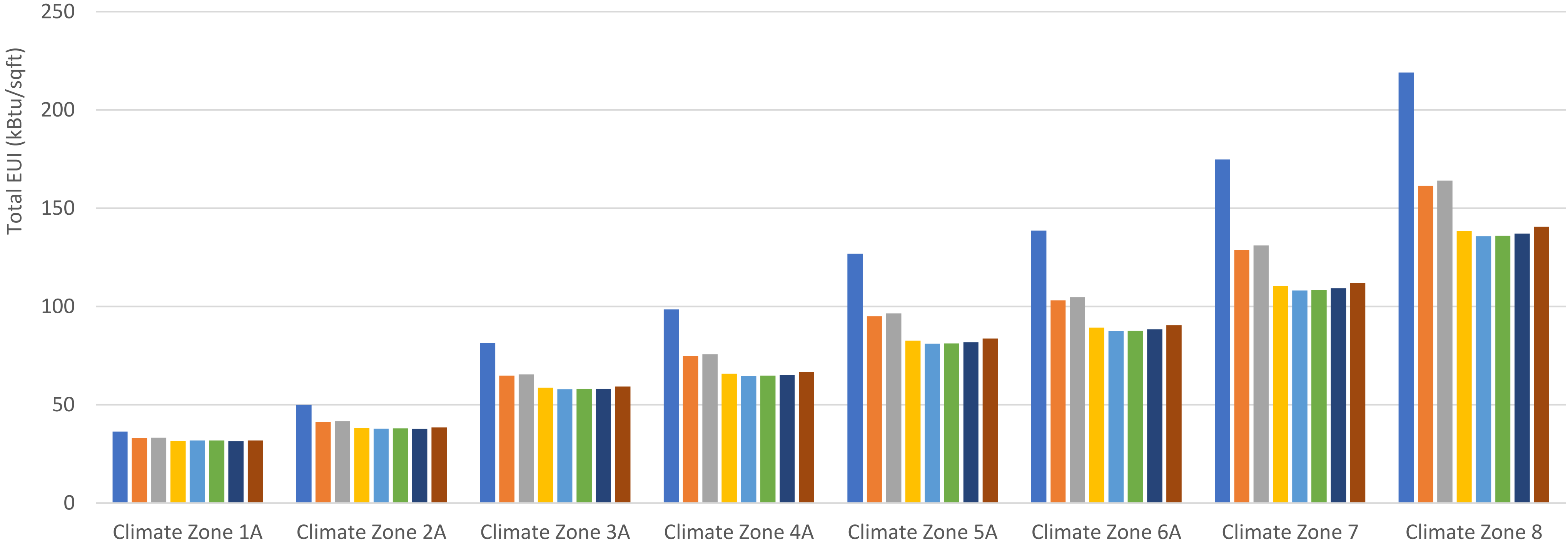
Annual Site Energy Use Savings Phase-2

Annual Energy Use Intensity for DOE Prototype Single-family Home

- Wall I: Baseline
- Wall J: Drill-and-Fill (Fiberglass)
- Wall K: Interior Polyiso Insulation
- Wall L: Exterior Polyiso Insulation (Siding Removed)
- Wall M: Realize EIFS Panel (Siding Removed)
- Wall N: ABC Fraunhofer Blocks

Percent Energy Savings compared to Wall-I Base Case

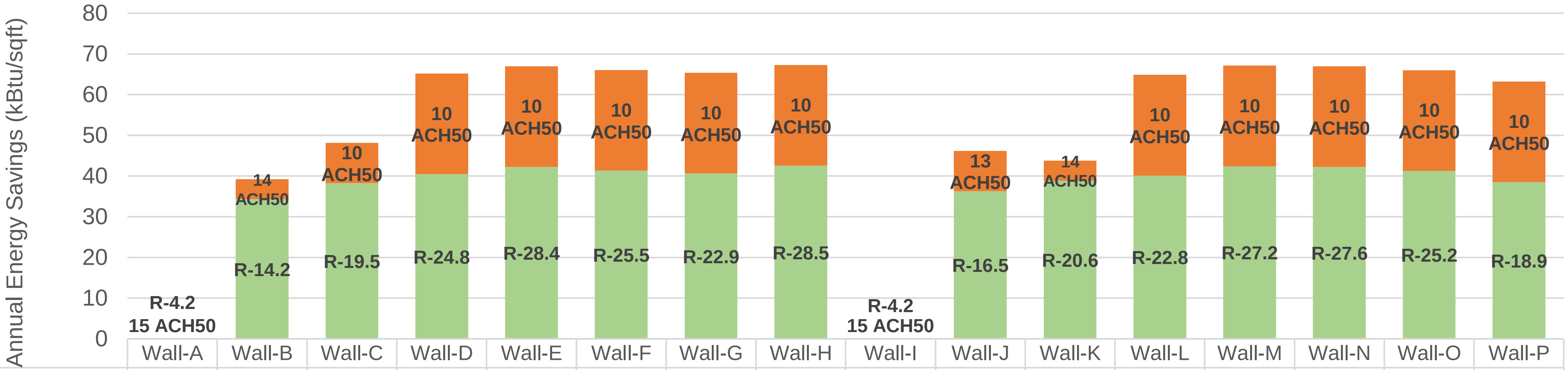
Wall-J	9.1%	17.4%	20.3%	24.2%	25.1%	25.6%	26.3%	26.3%
Wall-K	8.5%	16.8%	19.5%	23.2%	23.9%	24.5%	25.0%	25.1%
Wall-L	13.0%	23.9%	27.9%	33.3%	34.9%	35.7%	36.8%	36.8%
Wall-M	12.3%	24.3%	28.8%	34.4%	36.1%	36.9%	38.1%	38.0%
Wall-N	12.2%	24.1%	28.6%	34.3%	35.9%	36.8%	38.0%	37.9%
Wall-O	13.4%	24.6%	28.6%	33.9%	35.5%	36.3%	37.5%	37.4%
Wall-P	12.5%	23.0%	27.1%	32.3%	34.0%	34.7%	35.9%	35.8%



Sensitivity to Assumed Infiltration

- The baseline wall infiltration ACH 15 per ResStock
- The experiment design doesn't allow accurate whole house infiltration reduction
- Sensitivity analysis was used to separate the impact of air leakage and insulation

Breakdown of Energy Savings from Thermal Resistivity and Air Leakage Improvement in Duluth, MN (CZ7)



	Wall-A	Wall-B	Wall-C	Wall-D	Wall-E	Wall-F	Wall-G	Wall-H	Wall-I	Wall-J	Wall-K	Wall-L	Wall-M	Wall-N	Wall-O	Wall-P
Air Leakage (kBtu/sqft)	0	4.95	9.9	24.74	24.74	24.74	24.74	24.74	0	9.9	4.95	24.74	24.74	24.74	24.74	24.74
Thermal Resistivity (kBtu/sqft)	0	34.29	38.24	40.44	42.24	41.29	40.62	42.54	0	36.26	38.84	40.1	42.38	42.21	41.24	38.46

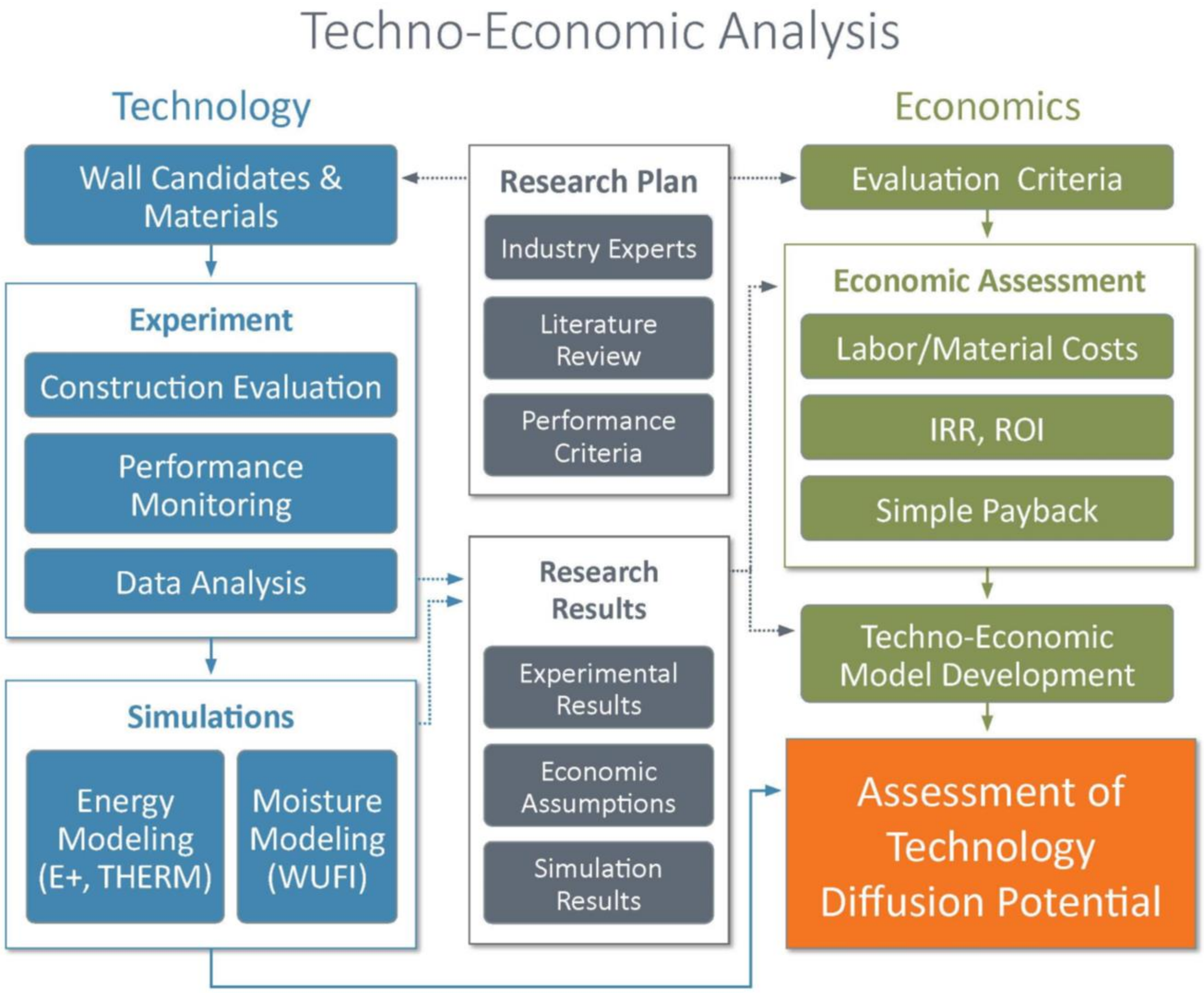
Summary

- An energy modeling methodology with THERM and EnergyPlus was implemented to evaluate the retrofit walls
- 9 of 14 retrofit walls have higher R-values than IECC code
- Cavity-only retrofits have less savings
  - B – Drill-and-Fill (Cellulose), C – Minimally Invasive Cavity Spray Foam, and J – Drill-and-Fill (Fiberglass)
- Deep retrofit with or without removing cladding can have great savings
  - 30-38% whole building energy savings for CZ 5-8 and 25-35% for CZ4
  - A third of the savings is from the assumed air leakage reduction
- Benchmarked energy models can predict retrofit performance for more wall configurations and climates
- The results are used by the techno-economic analysis

Techno-Economic Analysis

Techno-Economic Study Objectives

- Synthesize experimental data, model/simulations and economic data to understand energy, cost and environmental impacts of wall systems.
- Goal: identify options that will save energy, be moisture durable, and promote residential building retrofits at scale.



Cost Data

- Cost estimates provided by Earth Advantage:
  - Earth Advantage worked with three local retrofit contractors to determine:
    - ✓ Material cost
    - ✓ Labor cost
    - ✓ Additional overhead or miscellaneous costs if necessary.
  - Cost estimates include large and small local contractors.
  - Three cost estimates for each wall was provided.
- Additional cost data gathered from manufacturers and RS Means
- Cost data from one local region (Portland, OR) extrapolated to other regions using RS Means regional indices. Costs will match the regional energy and moisture model analyses.
- Shows the performance of walls across the different climate zones (material, labor and energy cost savings over a 30-year period)
- All costs calculated as departures from the baseline wall (Delta Method)

Limitations to Cost Data

- Injected foam and VIP panels not commercially available. g-EPS “Energie Sprong” technology is not fully developed. The same is true for the EIFS and Fraunhofer retrofits. Material and labor costs are estimates at this point.
- Labor costs for emerging technologies are not well known. Contractors found it more difficult to bid labor for wall systems they weren’t familiar with.
- Significant variability in costs regionally
- Significant variability in costs depending on purchasing power of the contractor
- Utility programs, WAP, and other EE programs around the country have impacts of final costs of materials.
- Energy costs are moving up, so future cost effectiveness will change accordingly.
- Costs for labor and materials are crazy right now!

Cost Data Sources

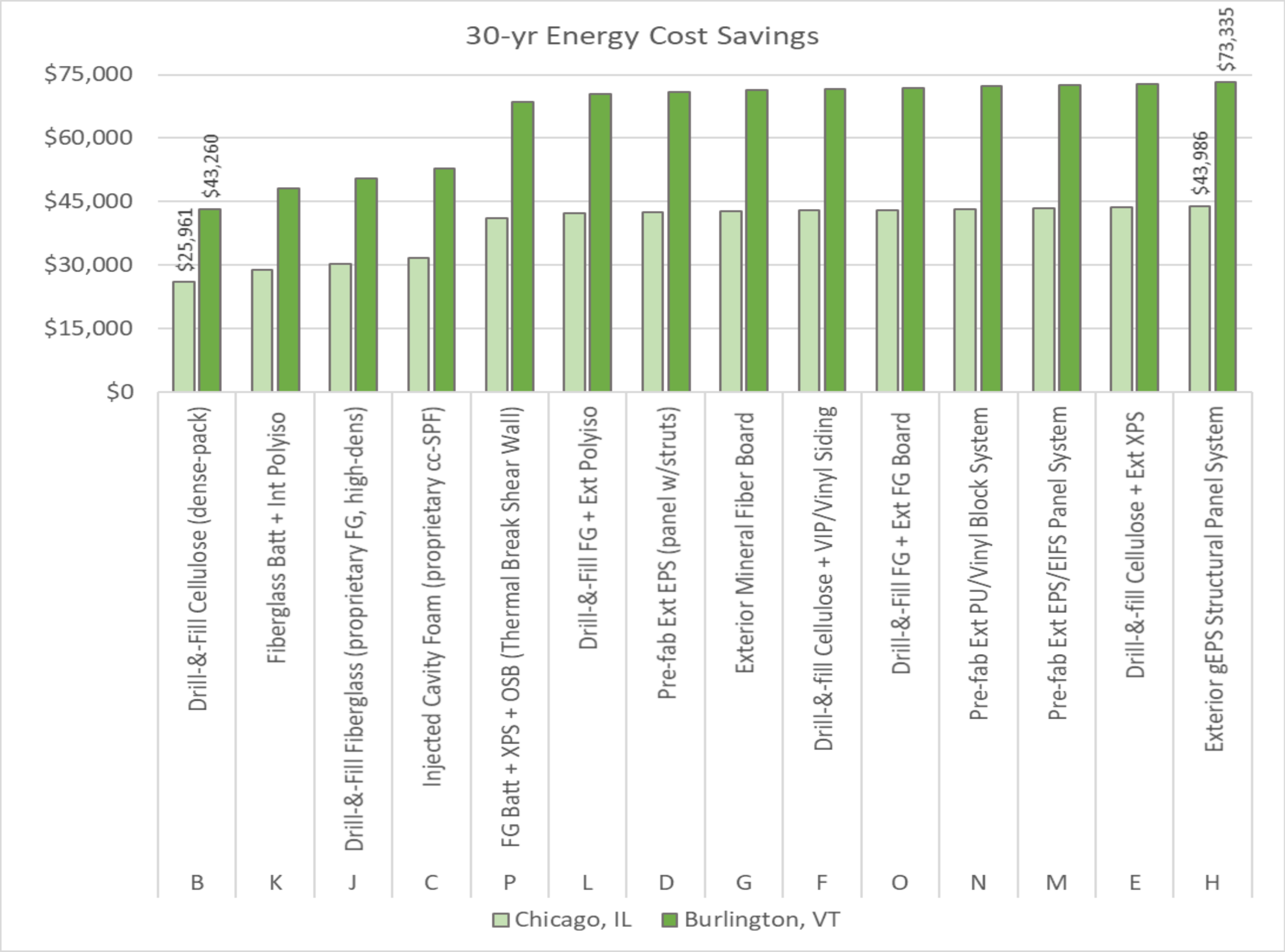
ID	Wall Name	Cost Data Source(s)
B	Drill-&-Fill Cellulose (dense-pack)	Cost Estimator, RS Means
C	Injected Cavity Foam (proprietary cc-spu)	Manufacturer
D	Pre-fab Ext EPS (panel w/struts)	Cost Estimator, RS Means
E	Drill-&-fill Cellulose + Ext XPS	Cost Estimator, RS Means
F	Drill-&-fill Cellulose + VIP/Vinyl Siding	Cost Estimator, Manufacturer
G	Exterior Mineral Fiber Board	Cost Estimator
H	Exterior gEPS Structural Panel System	Cost Estimator
J	Drill-&-Fill Fiberglass (proprietary FG, high-density)	Cost Estimator, RS Means
K	Fiberglass Batt + Int Polyiso	Cost Estimator, RS Means
L	Drill & Fill FG + Ext Polyiso	Cost Estimator, RS Means
M	Pre-fab Ext EPS/EIFS Panel System	Manufacturer
N	Pre-fab Ext PU/Vinyl Block System	Manufacturer
O	Drill-&-Fill FG + Ext FG Board	Cost Estimator, RS Means
P	FG Batt + XPS + OSB (Thermal Break Shear Wall)	Cost Estimator, RS Means

Material, Labor + Total Costs for All Walls

		Chicago Illinois (USD)			Burlington, Vermont (USD)			
Title	**Wall Description**	**Labor Cost ($/ft^2)**	**Material Cost ($/ft^2)**	**Total Cost ($/ft^2)**	**Labor Cost ($/ft^2)**	**Material Cost ($/ft^2)**	**Total Cost ($/ft^2)**	**Rank (least to most expensive)**
Wall B	Drill-&-Fill Cellulose (dense-pack)	1.45	0.40	1.85	1.46	0.41	1.87	1
Wall C	Injected Cavity Foam (proprietary cc-spu)	2.16	4.16	6.32	2.20	4.20	6.40	5
Wall D	Pre-fab Ext EPS (panel w/struts)	13.42	6.95	20.37	13.55	7.02	20.57	12
Wall E	Drill-&-fill Cellulose + Ext XPS	14.88	4.08	18.95	15.02	4.12	19.14	11
Wall F	Drill-&-fill Cellulose + VIP/Vinyl Siding	11.37	3.00	14.38	11.49	3.03	14.52	6
Wall G	Exterior Mineral Fiber Board	11.74	6.09	17.82	11.86	6.15	18.00	10
Wall H	Exterior gEPS Structural Panel System	14.99	6.94	21.93	15.14	7.01	22.15	13
Wall J	Drill-&-Fill Fiberglass (proprietary FG, high-density)	1.45	0.40	1.85	1.46	0.41	1.87	2
Wall K	Fiberglass Batt + Int Polyiso	3.78	0.82	4.60	3.82	0.83	4.64	3
Wall L	Drill & Fill FG + Ext Polyiso	12.05	2.33	14.38	12.17	2.36	14.53	7
Wall M	Pre-fab Ext EPS/EIFS Panel System	22.50	22.50	45.00	22.73	22.73	45.45	14
Wall N	Pre-fab Ext PU/Vinyl Block System	1.50*	3.56*	5.06*	1.52*	3.60*	5.11*	4*
Wall O	Drill-&-Fill FG + Ext FG Board	11.87	4.66	16.53	11.99	4.71	16.70	9
Wall P	FG Batt + XPS + OSB (Thermal Break Shear Wall)	13.17	2.75	15.92	13.31	2.77	16.08	8

* Costs for Wall N assume the block system is manufactured in volume.

30-Year Energy Cost Savings



		Construction / Performance							Economics Burlington					
ID	Name	Materials Acquisition	# Operations	Speed of Installation	Ease of Installation	Added thickness, in.	Moisture Risk by CZ	Assembly R-Value (eff)	Energy Cost Savings, %	EUI Savings, %	Cost $/sf Wall	IRR	Simple Payback
B	Drill-&-Fill Cellulose (dense-pack)	1	2	1	1	0	4C 5 6 7 8	14.2	18%	22%	$2	36%	3
C	Injected Cavity Foam (proprietary cc-spu)	X	2	2	1	0		19.5	22%	27%	$6	12%	8
D	Pre-fab Ext EPS (panel w/struts)	3	3	1	2	5.3		24.8	30%	36%	$21	3%	19
E	Drill-&-fill Cellulose + Ext XPS	1	5	3	3	2.5		28.4	31%	37%	$19	4%	17
F	Drill-&-fill Cellulose + VIP/Vinyl Siding	X	4	3	2	0.5		25.5	31%	36%	$14	6%	13
G	Exterior Mineral Fiber Board	3	3	2	3	5.3		22.9	30%	36%	$18	4%	16
H	Exterior gEPS Structural Panel System	3	4	3	2	7		28.5	31%	37%	$22	3%	20
J	Drill-&-Fill Fiberglass (proprietary FG, high-dens)	2	2	1	1	0	4C 7 8	16.5	22%	26%	$2	42%	2
K	Fiberglass Batt + Int Polyiso	1	4	2	3	1		20.6	21%	24%	$5	16%	6
L	Drill-&-Fill FG + Ext Polyiso	1	5	3	3	1.5		22.8	30%	36%	$15	6%	13
M	Pre-fab Ext EPS/EIFS Panel System	4	3	2	2	5.8		27.2	31%	37%	$45	-2%	41
N	Pre-fab Ext PU/Vinyl Block System	X	2	1	2	4		27.6	31%	37%	$5	22%	5
O	Drill-&-Fill FG + Ext FG Board	3	4	2	3	3.3		25.2	31%	36%	$17	5%	15
P	FG Batt + XPS + OSB (Thermal Break Shear Wall)	1	6	4	4	0.8		18.9	29%	35%	$16	5%	15

Synthesizing Techno – Economic Performance

- Developed an adoption score method, using previous study (Fleiter 2012, Hanes, 2017).
- Quantified monetary and non-monetary benefits based on three categories:
  - Relative advantage
  - Technical context
  - Information context
- Results support market diffusion of emerging technologies/approaches

Precursor Model	Project Model	Notes	Weight	Notes
Relative advantage		***Economic and other monetary benefits, costs***	***0.46***	***Primary - cost, savings, investment***
IRR	**IRR**	The expected compound annual rate of return that will be earned on a project or investment. The higher an internal rate of return, the more desirable an investment is to undertake.	0.06	IRR is uniform for investments of varying types and can be used to rank multiple prospective investments or projects on a relatively even basis.
No analog	**NPV**	The value (in dollars) of all future cash flows (+ & -) over the entire life of an investment, discounted to the present (here, 7%). NPV of 0 means the inflows equal the outflows.	0.06	A total dollar figure representing the positive or negative raw value outcome at the end of the term (here, T=30); can't be used to compare different initial investment quantities.
Payback	**Payback**	The number of years it takes for a business to recoup an investment. A common metric in the residential construction market, which typically targets 10 years or less as worthwhile.	0.1	Simple to understand, but does not take into account the time value of money or changes in future circumstances; can't be used to compare the value of an energy efficient upgrade against other potential investments.
Initial cost	**Initial material cost**	e.g. insulation, sheathing, fasteners, air and water barriers; prefab products or panelized systems	0.12	First-cost is identified in the literature and anecdotally as a primary barrier to adoption
	Initial labor cost	all non-material costs	0.12	Though cost in general is a barrier, high labor costs are exacerbated by system complexity and novel materials and methods; higher labor costs potentially indicate opportunity for cost compression
Non-energy benefits	**No analog**	Could have been new siding (universal), or a secondary performance attribute like added strength or fire resistance (need-specific)		
Technical context		***Adoption and implementation***	***0.39***	***Secondary - practical considerations***
Distance to core process	**Ease of installation**	From the constructability index developed by the UMN team in the course of building the test walls - both complexity and number of steps.	0.15	This subjective assessment was for building and installing the test walls; did not account for greater complexities associated with whole-house projects.
Type of modification	**No analog**	??? Would be uniform for all configurations		
Scope of impact	**Energy savings**	Simulated total energy cost savings for each wall system in each climate zone (T=30- yrs)	0.15	Energy savings can be associated with reduced carbon emissions. Raw energy savings often contribute to above-code certifications and local utility program incentives.
Lifetime	**Mold index**	The mold risk index in each climate zone, determined by hygrothermal modeling; a binary variable: pass/fail (1/0)	0.09	Climate zone/wall configurations with mold indices above 3 should not be used without modification to ensure moisture durability.
Information context		***Knowledge required for implementation***	***0.15***	***Tertiary - potential for improvement***
Transaction costs	**No analog**	No attempt made to determine; closest may be something like marketing or franchising		
Knowledge for planning, implementation	**Speed of installation (proxy for workforce knowledge)**	Walls that are faster to install indicate a faster, easier training process for the workforce.	0.1	Walls that are faster to install indicate a faster, easier training process for the workforce.
Diffusion progress	**Ease of acquisition**	The availability of the material, product, trained contractor, or specialized installation equipment at the time of the project indicates current acceptance in the market.	0.05	Ubiquitous materials, readily available work crews, and standard tools contribute to on-time scheduling and low, local pricing.
Sectoral applicability	**No analog**	???		

Adoption Score Results

<$2/ft²

B: Drill-&-Fill Cellulose (dense-pack)	
Baltimore, MD	0.90
Alberquerque, NM	0.91
Salem, OR	0.94
Chicago, IL	0.90
Boise, ID	0.90
Burlington, VT	0.94
Helena, MT	0.94

J: Drill-&-Fill Fiberglass (proprietary FG, high-dens)	
Baltimore, MD	0.97
Alberquerque, NM	0.89
Salem, OR	0.85
Chicago, IL	0.89
Boise, ID	0.89
Burlington, VT	0.98
Helena, MT	0.93

$4.50-$6.50 /ft²

K: Fiberglass Batt + Int Polyiso	
Baltimore, MD	0.84
Alberquerque, NM	0.84
Salem, OR	0.84
Chicago, IL	0.92
Boise, ID	0.84
Burlington, VT	0.92
Helena, MT	0.88

N: Pre-fab Ext PU/Vinyl Block System	
Baltimore, MD	0.90
Alberquerque, NM	0.85
Salem, OR	0.89
Chicago, IL	0.93
Boise, ID	0.85
Burlington, VT	0.91
Helena, MT	0.86

C: Injected Cavity Foam (proprietary cc-SPF)	
Baltimore, MD	0.85
Alberquerque, NM	0.80
Salem, OR	0.85
Chicago, IL	0.89
Boise, ID	0.80
Burlington, VT	0.89
Helena, MT	0.87

$14.50-$22/ft²

F: Drill-&-fill Cellulose + VIP/Vinyl Siding	
Baltimore, MD	0.75
Alberquerque, NM	0.69
Salem, OR	0.77
Chicago, IL	0.82
Boise, ID	0.86
Burlington, VT	0.76
Helena, MT	0.82

L: Drill-&-Fill FG + Ext Polyiso	
Baltimore, MD	0.84
Alberquerque, NM	0.71
Salem, OR	0.76
Chicago, IL	0.84
Boise, ID	0.71
Burlington, VT	0.86
Helena, MT	0.80

P: FG Batt + XPS + OSB (Thermal Break Shear Wall)	
Baltimore, MD	0.78
Alberquerque, NM	0.64
Salem, OR	0.70
Chicago, IL	0.78
Boise, ID	0.64
Burlington, VT	0.81
Helena, MT	0.71

O: Drill-&-Fill FG + Ext FG Board	
Baltimore, MD	0.81
Alberquerque, NM	0.69
Salem, OR	0.74
Chicago, IL	0.81
Boise, ID	0.69
Burlington, VT	0.84
Helena, MT	0.74

G: Exterior Mineral Fiber Board	
Baltimore, MD	0.70
Alberquerque, NM	0.62
Salem, OR	0.65
Chicago, IL	0.71
Boise, ID	0.67
Burlington, VT	0.81
Helena, MT	0.75

E: Drill-&-fill Cellulose + Ext XPS	
Baltimore, MD	0.69
Alberquerque, NM	0.63
Salem, OR	0.66
Chicago, IL	0.74
Boise, ID	0.66
Burlington, VT	0.80
Helena, MT	0.74

D: Pre-fab Ext EPS (panel w/struts)	
Baltimore, MD	0.65
Alberquerque, NM	0.65
Salem, OR	0.67
Chicago, IL	0.75
Boise, ID	0.68
Burlington, VT	0.79
Helena, MT	0.75

H: Exterior gEPS Structural Panel System	
Baltimore, MD	0.64
Alberquerque, NM	0.58
Salem, OR	0.62
Chicago, IL	0.66
Boise, ID	0.62
Burlington, VT	0.74
Helena, MT	0.70

$45/ft²

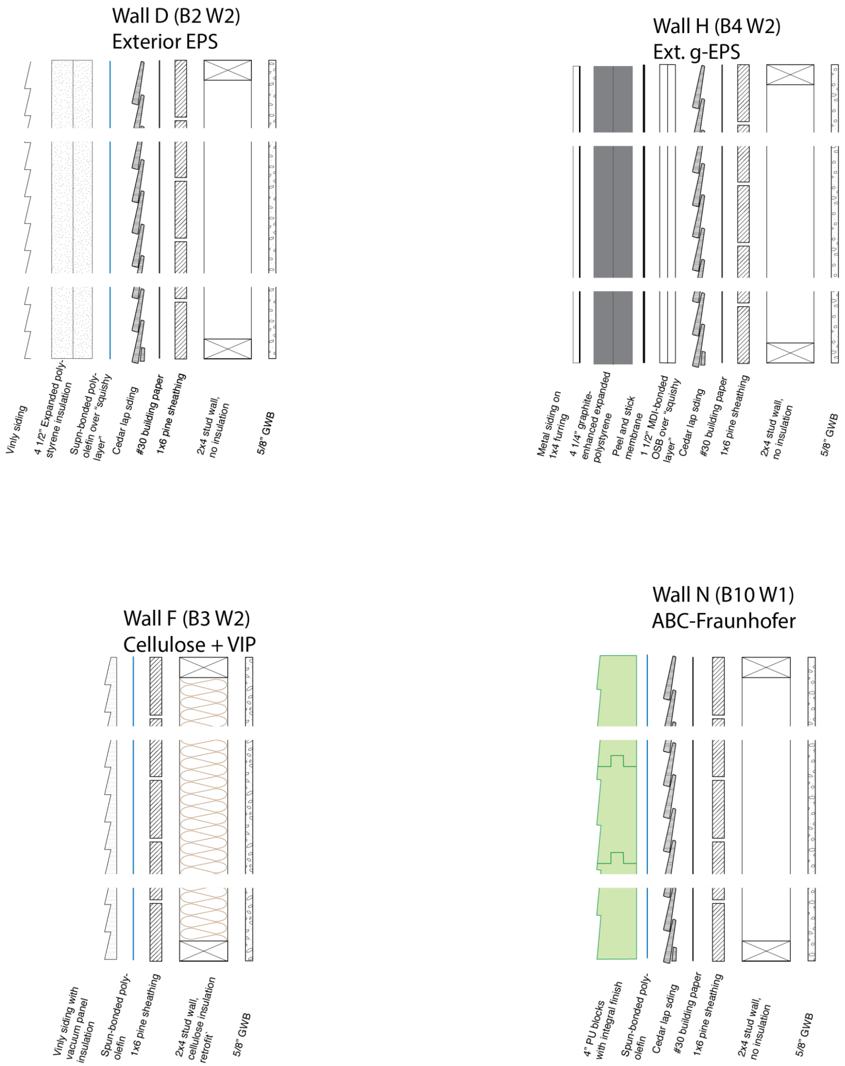
M: Pre-fab Ext EPS/EIFS Panel System	
Baltimore, MD	0.60
Alberquerque, NM	0.50
Salem, OR	0.56
Chicago, IL	0.60
Boise, ID	0.53
Burlington, VT	0.65
Helena, MT	0.56

Primary Findings

- The mold index was less than 3 for most walls in most climate zones; care should be taken for both Wall B (drill and fill cellulose) and Wall J (drill-and-fill fiberglass) in Subarctic, Very Cold and Marine climates.
- Energy modeling results showed that the climate zones with the highest potential for retrofit savings are those which are heating-dominated (i.e., Cold and Very Cold climate designations) with heating and cooling energy use intensity (EUI) savings due to the wall retrofits alone ranging from 21.5% to 38.2%.
- Five of the studied wall upgrades can be built for between $1.90 and $6.30 per square foot of enclosure. These same walls provide strong, double-digit IRRs and Simple Payback periods of less than 10 years in cold climates.

Primary Findings (cont.)

- Lower cost wall upgrades typically pay back faster, despite producing more modest energy savings.
- Prefabricated products (Walls D, F, H and N) provide a degree of predictability and efficiency that could possibly offset their cost premiums.
- Wall thickness is an important issue. Even for the test building, thicker walls required more attention to detail at top and bottom and edge connections.
- Energy and cost savings potential is the greatest in cold climates.



Garrett’s Comments

- Cost is, by far, the biggest driver of Adoption Scores. So we need to make exterior retrofits much, much cheaper (prefabrication / materials innovations).
- Air leakage is a tremendously important variable driving energy savings. It unfortunately could not be appropriately measured in this experiment, and systems with similar energy savings in this project could actually differ significantly based on the air tightness improvement. We need to retrofit whole houses to continue that research—any volunteers?

Whew.

Any questions?

Garrett Mosiman
mosi0019@umn.edu

Pacific Northwest National Laboratory

Oak Ridge National Laboratory

University of Minnesota
Driven to Discover℠