ENERGY SAVINGS FROM AIR SEALING LARGE BUILDINGS

Energy Design Conference & Expo, Duluth, MN

Dave Bohac P.E.
Director of Research
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October 28, 2013 Chris is presenting on the outcomes and benefits of PBEEEP, Minnesota’s Public Building Retro-Commissioning Program.

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Featured Staff

Mark Hancock, P.E.
Senior Mechanical Engineer
Full Bio

Brenda Yaritz
Senior Loan Officer
Full Bio
Project Team

**Center for Energy and Environment**
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- Martha Hewett
- Andrew Lutz
- Kirk Kholehma

**Air Barrier Solutions**
- Larry Harmon

**The Energy Conservatory**
- Gary Nelson
- Paul Morin
- Peter Burns

Air Leakage Test Staff:
CEE - Alex Haynor, Jerry Kimmen, Joel Lafontaine, Dan May, Erik Moe, Tom Prebich, and Isaac Smith

Bruce Stahlberg of Affordable Energy Solutions
Large Building Tightness Specification

- Measure the air flow rate needed to pressurize & depressurize the building by 75Pa (0.3 in. wc.)

- Divide by the building envelope area – typically the exterior walls + roof + floor (6 sides)

- Results from 387 US C&I buildings
  - Average = 0.72 cfm/ft²
  - Range 0.03 – 4.3 cfm/ft²
Code Requirements

- **US Army Corp Engineers = 0.25 cfm/ft$^2$**
  - Tested over 300 buildings
  - Average = 0.16 cfm/ft$^2$
- **IECC 2012 (7 states) whole building compliance path = 0.40 cfm/ft$^2$**
- **Washington State**: Buildings over five stories require a whole building test, but do not have to pass a prescribed value.
- **City of Seattle**: All buildings require a whole building test, but do not have to pass a prescribed value.
Why do we care about building air leakage?

• HVAC systems pressurize buildings to **eliminate** infiltration – don’t they?

• When HVAC is off => air infiltration

• Pressurization not always effective or implemented correctly

• NIST/Persily tracer gas results – infiltration can be significant
Air Handler Pressurization

WARM WEATHER - HVAC OFF

- Temp out = 68°F
- Infiltration = 0 cfm
- Exfiltration = 0 cfm

Pressure = 0 Pa 0 In wc

10,500 cfm

WARM WEATHER - HVAC ON

- Temp out = 68°F
- Infiltration = 0 cfm
- Exfiltration = 8,425 cfm

Pressure = 12.5 Pa 0.5 In wc

2,075 cfm

=10,500 – 2,075 cfm

4 Story 60,000sf Office Building: leakage = 27,000 cfm@75Pa, 0.5 cfm@75/ft²
Roof Top Unit Operation

MINIMUM OUTSIDE AIR
(Cooling Mode)

2,075 cfm

10,500 cfm

Center for Energy and Environment
Single-zone Constant Volume AHU

- Supply and Return Fans turn on/off by schedule
- Outside Air Damper has a minimum position setpoint for ventilation
- Relief Damper controls air exhausted from the building
Air Handler Pressurization

COLD WEATHER - HVAC OFF

Temp out = 20°F
Infiltration = 2,350 cfm
Exfiltration = 2,350 cfm

Pressure = 5.0 Pa
0.02 in wc

10,500 cfm

2,075 cfm

COLD WEATHER - HVAC ON

Temp out = 20°F
Infiltration = 0 cfm
Exfiltration = 8,425 cfm

Pressure = 18.4 Pa
0.08 in wc

Pressure = 1.0 Pa
0.01 in wc

4 Story 60,000sf Office Building: leakage = 27,000 cfm@75Pa, 0.5 cfm@75/ft²
Air Handler Pressurization

COLD WEATHER - HVAC OFF

Temp out = 20° F
Infiltration = 2,350 cfm
Exfiltration = 2,350 cfm

Pressure = 5.0 Pa
0.02 in wc

COLDER WEATHER - HVAC ON

Temp out = 0° F
Infiltration = 292 cfm
Exfiltration = 8,717 cfm

Pressure = 24.7 Pa
0.10 in wc

4 Story 60,000sf Office Building: leakage = 27,000 cfm@75Pa, 0.5 cfm@75/ft²
Air Handler Pressurization

COLD WEATHER - HVAC ON

Temp out = 20° F
Infiltration = 418 cfm
Exfiltration = 8,843 cfm

Wind = 15 mph

Pressure = 5.0 Pa
0.02 in wc

Pressure = 12.4 Pa
0.05 in wc

Pressure = 22.8 Pa
0.09 in wc

Pressure = 5.4 Pa
0.02 in wc

10,500 cfm

2,075 cfm

Infiltration >>

4 Story 60,000sf Office Building: leakage = 27,000 cfm@75Pa, 0.5 cfm@75/ft²
Roof Top Unit Operation

MINIMUM OUTSIDE AIR
(Cooling Mode)

FULLY ECONOMIZED
Single-zone Constant Volume AHU

- **Economizer operation**
  - Mild weather when building needs cooling
  - Open outdoor air dampers, exhaust dampers follow; OA – EA stays the same?

### AHU Schematic

- **Relief Air**
  - 16,175 cfm – Exhaust Fans
  - 60% open

- **Outside Air**
  - 24,600 cfm
  - 60% open

- **Mixed Air**
  - 40% open

- **Return Fan**

- **Supply Fan**

- **DAT Sensor**

- **MAT Sensor**

From Space to Space
Variable Volume AHU with VAV Boxes

- Supply and Return Fans
  - Supply fan VFD modulates to meet Duct Static Pressure (DSP) Setpoint
  - Return fan lags supply fan to maintain positive pressure
Model Infiltration: Range of Flow Imbalance

HVAC Flow Imbalance
- -3,450cfm 0.75 (-1.5Pa)
- 0cfm 0.75
- 3,450cfm 0.75 (1.5Pa)
- 6,900cfm 0.75 (4Pa)
- 17,250cfm 0.75 (17Pa)

1 Story 60,560ft² Elementary School: leakage = 44,670 cfm@75Pa (0.75cfm@75/ft²)
Model Infiltration: Range of Flow Imbalance

1 Story 60,560ft² Elementary School: leakage = 14,890 cfm@75Pa (0.25cfm@75/ft²)
# Model Infiltration: Range of Flow Imbalance

Envelope Leakage = 0.75 cfm@75Pa/ft²

<table>
<thead>
<tr>
<th>HVAC Flow Imbalance, OA - EA (cfm)</th>
<th>-3,450</th>
<th>0</th>
<th>3,450</th>
<th>6,900</th>
<th>17,250</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg Infil. (cfm)</td>
<td>2,986</td>
<td>2,444</td>
<td>2,077</td>
<td>1,849</td>
<td>1,652</td>
</tr>
<tr>
<td>Avg Infil. (ach)</td>
<td>0.25</td>
<td>0.20</td>
<td>0.17</td>
<td>0.15</td>
<td>0.14</td>
</tr>
<tr>
<td>Heat Load (therms/yr)</td>
<td>7,264</td>
<td>6,114</td>
<td>5,260</td>
<td>4,732</td>
<td>4,308</td>
</tr>
<tr>
<td>% Space Heating</td>
<td>19%</td>
<td>16%</td>
<td>14%</td>
<td>12%</td>
<td>11%</td>
</tr>
<tr>
<td>Cost ($)</td>
<td>$4,213</td>
<td>$3,546</td>
<td>$3,051</td>
<td>$2,745</td>
<td>$2,499</td>
</tr>
</tbody>
</table>
# Model Infiltration: Range of Flow Imbalance

**Envelope Leakage= 0.75 cfm@75Pa/ft²**

<table>
<thead>
<tr>
<th>HVAC Flow Imbalance, OA - EA (cfm)</th>
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**Envelope Leakage= 0.25 cfm@75Pa/ft²**

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<tr>
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<th>3,450</th>
<th>6,900</th>
<th>17,250</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg Infil. (cfm)</td>
<td>1,725</td>
<td>951</td>
<td>708</td>
<td>678</td>
<td>676</td>
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<tr>
<td>Avg Infil. (ach)</td>
<td>0.14</td>
<td>0.08</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
</tr>
<tr>
<td>Heat Load (therms/yr)</td>
<td>4,004</td>
<td>2,439</td>
<td>1,875</td>
<td>1,813</td>
<td>1,809</td>
</tr>
<tr>
<td>% Space Heating</td>
<td>10%</td>
<td>6%</td>
<td>5%</td>
<td>5%</td>
<td>5%</td>
</tr>
<tr>
<td>Cost ($)</td>
<td>$2,322</td>
<td>$1,414</td>
<td>$1,087</td>
<td>$1,052</td>
<td>$1,049</td>
</tr>
</tbody>
</table>
What about Energy Recovery Ventilators?

- Why not run the exhaust air through an ERV to recovery some of that energy instead of forcing it out through the envelope?
- Need a tighter envelope to accomplish ERVs with infiltration control
Air Leakage Test Video

This slide contains a 5 minute video that provides an overview of the whole building air leakage test process.

The video can be found on CEE’s web site at: www.mncee.org/Innovation-Exchange/Projects/Current/Capturing-energy-Savings-from-Large-Building-Envel/
How leaky or tight are US buildings?

- Test results compiled by the National Institute of Standards and Technology (NIST) – Emmerich and Persily – over the past 15 years
  - 387 commercial and institutional buildings
  - **NOT RANDOM**: researchers, low-energy programs, private testing firms
  - Used to model air infiltration energy loads and help establish leakage standards
# NIST Results from US whole building tests

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Qty</th>
<th>Mean</th>
<th>Std Dev</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency Vermont</td>
<td>36</td>
<td>0.35</td>
<td>0.38</td>
<td>0.03</td>
<td>1.78</td>
</tr>
<tr>
<td>ASHRAE RP 1478</td>
<td>16</td>
<td>0.29</td>
<td>0.20</td>
<td>0.06</td>
<td>0.75</td>
</tr>
<tr>
<td>Washington</td>
<td>18</td>
<td>0.40</td>
<td>0.15</td>
<td>0.11</td>
<td>0.64</td>
</tr>
<tr>
<td>Other VT/NH</td>
<td>79</td>
<td>0.54</td>
<td>0.40</td>
<td>0.05</td>
<td>1.73</td>
</tr>
<tr>
<td>Other</td>
<td>10</td>
<td>0.30</td>
<td>0.23</td>
<td>0.09</td>
<td>0.75</td>
</tr>
<tr>
<td><strong>All new data</strong></td>
<td>159</td>
<td><strong>0.36</strong></td>
<td><strong>0.30</strong></td>
<td><strong>0.03</strong></td>
<td><strong>1.78</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Qty</th>
<th>Mean</th>
<th>Std Dev</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>All previous data</strong></td>
<td>228</td>
<td><strong>0.92</strong></td>
<td><strong>0.70</strong></td>
<td><strong>0.09</strong></td>
<td><strong>4.28</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Qty</th>
<th>Mean</th>
<th>Std Dev</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Buildings</td>
<td>387</td>
<td>0.72</td>
<td>0.63</td>
<td>0.03</td>
<td>4.28</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Qty</th>
<th>Mean</th>
<th>Std Dev</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>USACE &amp; Navy</strong></td>
<td>300</td>
<td><strong>0.16</strong></td>
<td>USACE Std = 0.25</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

Emmerich and Persily 2013
NIST Results: Frequency Histogram

USACE Std = 4.5
20-25% meet Std

Multiply by 0.055 >> cfm/ft$^2$
NIST Results: Weak Trends

- Tighter – office, education, public assembly & long-term health care
- Leakier – retail, restaurants, industrial
- Leakier exterior walls – frame, masonry/metal, & frame/masonry
NIST Results: Effect of Building Size

Buildings > 54,000ft² twice as tight

Emmerich and Persily 2013
NIST Results: Effect of Climate

Heating degree days > 3,600 one third tighter

Emmerich and Persily 2013
NIST Results: Effect of Age

138 buildings with no air barriers built since 1950 – no strong trend

Emmerich and Persily 2013
NIST Results: LEED Buildings

- 23 LEED buildings; average = 0.29 cfm/ft²
- Significantly tighter than average of other 364 buildings
- Slightly (5%) leakier than other 56 buildings with an air barrier
NIST Results: Effect of Air Barrier

Buildings with air barrier are 70% tighter

USACE Std = 4.5, 0.25 cfm/ft²

Emmerich and Persily 2013
NIST Results: Effect of Air Barrier

Compare no air barrier to tight construction

USACE Std = 4.5, 0.25cfm/ft$^2$
NIST Building Infiltration & Energy Models

- Multizone infiltration and energy model
- Compared air infiltration and energy use for:
  - “typical” - no air barrier reported leakage (4x USACE)
  - “target” – good practice (40% below USACE)
- Five cities in different climate zones
### Two-Story, 24,000ft² Office Building

<table>
<thead>
<tr>
<th>City</th>
<th>Annual Average Infiltration (h⁻¹)</th>
<th>Gas Savings</th>
<th>Electrical Savings</th>
<th>Total Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Baseline Target</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bismarck</td>
<td>0.22</td>
<td>0.05</td>
<td>$1,854</td>
<td>42%</td>
</tr>
<tr>
<td><strong>Minneapolis</strong></td>
<td>0.23</td>
<td>0.05</td>
<td><strong>$1,872</strong></td>
<td><strong>43%</strong></td>
</tr>
<tr>
<td>St. Louis</td>
<td>0.26</td>
<td>0.04</td>
<td>$1,460</td>
<td>57%</td>
</tr>
<tr>
<td>Phoenix</td>
<td>0.17</td>
<td>0.02</td>
<td>$124</td>
<td>77%</td>
</tr>
<tr>
<td>Miami</td>
<td>0.26</td>
<td>0.03</td>
<td>$0</td>
<td>0%</td>
</tr>
</tbody>
</table>

### One-Story, 12,000ft² Retail Building

<table>
<thead>
<tr>
<th>City</th>
<th>Annual Average Infiltration (h⁻¹)</th>
<th>Gas Savings</th>
<th>Electrical Savings</th>
<th>Total Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Baseline Target</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bismarck</td>
<td>0.20</td>
<td>0.02</td>
<td>$1,835</td>
<td>26%</td>
</tr>
<tr>
<td><strong>Minneapolis</strong></td>
<td>0.22</td>
<td>0.02</td>
<td><strong>$1,908</strong></td>
<td><strong>28%</strong></td>
</tr>
<tr>
<td>St. Louis</td>
<td>0.24</td>
<td>0.01</td>
<td>$1,450</td>
<td>38%</td>
</tr>
<tr>
<td>Phoenix</td>
<td>0.13</td>
<td>0.00</td>
<td>$176</td>
<td>64%</td>
</tr>
<tr>
<td>Miami</td>
<td>0.21</td>
<td>0.01</td>
<td>$6</td>
<td>98%</td>
</tr>
</tbody>
</table>

Emmerich and Persily 2013
Model Infiltration: Range of Envelope Leakage

1 Story 60,560ft² Elementary School: HVAC Imbalance = 3,450 cfm
Model Infiltration: Range of Envelope Leakage

1 Story 60,560ft² Elementary School: HVAC Imbalance = 3,450 cfm

<table>
<thead>
<tr>
<th>Building Envelope Leakage (cfm@75/ft²)</th>
<th>0.05</th>
<th>0.1</th>
<th>0.15</th>
<th>0.25</th>
<th>0.4</th>
<th>0.75</th>
<th>1.25</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg Infil. (cfm)</td>
<td>305</td>
<td>417</td>
<td>481</td>
<td>708</td>
<td>1,094</td>
<td>2,077</td>
<td>3,539</td>
<td>5,751</td>
</tr>
<tr>
<td>Avg Infil. (ach)</td>
<td>0.03</td>
<td>0.03</td>
<td>0.04</td>
<td>0.06</td>
<td>0.09</td>
<td>0.17</td>
<td>0.29</td>
<td>0.47</td>
</tr>
<tr>
<td>Heat Load (therms/yr)</td>
<td>855</td>
<td>1,139</td>
<td>1,305</td>
<td>1,875</td>
<td>2,832</td>
<td>5,260</td>
<td>8,867</td>
<td>14,322</td>
</tr>
<tr>
<td>% Space Heating</td>
<td>2%</td>
<td>3%</td>
<td>3%</td>
<td>5%</td>
<td>7%</td>
<td>14%</td>
<td>23%</td>
<td>37%</td>
</tr>
<tr>
<td>Cost ($)</td>
<td>$496</td>
<td>$661</td>
<td>$757</td>
<td>$1,087</td>
<td>$1,643</td>
<td>$3,051</td>
<td>$5,143</td>
<td>$8,306</td>
</tr>
</tbody>
</table>

NIST office building model:
1.0 cfm/ft² = 0.23 ach
0.1 cfm/ft² = 0.05 ach
ASHRAE Research: selection criteria

- Goal: 24 to 36 existing mid- and high-rise buildings (16 Completed)
- Non-residential
- 4 stories or higher
- Sustainability certification (14 of 16)
- Built after the year 2000
- Climate zones 2-7 (All 6 Zones Represented)
ASHRAE Research Project: leakage results

- Average = 0.29 cfm/ft²

- Green building = 0.32 cfm/ft²; others = 0.22 cfm/ft²

- Air barrier specified and envelope expert = 0.13 cfm/ft²; others = 0.39 cfm/ft²

- Unsealing HVAC penetrations increased leakage by average of 27% with range of 2% to 51%
ASHRAE Research Project: leakage sites

- Roof/wall intersection
- Soffits and overhangs
- Mechanical rooms, garages, basements, loading docks
- Roll-up and overhead doors
Minnesota Leakage Study: work scope

- Conduct investigations on 25 buildings: floor area of 25,000 to 500,000 ft\(^2\)
- Air seal and pre/post leakage tests on 7 buildings
- Continuous building pressure and HVAC operation data for 50 to 200 days
- CONTAM pre/post air flow models that include mechanical system leakage and pressure effects
- Compute infiltration/energy reductions
Building Characteristics

<table>
<thead>
<tr>
<th>Building ID</th>
<th>Area (sf)</th>
<th>Stories</th>
<th>Year</th>
<th>Wall Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elem School TF</td>
<td>59,558</td>
<td>1</td>
<td>1951</td>
<td>Masonry &amp; corrugated metal panel</td>
</tr>
<tr>
<td>Middle School</td>
<td>138,887</td>
<td>3</td>
<td>1936</td>
<td>Cast concrete w/CMU infill</td>
</tr>
<tr>
<td>Small Office</td>
<td>26,927</td>
<td>1</td>
<td>1998</td>
<td>EFIS tip up (3 walls) and CMU block</td>
</tr>
<tr>
<td>Univ Library</td>
<td>246,365</td>
<td>3</td>
<td>1967</td>
<td>Cast concrete w/CMU infill &amp; brick ext</td>
</tr>
<tr>
<td>Elem School PS</td>
<td>60,968</td>
<td>1</td>
<td>1965</td>
<td>CMU w/brick exterior</td>
</tr>
<tr>
<td>Library/Office</td>
<td>55,407</td>
<td>1</td>
<td>2007</td>
<td>Steel studs &amp; brick or stone cladding</td>
</tr>
</tbody>
</table>

3 elementary & middle schools: 1936 to 1965 with additions 60,000 – 139,000sf
## Minnesota Leakage Study: leakage results

All 7 buildings at least 25% tighter than the US Army Corp standard of 0.25 cfm/ft²

<table>
<thead>
<tr>
<th>Building ID</th>
<th>Floor Area (ft²)</th>
<th>Envelope Area (ft²)</th>
<th>6 Sides² (cfm)</th>
<th>6 Sides² (cfm/ft²)</th>
<th>EqLA (ft²)</th>
<th># Stories</th>
<th>Constr Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elem School TF</td>
<td>59,558</td>
<td>146,977</td>
<td>27,425</td>
<td>0.19</td>
<td>15.2</td>
<td>1</td>
<td>1951</td>
</tr>
<tr>
<td>Comm. College</td>
<td>95,000</td>
<td>164,844</td>
<td>28,881</td>
<td>0.18</td>
<td>17.2</td>
<td>2</td>
<td>1996</td>
</tr>
<tr>
<td>Middle School</td>
<td>138,887</td>
<td>208,733</td>
<td>32,818</td>
<td>0.16</td>
<td>16.6</td>
<td>3</td>
<td>1936</td>
</tr>
<tr>
<td>Small Office</td>
<td>26,927</td>
<td>65,267</td>
<td>9,177</td>
<td>0.14</td>
<td>4.6</td>
<td>1</td>
<td>1998</td>
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<tr>
<td>Univ Library</td>
<td>246,365</td>
<td>171,712</td>
<td>23,356</td>
<td>0.14</td>
<td>13.1</td>
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<td>1967</td>
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<td>145,766</td>
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<td>1</td>
<td>1965</td>
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<tr>
<td>Library/Office</td>
<td>55,407</td>
<td>139,965</td>
<td>12,321</td>
<td>0.09</td>
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<td>2007</td>
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<tr>
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<td>26,927</td>
<td>65,267</td>
<td>9,177</td>
<td>0.09</td>
<td>4.6</td>
<td></td>
<td></td>
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<tr>
<td>Mean</td>
<td>97,587</td>
<td>149,038</td>
<td>21,654</td>
<td>0.14</td>
<td>11.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Median</td>
<td>60,968</td>
<td>146,977</td>
<td>23,356</td>
<td>0.14</td>
<td>13.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum</td>
<td>246,365</td>
<td>208,733</td>
<td>32,818</td>
<td>0.19</td>
<td>17.2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Comparison to US Buildings

7 building average is 85% less than the US average, slightly less than US Army Corp average
Tighter Buildings in Colder Climates?

7 building average is 85% less than the US average
Where Were the Leaks?

- Ext Doors: 17%
- Windows: 4%
- Mech Penetr.: 3%
- Soffit: 4%
- Other: 5%
- Roof/wall: 67%
Where Were the Leaks?

[Bar chart showing the percentage of identified enclosure leakage for various buildings, categorized by type of leak (Other, Soffit, Windows, Mech Penetr., Ext Doors, Roof/wall).]
Air Sealing Focused on Roof/wall

Canopy leakage at exterior wall
Air Sealing Focused on Roof/wall

Canopy leakage at exterior wall

IR Before

IR After
Where to look: IR view of rear CMU wall pre

Same wall post
Look inside: 10 beam pockets

Open above to parapet cap

Open to inside

Smoke shows airflow
Closed cell foam fill, don’t create fire hazard

See ICC ES 3228 approvals. maintain exhaust on work space adj. to occupied office
Sample MDI < 5ppb
Manage exposure

¾ cu ft foam block max temp rise check for building official and owner before injection.

Don’t start a fire
Beam Pockets

IR Before

IR After
Air Sealing Reduction

“Tight” buildings tightened by 9%

<table>
<thead>
<tr>
<th>Building ID</th>
<th>Air Leakage at 75Pa</th>
<th>6 Sides</th>
<th>Pre (cfm)</th>
<th>Post (cfm)</th>
<th>Reduction (cfm)</th>
<th>Reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elem School TF</td>
<td>0.19</td>
<td>27,425</td>
<td>22,699</td>
<td>4,726</td>
<td>17%</td>
<td></td>
</tr>
<tr>
<td>Comm. College</td>
<td>0.18</td>
<td>28,881</td>
<td>28,133</td>
<td>748</td>
<td>3%</td>
<td></td>
</tr>
<tr>
<td>Middle School</td>
<td>0.16</td>
<td>32,818</td>
<td>28,872</td>
<td>3,947</td>
<td>12%</td>
<td></td>
</tr>
<tr>
<td>Small Office</td>
<td>0.14</td>
<td>9,177</td>
<td>8,470</td>
<td>708</td>
<td>8%</td>
<td></td>
</tr>
<tr>
<td>Univ Library</td>
<td>0.14</td>
<td>23,356</td>
<td>21,963</td>
<td>1,392</td>
<td>6%</td>
<td></td>
</tr>
<tr>
<td>Elem School PS</td>
<td>0.12</td>
<td>17,602</td>
<td>15,837</td>
<td>1,765</td>
<td>10%</td>
<td></td>
</tr>
<tr>
<td>Library/Office</td>
<td>0.09</td>
<td>12,321</td>
<td>11,369</td>
<td>953</td>
<td>8%</td>
<td></td>
</tr>
<tr>
<td>Minimum</td>
<td>0.09</td>
<td>9,177</td>
<td>8,470</td>
<td>708</td>
<td>3%</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>0.14</td>
<td>21,654</td>
<td>19,620</td>
<td>2,034</td>
<td>9%</td>
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<tr>
<td>Median</td>
<td>0.14</td>
<td>23,356</td>
<td>21,963</td>
<td>1,392</td>
<td>8%</td>
<td></td>
</tr>
<tr>
<td>Maximum</td>
<td>0.19</td>
<td>32,818</td>
<td>28,872</td>
<td>4,726</td>
<td>17%</td>
<td></td>
</tr>
</tbody>
</table>

Air sealing work confirmed by visual, smoke puffer, and IR inspections
## Air Sealing Reduction

**More expensive to seal tighter buildings?**

<table>
<thead>
<tr>
<th>Building ID</th>
<th>Total</th>
<th>($/CFM75)</th>
<th>($/ft²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elem School TF</td>
<td>$18,550</td>
<td>$3.92</td>
<td>$6,822</td>
</tr>
<tr>
<td>Comm. College</td>
<td>$17,845</td>
<td>$23.86</td>
<td>$17,273</td>
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<tr>
<td>Middle School</td>
<td>$23,700</td>
<td>$6.00</td>
<td>$8,434</td>
</tr>
<tr>
<td>Small Office</td>
<td>$4,768</td>
<td>$6.73</td>
<td>$10,058</td>
</tr>
<tr>
<td>Univ Library</td>
<td>$15,918</td>
<td>$11.43</td>
<td>$65,159</td>
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<tr>
<td>Elem School PS</td>
<td>$26,700</td>
<td>$15.13</td>
<td>$38,132</td>
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<tr>
<td>Library/Office</td>
<td>$1,152</td>
<td>$1.21</td>
<td>$1,297</td>
</tr>
<tr>
<td>Median</td>
<td>$17,845</td>
<td>$6.73</td>
<td>$10,058</td>
</tr>
</tbody>
</table>

**Cost per sq ft of sealing**
## Air Sealing Reduction

Contractor estimates better for leakier buildings?

<table>
<thead>
<tr>
<th>Building ID</th>
<th>EqLA (ft²)</th>
<th>Reduction</th>
<th>Sealed Area (sf)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre</td>
<td>Post</td>
<td>(ft²)</td>
</tr>
<tr>
<td>Elem School TF</td>
<td>15.2</td>
<td>12.5</td>
<td>2.7</td>
</tr>
<tr>
<td>Comm. College</td>
<td>17.2</td>
<td>16.2</td>
<td>1.0</td>
</tr>
<tr>
<td>Middle School</td>
<td>16.6</td>
<td>13.8</td>
<td>2.8</td>
</tr>
<tr>
<td>Small Office</td>
<td>4.6</td>
<td>4.1</td>
<td>0.5</td>
</tr>
<tr>
<td>Univ Library</td>
<td>13.1</td>
<td>12.8</td>
<td>0.2</td>
</tr>
<tr>
<td>Elem School PS</td>
<td>9.6</td>
<td>8.9</td>
<td>0.7</td>
</tr>
<tr>
<td>Library/Office</td>
<td>6.9</td>
<td>6.0</td>
<td>0.9</td>
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</tbody>
</table>

Building Leakage < Estimated sealing
## Modeled Infiltration and Energy Savings

<table>
<thead>
<tr>
<th>Building ID</th>
<th>Total</th>
<th>Infiltration</th>
<th>Infil/Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elem School TF</td>
<td>40,224</td>
<td>2,389</td>
<td>6%</td>
</tr>
<tr>
<td>Comm. College</td>
<td>32,095</td>
<td>3,402</td>
<td>11%</td>
</tr>
<tr>
<td>Middle School</td>
<td>44,469</td>
<td>7,779</td>
<td>17%</td>
</tr>
<tr>
<td>Small Office</td>
<td></td>
<td>684</td>
<td></td>
</tr>
<tr>
<td>Univ Library</td>
<td></td>
<td>192</td>
<td></td>
</tr>
<tr>
<td>Elem School PS</td>
<td>26,563</td>
<td>2,387</td>
<td>9%</td>
</tr>
<tr>
<td>Library/Office</td>
<td>18,108</td>
<td>2,829</td>
<td>16%</td>
</tr>
<tr>
<td>Minimum</td>
<td></td>
<td></td>
<td>6%</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td></td>
<td>12%</td>
</tr>
<tr>
<td>Median</td>
<td></td>
<td></td>
<td>11%</td>
</tr>
<tr>
<td>Maximum</td>
<td></td>
<td></td>
<td>17%</td>
</tr>
</tbody>
</table>
## Air Sealing Energy Savings

### Modeled Infiltration and Energy Savings

<table>
<thead>
<tr>
<th>Building ID</th>
<th>Total (Therm/yr)</th>
<th>Infiltration (Therm/yr)</th>
<th>Infil/Total (%)</th>
<th>Gas Savings ($/yr)</th>
<th>Avg Infil (cfm)</th>
<th>Leakage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elem School TF</td>
<td>40,224</td>
<td>2,389</td>
<td>6%</td>
<td>549</td>
<td>$319</td>
<td>1,296</td>
</tr>
<tr>
<td>Comm. College</td>
<td>32,095</td>
<td>3,402</td>
<td>11%</td>
<td>174</td>
<td>$105</td>
<td>1,730</td>
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<tr>
<td>Middle School</td>
<td>44,469</td>
<td>7,779</td>
<td>17%</td>
<td>905</td>
<td>$525</td>
<td>4,330</td>
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<td>$6</td>
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<tr>
<td>Elem School PS</td>
<td>26,563</td>
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<tr>
<td>Library/Office</td>
<td>18,108</td>
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<td>107</td>
<td>$68</td>
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<td>$6</td>
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<td>287</td>
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<td></td>
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<td>174</td>
<td>$105</td>
<td>1,453</td>
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<tr>
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<td></td>
<td></td>
<td>17%</td>
<td>905</td>
<td>$525</td>
<td>4,330</td>
</tr>
</tbody>
</table>

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**Center for Energy and Environment**
## Air Sealing Energy Savings

### Modeled Infiltration and Energy Savings

<table>
<thead>
<tr>
<th>Building ID</th>
<th>Gas Savings (Therm/yr)</th>
<th>Gas Savings ($/yr)</th>
<th>Electric Savings (kWh/yr)</th>
<th>Electric Savings ($/yr)</th>
<th>Total Leakage ($/yr)</th>
<th>Leakage Red. (%)</th>
<th>Cost ($)</th>
<th>Payback (years)</th>
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</thead>
<tbody>
<tr>
<td>Elem School TF</td>
<td>549</td>
<td>$319</td>
<td>1,034</td>
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<td>$419</td>
<td>17%</td>
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<td>Comm. College</td>
<td>174</td>
<td>$105</td>
<td>232</td>
<td>$23</td>
<td>$127</td>
<td>3%</td>
<td>$17,845</td>
<td>140</td>
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<td>905</td>
<td>$525</td>
<td>2,523</td>
<td>$246</td>
<td>$771</td>
<td>12%</td>
<td>$23,700</td>
<td>31</td>
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<td>39</td>
<td>$24</td>
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<td>$2</td>
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<td>$6</td>
<td>79</td>
<td>$0</td>
<td>$6</td>
<td>6%</td>
<td>$15,918</td>
<td>2,872</td>
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<td>Elem School PS</td>
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<td>$129</td>
<td>487</td>
<td>$47</td>
<td>$177</td>
<td>10%</td>
<td>$26,700</td>
<td>151</td>
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<tr>
<td>Library/Office</td>
<td>107</td>
<td>$68</td>
<td>-232</td>
<td>-$24</td>
<td>$44</td>
<td>8%</td>
<td>$1,152</td>
<td>26</td>
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<tr>
<td>Minimum</td>
<td>11</td>
<td>$6</td>
<td>-232</td>
<td>-$24</td>
<td>$6</td>
<td>3%</td>
<td>$1,152</td>
<td>26</td>
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<tr>
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<td>287</td>
<td>$168</td>
<td>592</td>
<td>$56</td>
<td>$224</td>
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<td>492</td>
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<tr>
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<td>$105</td>
<td>232</td>
<td>$23</td>
<td>$127</td>
<td>8%</td>
<td>$17,845</td>
<td>140</td>
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<tr>
<td>Maximum</td>
<td>905</td>
<td>$525</td>
<td>2,523</td>
<td>$246</td>
<td>$771</td>
<td>17%</td>
<td>$26,700</td>
<td>2,872</td>
</tr>
</tbody>
</table>

Able to seal “tight” buildings, but work was not cost effective
Building Pressure Measurements

Average building pressure at ground level (Pa)

- Only 1 building operating greater than 12.5Pa at ground level

20F < outside temp <= 45F
Building Pressure Measurements

Average building pressure at ground level (Pa)

Ground level, occupied, all wind data

-70 < T < 90
-45 < T < 70
-20 < T < 45
0 < T < 0
0 < T < 20
-20 < T < 0

Center for Energy and Environment
Building Pressure Measurements

Difference between occupied and unoccupied pressure (Pa)

Pressure increase for almost all buildings

20F < outside temp <= 45F
Building Pressure Measurements

Difference between occupied and unoccupied pressure (Pa)

20F < outside temp <= 45F
Computing Savings For Your Project

- Can we divide cfm50 by 20 to get savings?
- It is not that simple for larger buildings
- HVAC pressurization effects savings
- Greater savings for taller buildings, open terrain, distance from neutral level, floor compartmentalization
- Internal heat gain = cooling more important
- Developing spreadsheets for savings calculations
Computing Savings For Your Project
Three Story Commercial Building

• Typical pressurization = 10% less
  6Pa       = 35% less
  12.5Pa = 60% less

• 1 story   = 40% less;
  5 story   = 30% more;
  10 story = 80% more

• Urban wind shielding = 35% less
  Open wind shielding = 70% more
Office Building Model: Heating & Cooling

The diagram shows the relationship between outside temperature (in °F) and space heating gas use (in kBtu/hr) for different days of the week, with a separate axis for space cooling electric use (in kWh/day). The data is color-coded by day: red for Sunday, blue for Weekday, yellow for Saturday, and black for other days. The distribution of points suggests a clear correlation between temperature and energy use, with higher energy use at lower temperatures and lower use at higher temperatures.
Mechanical System Leakage

Part of building envelope when not operating
Mechanical System Leakage

Part of building envelope when not operating

Mean
49%
0.06 cfm/ft²
(6 sides)

Range
17% to 103%
0.02 to 0.12 cfm/ft²

Two most recently built (1998 and 2007) had low leakage
Summary

• Tight buildings: 85% tighter than U.S. average & at least 25% below Army Corp standard – due to cold climate location?

• Sealing = 9% reduction, more reduction and less expensive for leakier buildings

• Contractor over-estimated sealing area

• Long paybacks for air sealing work

• Including mechanical systems increased leakage by 17 to 103% (0.02 to 0.12 cfm/ft²)

• HVAC systems tend to pressurize buildings. Not as great as typical design practice
When Is Air Sealing Worthwhile?

• You can see out the envelope gaps & leak is accessible
• Taller (5+ stories) in open terrain
• Reported problem that is likely to be caused by air leakage
• You live in portion of US that hasn’t had to worry about infiltration

Other Opportunities
• Older/leaky dampers (cost?)
• Building pressure control
Thank you!