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

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With funding from...

Honeywell

SPFA

American Chemistry Council

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March 16-17, Hilton Torrey Pines, San Diego, CA
OVERVIEW

• BACKGROUND
  – Physics of Heat Transfer
  – Material Thermal Performance
  – Building Envelope System Thermal Performance

• TEST METHOD
  – System Thermal Performance
  – Guarded Hot Box Apparatus
  – Wall Specimens

• TEST RESULTS
  – Data Table
  – Effects of Air Leakage
  – Effects of Exterior Temperature

• CONCLUSIONS
• NEXT STEPS
• ACKNOWLEDGEMENTS
**Conduction**: through a solid material

\[ Q = \frac{kA}{t} (T_{\text{hot}} - T_{\text{cold}}) \]
**BACKGROUND: Physics of Heat Transfer**

- **Conduction:** through a solid material
  \[ Q = \frac{kA}{t} (T_{hot} - T_{cold}) \]

- **Convection:** movement of gas or liquid
  \[ Q = hA(T_{hot} - T_{cold}) \]
  \[ Q = mc_p(T_{hot} - T_{cold}) \]
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- **Radiation:** transmission of light waves
  \[ Q = c\sigma(T_{hot}^4 - T_{cold}^4) \]
BACKGROUND: Physics of Heat Transfer

- **Conduction**: through a solid material
  \[ Q = \frac{kA}{t}(T_{\text{hot}} - T_{\text{cold}}) = \frac{A}{R}(T_{\text{hot}} - T_{\text{cold}}) \]

- **Convection**: movement of gas or liquid
  \[ Q = hA(T_{\text{hot}} - T_{\text{cold}}) \]
  *R-value or thermal resistance, is a material’s ability to resist heat flow*

- **Radiation**: transmission of light waves
  \[ Q = c\sigma(T_{\text{hot}}^4 - T_{\text{cold}}^4) \]

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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 = \( \frac{1}{2}(T_{hot} + T_{cold}) \), usually 75°F
  - Range = \( T_{hot} - T_{cold} \), usually 40°F

Source: LaserComp, Inc. (www.lasercomp.com)
## Current Thermal Testing Standards

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<tr>
<th>Insulation</th>
<th>ASTM Standard</th>
<th>Mean Test Temperature, °F</th>
<th>Temperature Differential, °F</th>
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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
• Real construction practices result in defects in the building envelope
• Improper material installation will compound the effects of these defects

Air Leakage + Improper Installation = Underperformance
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
TEST METHOD: Guarded Hot Box Apparatus

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

- \( Q \) measured by metering chamber
- \( T_{w-hot}, T_{w-cold} \) measured by thermocouples
- \( U_w, R_w \) calculated above

\[ WPI = \frac{R_w^*}{R_w} \times 100 \]

- \( R_w^* \) expected wall R-value, calculated from measured material R-values
- \( R_w \) determined experimentally

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How are the leakage ports sized?

- 0.5" paper-faced gypsum board
- 0.5" oriented strand board (OSB) sheathing or PIR insulated sheathing
- 0.125" dia. intentional leakage ports through OSB sheathing only (49 total)
TEST METHOD: Wall Specimens

March 16-17, Hilton Torrey Pines, San Diego, CA
### TEST RESULTS: Experimental Data

<table>
<thead>
<tr>
<th>Wall</th>
<th>Sheathing</th>
<th>Cavity Insulation</th>
<th>Rins</th>
<th>Warm room temp (F)</th>
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<th>Wind Speed (mph)</th>
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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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### TEST RESULTS: Experimental Data

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

---

*March 16-17, Hilton Torrey Pines, San Diego, CA*
### Assembly Air Leakage

<table>
<thead>
<tr>
<th>Wall</th>
<th>Sheathing</th>
<th>Cavity Insulation</th>
<th>Rins</th>
<th>Warm room temp (F)</th>
<th>Cold room temp (F)</th>
<th>Wind Speed (mph)</th>
<th>Cold room air press (psf)</th>
<th>Metering chamber air flow (CFM)</th>
<th>Uw</th>
<th>Rw</th>
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<td>0.094</td>
<td>10.60</td>
<td>95.4</td>
</tr>
</tbody>
</table>

Assembly air leakage measured under applied pressure difference (ASTM E283)
**TEST RESULTS: Experimental Data**

<table>
<thead>
<tr>
<th>Wall</th>
<th>Sheathing</th>
<th>Cavity Insulation</th>
<th>Rins</th>
<th>Warm room temp (°F)</th>
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<th>Metering chamber air flow (CFM)</th>
<th>Uw</th>
<th>Rw</th>
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<td>FiberGlas Batts 2006</td>
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</table>

*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

March 16-17, Hilton Torrey Pines, San Diego, CA
TEST RESULTS: Air Leakage Effect @ 25°F

Key Observations...

![Bar chart showing performance index for different types of cavity insulation under no wind and 15 mph wind conditions.]

- A: Fiberglass Batts
- B: Open-Cell SPF
- C: Closed-Cell SPF
- D: Closed-Cell SPF + PIR

Wall : Cavity Insulation

March 16-17, Hilton Torrey Pines, San Diego, CA
Key Observations…

- Without forced air leakage, fiberglass and closed-cell insulations appear to perform at or above expected performance.
TEST RESULTS: Air Leakage Effect @ 25ºF

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- Presence of air leakage from a 15 mph wind significantly reduces thermal performance of fiberglass walls.
Key Observations…

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

March 16-17, Hilton Torrey Pines, San Diego, CA
TEST RESULTS: Air Leakage vs. Ext. Temp.

Key Observations…

- A: Fiberglass Batts
- B: Open-Cell SPF
- C: Closed-Cell SPF
- D: Closed-cell SPF + PIR

March 16-17, Hilton Torrey Pines, San Diego, CA
Key Observations…

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

- As air leakage increases, thermal performance of all walls decrease
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- Effects of air leakage most significant in fiberglass walls
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- Unexpected high leakage and lower performance observed for closed-cell SPF applied to polyiso board.
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- 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?
Key Observations…
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- In presence of 15 mph simulated wind, fiberglass wall performs at about 82% of rated performance, decreasing down to 72% at high outdoor temperatures.
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- Closed-cell SPF applied to OSB sheathing performs consistently better than expected at all temperatures.
**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.
• 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.
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.
Open-Cell SPF R-value per inch decreases with thickness

March 16-17, Hilton Torrey Pines, San Diego, CA
Open-cell insulation was ‘short-filled’ to an average thickness of 3.25”
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
- \( \rho \) = air density, 0.075 lbm/ft\(^3\)
- \( \Delta P_r \) = 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
\( \rho_a \) = 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