Effects of Temperature and Air Infiltration and on Thermal Performance of Insulation and Insulated Frame Wall Assemblies

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With funding from…

SPRAY POLYURETHANE FOAM ALLIANCE SPFA

American Chemistry Council℠ Center for the Polyurethanes Industry

OVERVIEW

- **BACKGROUND**
  - Physics of Heat Transfer
  - Material Thermal Performance
  - Building Envelope System Thermal Performance
- **TEST METHOD**
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  - Guarded Hot Box Apparatus
  - Wall Specimens
- **TEST RESULTS**
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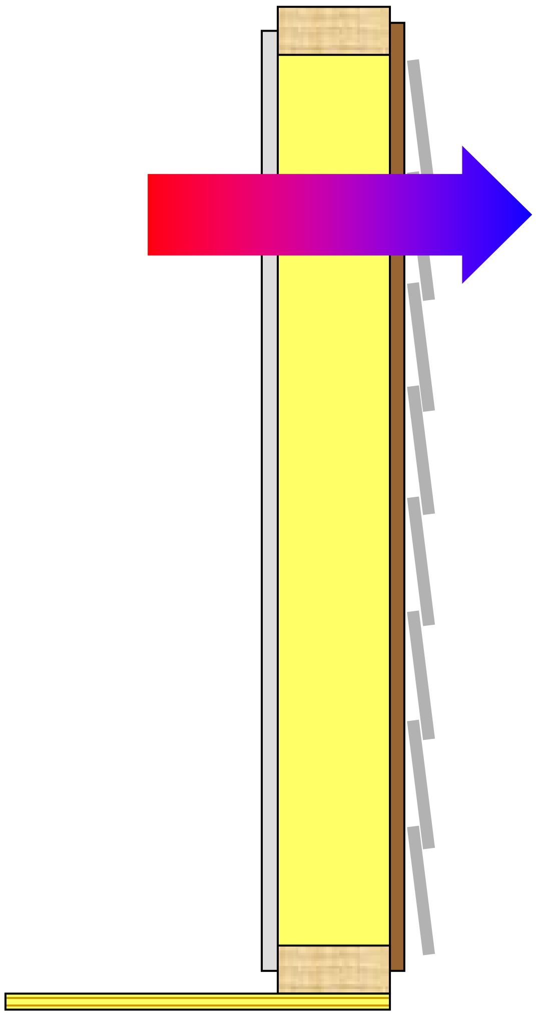
  - Effects of Air Leakage
  - Effects of Exterior Temperature
- **CONCLUSIONS**
- **NEXT STEPS**
- **ACKNOWLEDGEMENTS**

BACKGROUND: Physics of Heat Transfer

- **Conduction:** through a solid material

$$Q = \frac{kA}{t}(T_{hot} - T_{cold})$$



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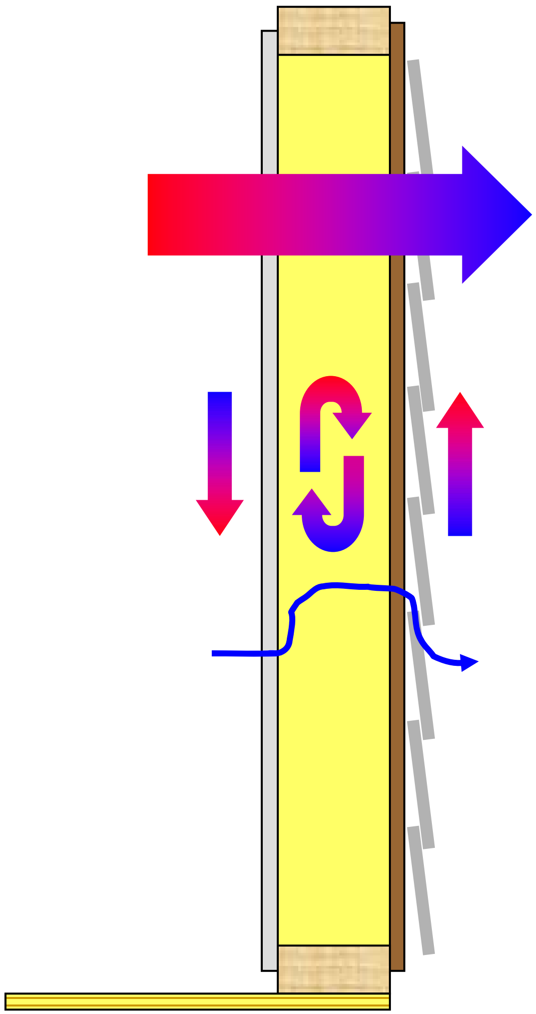

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- **Radiation:** transmission of light waves

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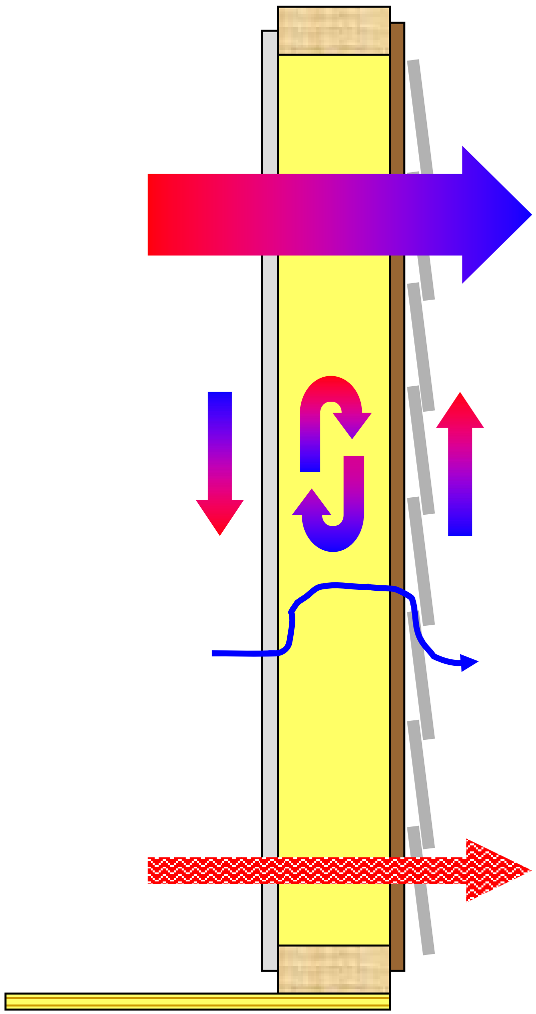


BACKGROUND: Physics of Heat Transfer

- **Conduction:** through a solid material

$$Q = \frac{kA}{t}(T_{hot} - T_{cold}) = \frac{A}{R}(T_{hot} - T_{cold})$$

- **Convection:** movement of gas or liquid

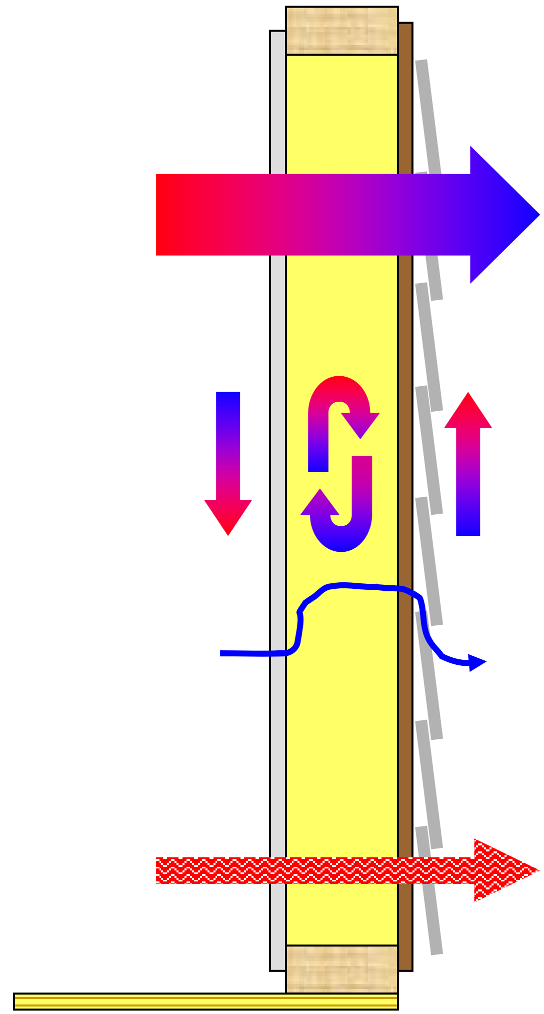
$$Q = hA(T_{hot} - T_{cold})$$

$$(T_{hot} - T_{cold})$$

R-value or thermal resistance, is a **material's** ability to resist heat flow

- **Radiation:** transmission of light waves

$$Q = c\sigma(T_{hot}^4 - T_{cold}^4)$$



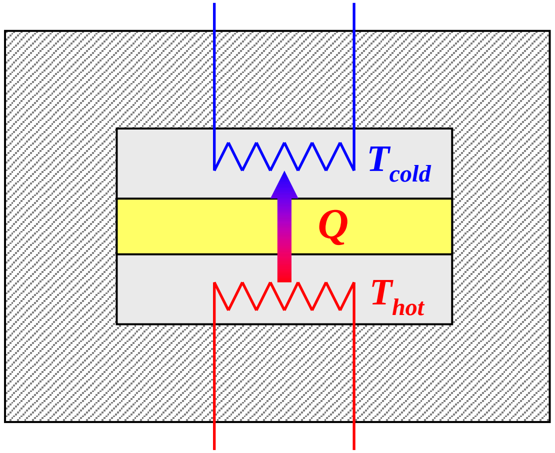
BACKGROUND: Material Thermal Performance

- R-value laboratory measurement
  - Guarded hot plate (ASTM C177)
  - Heat flow meter (ASTM C518)

$$Q = \frac{kA}{t}(T_{hot} - T_{cold}) = \frac{A}{R}(T_{hot} - T_{cold})$$

- Both methods minimize heat flow by convection and radiation

- Performed at prescribed mean temperature and temperature difference
  - Mean = ½$(T_{hot}+T_{cold})$, *usually 75ºF*
  - Range = T_{hot} - T_{cold}, *usually 40ºF*



Source: LaserComp, Inc. (www.lasercomp.com)

BACKGROUND: Material Thermal Performance

Current Thermal Testing Standards

Insulation	ASTM Standard	Mean Test Temperature, °F	Temperature Differential, °F
R-13 Fiberglass batt with paper facing	ASTM C 653	75	40 or 50
Extruded polystyrene	ASTM C 578	25, 40, 75, 110	Min 40
Polyisocyanurate	ASTM C 1289	40, 75, 110	Min 40
Closed cell spray foam insulation	ASTM C 1029	40, 75, 110	Min 40
Open cell spray foam insulation	None	75	Min 40

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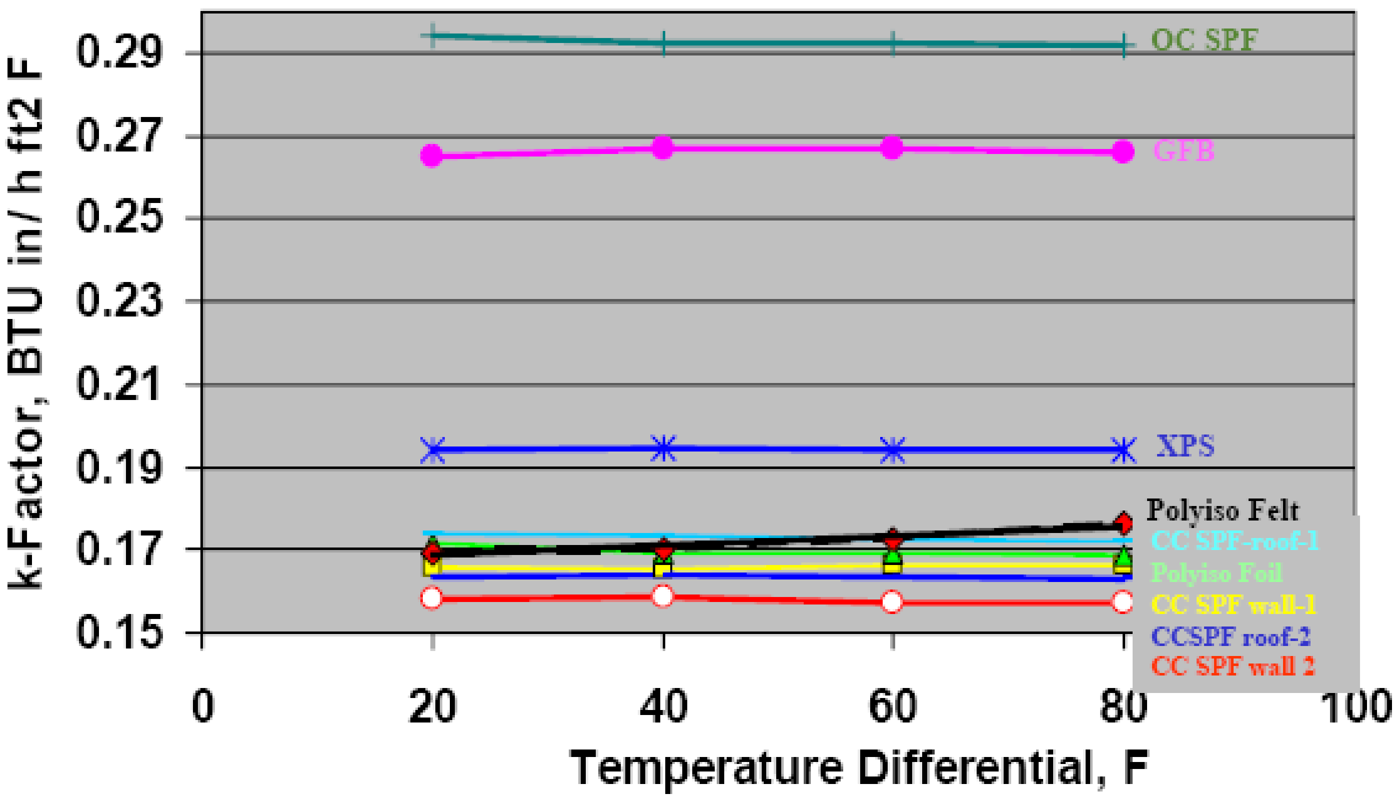
Impact of Test Temperature Difference



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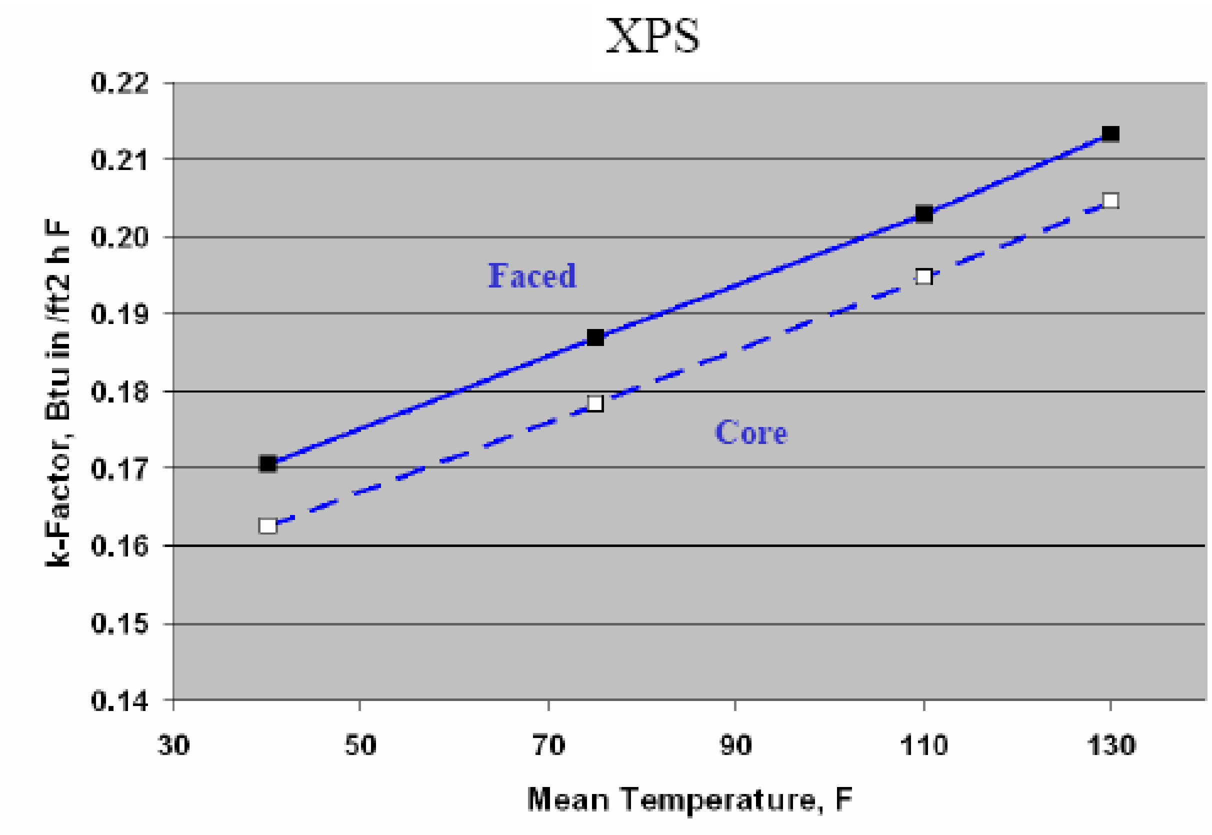
BACKGROUND: Material Thermal Performance

Impact of Surface Condition



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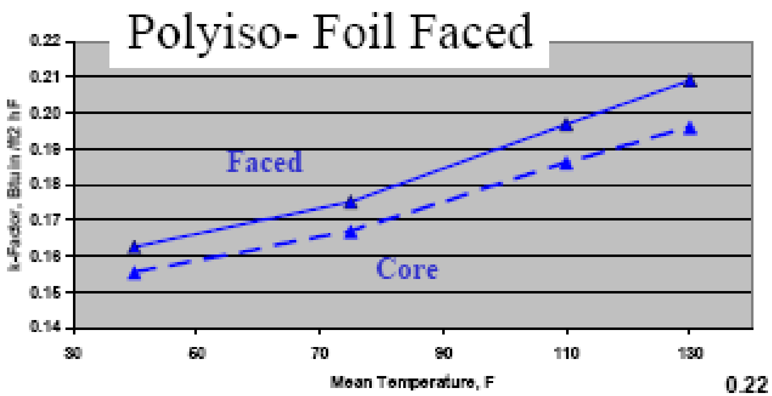

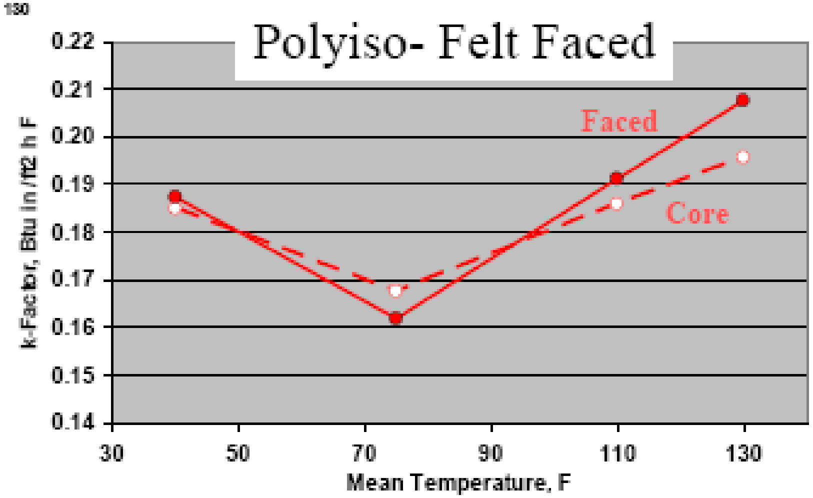

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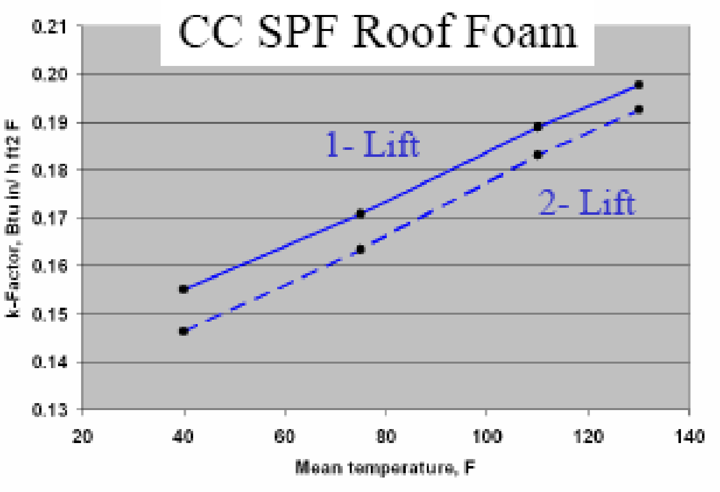
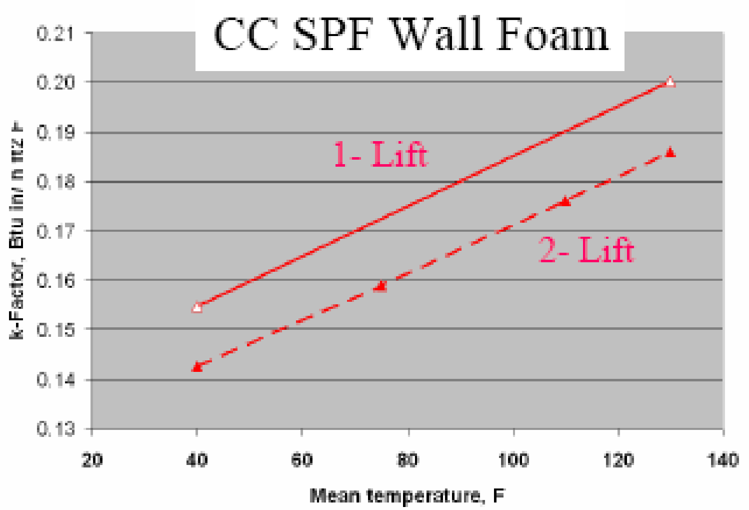


Roof insulation= 4% lower k-factor with knit line



Wall insulation= 8% lower k-factor with knit line

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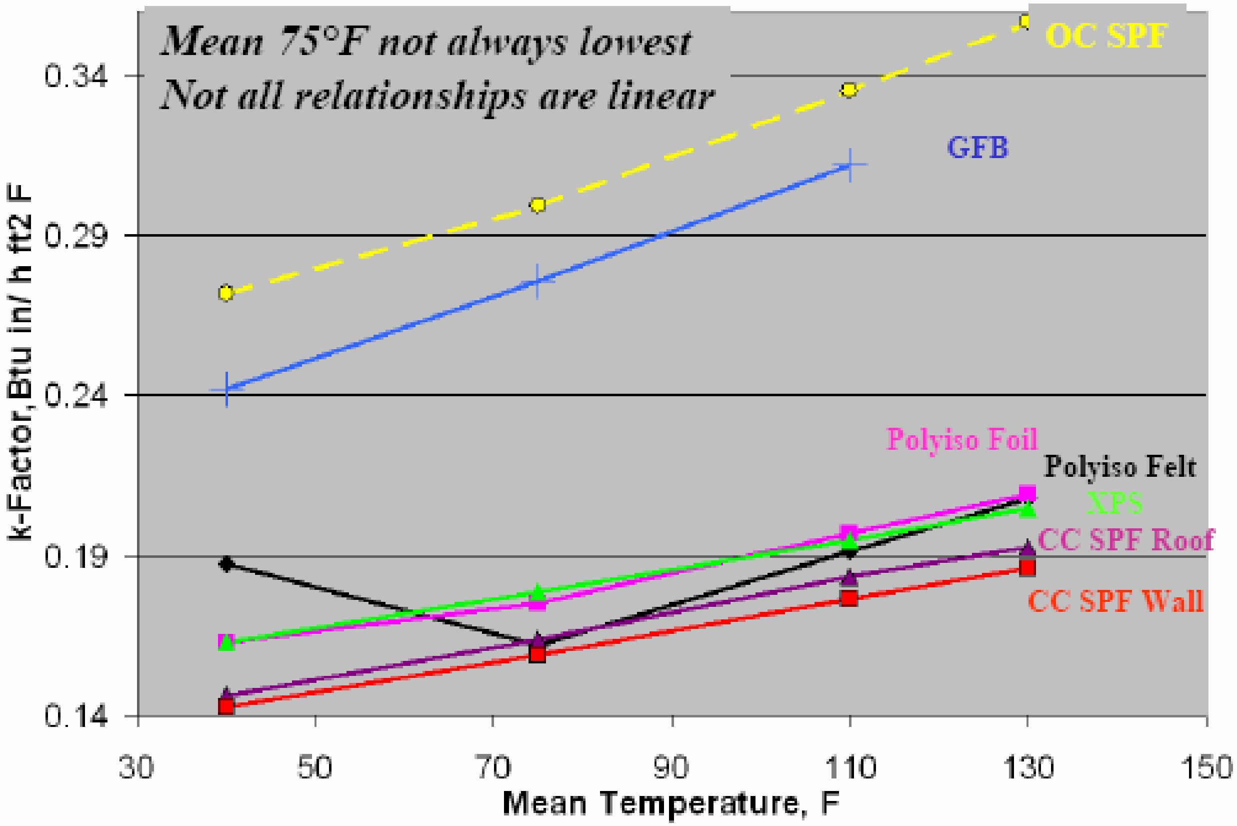
Impact of Mean Temperature



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BACKGROUND: Building Thermal Performance

- Real construction practices result in defects in the building envelope

Cracks

Gaps

Holes

BACKGROUND: Building Thermal Performance

- Real construction practices result in defects in the building envelope
- Improper material installation will compound the effects of these defects

Compression

Inset Stapling

BACKGROUND: Building Thermal Performance

- Real construction practices result in defects in the building envelope
- Improper material installation will compound the effects of these defects

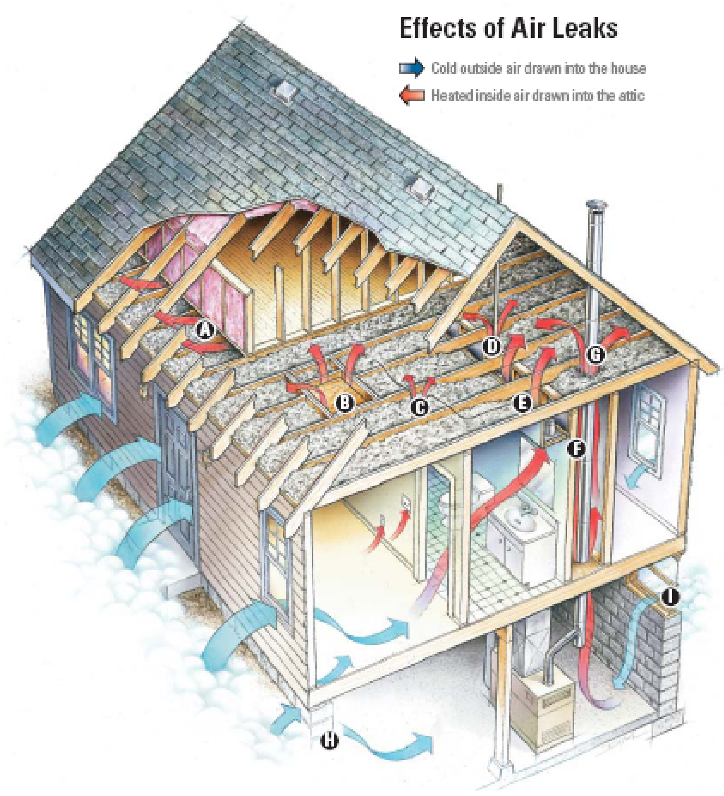
Compression

Inset Stapling

Air Leakage + Improper Installation = Underperformance

BACKGROUND: Building Thermal Performance

- Components of the building envelope (wall), including insulation, can transfer heat via all three modes
- Most accurate solution: in-situ energy measurements over 1+ years
- Whole-house solution is expensive



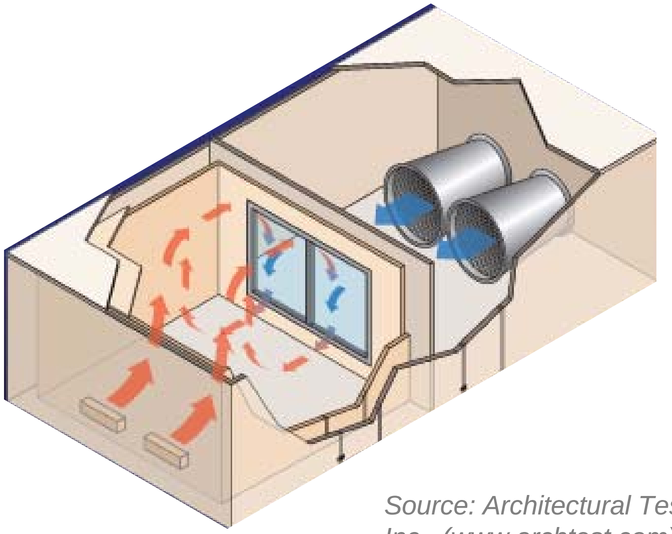
Source: ENERGY STAR

TEST METHOD: System Thermal Performance

- Laboratory measurement of wall section is a suitable compromise
  - Guarded hot box (ASTM C1363)

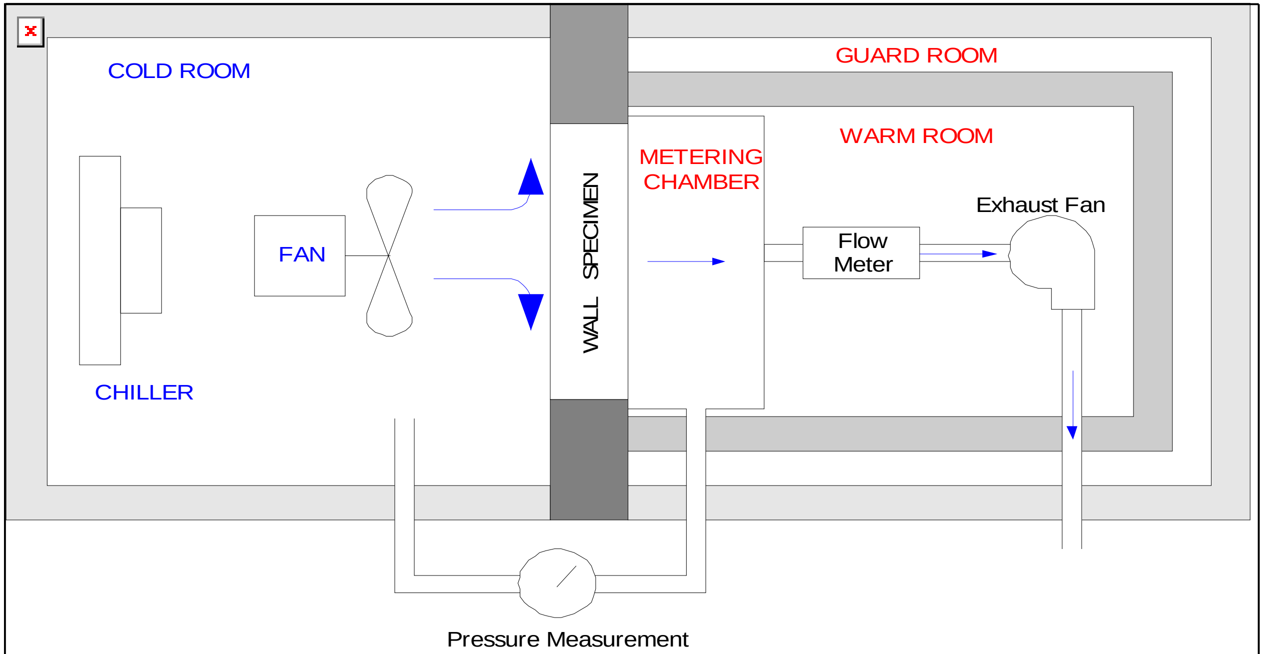
$$Q_w = U_w A(T_{hot} - T_{cold}) = \frac{A}{R_w}(T_{hot} - T_{cold})$$

- Real wall section = system of components
- All three modes of heat transfer
- Environmental effects
  - perforations/defects
  - air leakage
  - fenestration
  - moisture movement
  - wall orientation



Source: Architectural Testing, Inc. (www.archtest.com)

TEST METHOD: Guarded Hot Box Apparatus



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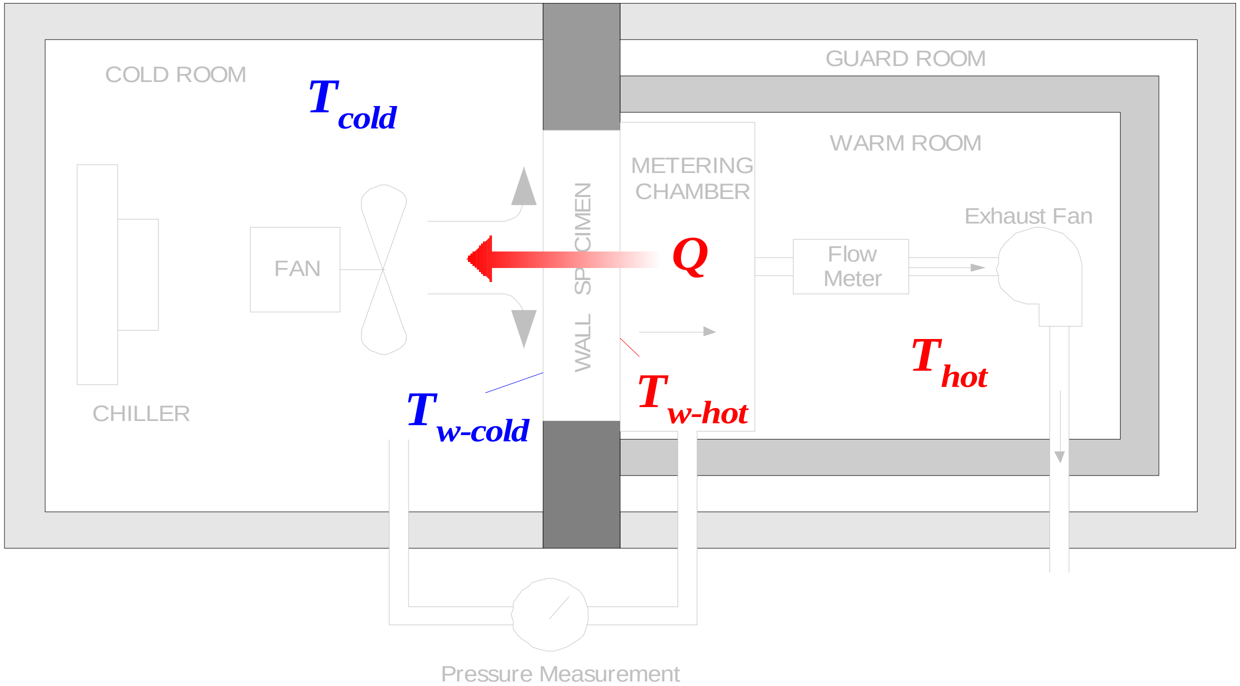


$$Q = U_w A(T_{w-hot} - T_{w-cold}) = \frac{A}{R_w}(T_{w-hot} - T_{w-cold})$$

Q measured by metering chamber

$T_{w\text{-}hot}$, $T_{w\text{-}cold}$ measured by thermocouples

U_w, R_w calculated above

$$WPI = \frac{R_w}{R_w^*} \times 100$$

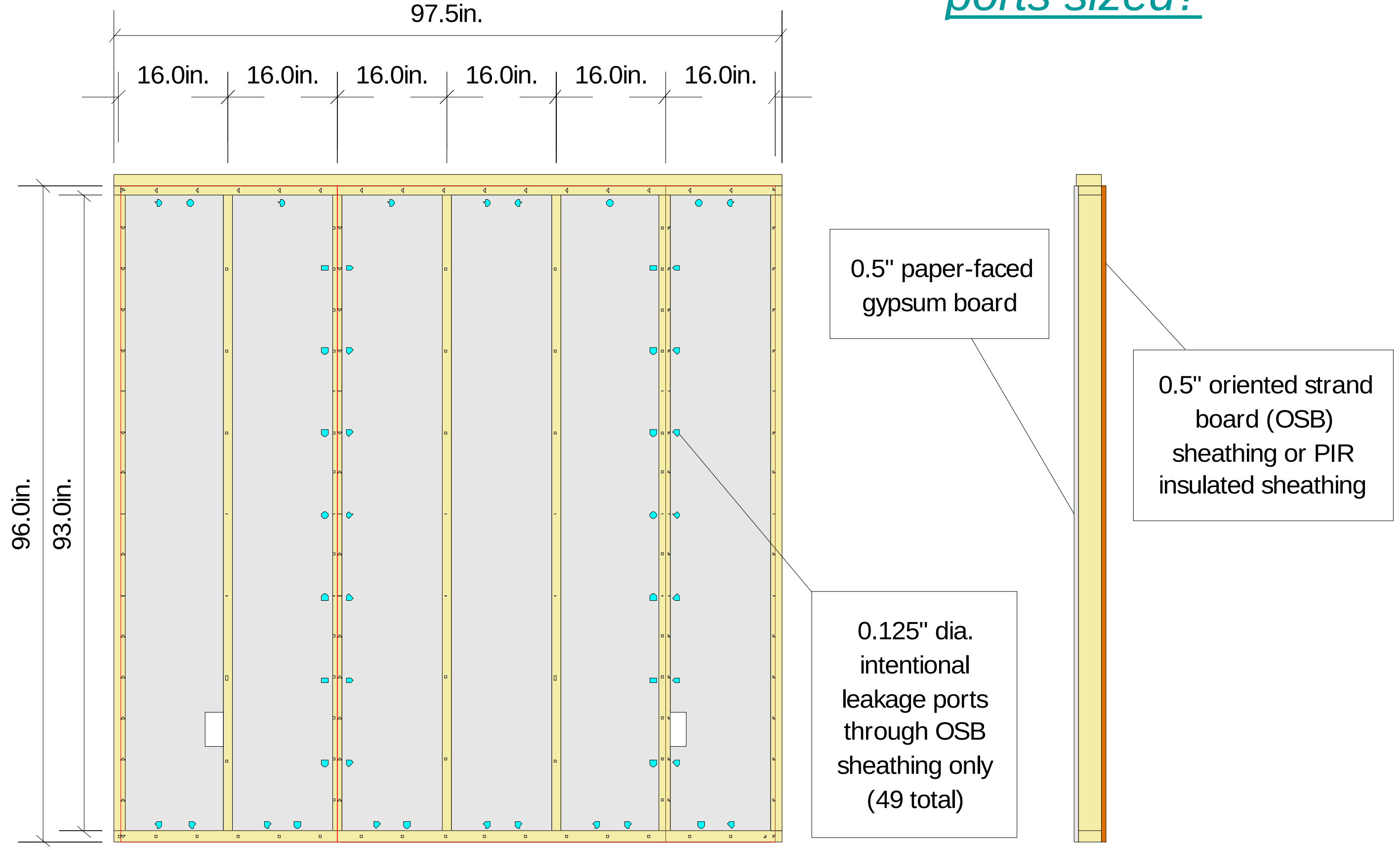
Wall Performance Index

R_w, determined experimentally

R^*_w expected wall R-value, calculated from measured material R-values

TEST METHOD: Wall Specimens

How are the leakage ports sized?



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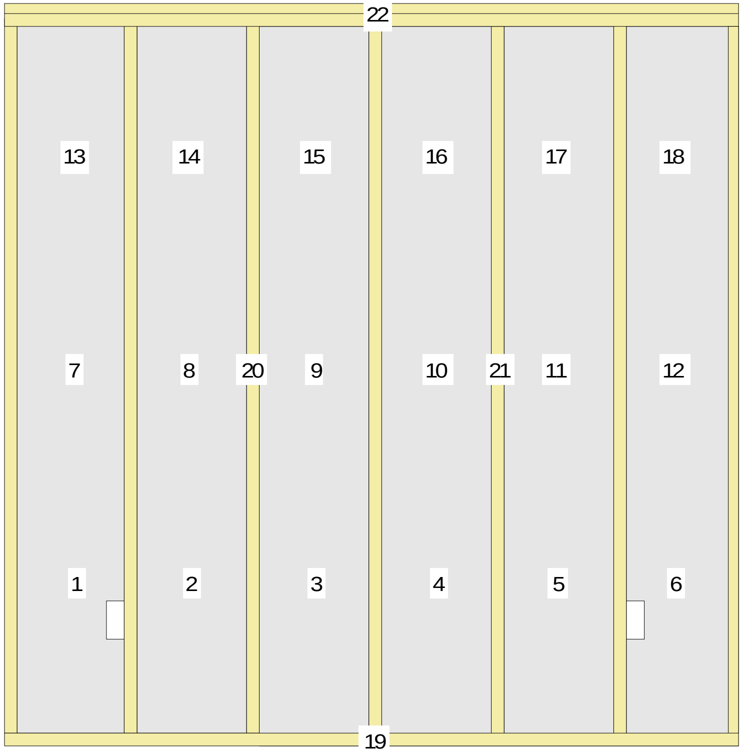

TEST RESULTS: Experimental Data

Wall	Sheathing	Cavity Insulation	Rins	Warm room temp (F)	Cold room temp (F)	Wind Speed (mph)	Cold room air press (psi)	Metering chamber air flow (CFM)	Uw	Rw	R*w	WPI
A	0.5" OSB	Fiberglass Batts 2005	13.0	70	25	0	0.013	0.00	0.081	12.28	11.66	105.3
				70	-15	15	0.126	1.85	0.110	9.08		77.8
				70	25	15	0.115	1.71	0.105	9.53		81.7
				115	70	15	0.099	2.10	0.121	8.25		70.8
B		**Open-Cell SPF** February 2007 ATI Report 68379.02-116-46	12.1	70	25	0	0.000	0.00	0.094	10.60	11.11	95.4
				70	-15	15	0.127	0.34	0.100	10.00		90.0
				70	25	15	0.115	0.34	0.098	10.19		91.8
				115	70	15	0.097	0.28	0.111	9.02		81.2
C		**Closed-Cell SPF** October 2006 ATI Report 68379.01-116-46-R0	10.5	70	25	0	0.000	0.00	0.090	11.17	10.14	110.2
				70	-15	15	0.109	0.27	0.095	10.55		104.1
				70	25	15	0.101	0.21	0.092	10.91		107.6
				115	70	15	0.082	0.18	0.100	9.98		98.5
D	0.5 polyiso board	**Closed-Cell SPF** August 2006 ATI Report 66614.01-116-46	10.5	70	25	0	0.026	0.00	0.071	14.09	12.74	110.6
				70	-15	15	0.125	0.53	0.087	11.54		90.6
				70	25	15	0.114	0.36	0.079	12.70		99.7
				115	70	15	0.096	0.62	0.094	10.64		83.5

Four wall constructions: All 2”x4”-16oc. Three with OSB, one with R3 PIR sheathing

Three cavity insulations: R13 kraft-faced fiberglass, open-cell SPF, closed-cell SPF

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Nominal R-value of cavity insulations based on label or extrapolation.

Open cell sprayed at ~3.25” to minimize waste, less than R13

Closed-cell sprayed at 1.5”, intentionally not R13 to show equivalent performance

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Real exterior conditions – avg. temp. *not* 75F, free convection, leakage induced:

1. Cold exterior(25ºF), no wind
2. Cold exterior (25ºF), simulated 15 mph wind
3. Extreme cold exterior (-15ºF), simulated 15 mph wind
4. Extreme hot exterior (115ºF), simulated 15 mph wind

How is the pressure difference determined?

TEST RESULTS: Experimental Data

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Assembly air leakage measured under applied pressure difference (ASTM E283)

TEST RESULTS: Experimental Data

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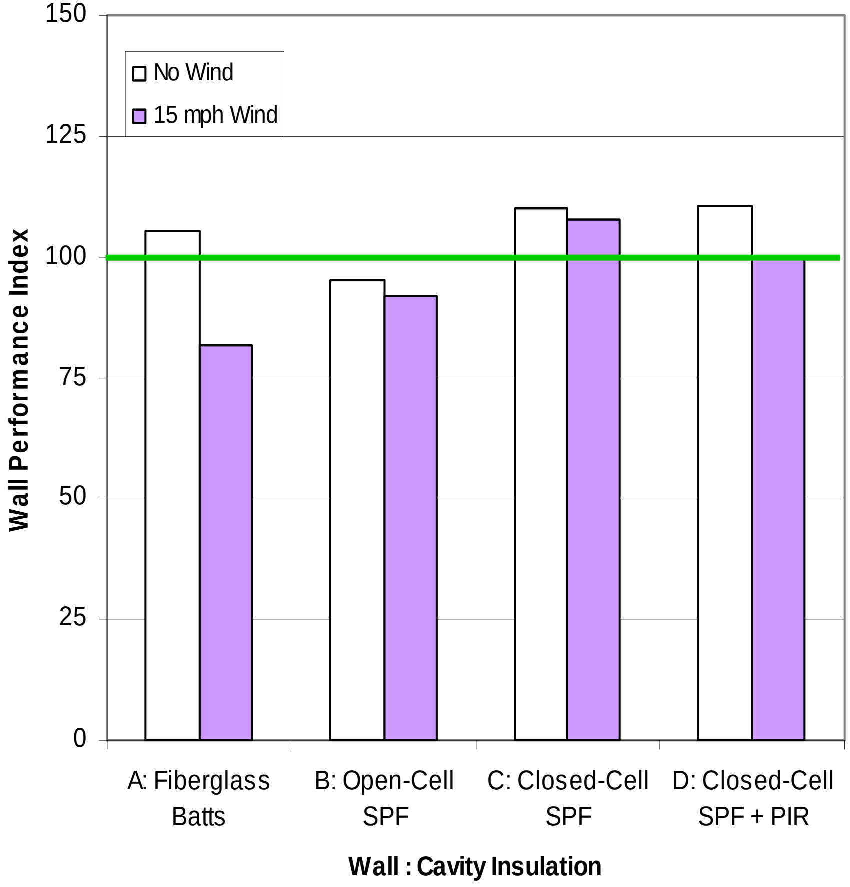
Rw: measured R-value for the wall

R*w: calculated R-value for the wall component properties (isothermal planes)

WPI: Wall Performance Index = (Rw / R*w) x 100

TEST RESULTS: Air Leakage Effect @ 25°F

Key Observations…



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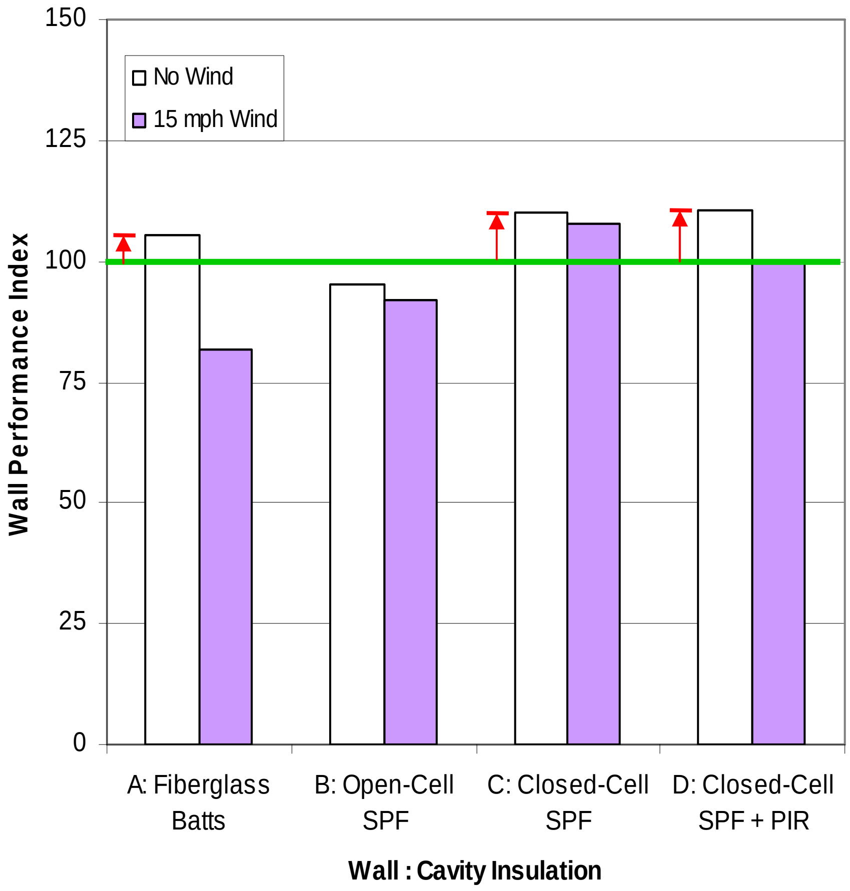

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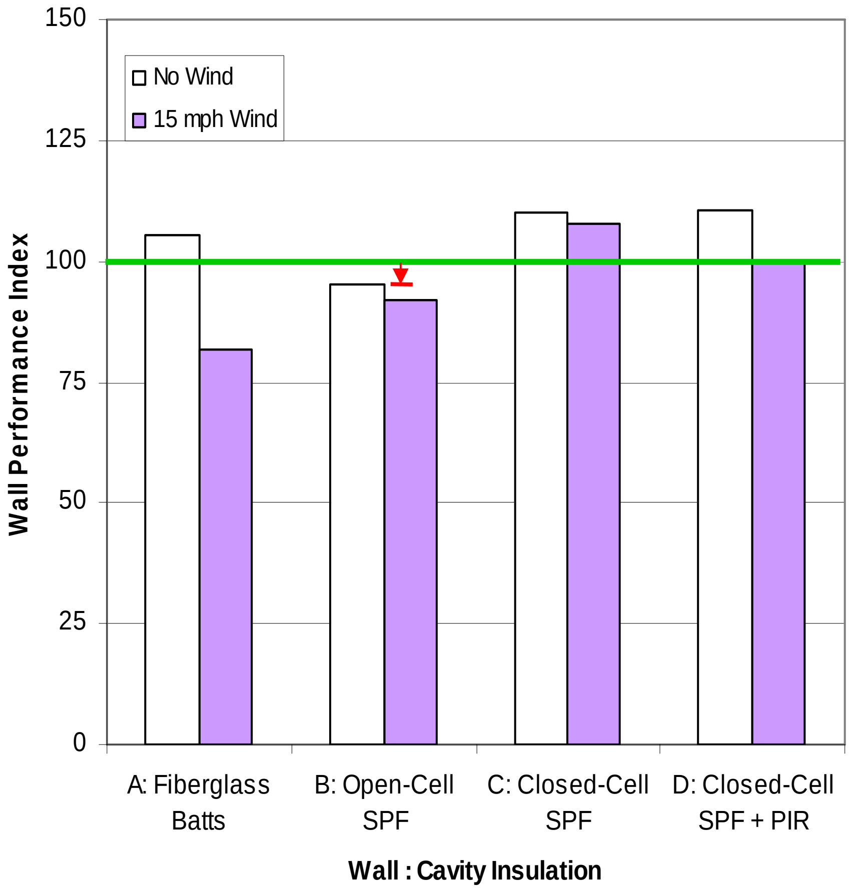

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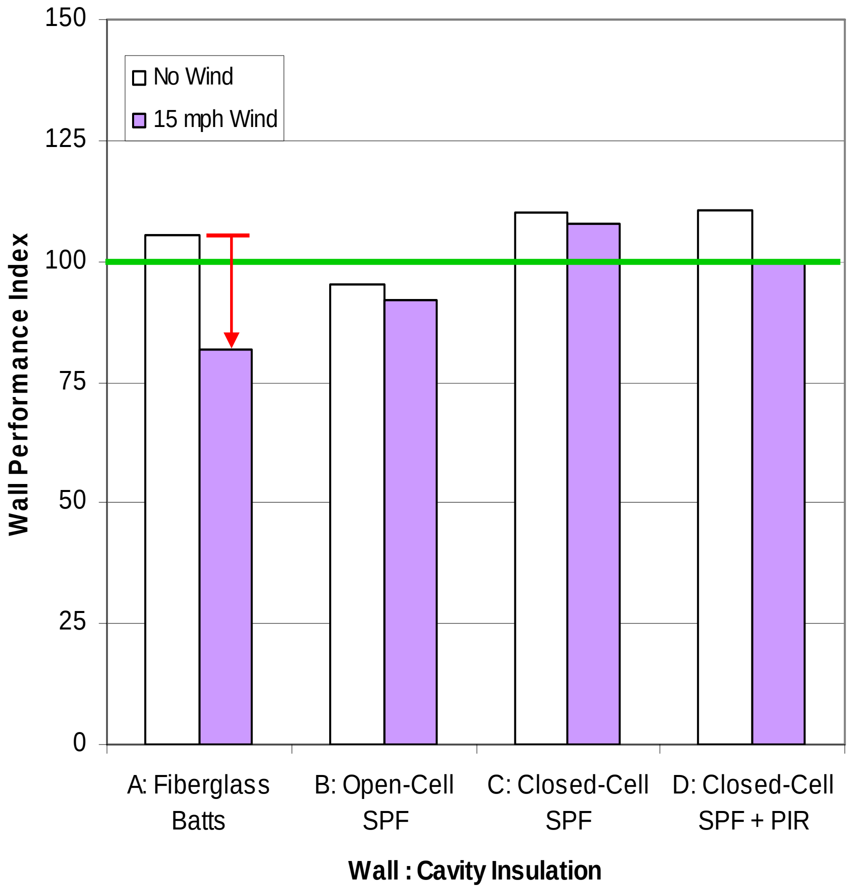

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- Without forced air leakage, fiberglass and closed-cell insulations appear to perform at or above expected performance
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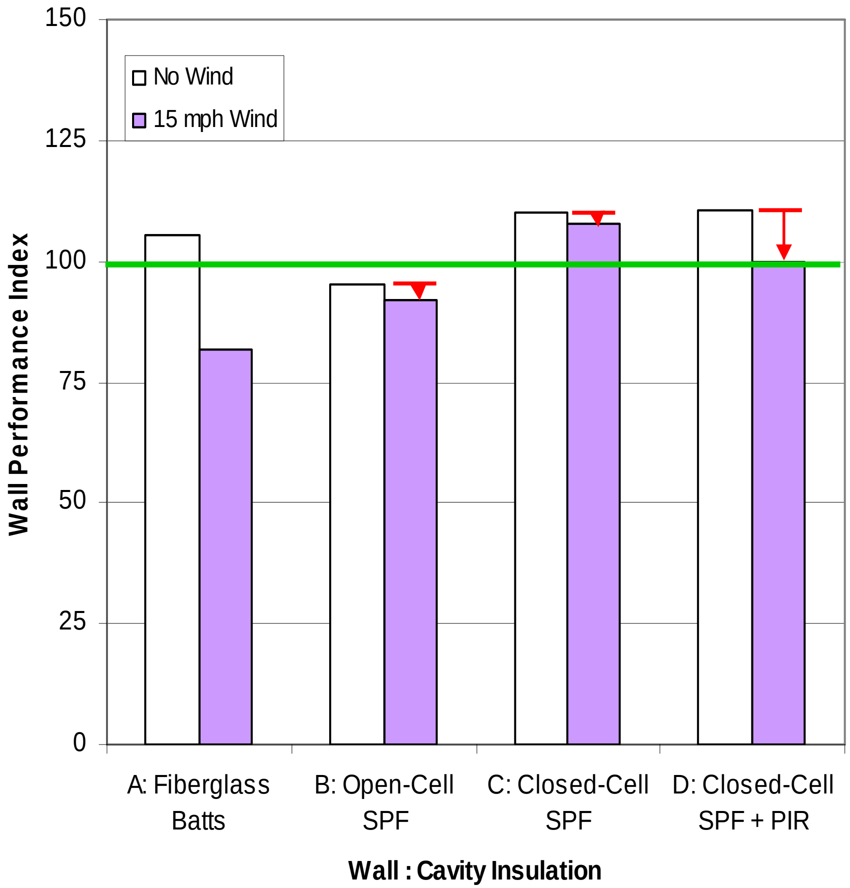

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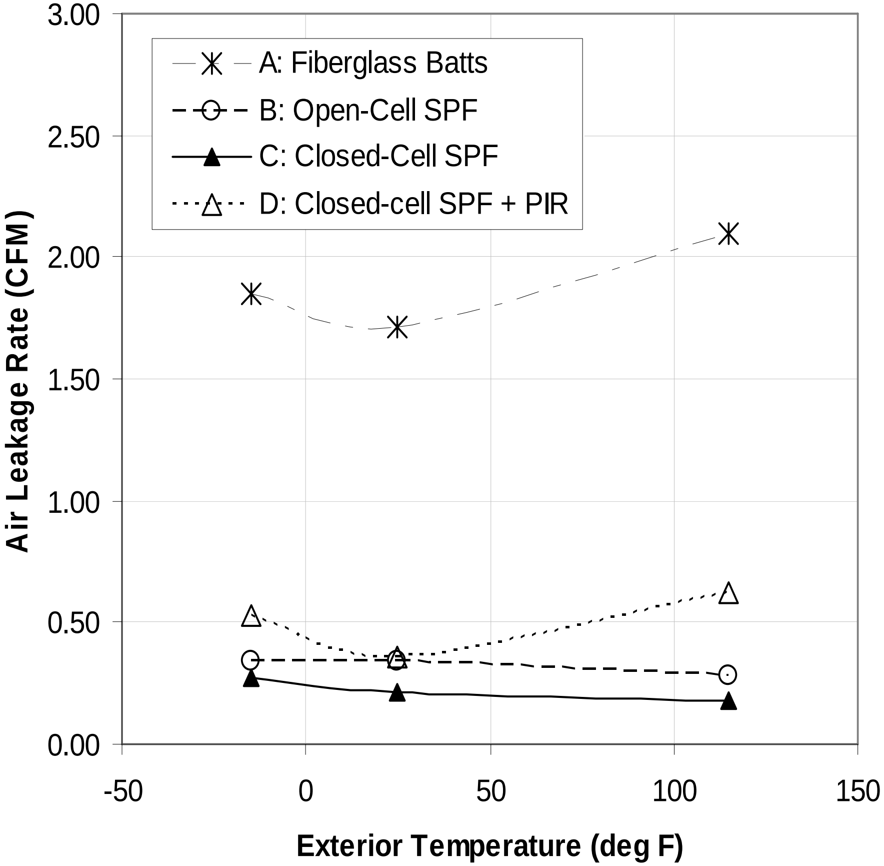
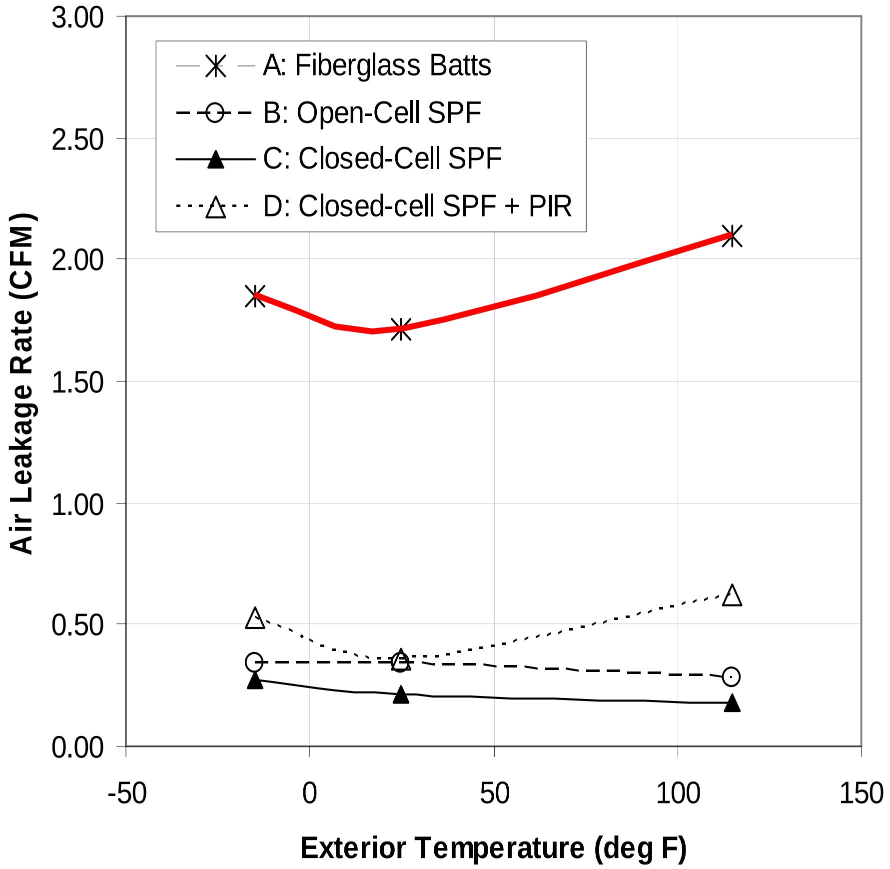
- Open-cell SPF is slightly below expected performance without wind due to extrapolation error
- Presence of air leakage from a 15 mph wind significantly reduces thermal performance of fiberglass walls.
- Much less reduction in performance observed for spray foam walls

TEST RESULTS: Air Leakage vs. Ext. Temp.



Key Observations…

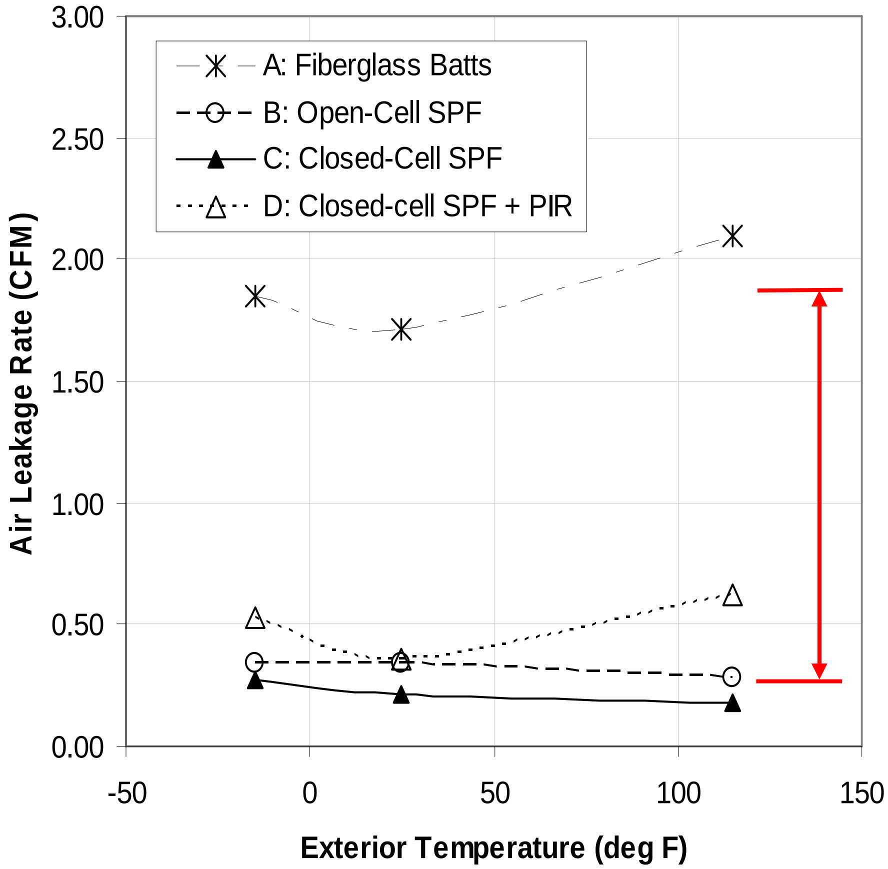
TEST RESULTS: Air Leakage vs. Ext. Temp.



Key Observations…

- The most air-permeable cavity insulation is fiberglass

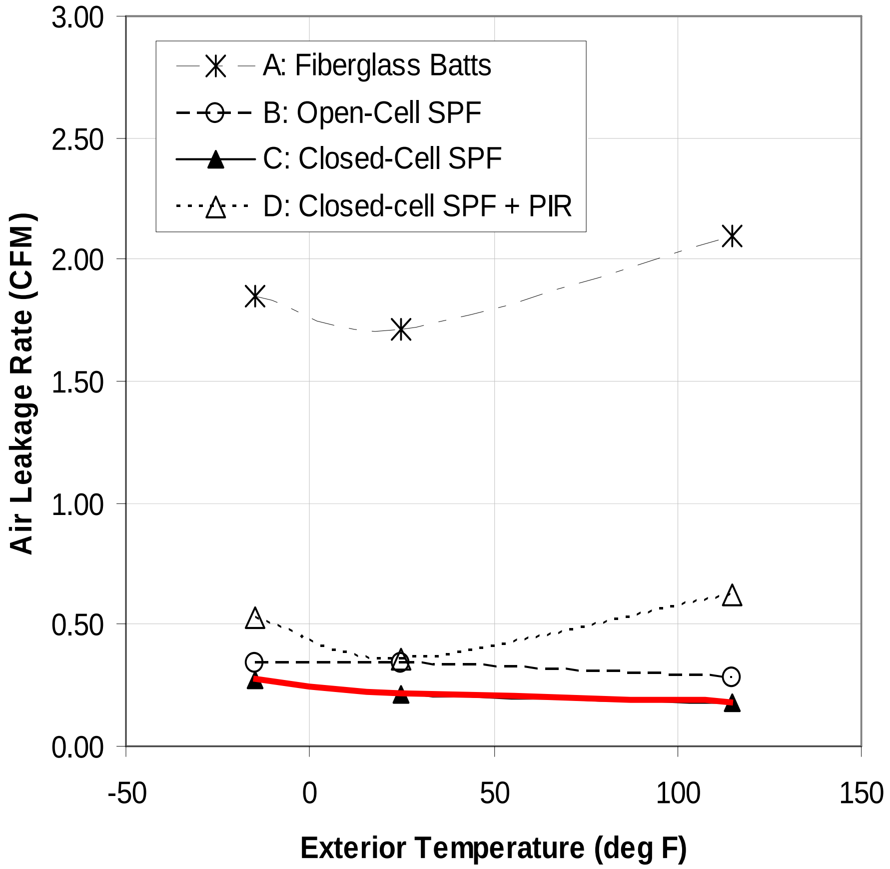
TEST RESULTS: Air Leakage vs. Ext. Temp.



Key Observations…

- The most air-permeable cavity insulation is fiberglass
- Walls using spray foam have significantly less air leakage

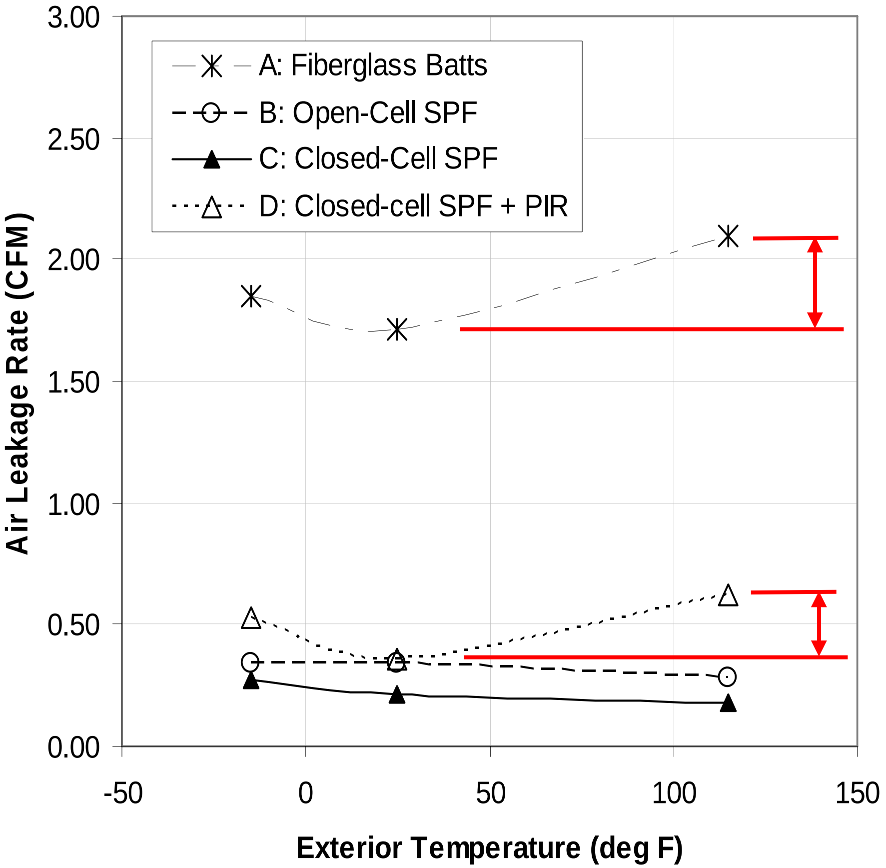
TEST RESULTS: Air Leakage vs. Ext. Temp.



Key Observations…

- The most air-permeable cavity insulation is fiberglass
- Walls using spray foam have significantly less air leakage
- Closed-cell spray foam has the lowest leakage rate, about 10% that of fiberglass

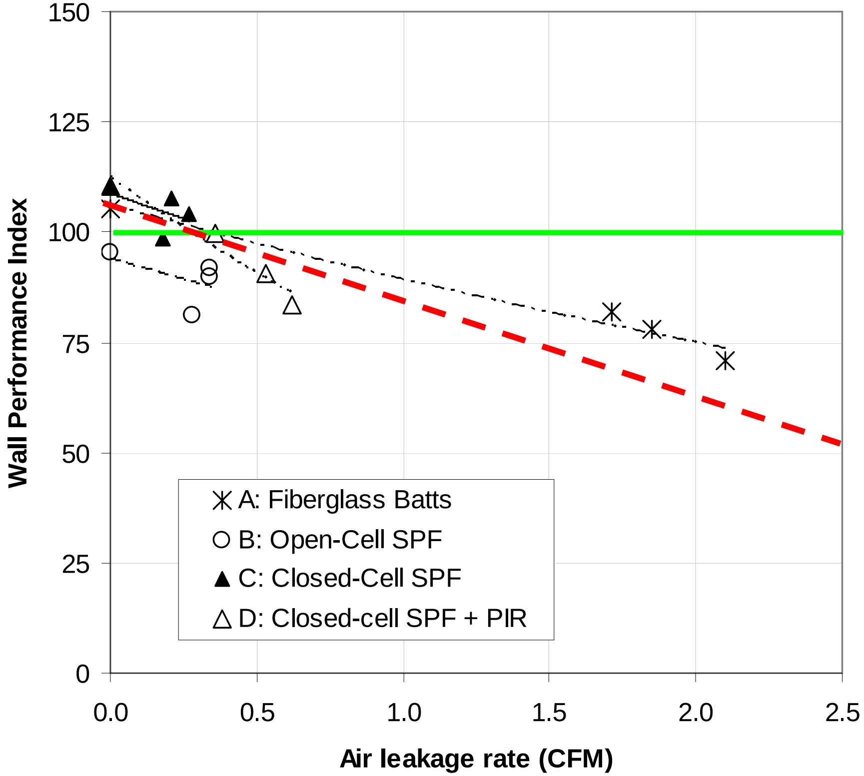
TEST RESULTS: Air Leakage vs. Ext. Temp.



Key Observations…

- The most air-permeable cavity insulation is fiberglass
- Walls using spray foam have significantly less air leakage
- Closed-cell spray foam has the lowest leakage rate, about 10% that of fiberglass
- Extreme hot/cold temperatures appear to increase leakage in fiberglass and ccSPF-polyiso walls.

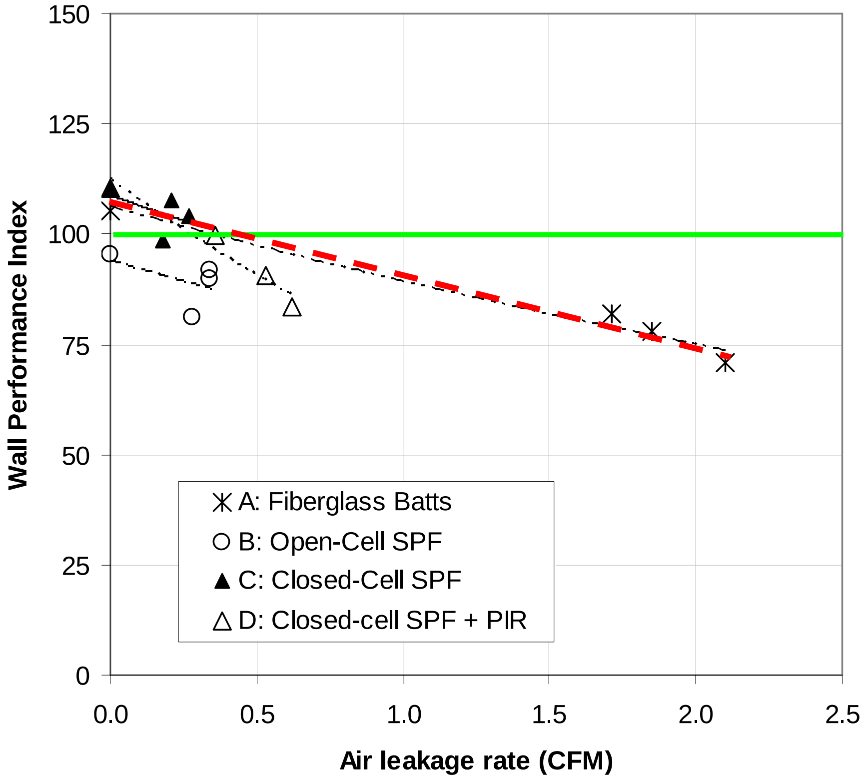
TEST RESULTS: WPI vs. Air Leakage Rate



Key Observations…

- As air leakage increases, thermal performance of all walls decrease

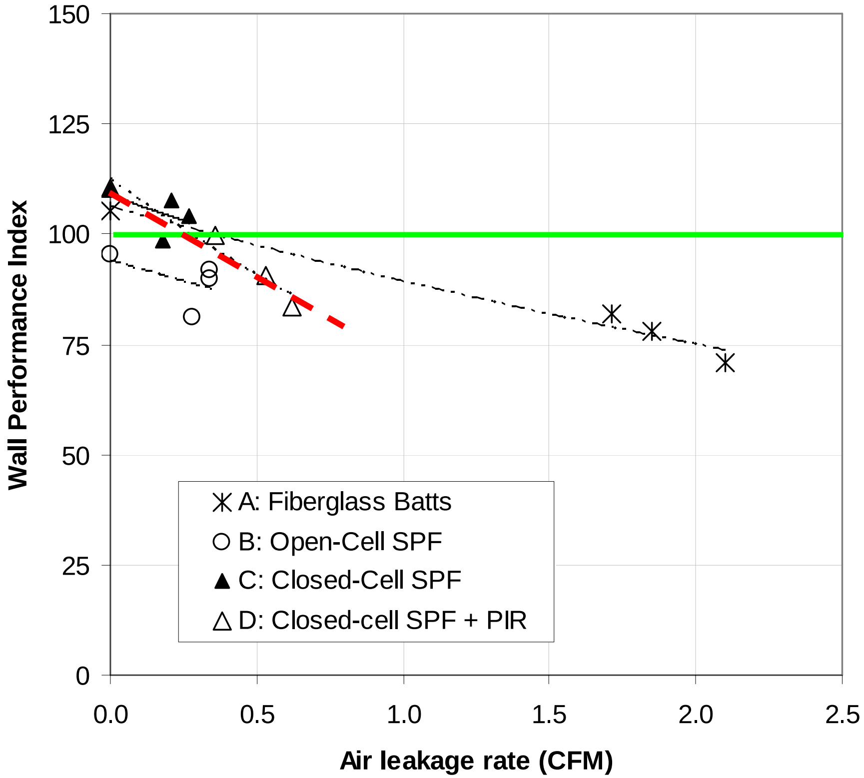
TEST RESULTS: WPI vs. Air Leakage Rate



Key Observations…

- As air leakage increases, thermal performance of all walls decrease
- Effects of air leakage most significant in fiberglass walls

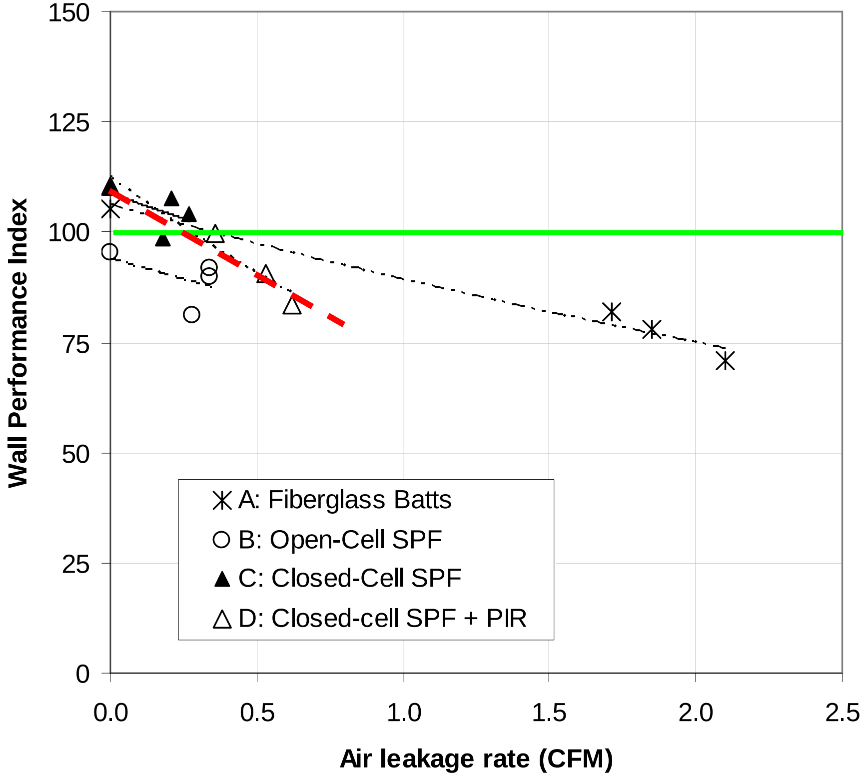
TEST RESULTS: WPI vs. Air Leakage Rate



Key Observations…

- As air leakage increases, thermal performance of all walls decrease
- Effects of air leakage most significant in fiberglass walls
- Unexpected high leakage and lower performance observed for closed-cell SPF applied to polyiso board.

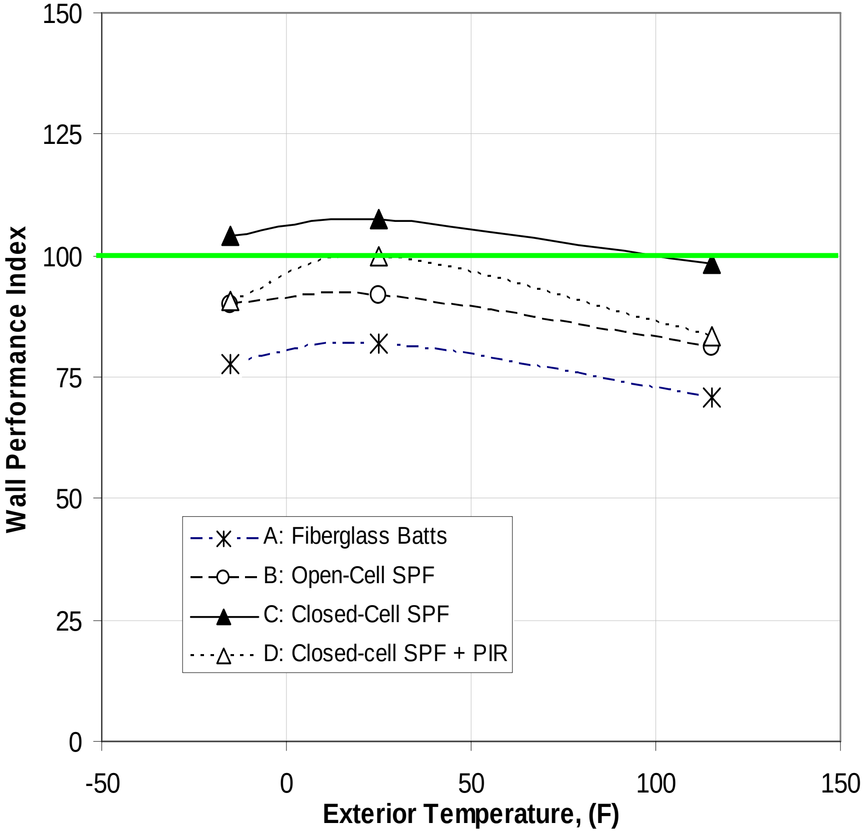
TEST RESULTS: WPI vs. Air Leakage Rate



Key Observations…

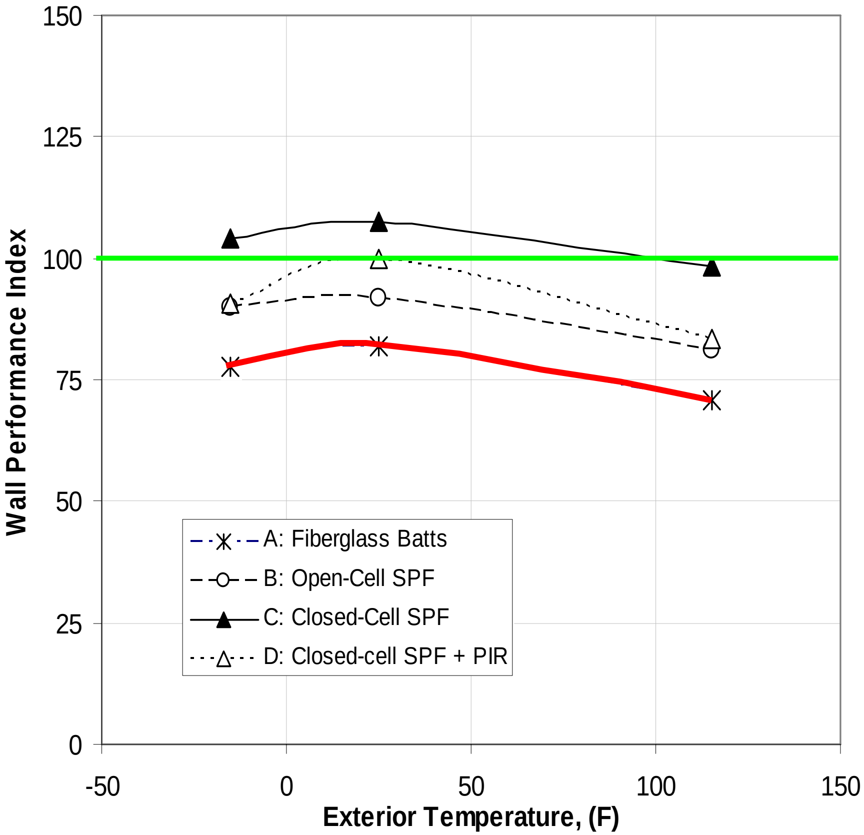
- As air leakage increases, thermal performance of all walls decrease
- Effects of air leakage most significant in fiberglass walls
- Unexpected high leakage and lower performance observed for closed-cell SPF applied to polyiso board.
- Possible delamination or thermal shrinkage at extreme temperatures ?

TEST RESULTS: WPI vs. Exterior Temperature



Key Observations…

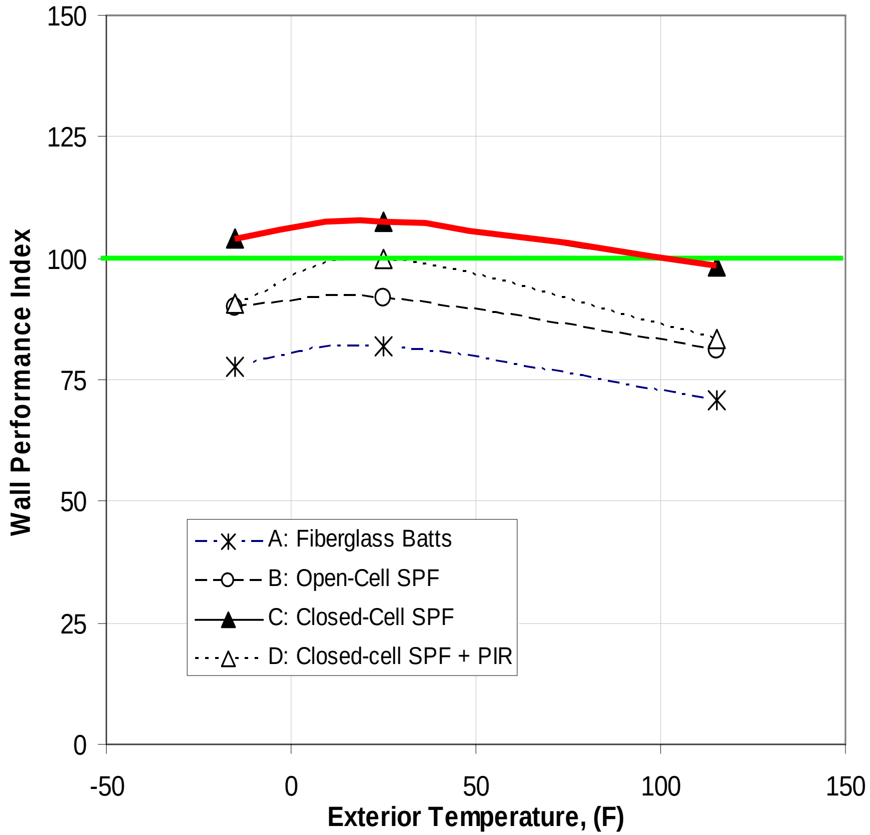
TEST RESULTS: WPI vs. Exterior Temperature



Key Observations…

- In presence of 15 mph simulated wind, fiberglass wall performs at about 82% of rated performance, decreasing down to 72% at high outdoor temperatures.

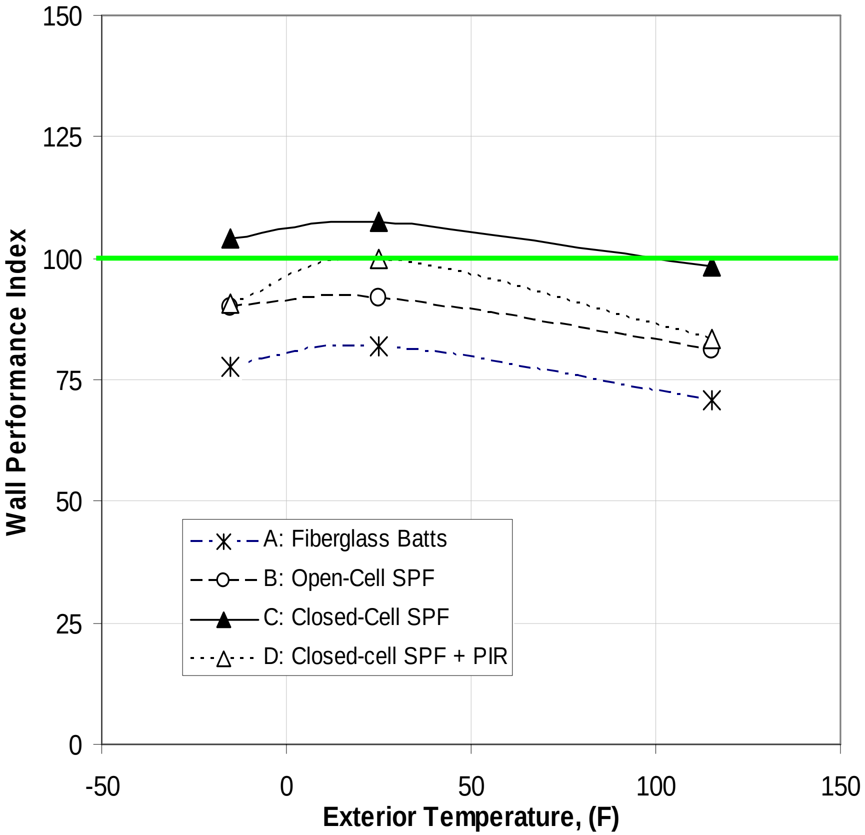
TEST RESULTS: WPI vs. Exterior Temperature



Key Observations…

- In presence of 15 mph simulated wind, fiberglass wall performs at about 82% of rated performance, decreasing down to 72% at high outdoor temperatures.
- Closed-cell SPF applied to OSB sheathing performs consistently better than expected at all temperatures.

TEST RESULTS: WPI vs. Exterior Temperature



Key Observations…

- In presence of 15 mph simulated wind, fiberglass wall performs at about 82% of rated performance, decreasing down to 72% at high outdoor temperatures.
- Closed-cell SPF applied to OSB sheathing performs consistently better than expected at all temperatures
- Cannot separate effects of mean temperature on material thermal conductivity (R-value) from effects of air leakage

CONCLUSIONS

- Fiberglass and ccSPF walls perform as expected without wind load, while ocSPF wall performs slightly below expectations, possibly due to extrapolated R-value.
- SPF insulated walls exhibit nearly 10 times less air leakage than walls insulated with fiberglass insulation under a 15 mph simulated wind load.
- Thermal performance of all SPF walls not significantly affected by wind compared to fiberglass insulated walls
- Extreme exterior temperatures increase air leakage and decrease thermal performance of all walls, possibly due to mismatched thermal expansion.
- Although it is known that insulation thermal conductivity is dependent on mean test temperature, it was not possible to delineate effects of air leakage and temperature-dependent thermal conductivities on the performance of the wall.

NEXT STEPS

- More test data is needed. Data from this study are based on single specimen of each wall type.
- Testing at extreme temperatures, with and without a simulated wind load, is needed to delineate of air leakage and mean temperature effects on wall thermal performance.
- Need to determine if cracking, shrinkage or delamination occurs at extreme temperatures – durability of air barrier materials and systems are important.
- Thermal performance of walls is dependent on air leakage. Insulations installed to the same R-value with and without integral air barriers can perform differently under wind/pressure loads.

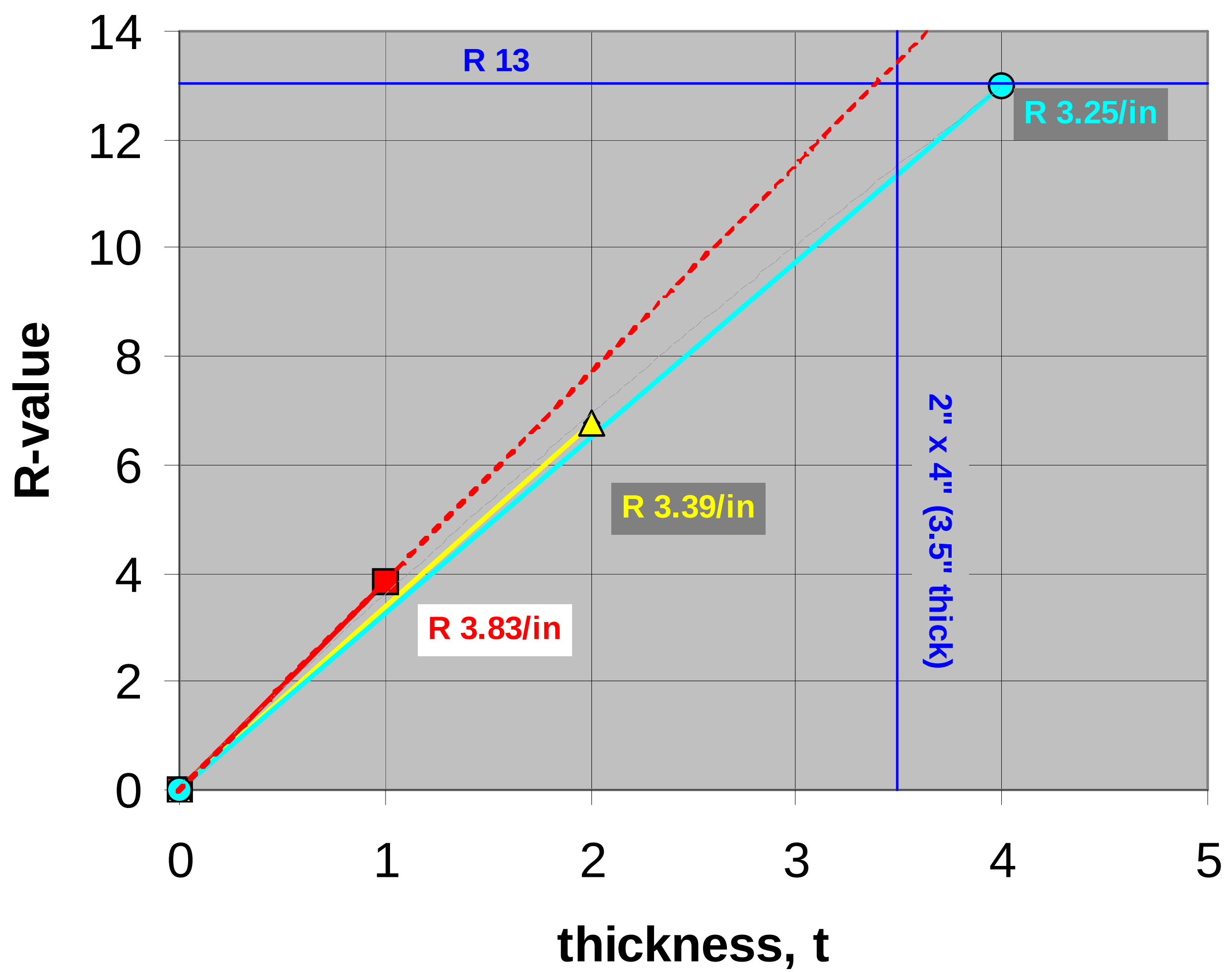
ACKNOWLEDGEMENTS

The authors of this paper would like to thank the **Spray Polyurethane Foam Alliance** and **American Chemistry Council - Center for the Polyurethanes Industry** for their management and support of this important research project.

Also, we would like to thank **Craig Drumheller of NAHB** and **Mike Toman of Architectural Testing, Inc**. for their technical insight regarding the guarded hot box test procedure.

QUESTIONS?

APPENDIX



Open-Cell SPF R-value per inch decreases with thickness

Data: Bio-Based 501.

APPENDIX

Open-cell insulation was 'short-filled' to an average thickness of 3.25"

APPENDIX

Effective Air Leakage (orifice) Area

$$A_{L:} = KQ_r \frac{\sqrt{\rho / 2\Delta P_r}}{C_D}$$

where

A_L = effective air leakage area, in^2

Q_r = air flow rate, 4.8 cfm

ρ = air density, 0.075 lbm/ft^3

ΔP_r = reference pressure difference, 0.3 in of water column

C_D = discharge coefficient (assumed to be 0.6)

K = unit conversion factor = 0.186

Equivalent Wind Velocity Pressure

$$p_v = \frac{\rho_a U^2}{2cg_c}$$

where
p_v = wind velocity pressure on the wall (inches of water)
Q_r = air flow rate, 4.8 cfm
ρ_a = air density in cold room, lbm/ft^3
U = wind velocity
g_c = gravitational constant, (32.2 ft/s^2)
c= unit conversion factor = 0.414