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When R-Value Doesn’t Measure Up

NESEA Building Energy10

Building Science Corporation

Outline

- Why R-Values?
- Heat, Temperature & Heat Flow
- Insulating Materials
- Building Enclosure Assemblies
  - Thermal Bridging
  - Air Movement
- The Thermal Metric Research Project

Why Insulate?

- Occupant Comfort
- Energy Savings
- Control surface and interstitial condensation
- Save distribution and plant costs (Capitol)
- Meet Codes and specs – minimum required R-Values

Why R-Values?

- FTC 16 CFR Part 460

  "The R-value Rule specifies substantiation and disclosure requirements for thermal insulation products used in the residential market, and prohibits certain claims unless they are true."

What are R-Values?

- FTC 16 CFR Part 460

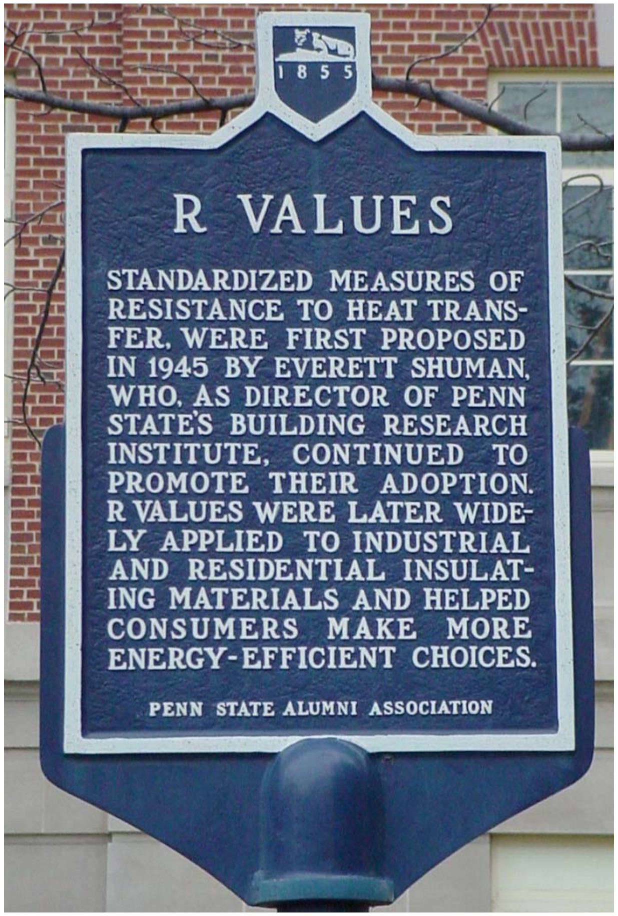
  "R-value is the numerical measure of the ability of an insulation product to restrict the flow of heat and, therefore, to reduce energy costs—the higher the R-value, the better the product's insulating ability."

R-Value

- Proposed in 1945 by Everett Schuman, Penn State's Housing Research Institute

- Property of a material

- Measurement of resistance to heat flow



Heat Flow

- Heat
  - A form of energy
- Temperature
  - A measure of the amount of thermal energy

Form of Energy	Measure
Light	Lux, Lumens
Sound	Decibels
Air Pressure	Pa, in. H20
Heat	°C, °F

- Heat Flow
  - The movement of heat energy from one area to another

Heat Flow

- *Almost always* moves from more to less

- Rate of flow depends on
  - Temperature Difference
  - Material Properties
  - Type & Mode of Heat Flow

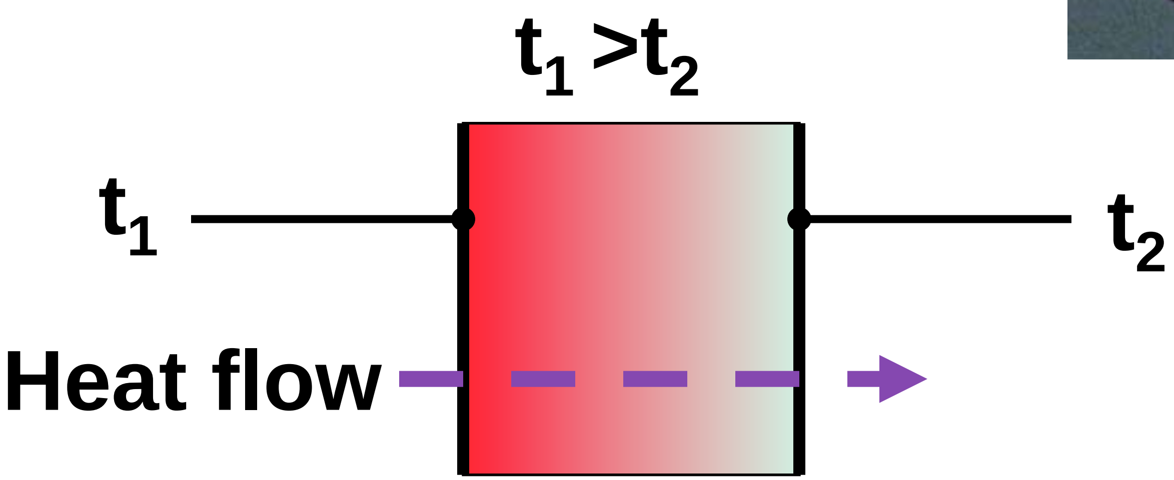
Heat Flow

- Type of Heat flow
  - steady-state or dynamic
  - one-, two- or three-dimensional

- Mode of Heat Flow
  - Conduction
  - Convection
  - Radiation

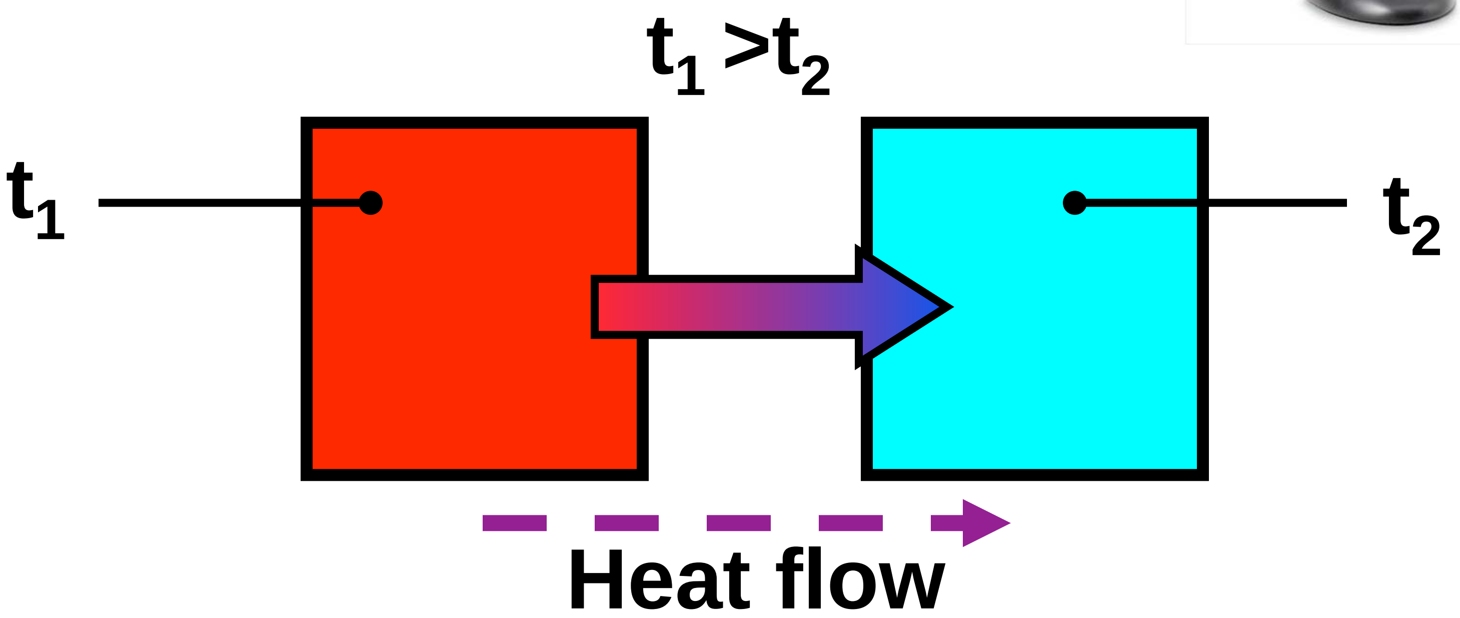
Conduction

- Heat Flow by direct contact
- Vibrating molecules
- Most important for solids
(e.g. holding a bag of ice)



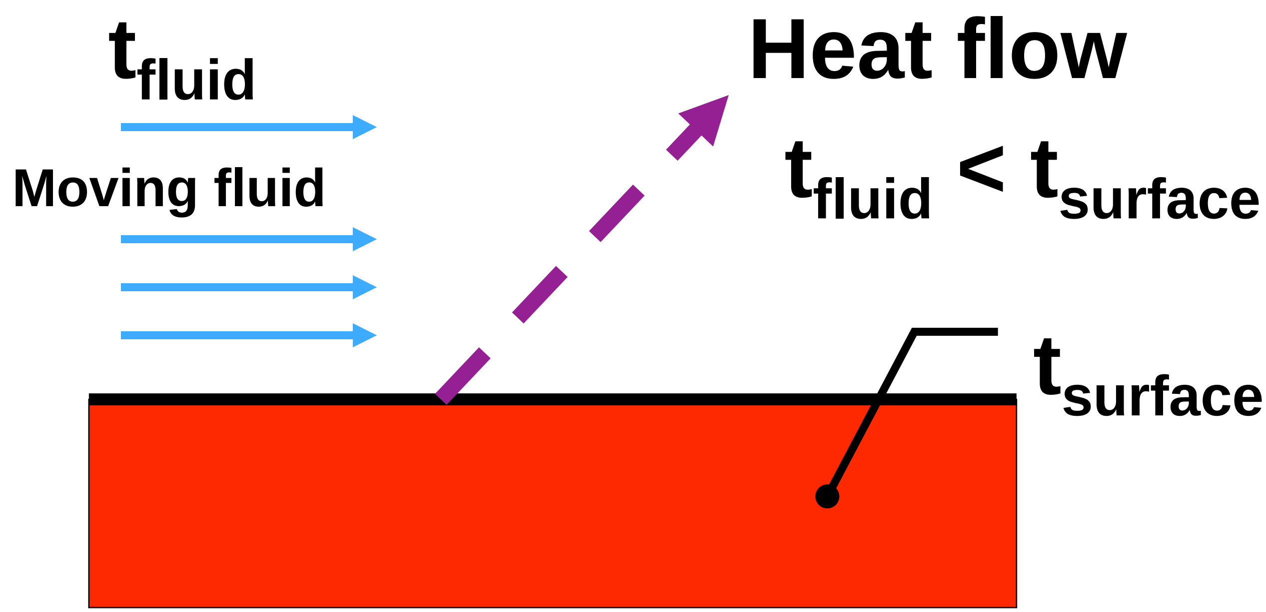
Convection

- Heat Flow by bulk movement of molecules
- Most important for liquids and gases (e.g. air flow forced by fan)



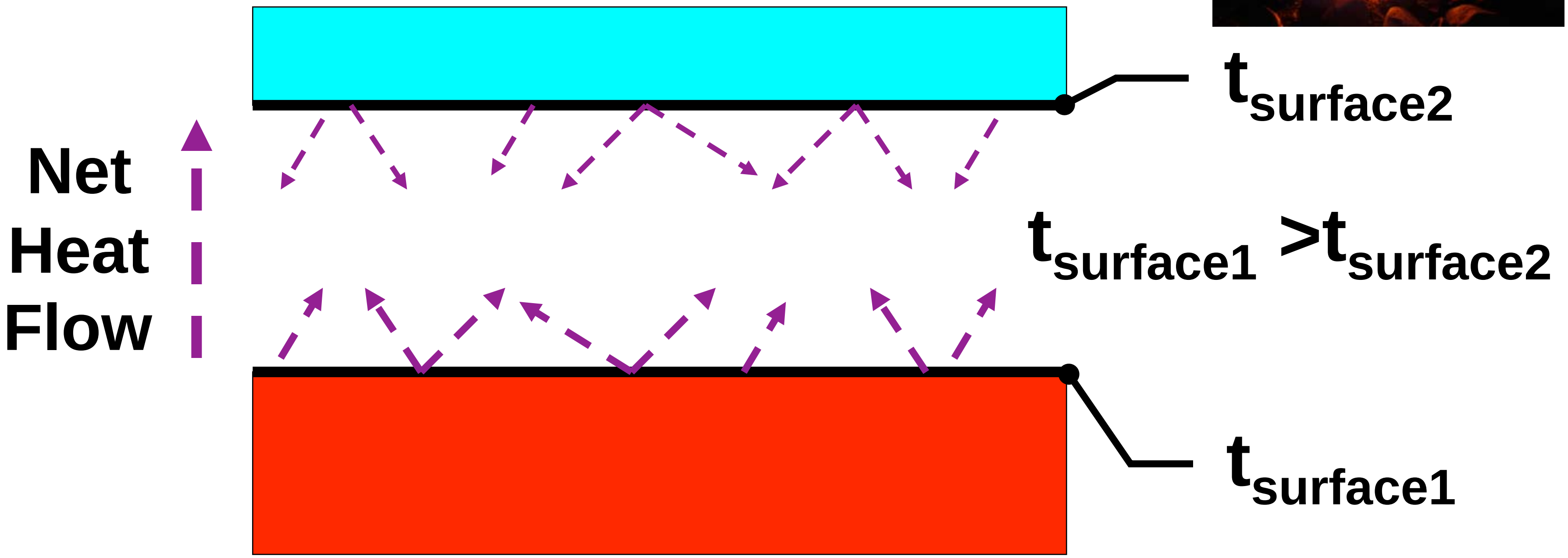
Convection

- Also heat flow from solid to liquid or gas
- Critical for surface heat transfer (e.g. radiators)



Radiation

- Heat flow by electromagnetic waves
- Heat radiates from *all* materials (e.g. campfire)
- Passes through gases & vacuum (*not* solids)

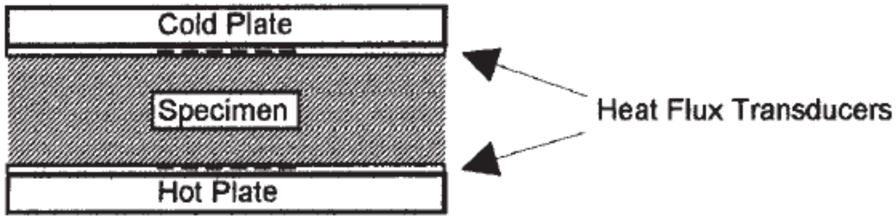


Radiation

- Important for surfaces, air spaces, voids
- Foil faced insulation, radiant barriers only work when facing an air space
- Radiation within *pores* important for high void insulation (e.g., glass batt)
- e.g. Thermos bottle

Measuring R-Values: ASTM C518

- Conductivity Machine

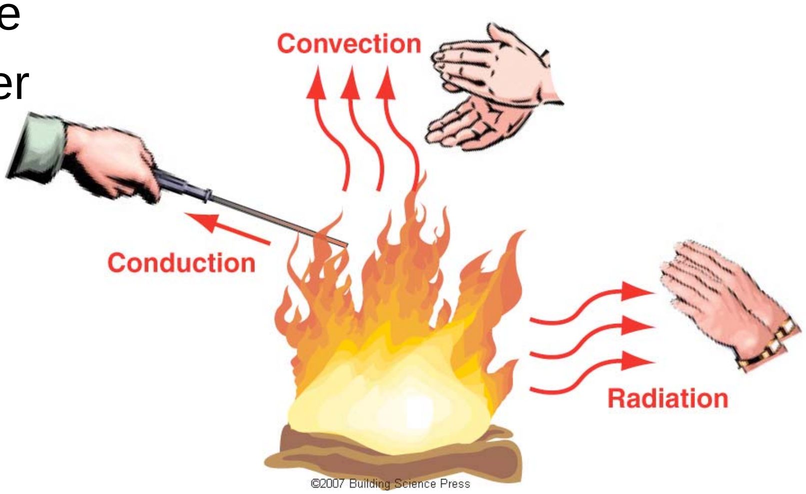


- Known Area & Temperatures
  - typically 12x12 or 24x24 in.
  - mean 75F, cold side 50-55F, hot side 95-100F
- Measure Heat Flow
- Calculate

$$R - Value = \frac{Temp\ Diff}{Area \times Heat\ Flow}$$

Benefits of R-Value

- Widely Accepted
  - FTC Regulation
- Simple to Measure
  - Material property
  - Commercially available test machines
- Easy to Communicate
  - ONE Number at standard temperature
  - Lumps all three modes of heat transfer into an *effective* conductivity
    - Conduction
    - Convection
    - Radiation



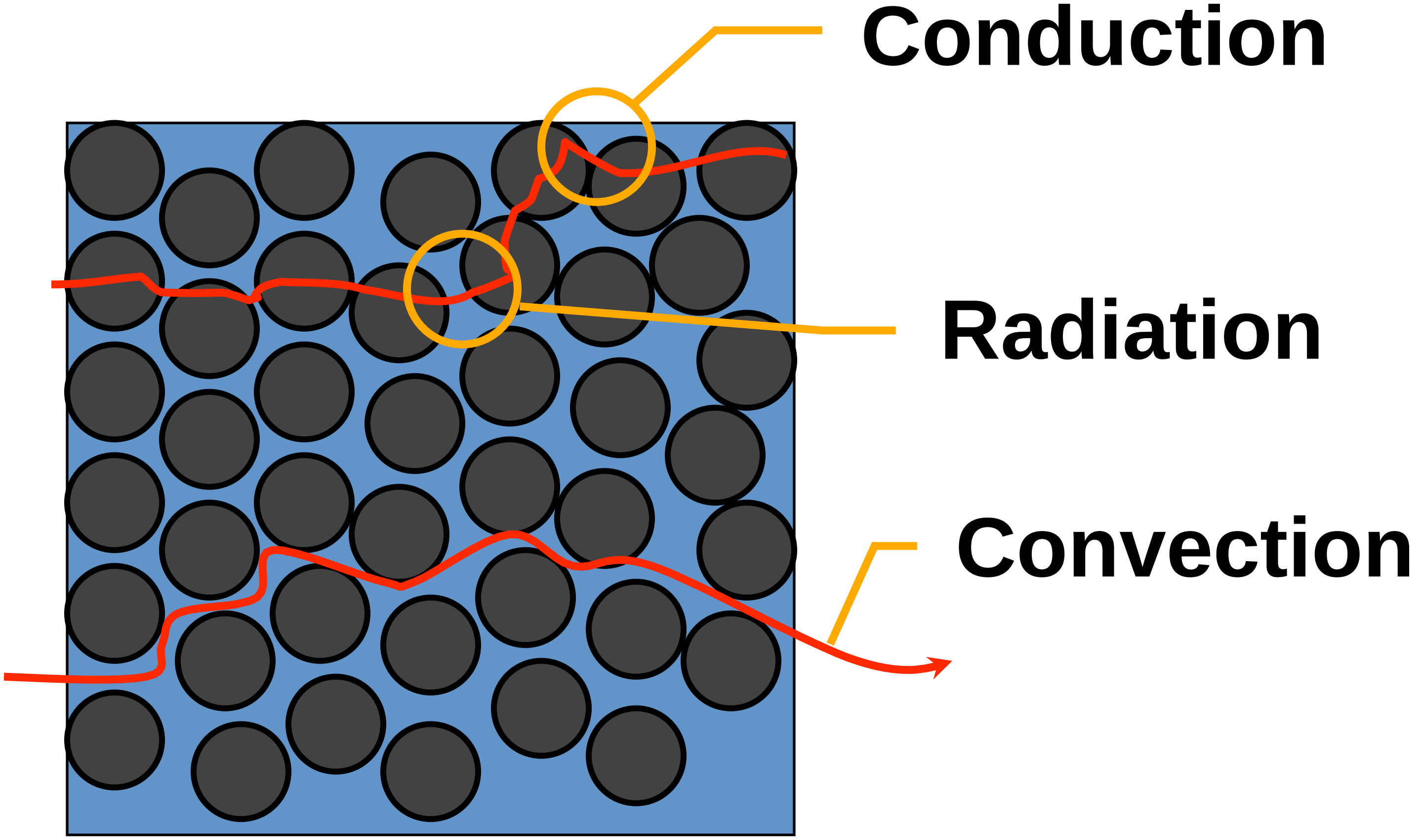
Limitations of R-Value

- Definition implies that R-Value is inverse of thermal conductivity
  - R = thickness / conductivity
- Only true if
  - *Effective* conductivity is constant
  - Material is homogenous
  - No temperature or airflow sensitivity
- Reasonable for *some* materials but probably not for real building assemblies under real conditions

Materials

- Thermal conductivity (& resistance) varies with
  - material type (conduction, radiation)
  - density and pore structure
  - moisture content
  - temperature difference
- Combination of insulation of air + material
- *Still* air is about R6/inch
- Only gas fills (e.g. HCFC) can improve this

Materials



Hypothetical porous material

Fiberglass Insulation

- Little material
- Lots of interconnected voids
- Little surface area

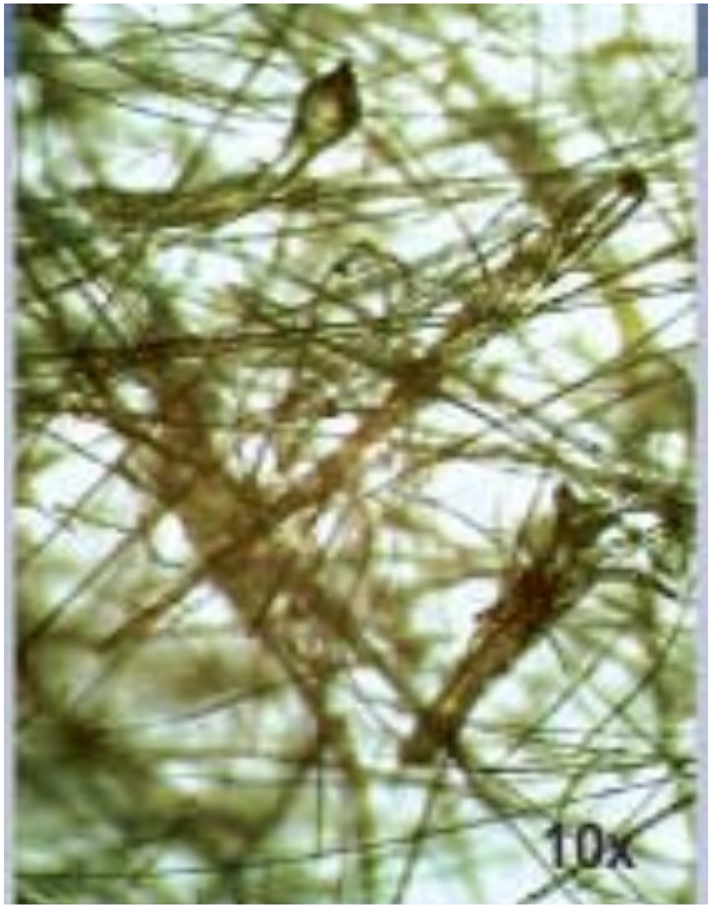


Photo: www.thermapan.com

Expanded Polystyrene (EPS)

- Little material
- Some interconnected voids
- Lots of surface area

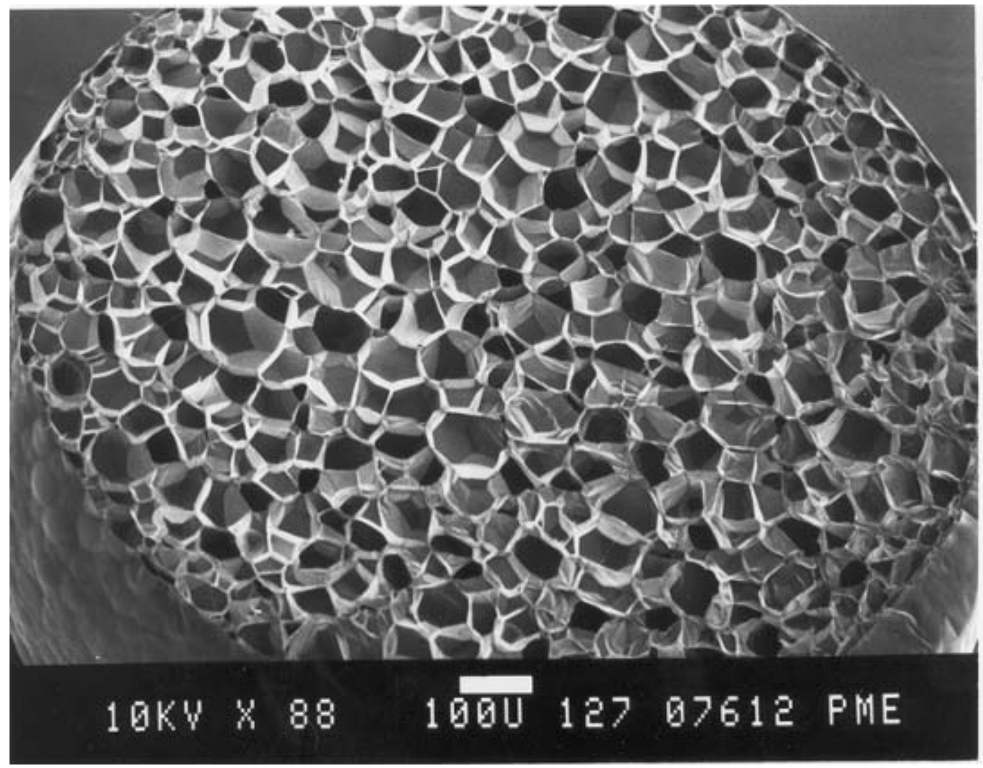


Photo: www.styreneproducts.com

Open Cell Polyurethane Foam (0.5lb ocSPF)

- More material
- Many interconnected voids
- Lots of surface area

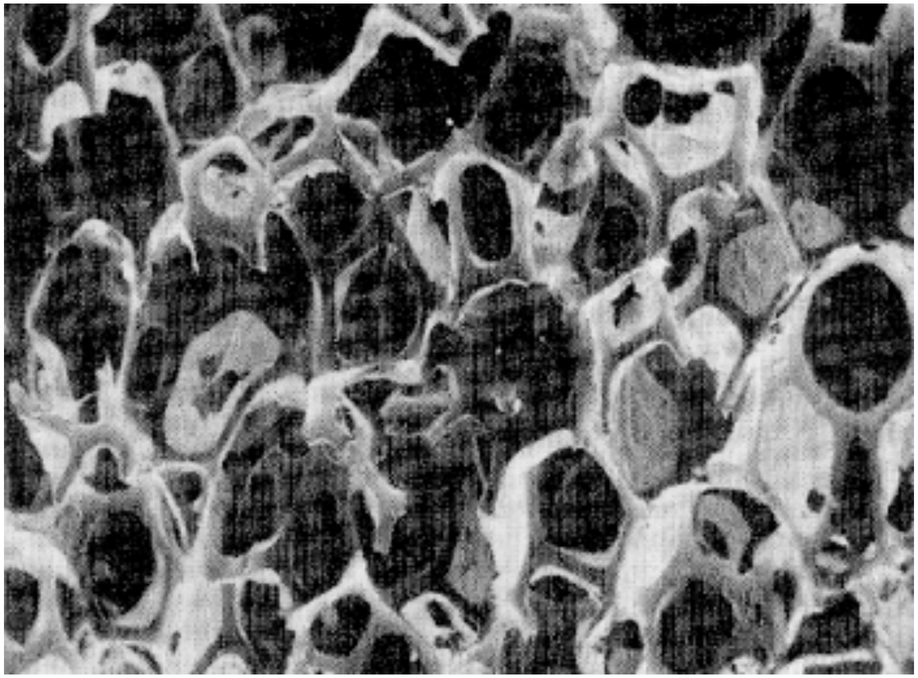


Photo: NRC-IRC

Closed Cell Polyurethane Foam (2lb ccSPF)

- More material
- Few interconnected voids
- Lots of surface area

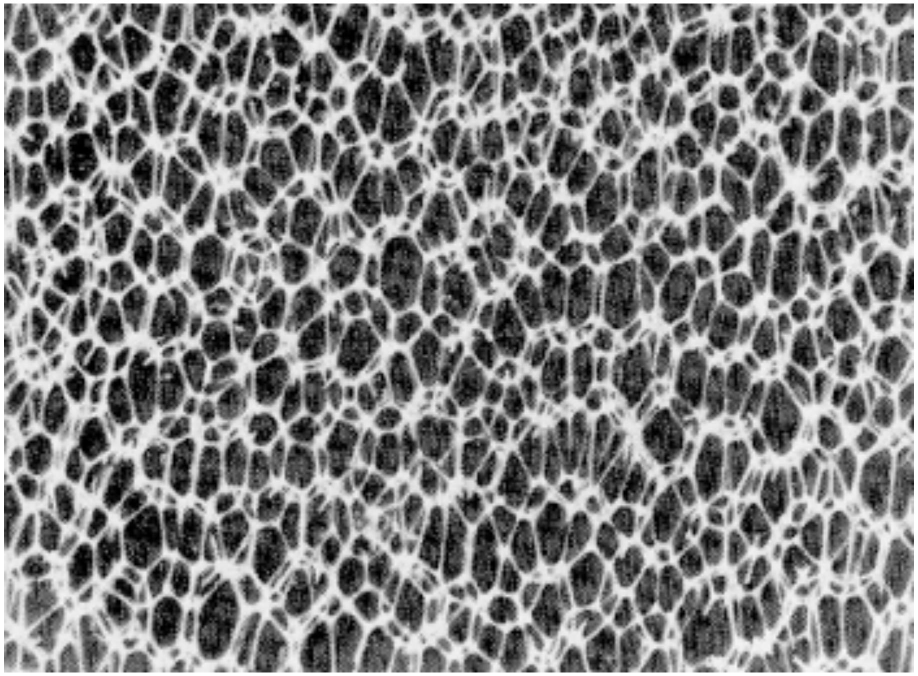


Photo: NRC-IRC

Phenolic Foam

- More material
- Few interconnected voids
- Lots of surface area

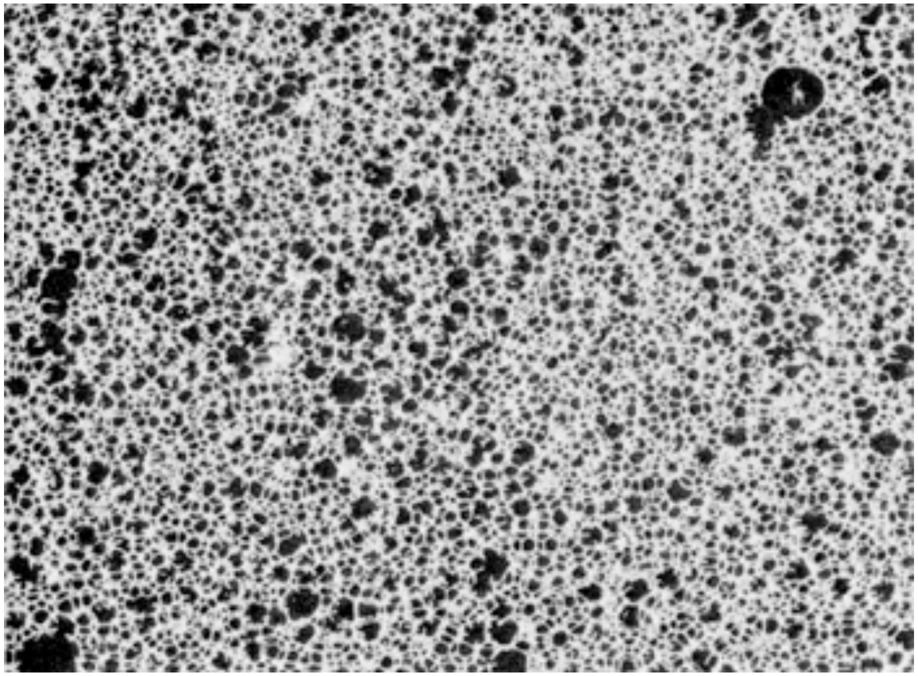
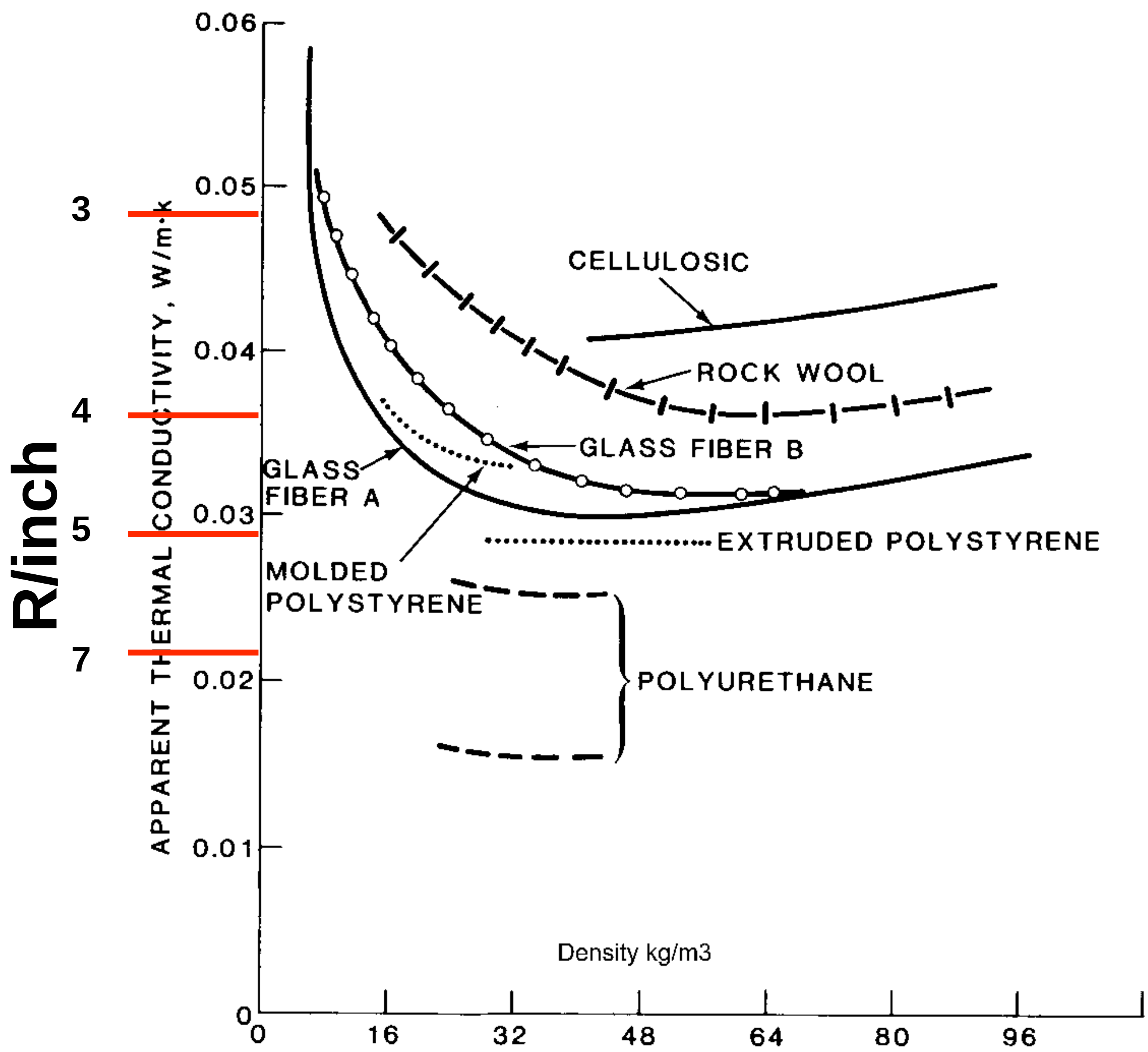


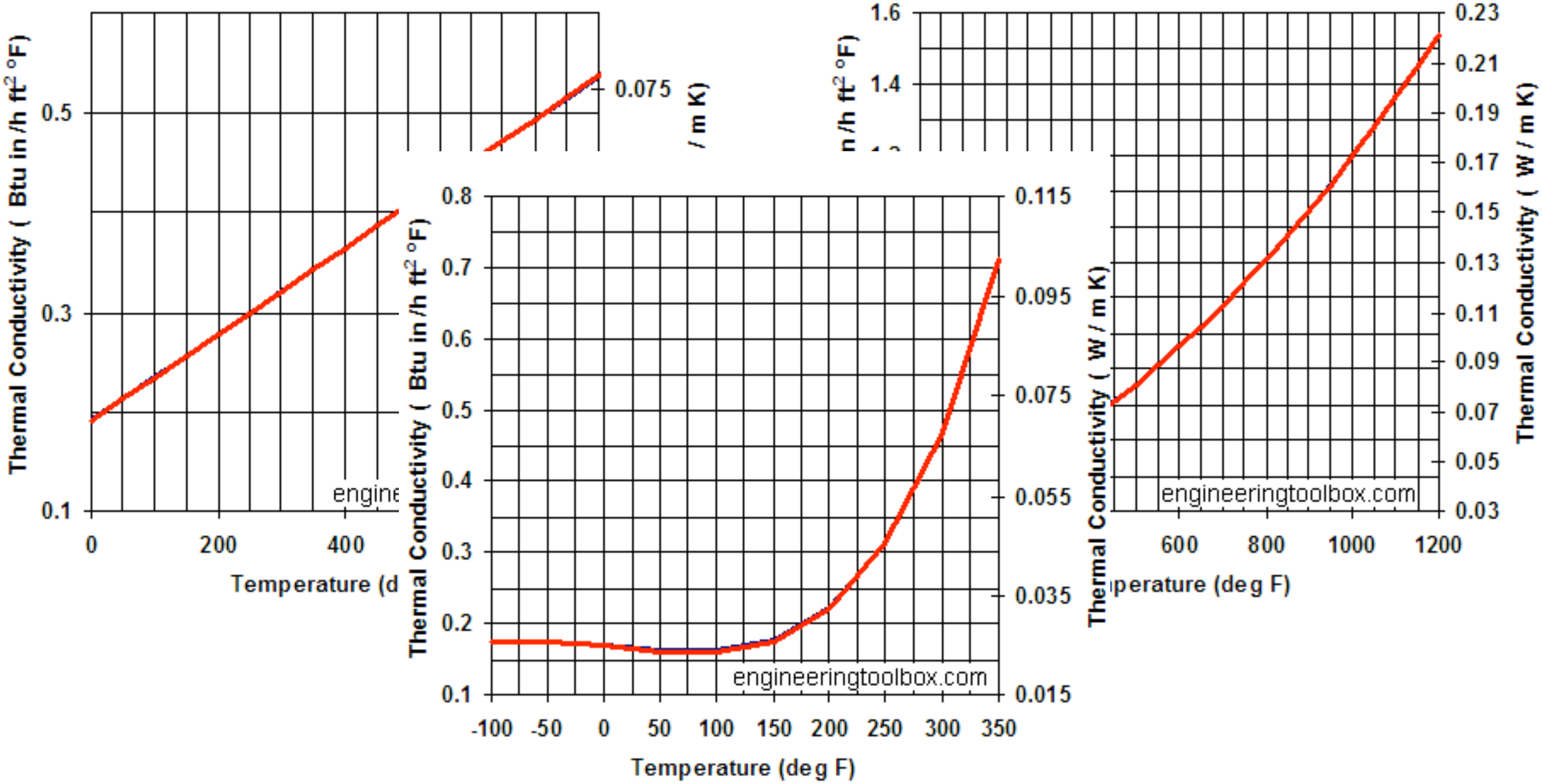
Photo: NRC-IRC

R-Value vs Material Density

- High conductivity and high density
  - e.g. wood R1/inch and 45 pcf
  - versus concrete R0.1/inch and 140 pcf
- Low conductivity and low density
  - e.g. glass batt R3.5/inch and 1 pcf
- Compromise
  - cellulose, R3.5/inch and 3 pcf

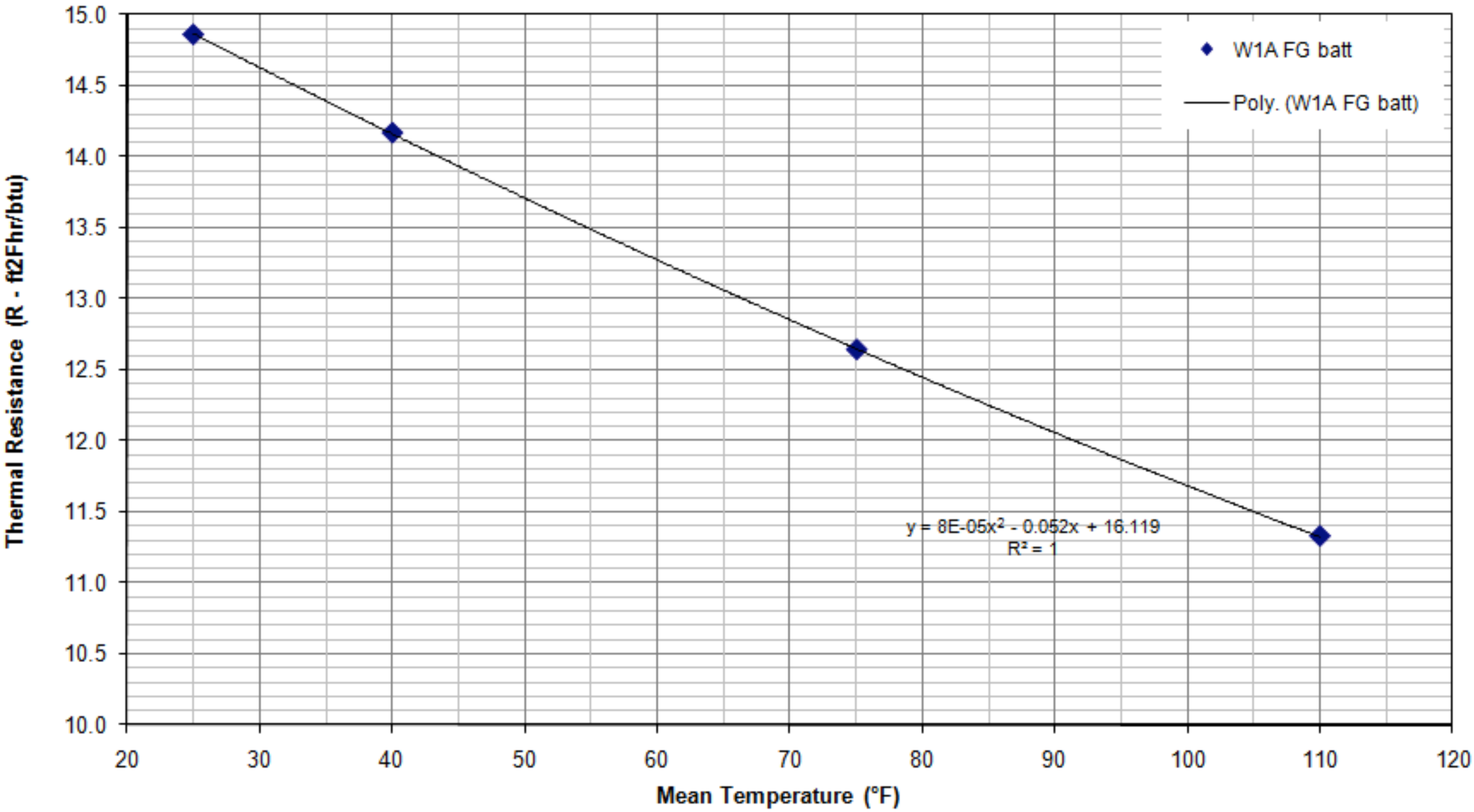

R/inch
3
4
5
7
APPARENT THERMAL CONDUCTIVITY, W/m·k
0.06
0.05
0.04
0.03
0.02
0.01
0
CELLULOSIC
ROCK WOOL
GLASS FIBER B
GLASS FIBER A
EXTRUDED POLYSTYRENE
MOLDED POLYSTYRENE
POLYURETHANE
Density kg/m3
0
16
32
48
64
80
96

R-value vs temperature

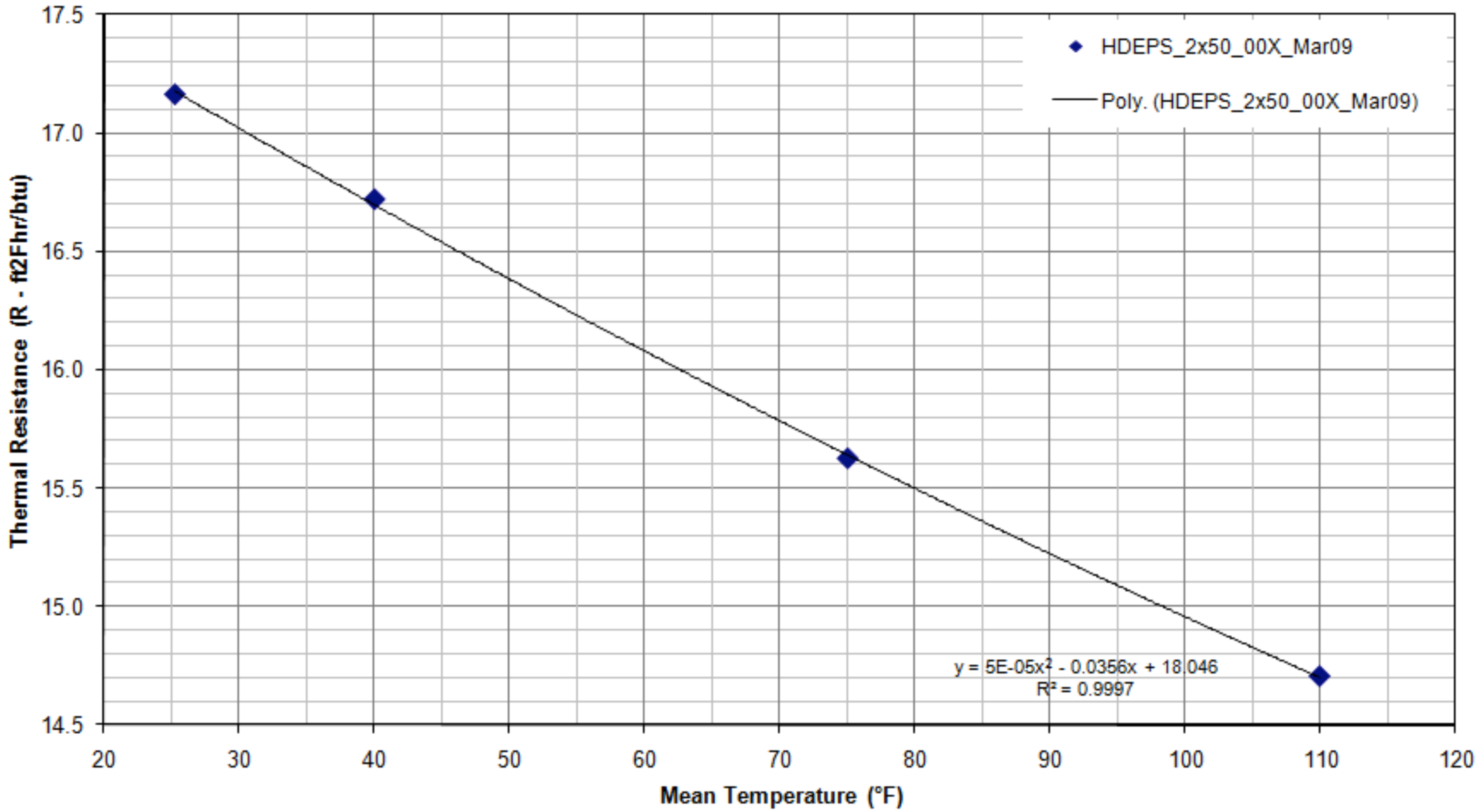


Some R-Value Measurements…

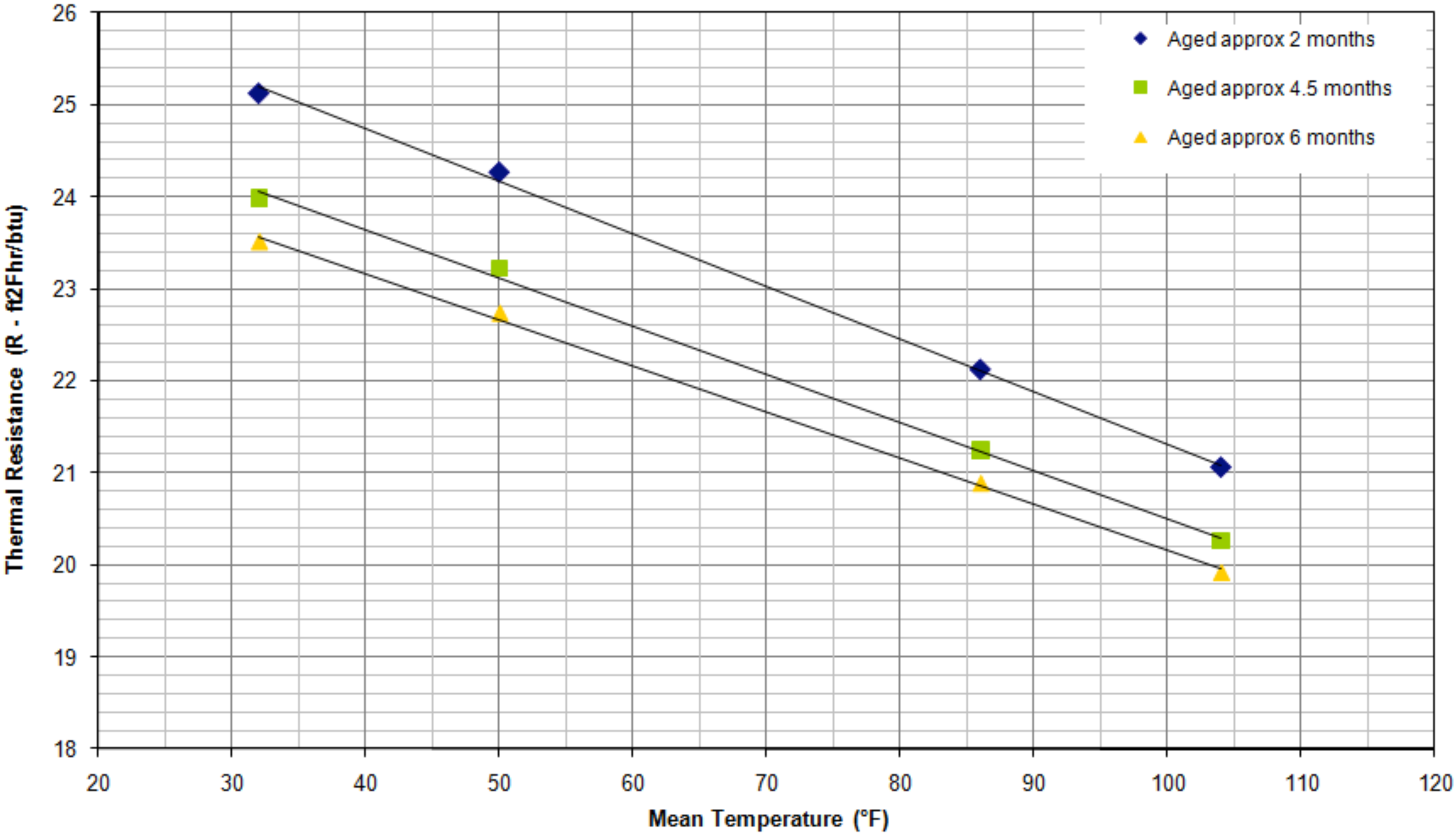
R13 Fiberglass Batt



R16 High Density EPS



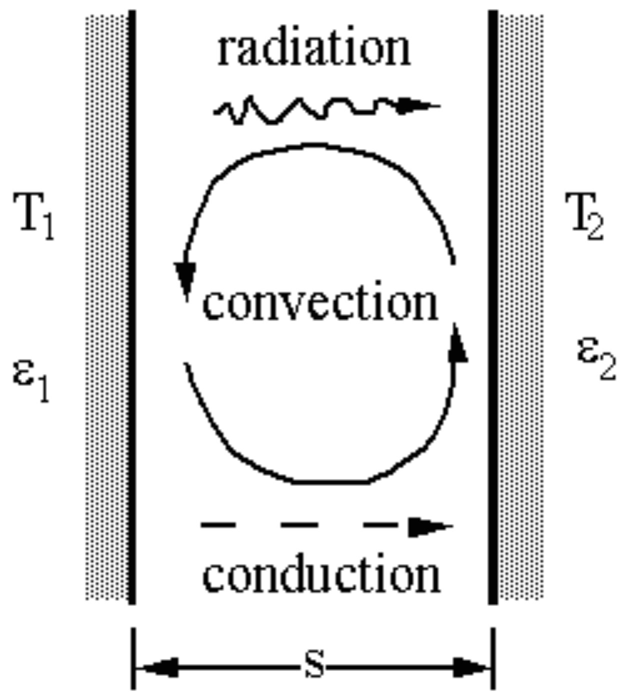
R20 XPS



Aged approx 2 months
Aged approx 4.5 months
Aged approx 6 months
Thermal Resistance (R - ft2Fhr/btu)
Mean Temperature (°F)
26
25
24
23
22
21
20
19
18
20
30
40
50
60
70
80
90
100
110
120

Air Spaces & Surface Films

- All 3 modes of heat transfer play a role
- The effects are lumped into a coefficient, **h_o** , which can be used in the conduction equation as an ***effective conductance***



Air Spaces

Situation (non reflective surfaces)	RSI Value	R Value
Heat Flow Down 20-100 mm (3/4 to 4 in.)	0.18	1.0
Heat Flow Across 20-100 mm (3/4 to 4 in.)	0.17	0.97
Heat Flow Up 20-100 mm (3/4 to 4 in.)	0.15	0.85

Surface Films

Surface Position	Flow Direction	RSI [m²K/W]	R [ft²Fhr/btu]
Still Air (e.g. indoors)			
Horizontal (i.e. ceilings & floors)	Upward	0.11	0.62
	Downward	0.16	0.91
Vertical (i.e. walls)	Horizontal	0.12	0.68
Moving Air (e.g. outdoors)			
Stormy 6.7m/s (winter)	Any	0.03	0.17
Breeze 3.4m/s (summer)	Any	0.04	0.23
Average Conditions	Any	0.06	0.34

Building Enclosure Assemblies

- Building enclosures are typically assemblies of several layers of different materials
- The overall resistance must be calculated

$$R_{tot} = R_1 + R_2 + R_3 \ldots$$

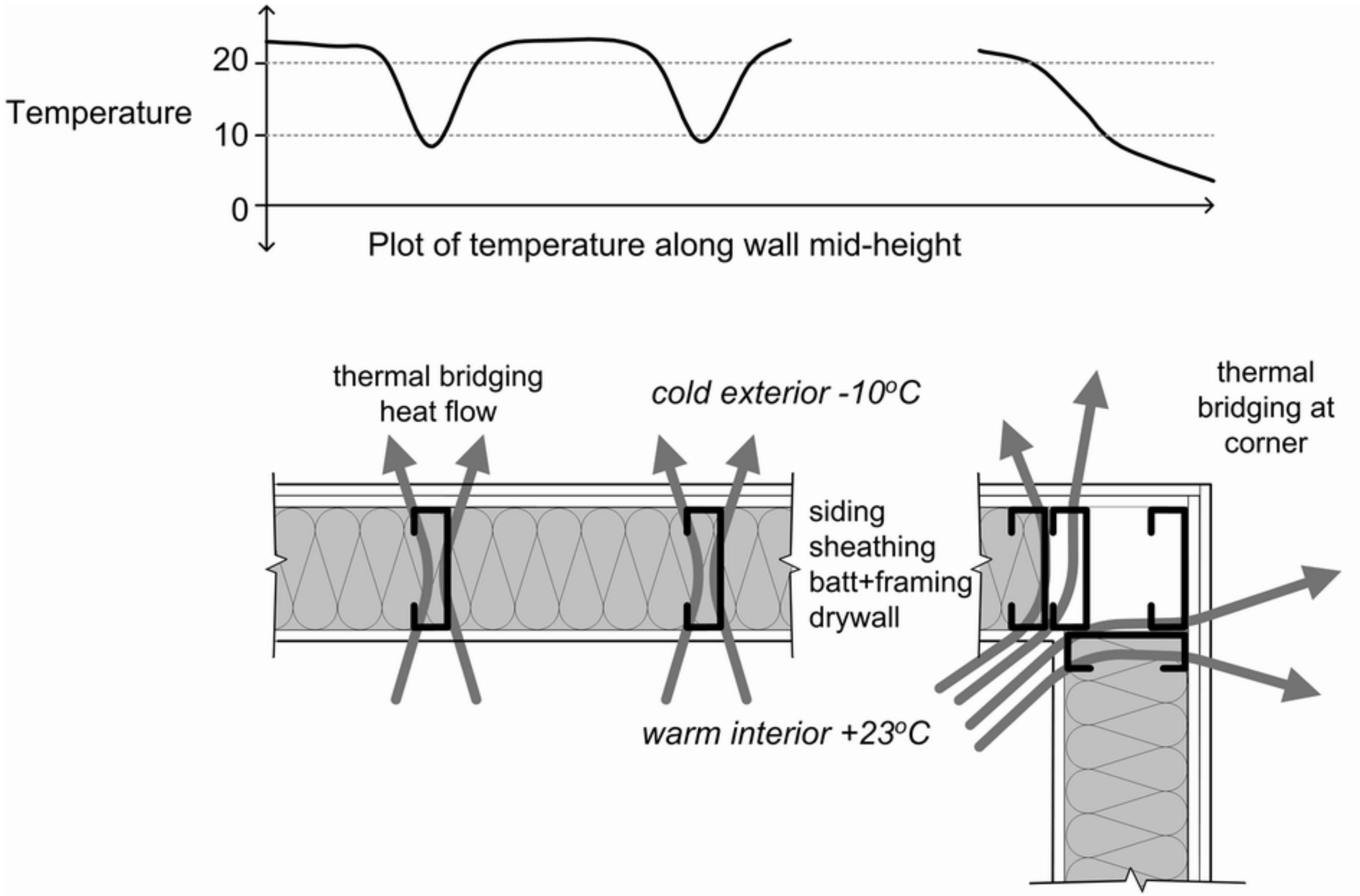
- The conductance of the assembly is then

$$U = 1/R_{tot}$$

But There Are Complications…

- Material properties change over time
  - Diffusion of blowing agents
  - Shrinking
  - Settling
- Real Weather Conditions
  - Temperature
  - Moisture
- Thermal bridges
- Air movement
- Thermal mass (Not going to deal with this today…)

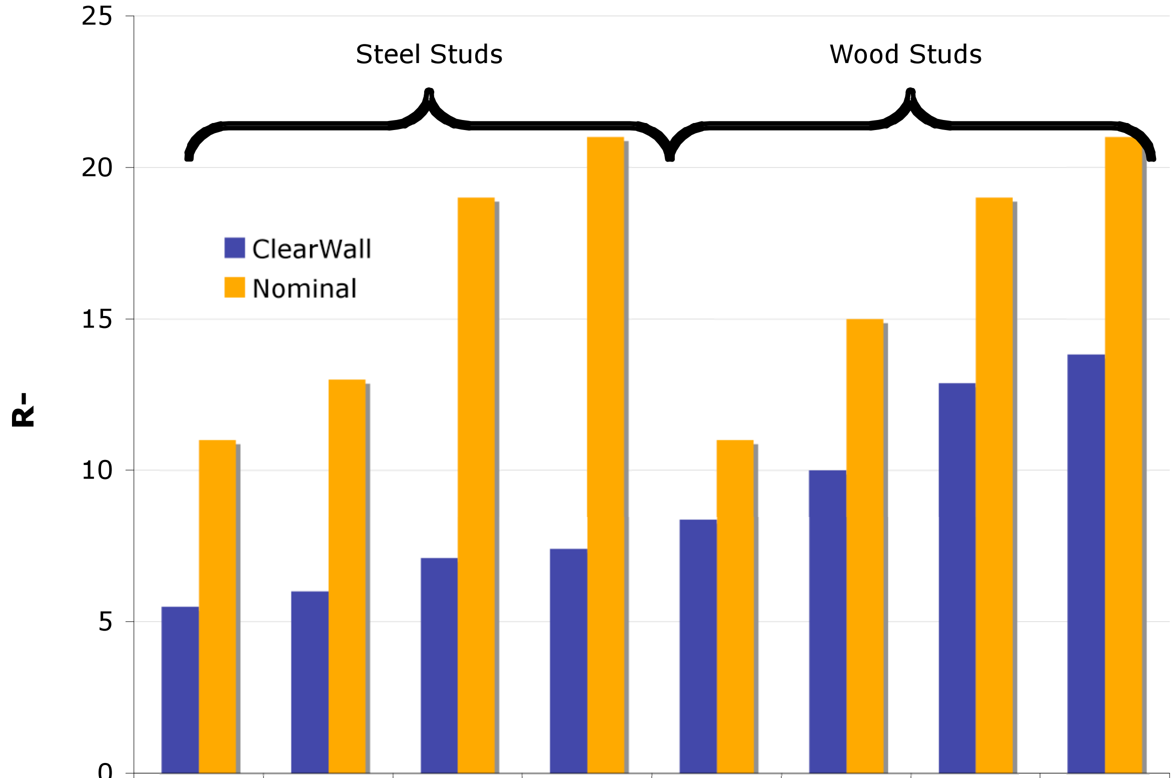
Thermal Bridging



Thermal Bridging

- Heat is ‘bridged’ across insulation
- Impact higher as R-Value of insulation in stud space increases
- Issues related to cold spots
  - Thermal comfort
  - Aesthetic
  - Durability
- Potential energy issue if
  - Large enough area
  - Intense enough flow (high conductivity)
  - Frequent enough

Energy Impact of Thermal Bridging



	R-11 3.5in	R-13 3.5in	R-19 6in	R-21 6in	R-11 3.5in	R-15 3.5in	R-19 6in	R-21 6in
ClearWall	5.5	6.0	7.1	7.4	8.4	10.0	12.9	13.8
Nominal	11	13	19	21	11	15	19	21

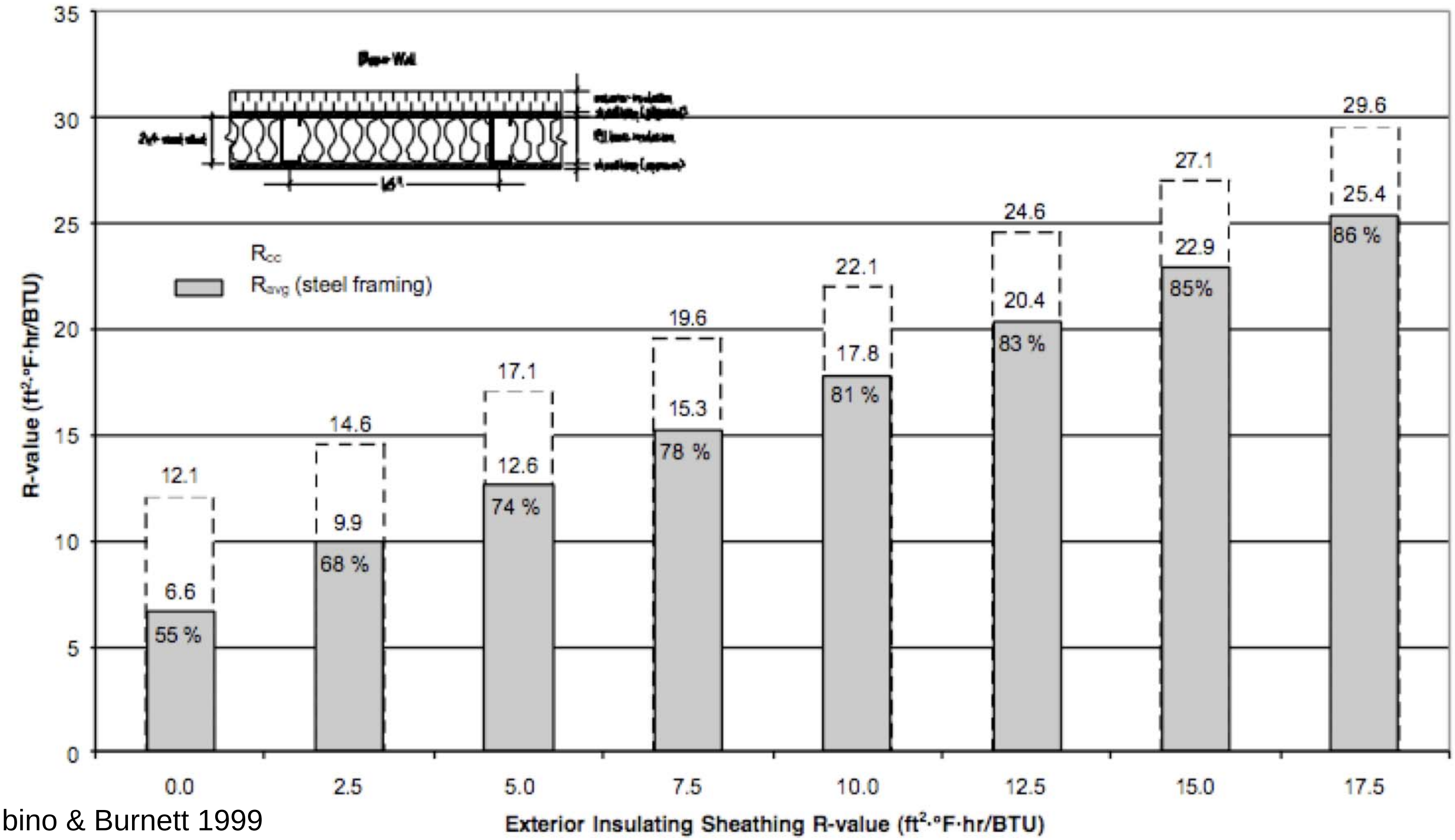
But the Energy Impact May be Worse!

- Energy codes usually define thermal performance using clear wall R-Values
- 2x framed wall @ 16” O/C has a framing factor of ~9.4%

- Houses have become more complicated
- ASHRAE Framing Factor Study suggests that framing factor could be as high as 25%!

Mitigating Thermal Bridges

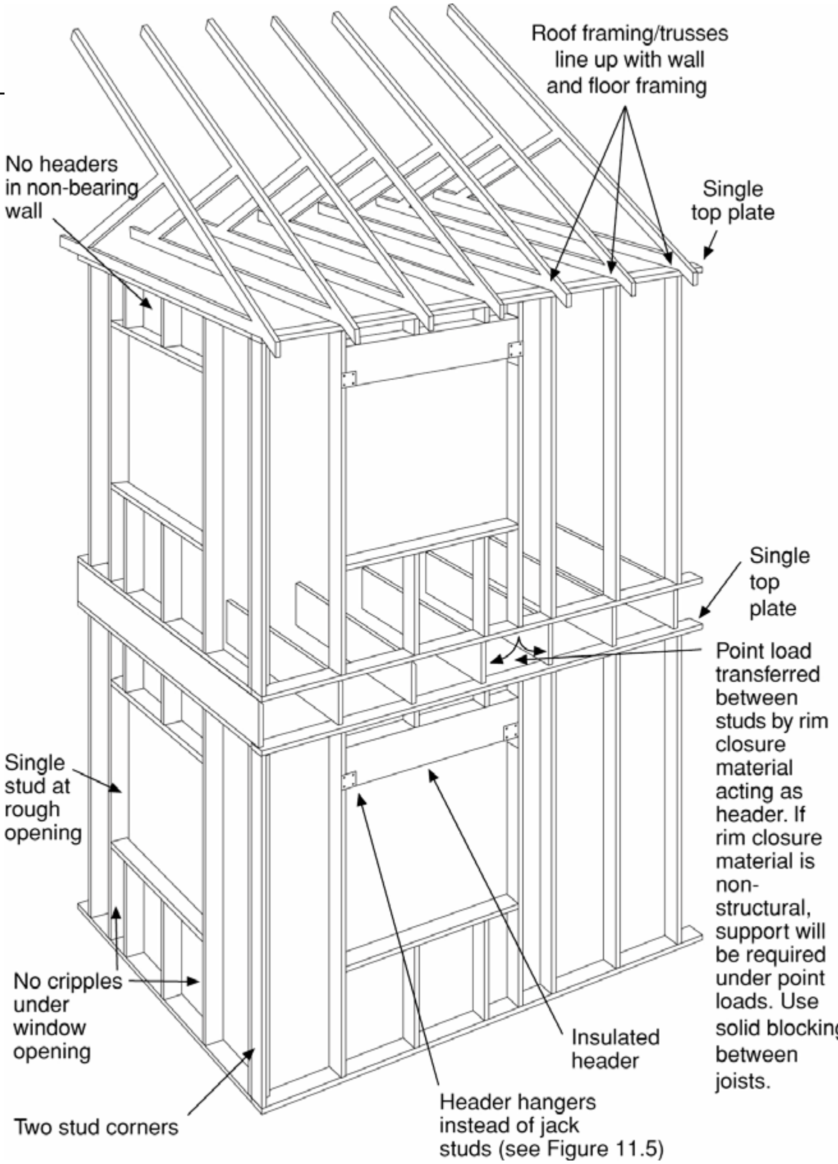
- Exterior Insulation



Bombino & Burnett 1999

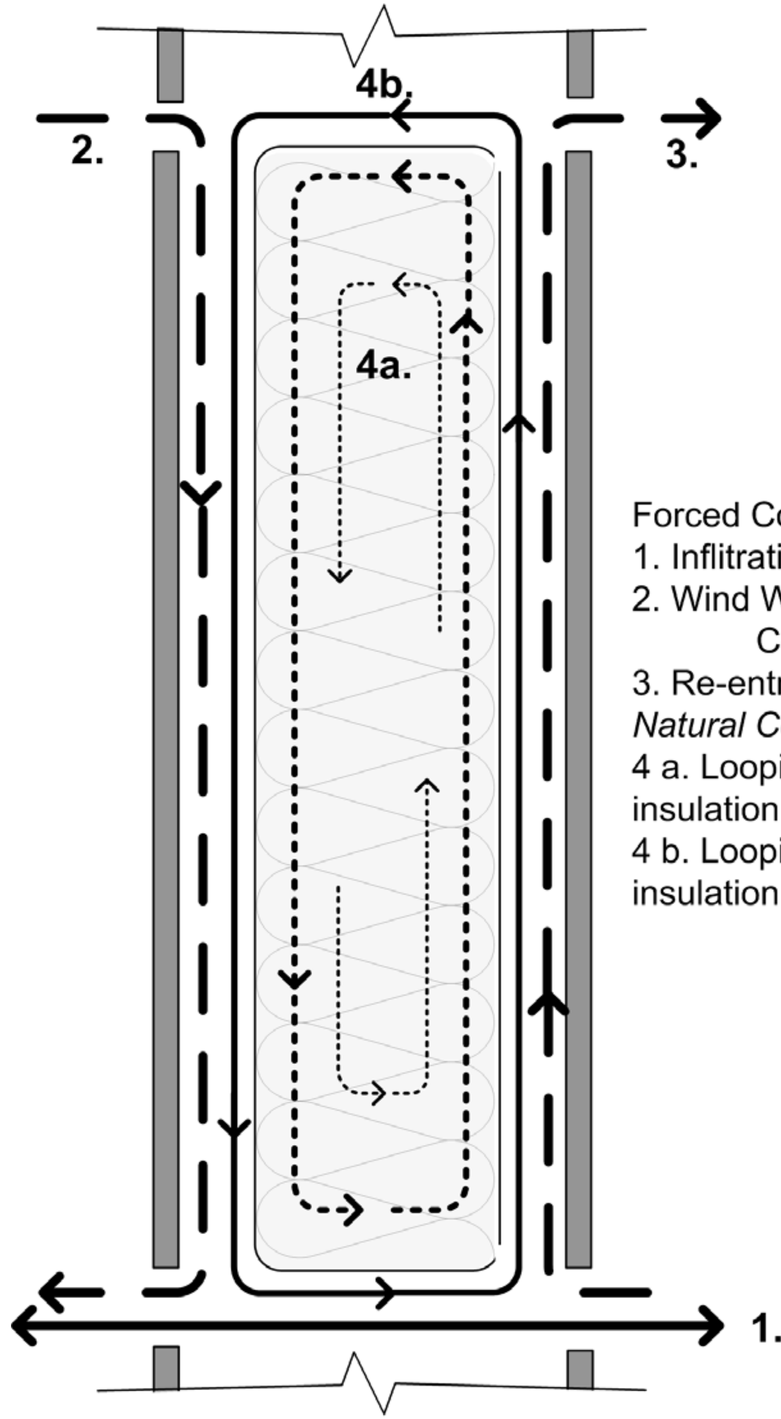
Mitigating Thermal Bridges

- Simplify Geometry
- Advanced Framing



Airflow

- Air Leakage is only part of the picture



Forced Convection
1. Inflitration / Exfiltration
2. Wind Washing (Forced Convection)
3. Re-entrant Loop

Natural Convection

4 a. Looping in air permeable insulation

4 b. Looping through gaps around insulation

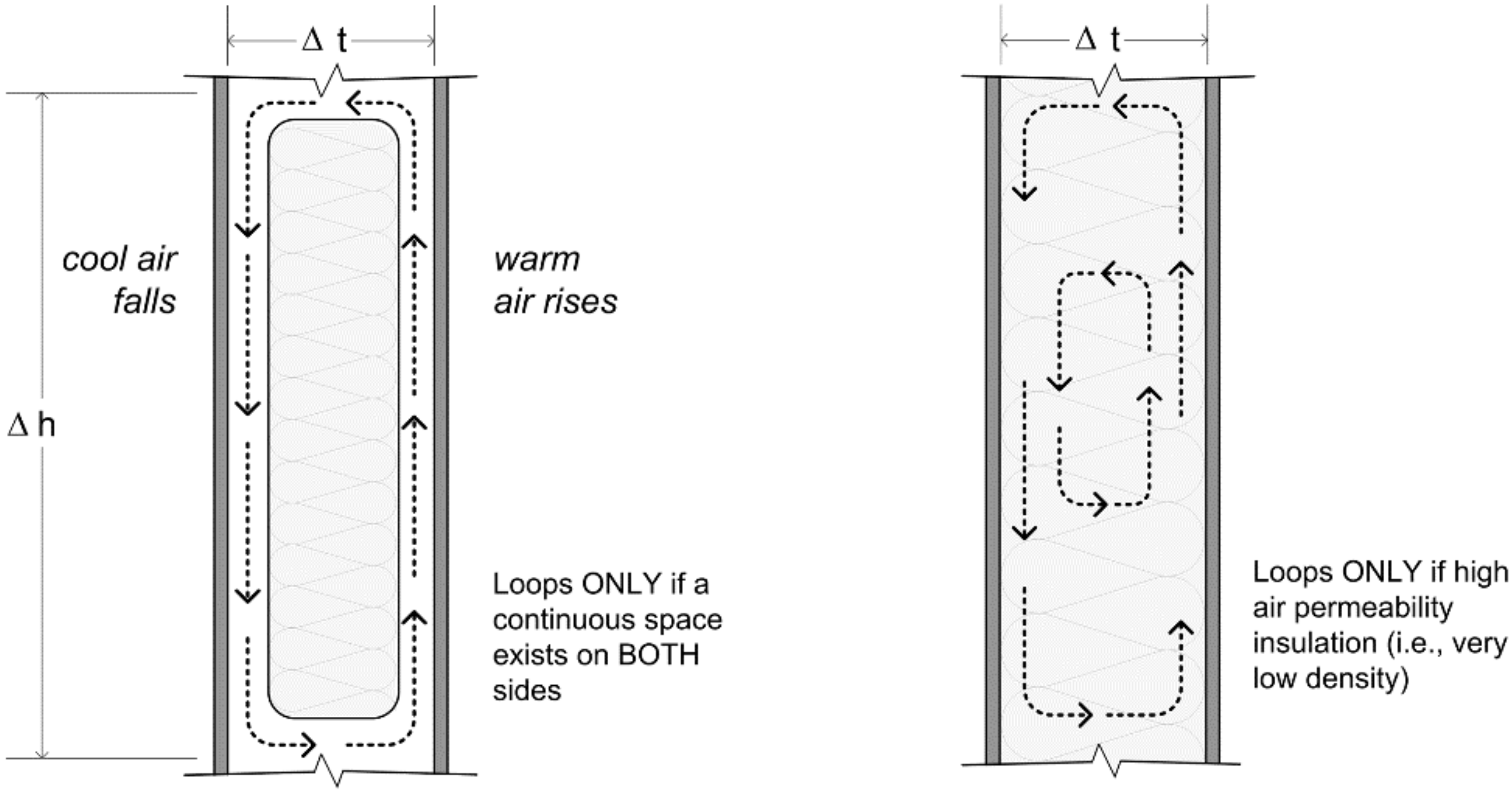
Air Leakage

- Can be easily measured (e.g. blower door)
- Path is rarely straight through

- Energy Impact:
  - Building America requires max air leakage of 1.65 lps/m²@75Pa so associated heat loss would be 0.18 W/m²C (0.031 Btuh/ft²F)
  - For an R20 wall, the nominal conducted heat loss would be 0.28 W/m²C (0.050 Btuh/ft²F)
  - If we ignore thermal bridging & other effects the total heat flow is 160% of expected (i.e. the wall acts like ~R12)

- Real impact hard to determine because of interaction between conductive & convective heat flow (Yarborough & Graves 2006)

Convective Loops

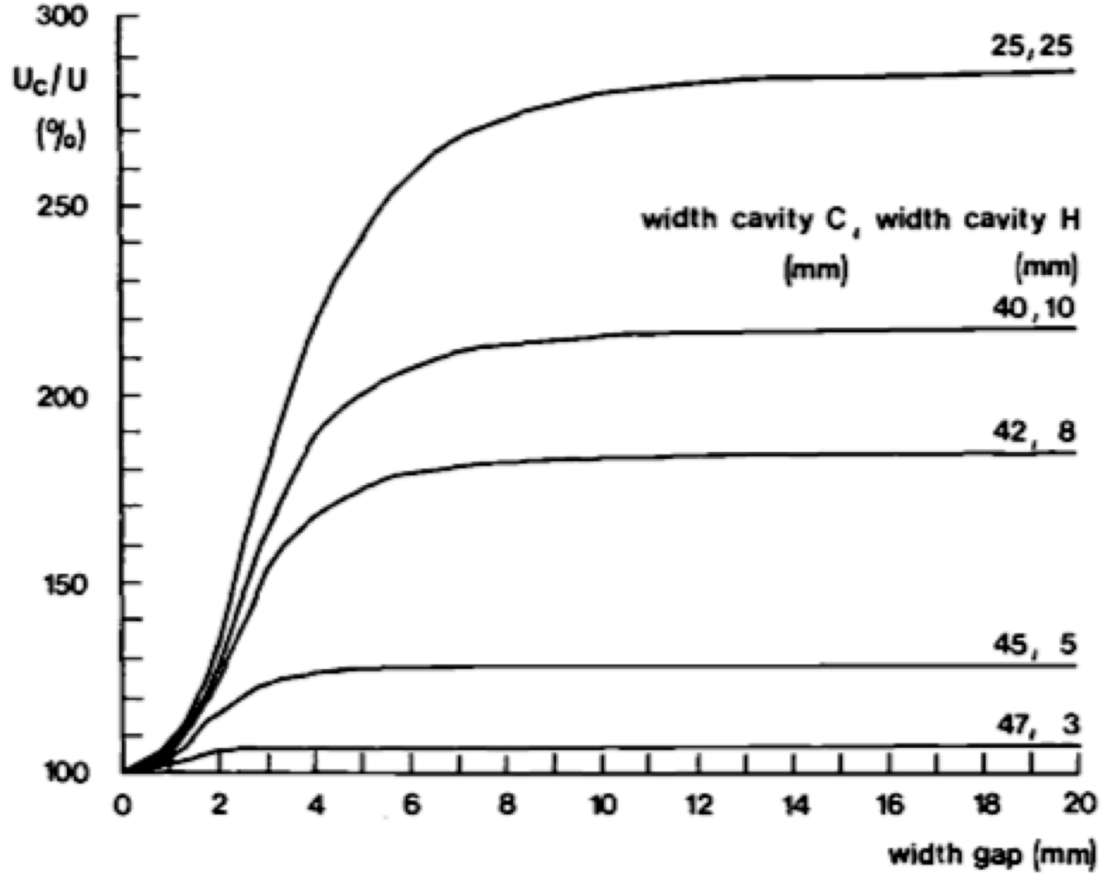


A: Air Loops Around Insulation

B: Air Loops Through Insulation

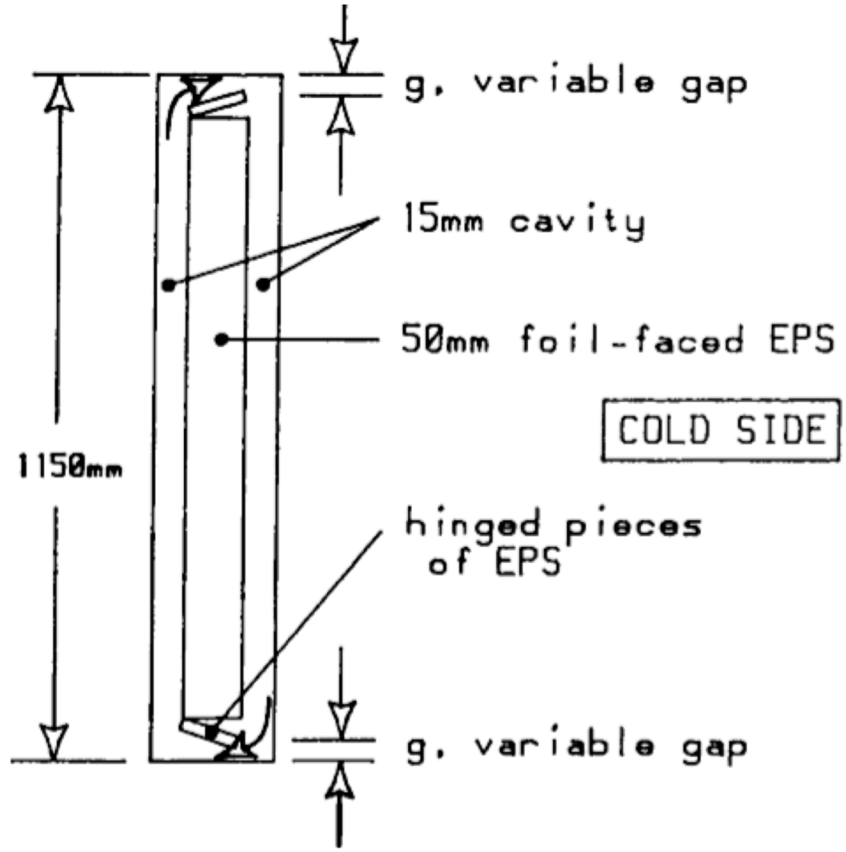
Convective Loops

- 25% reduction in R-Value measured for 3/16" (5mm) gap between insulation & sheathing / backup (Lacompte 1991)



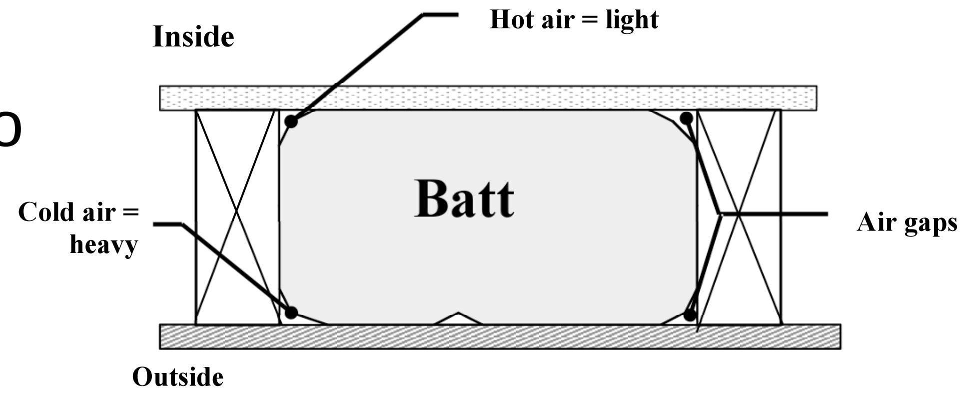
Convective Loops

- 50% reduction in thermal performance for 5/8" (15mm) gap front & back and 1/8" (3mm) gap top & bottom
  (Trethewen 1991)

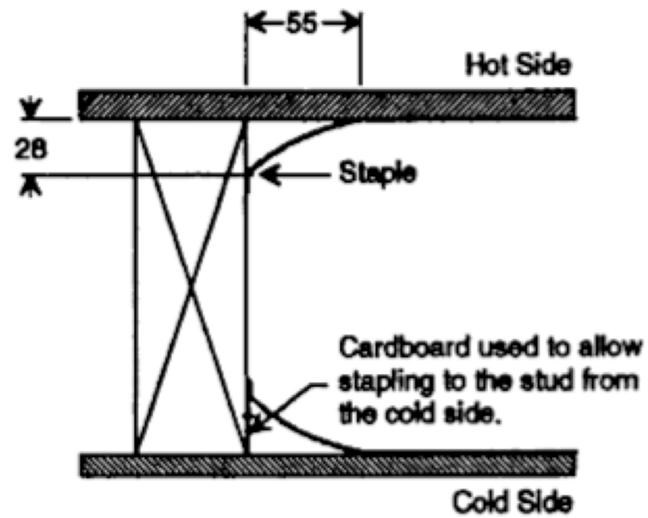


Convective Loops

- Gaps in the corners can allow convective loops to bypass heat around the insulation

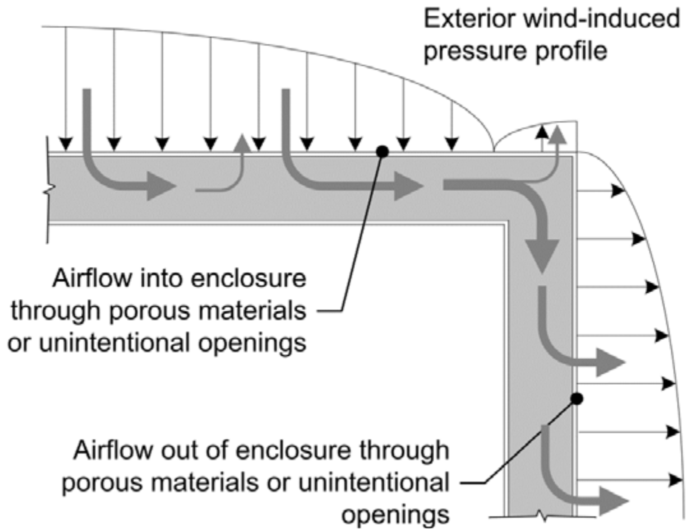


- Measurements suggest a possible 25-33% reduction in R-Value (Bomberg & Brown 2003)



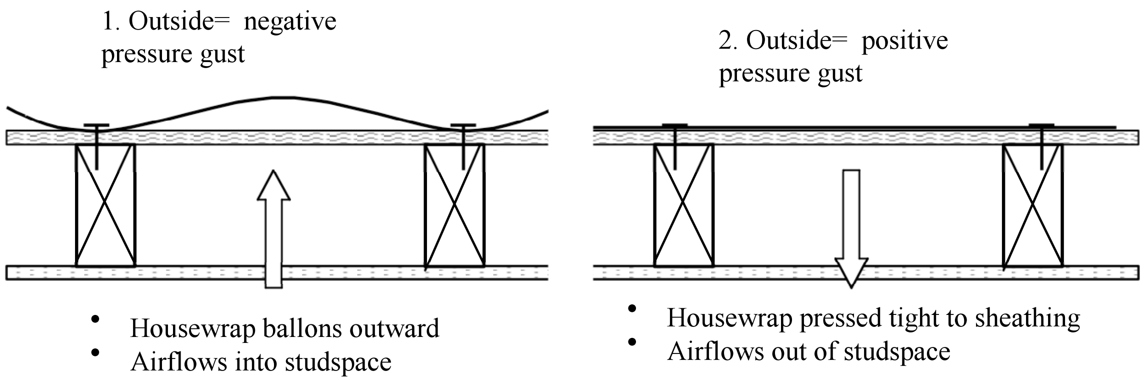
Wind Washing

- Wind can easily generate pressure differences of >10Pa
- Outdoor air is driven into, through the wall and back out
- Increase heat flow 10-30% depending on wind speed
  (Uvloskk 1996)



Wind Pumping

- Deflection of WRB draws indoor air through wall and pushes it back indoors
- Observed in the field but never measured



Controlling Heat Loss due to Airflow

- Install & commission (i.e. measure & address leaks) either:
  - Air Barrier IN & Wind Washing Barrier OUT
  - Air Barrier OUT & Secondary Air Barrier IN
- When using air permeable insulation make sure density is high enough to prevent internal convective looping
- Ensure that insulation is installed tight against at least one side (preferably both) of an insulated cavity
- Avoid gaps at top and bottom of insulation

Summary

- R-Value is a material property that quantifies resistance to heat flow for specific conditions
- Reasonable for materials but probably not real building assemblies under real conditions
- Heat flow in assemblies is complicated by
  - Material properties change over time
  - Real Weather Conditions
  - Thermal bridges
  - Air movement

The Thermal Metric Research Project

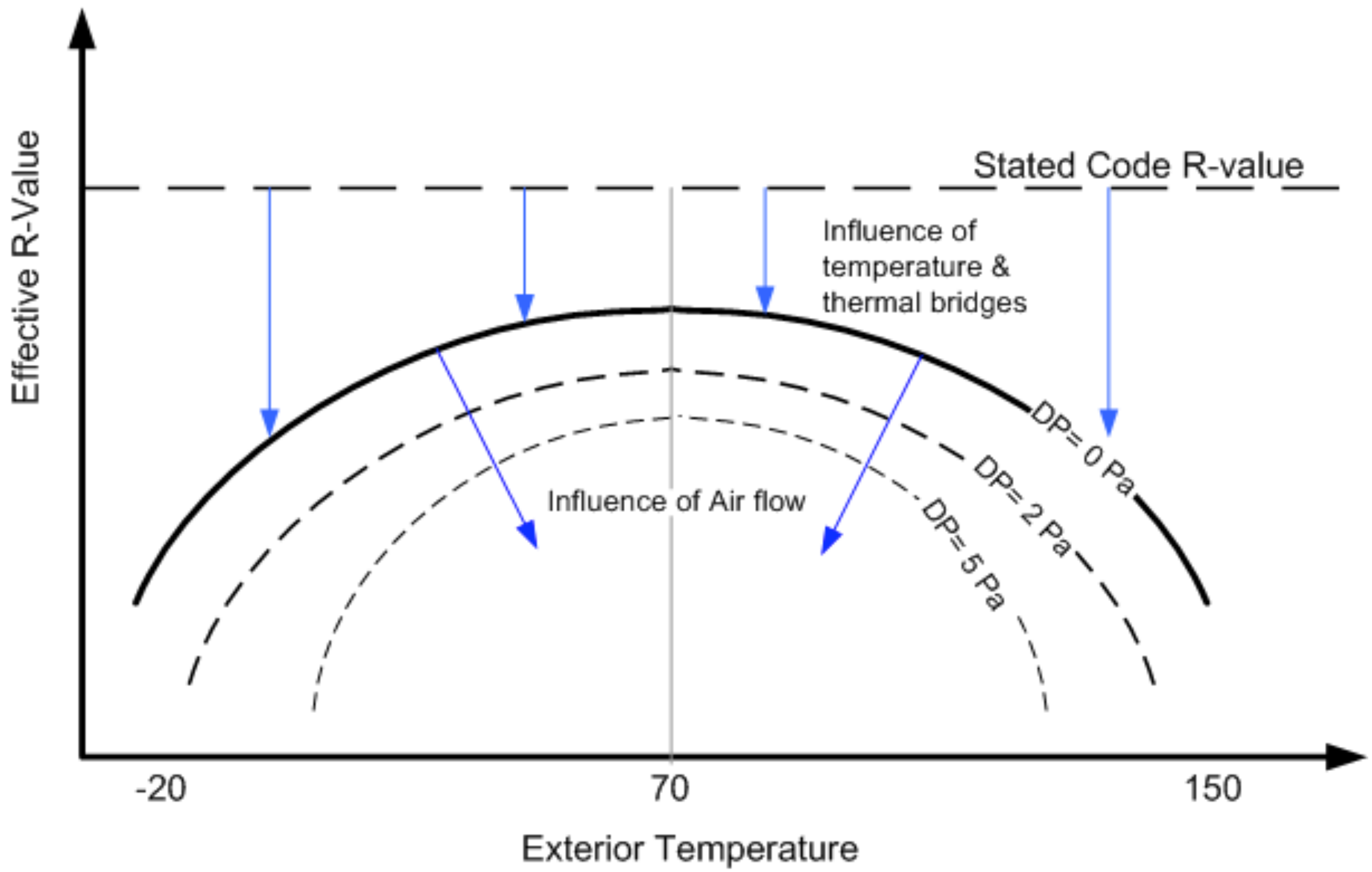
- BSC research project
- Industry Partners
  - Experience & technical support
  - Part funding for testing but ‘hands off’ arrangement
- Building America
  - Support for literature reviews (i.e. the first half of this presentation), theoretical studies & data analysis

The Thermal Metric Research Project

- Objective: Develop a new metric for thermal performance of building assemblies

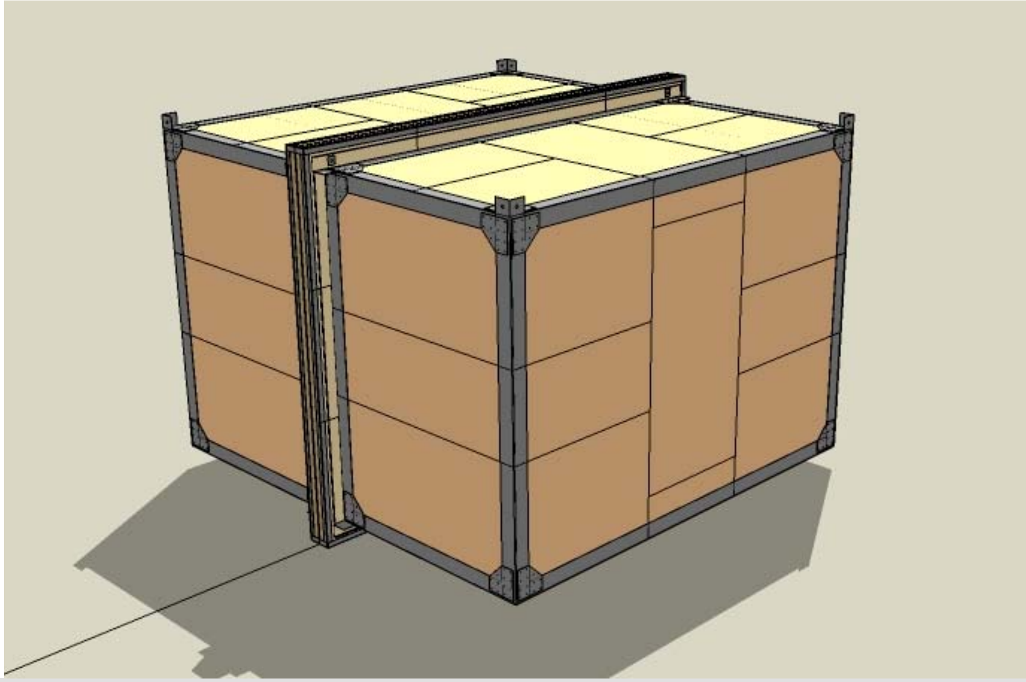
- Test Assemblies, not individual Materials
  - ASTM 1363 (rolls in 236 & 976)
- Real temperature conditions
  - *Room* side at 72°F (22°C)
  - Climate side down to -18°F (-28°C) and up to 136°F (58°C)
- Account for real air movement

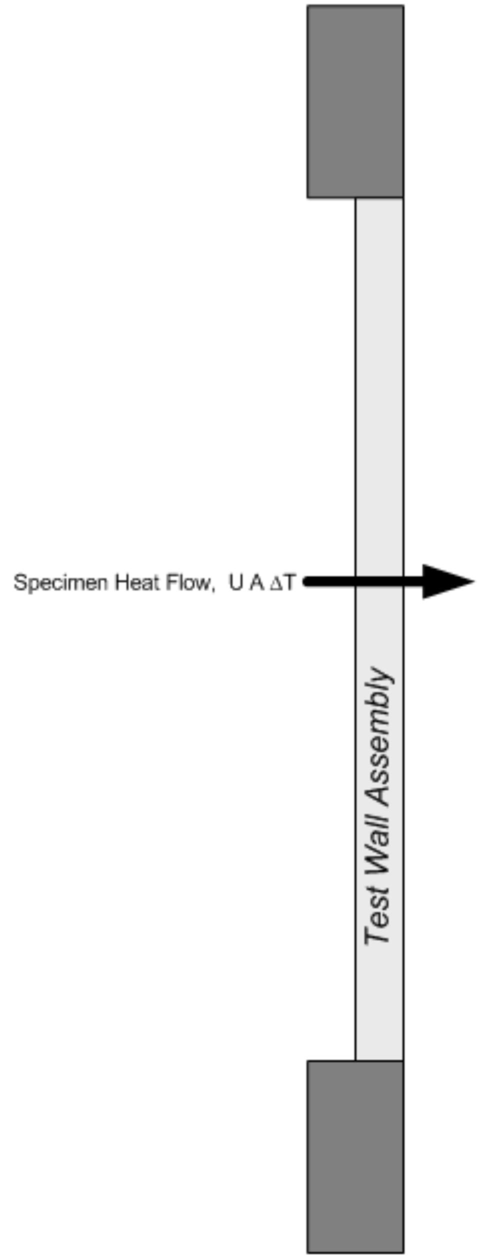
Possible Thermal Metric

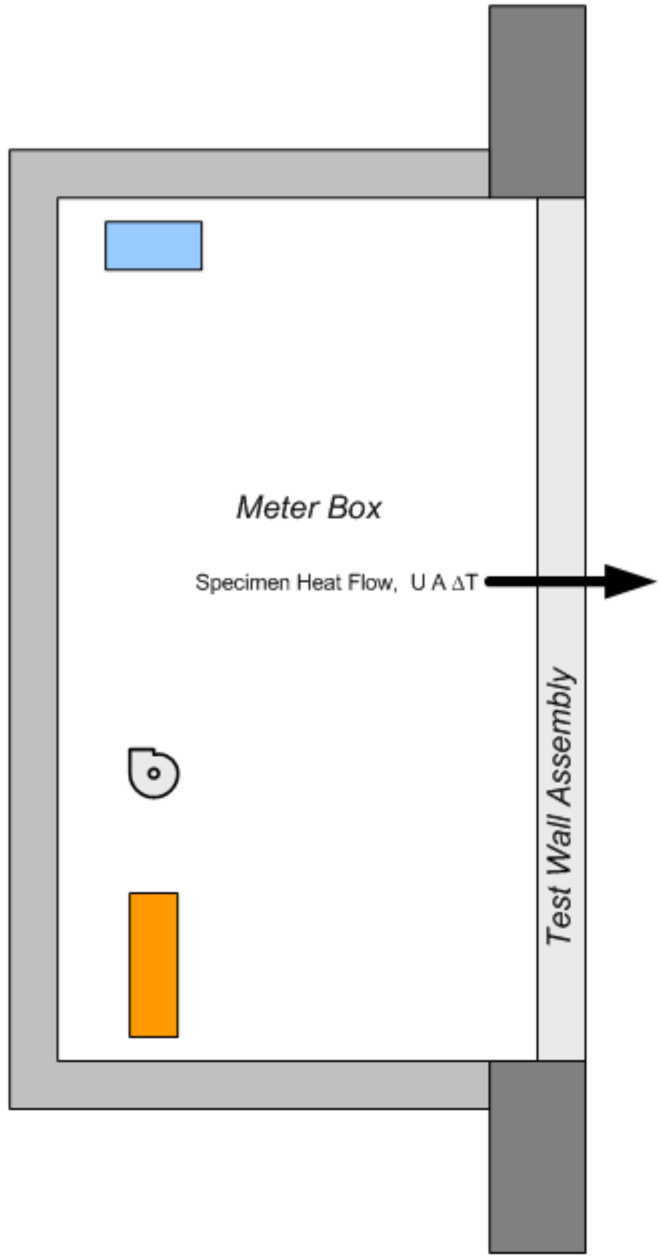


Getting it Done

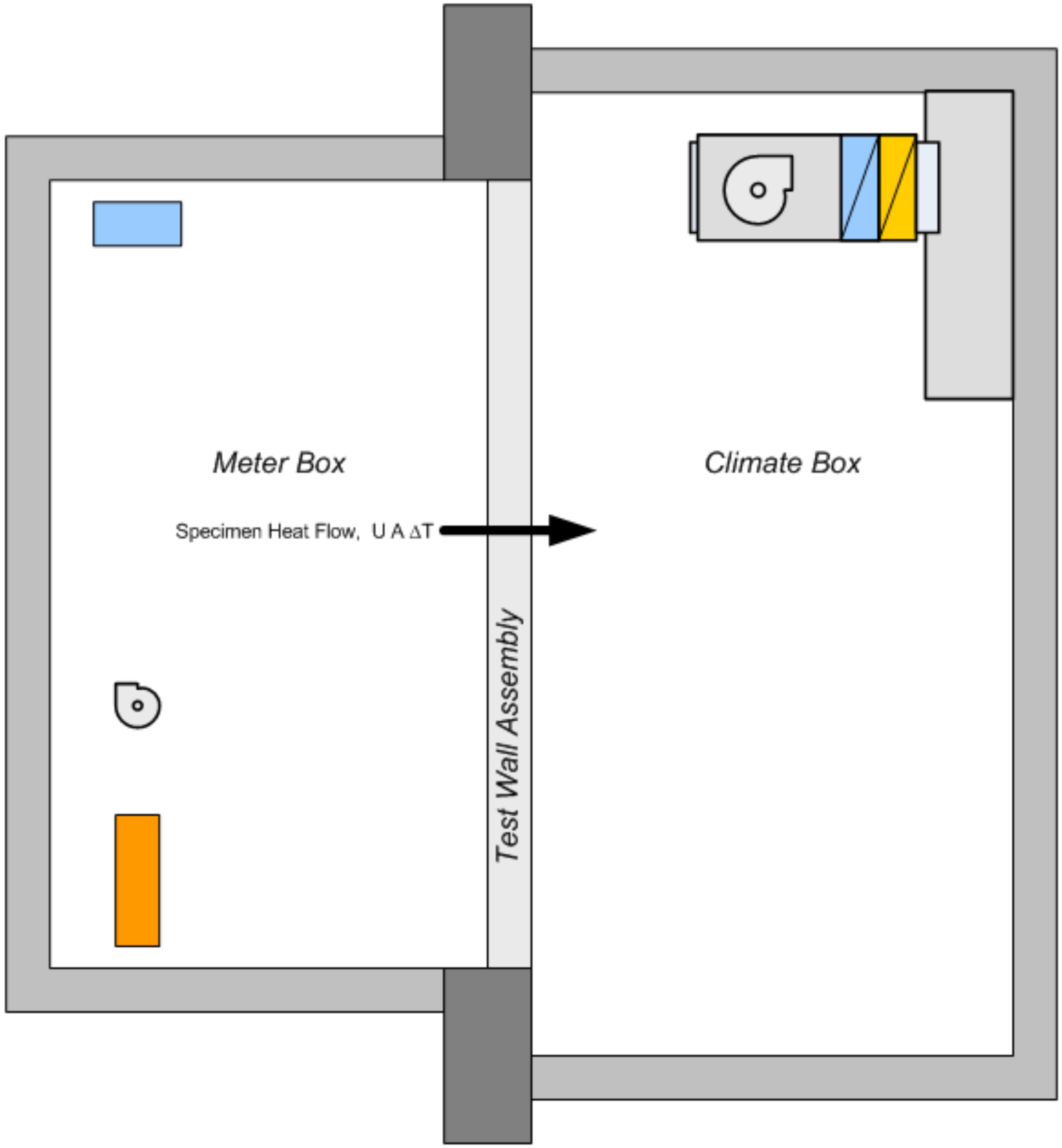
- Designing & Building a *Double* Guarded Hot Box

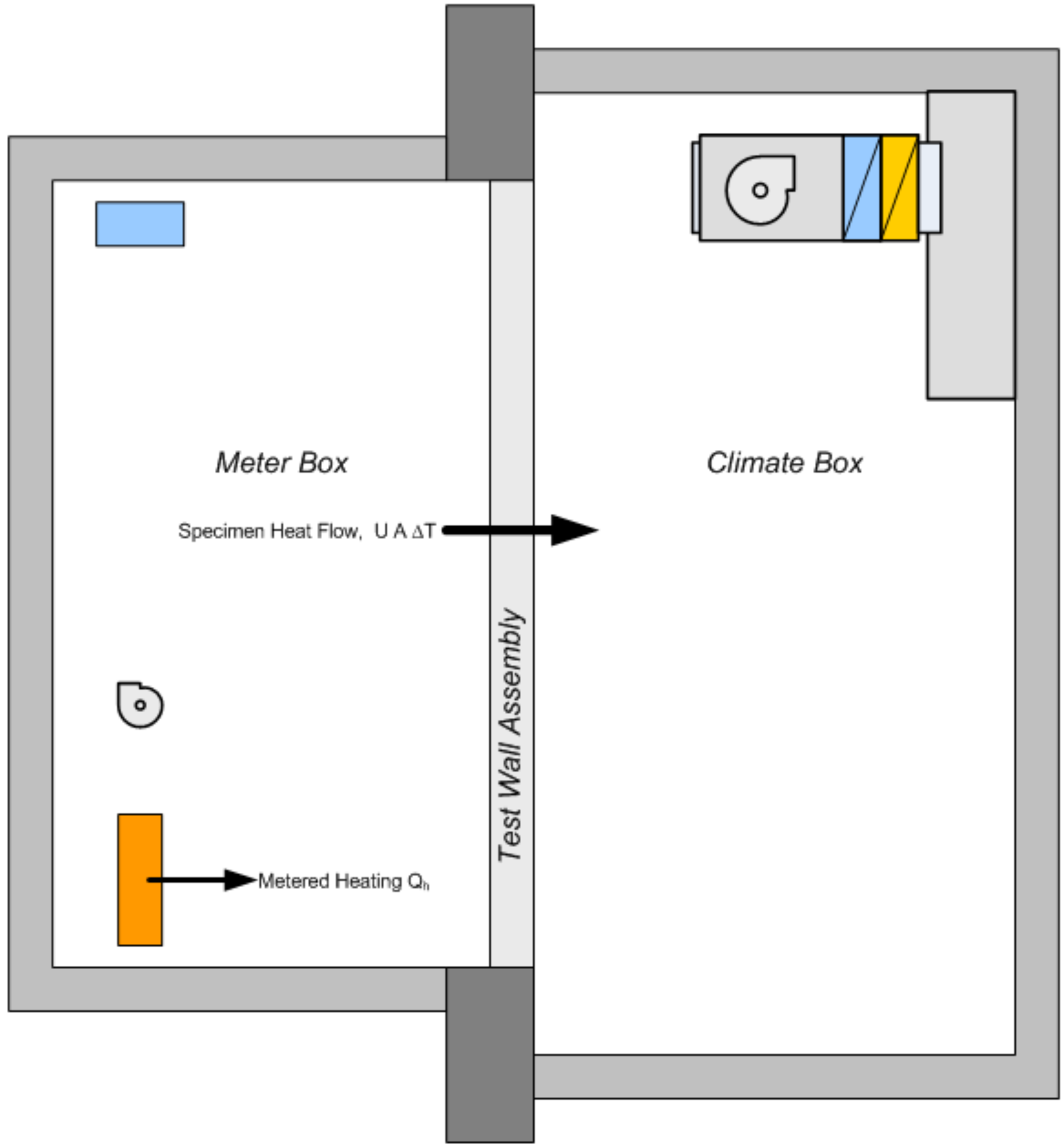



Specimen Heat Flow, U A ΔT
Test Wall Assembly

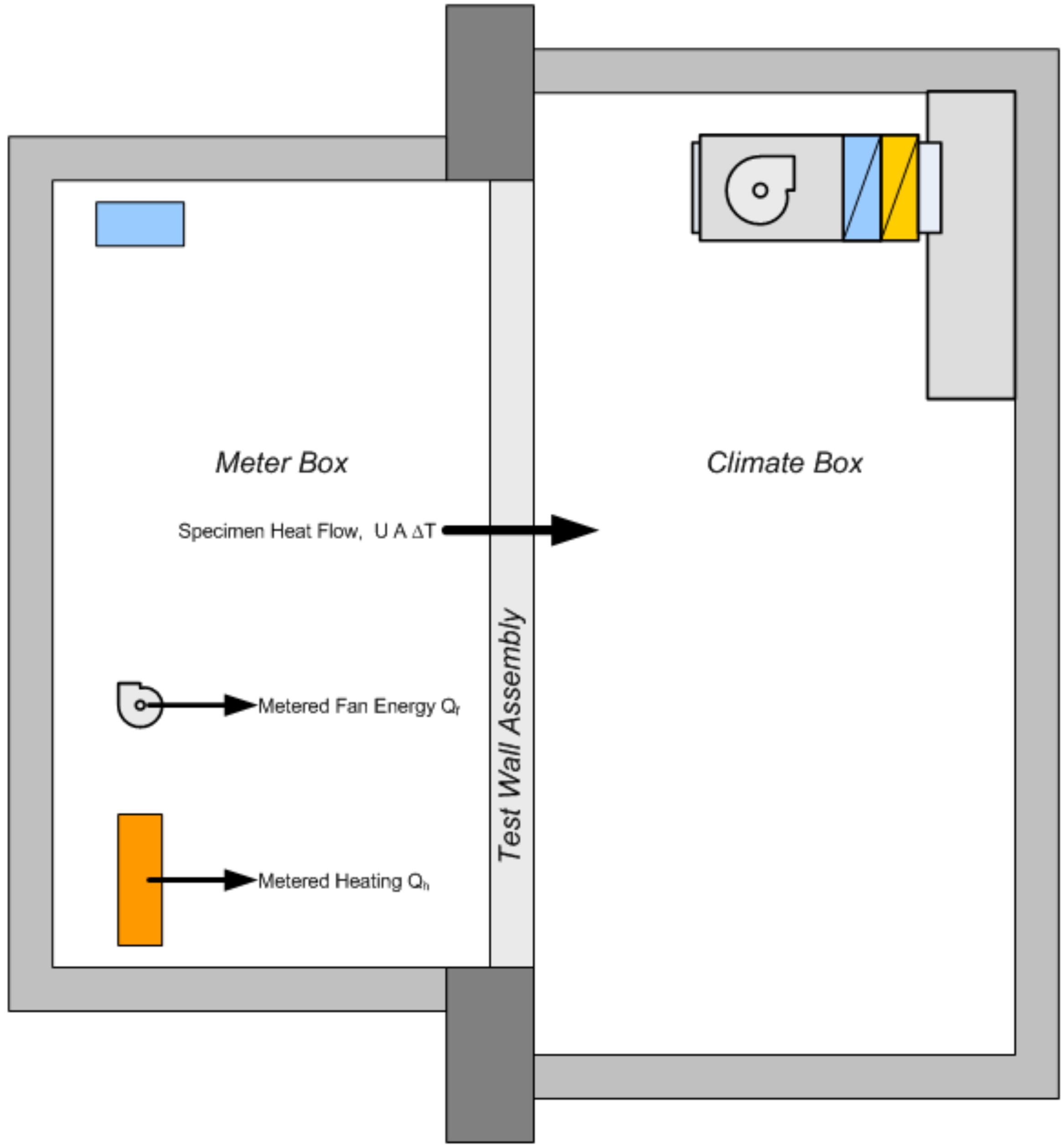


Meter Box
Specimen Heat Flow, U A ΔT
Test Wall Assembly

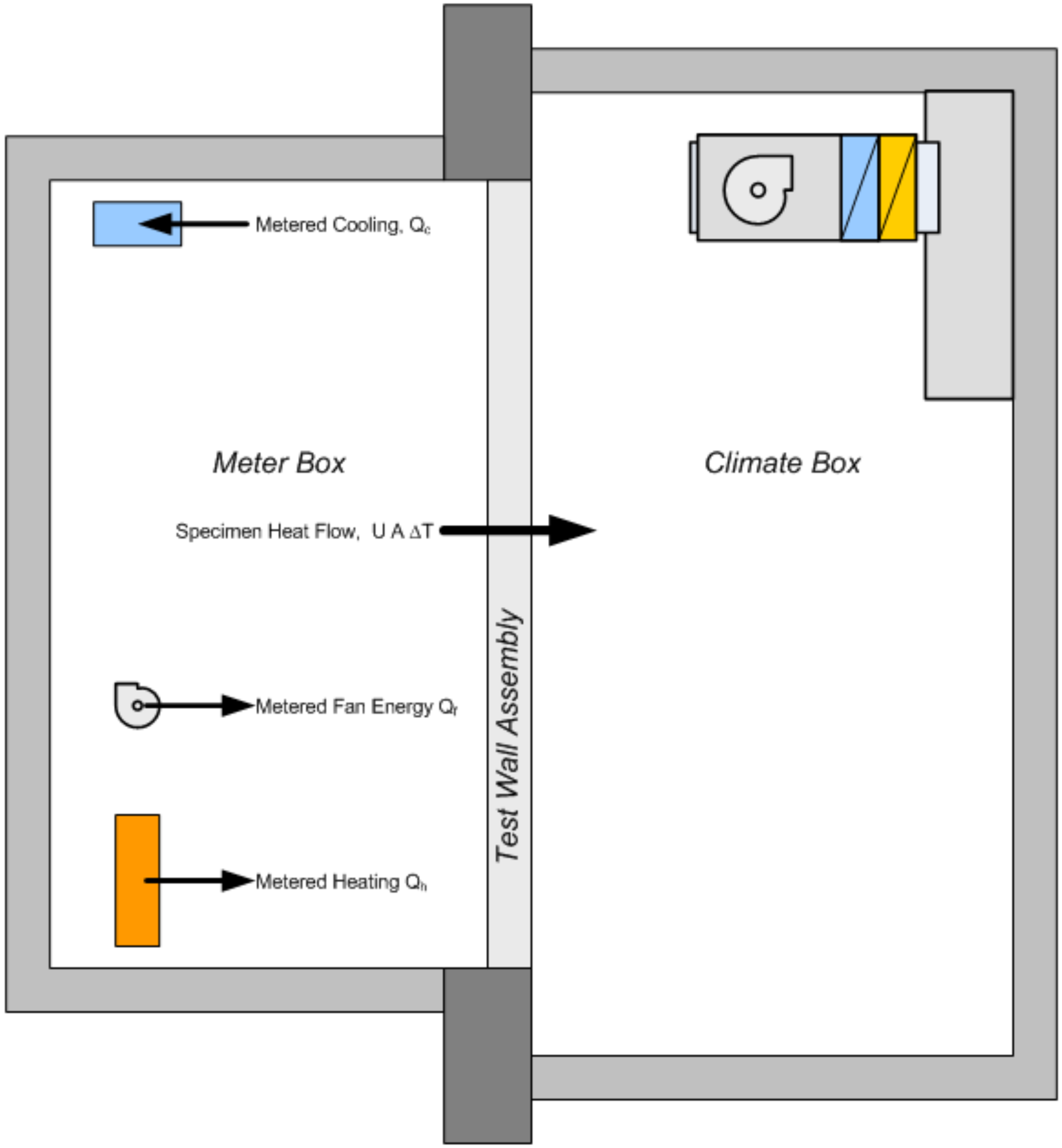

Meter Box
Climate Box
Specimen Heat Flow, U A ΔT
Test Wall Assembly



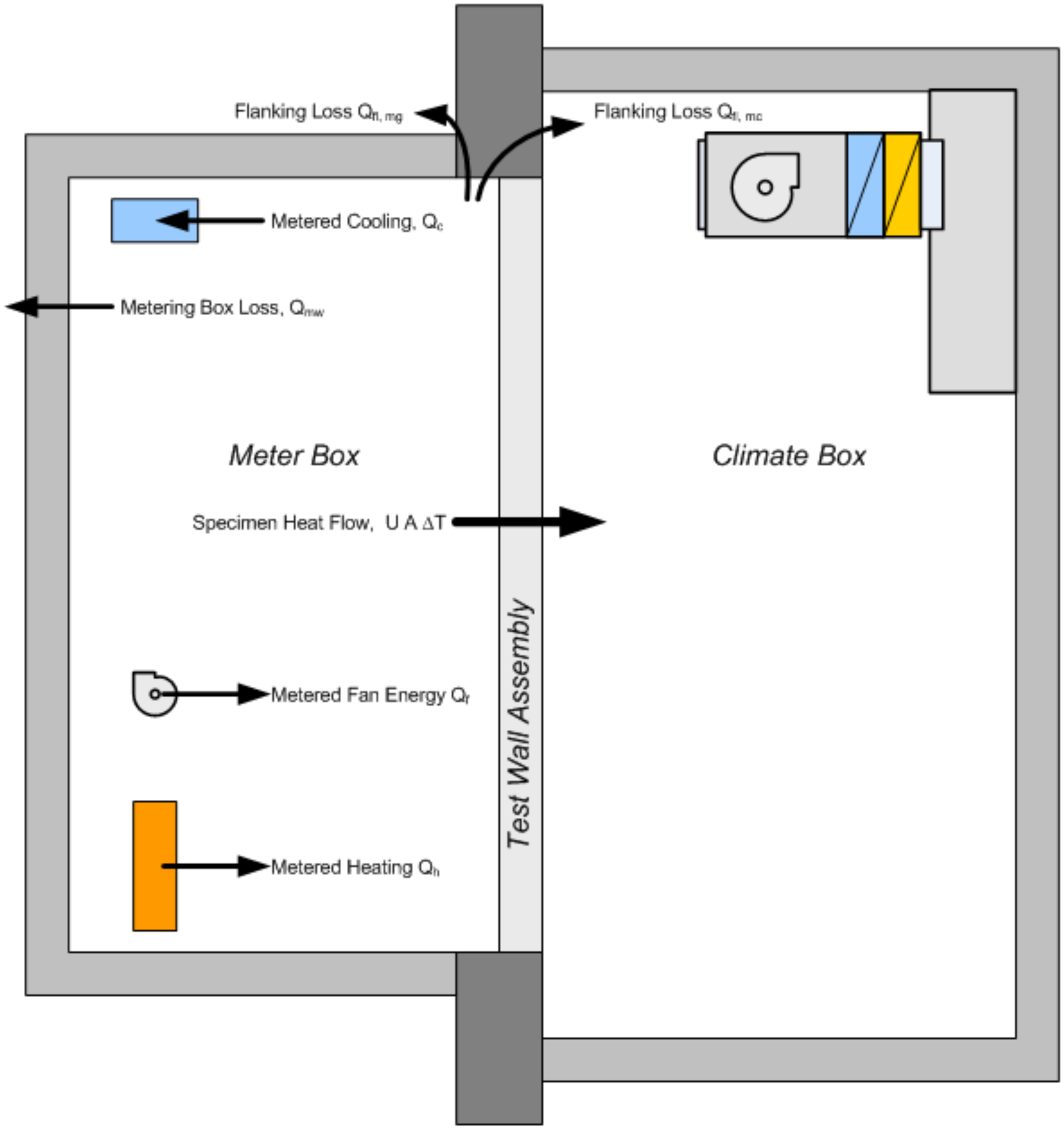
Meter Box
Climate Box
Specimen Heat Flow, U A ΔT
Test Wall Assembly
Metered Heating Q_h



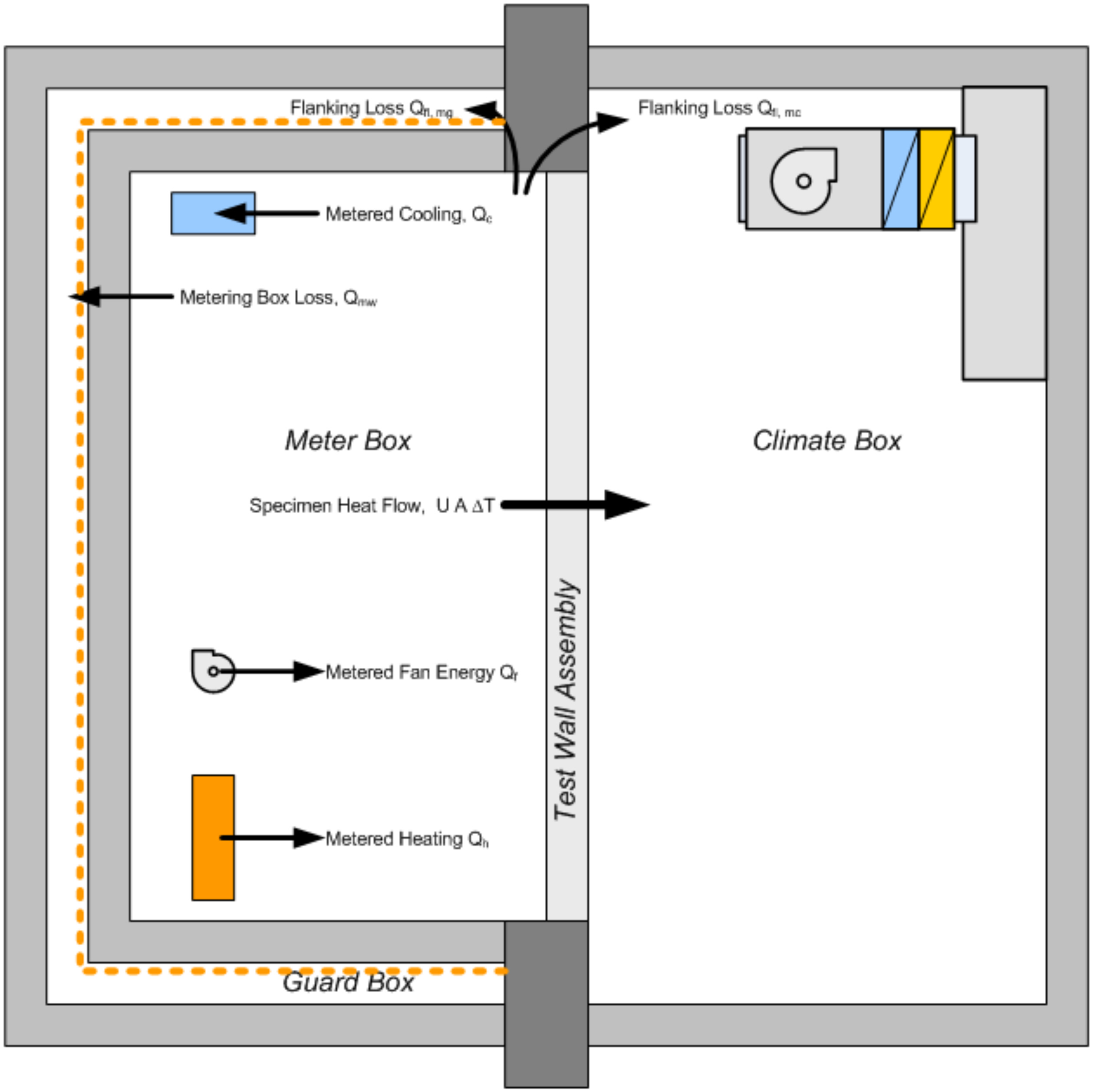
Meter Box
Climate Box
Specimen Heat Flow, U A ΔT
Metered Fan Energy Q
Metered Heating Q
Test Wall Assembly



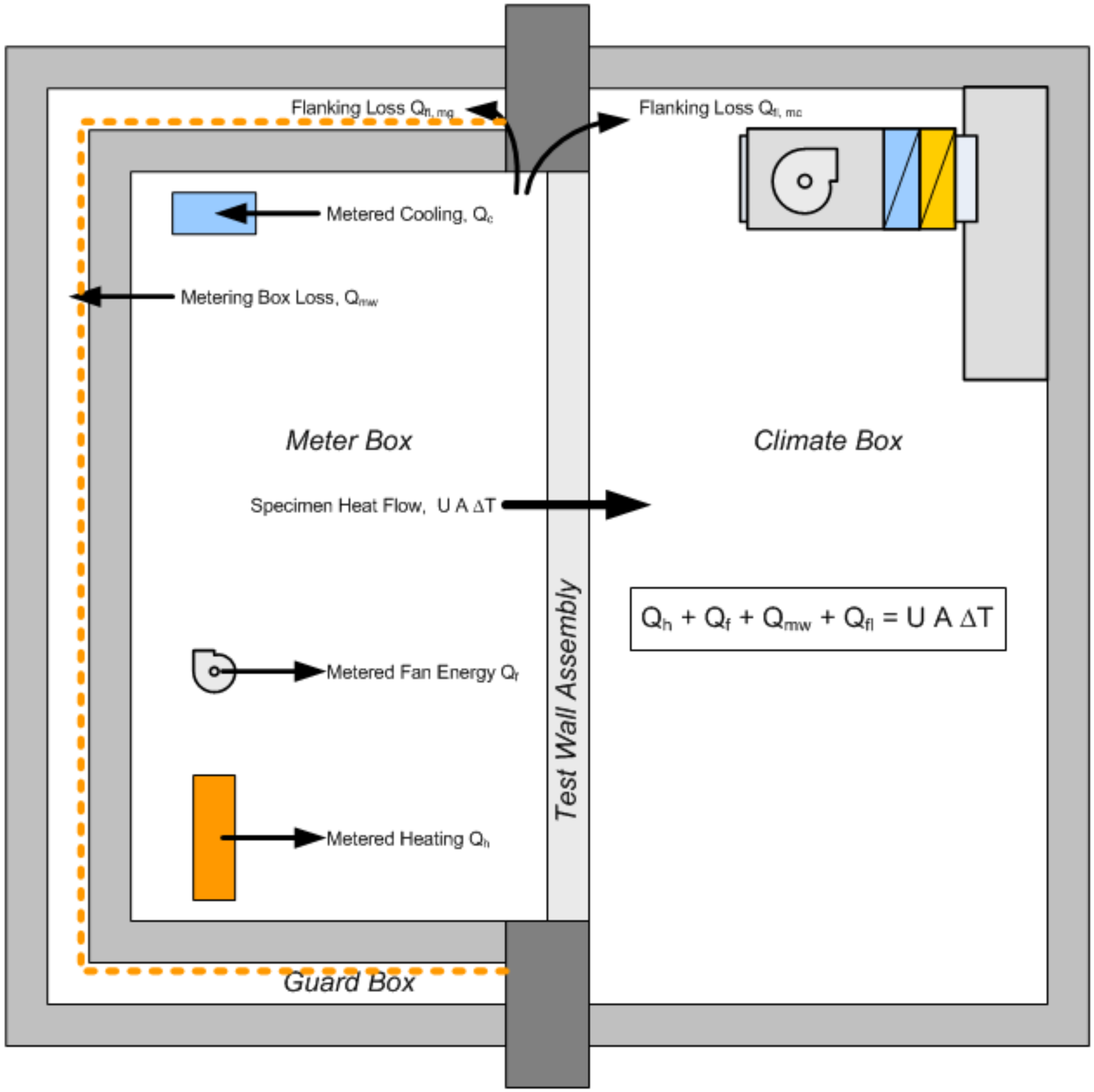
Metered Cooling, Q_c
Meter Box
Climate Box
Specimen Heat Flow, U A ΔT
Test Wall Assembly
Metered Fan Energy Q_f
Metered Heating Q_h

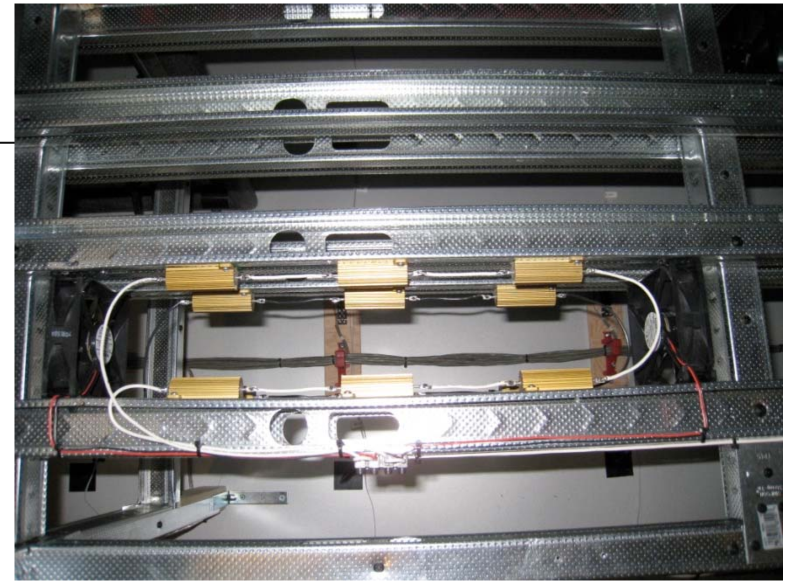


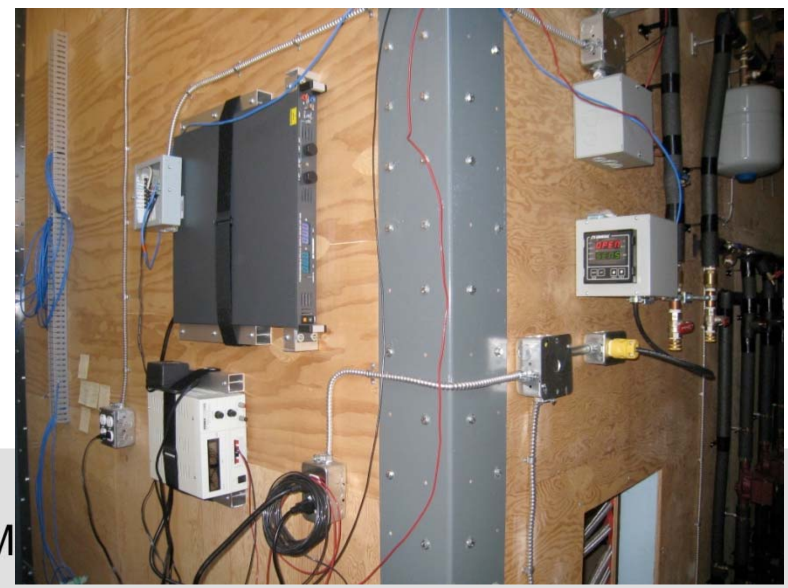
Flanking Loss Qfl, mg
Flanking Loss Qfl, mc
Metered Cooling, Qc
Metering Box Loss, Qmw
Meter Box
Climate Box
Specimen Heat Flow, U A ΔT
Metered Fan Energy Qf
Metered Heating Qh
Test Wall Assembly

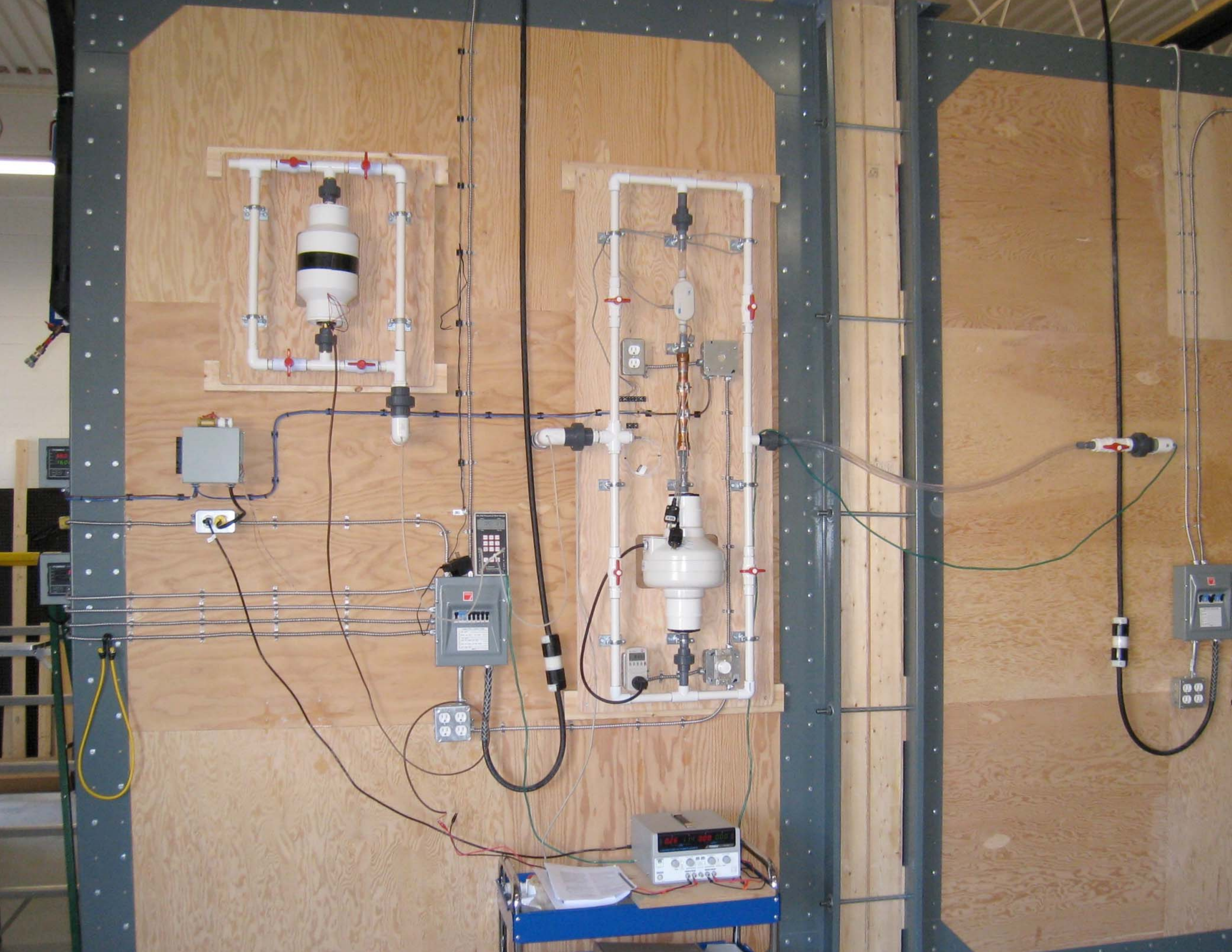


Flanking Loss $Q_{fl, mg}$
Flanking Loss $Q_{fl, mc}$
Metered Cooling, Q_c
Metering Box Loss, Q_{mw}
Meter Box
Climate Box
Specimen Heat Flow, U A ΔT
Test Wall Assembly
Metered Fan Energy Q_f
Metered Heating Q_h
Guard Box


Flanking Loss $Q_{fl,\ mg}$
Flanking Loss $Q_{fl,\ mc}$
Metered Cooling, Q_c
Metering Box Loss, Q_{mw}
Meter Box
Climate Box
Specimen Heat Flow, $U\ A\ \Delta T$
$Q_h + Q_f + Q_{mw} + Q_{fl} = U\ A\ \Delta T$
Metered Fan Energy Q_f
Test Wall Assembly
Metered Heating Q_h
Guard Box







Calibration Runs

Testing Completed

Wall Specimen	Air Sealing	22 | 62 | none	22 | 42 | none	22 | 42 | infiltration	22 | 42 | exfiltration	22 | 2 | none	22 | -18 | none	22 | -18 | infiltration	22 | -18 | exfiltration	22 | -28 | none
		72 / 144	72 / 108	72 / 108	72 / 108	72 / 36	72 / 0	72 / 0	72 / 0	72 / 0
1A	None	X	X			X	X	X	X	X
1B	In	X	X	X	X	X	X			X
1C	Out	X	X	X	X	X	X	X	X	X
1D	In+Out	X	X	X	X	X	X	X	X	X

32 Tests!

Results

- Data from first 32 tests have generated significant discussion
- Watch this summer for published results from first round of testing

Thank You

Questions?

Building
Science
Corporation