A Protocol for Establishing Accurate Boundary Condition Inputs to Contaminant Propagation Models

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Issues

- CFD can provide detailed output, but requires detailed input – localized parameters
- Protocol for determination of leakage parameters for CB transport modeling that characterize entire building
- Measurement techniques for exterior and interior partitions and components that provide the necessary accuracy
Building Air Leakage

- Unintentional airflow
  - exterior envelope
  - interior partitions

- Leak sources
  - joints in materials/assemblies
  - penetrations

# Building Component Air Leakage

<table>
<thead>
<tr>
<th></th>
<th>Units (see note)</th>
<th>Best Estimate</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceiling General</td>
<td>in²/ft²</td>
<td>0.026</td>
<td>0.011</td>
<td>0.04</td>
</tr>
<tr>
<td>Drop</td>
<td>in²/ft²</td>
<td>0.0027</td>
<td>0.00066</td>
<td>0.003</td>
</tr>
<tr>
<td>Ceiling penetrations</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Whole-house fans</td>
<td>in² ea</td>
<td>3.1</td>
<td>0.25</td>
<td>3.3</td>
</tr>
<tr>
<td>Recessed lights</td>
<td>in² ea</td>
<td>1.6</td>
<td>0.23</td>
<td>3.3</td>
</tr>
<tr>
<td>Ceiling/Flue vent</td>
<td>in² ea</td>
<td>4.8</td>
<td>4.3</td>
<td>4.8</td>
</tr>
<tr>
<td>Surface-mounted lights</td>
<td>in² ea</td>
<td>0.13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chimney</td>
<td>in² ea</td>
<td>4.5</td>
<td>3.3</td>
<td>5.6</td>
</tr>
<tr>
<td>Crawl space</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>General (area for exposed wall)</td>
<td>in²/ft²</td>
<td>0.144</td>
<td>0.1</td>
<td>0.24</td>
</tr>
<tr>
<td>8 in. by 16 in. vents</td>
<td>in² ea</td>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Door frame</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>General</td>
<td>in² ea</td>
<td>1.9</td>
<td>0.37</td>
<td>3.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Piping/Plumbing/Wiring penetrations</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uncaulked</td>
<td>in² ea</td>
<td>0.9</td>
<td>0.31</td>
<td>3.7</td>
</tr>
<tr>
<td>Caulked</td>
<td>in² ea</td>
<td>0.3</td>
<td>0.16</td>
<td>0.3</td>
</tr>
<tr>
<td>Vents</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bathroom with damper closed</td>
<td>in² ea</td>
<td>1.6</td>
<td>0.39</td>
<td>3.1</td>
</tr>
<tr>
<td>Bathroom with damper open</td>
<td>in² ea</td>
<td>3.1</td>
<td>0.95</td>
<td>3.4</td>
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<tr>
<td>Dryer with damper</td>
<td>in² ea</td>
<td>0.46</td>
<td>0.45</td>
<td>1.1</td>
</tr>
<tr>
<td>Dryer without damper</td>
<td>in² ea</td>
<td>2.3</td>
<td>1.9</td>
<td>5.3</td>
</tr>
<tr>
<td>Kitchen with damper open</td>
<td>in² ea</td>
<td>6.2</td>
<td>2.2</td>
<td>11</td>
</tr>
<tr>
<td>Kitchen with damper closed</td>
<td>in² ea</td>
<td>0.8</td>
<td>0.16</td>
<td>1.1</td>
</tr>
<tr>
<td>Kitchen with tight gasket</td>
<td>in² ea</td>
<td>0.16</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Walls (exterior)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cast-in-place concrete</td>
<td>in²/ft³</td>
<td>0.007</td>
<td>0.0007</td>
<td>0.026</td>
</tr>
<tr>
<td>Clay brick cavity wall, finished</td>
<td>in²/ft³</td>
<td>0.0098</td>
<td>0.0007</td>
<td>0.033</td>
</tr>
</tbody>
</table>

Air Leakage Measurements/Techniques

• Historical motivation
  – Energy, building comfort, mold
  – Improvements in design/construction
  – Assess remedial actions

• Fan pressurization
  – Scale (whole building, zones, components)
  – Accommodates different of weather conditions
  – Provides leakage vs. pressure relationship \( Q = C \cdot \Delta P^n \)

• Tracer gas dilution
  – Scale (single zone)
  – Results valid for ambient conditions during test
Whole Building Pressurization

- Single Zone
  - ASTM E779
  - CGSB 149.10
  - CGSB 149.15 (HVAC)

\[ Q = C \Delta p^n \]
Small-Scale Fan Pressurization - Building Components

- Standardized tests
  - Laboratory
    - ASTM E 283
  - Field
    - ASTM E 783
- Research methods
  - NRC Canada
  - Technical Research Centre Finland

Air Leakage Measurements for Establishing CFD Boundary Conditions

- Several laboratory and field techniques to draw from
- No existing methodology for characterizing localized leakage parameters for a whole building
- Individual comprehensive component testing would be tedious, resource intensive, and in some cases impractical
CFD Benchmarking Facility

- Existing Classroom – Administration
  - two storeys
  - 26,000 s.f.
- Physical description
  - HVAC
    - 3 AHUS, 22 VAV boxes
    - Return air plenum
  - Construction
    - Brick masonry cladding
    - Interior walls - painted gypsum board
    - EPDM membrane roof
    - Poured concrete floors
Establishment of Boundary Condition
Inputs for Envelope Air Flow

- Stage 1 – Conduct Preliminary Site Investigations
- Stage 2 – Perform Building Leakage Measurements
- Stage 3 – Develop Leakage Parameters for Zones, Interfaces and Components
Preliminary Investigations

- Review as-builts
- Visual inspection
- Single zone fan pressurization tests
  - masking envelope components
Preliminary Investigations

• Diagnostic surveys
  – IR
  – smoke
Preliminary Investigations

- Good overall design and construction
- Overall leakage of protective zone
  \[ Q_{50} = 9500 \text{ cfm,} \]
  \[ \text{ELA}_{(4\text{Pa})} = 540 \text{ in.}^2 \text{ (LBL)} \]
  \[ \text{ACH} = 1.6 \]

Airflow at 50 Pascals
- 9018 CFM (± 0.6 %)

Leakage Areas
- 1070.6 in² (± 2.4 %) Canadian EqLa @ 10 Pa
- 594.2 in² (± 3.9 %) LBL ELA @ 4 Pa

Building Leakage Curve
- Flow Coefficient (C) = 908.3 (± 6.1 %)
- Exponent (n) = 0.603 (± 0.016)
- Correlation Coefficient = 0.99883
Building Leakage Measurements

Fan Pressurization - Guarded Zone

Measure $Q_A$ and $\Delta P_A$

$\Delta P_{AB} = 0$

$P_{ambient}$
Building Leakage Measurements

Upper Level

UC – Upper Classroom
UH – Upper Hallway
UL – Upper Lobby
UA – Upper Admin
NS – North Stairwell
SS – South Stairwell
WS – West Stairwell
Building Leakage Measurements

Lower Level

LC – Upper Classroom
LH – Upper Hallway
LA – Upper Admin
NS – North Stairwell
SS – South Stairwell
WS – West Stairwell
Building Leakage Measurements

Fan Pressurization Tests

Four site visits - 59 tests

- Whole building
- Primary zones
  - individual single zone
  - guarded zone
- Additional tests
  - stairwell doors
  - exterior doors
  - individual rooms
# Building Leakage Measurements

## Fan Pressurization Tests

<table>
<thead>
<tr>
<th>Description</th>
<th>Delta</th>
<th>P</th>
<th>C</th>
<th>n</th>
<th>Q50</th>
<th>ELA 4Pa*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protection Zone (PZ)</td>
<td>Neg.</td>
<td>796.5</td>
<td>0.633</td>
<td>9474</td>
<td>543</td>
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<tr>
<td></td>
<td>Pos.</td>
<td>1295.1</td>
<td>0.601</td>
<td>13575</td>
<td>844.2</td>
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<tr>
<td>Upper Classrooms (balanced with PZ)</td>
<td>Neg.</td>
<td>246.3</td>
<td>0.496</td>
<td>1718</td>
<td>139</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pos.</td>
<td>82.5</td>
<td>0.805</td>
<td>1927</td>
<td>71.5</td>
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<tr>
<td>Upper Classrooms (single zone)</td>
<td>Neg.</td>
<td>390.9</td>
<td>0.605</td>
<td>4169</td>
<td>256.4</td>
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<tr>
<td></td>
<td>Pos.</td>
<td>439.4</td>
<td>0.602</td>
<td>4631</td>
<td>287</td>
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<tr>
<td>Upper Administration (balanced with PZ)</td>
<td>Neg.</td>
<td>163.6</td>
<td>0.597</td>
<td>1691</td>
<td>106.1</td>
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<tr>
<td></td>
<td>Pos.</td>
<td>222.9</td>
<td>0.612</td>
<td>2438</td>
<td>147.5</td>
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<tr>
<td>Upper Administration (single zone)</td>
<td>Neg.</td>
<td>575.8</td>
<td>0.608</td>
<td>6201</td>
<td>379</td>
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<tr>
<td></td>
<td>Pos.</td>
<td>572.7</td>
<td>0.612</td>
<td>6278</td>
<td>379.3</td>
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<tr>
<td>Lobby (balanced with PZ)</td>
<td>Neg.</td>
<td>53.4</td>
<td>0.59</td>
<td>536</td>
<td>34.3</td>
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<tr>
<td></td>
<td>Pos.</td>
<td>47.2</td>
<td>0.675</td>
<td>662</td>
<td>34.1</td>
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<tr>
<td>Lobby (single zone)</td>
<td>Neg.</td>
<td>188.9</td>
<td>0.531</td>
<td>1507</td>
<td>111.8</td>
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<tr>
<td></td>
<td>Pos.</td>
<td>176</td>
<td>0.548</td>
<td>1502</td>
<td>106.7</td>
<td></td>
</tr>
</tbody>
</table>

* LBL Method
Envelope Leakage – Whole Building

![Graph showing Envelope Leakage with Pressure Difference (Pa) on the x-axis and Leakage Flow (cfm) on the y-axis. The graph includes two lines: one for Negative Protection Zone (PZ) and one for Positive Protection Zone (PZ).]
Envelope Leakage - Individual Zones

- 5 Neg Envelope Lower Classrooms (LC)
- 7 Neg Envelope Upper Classrooms (UC)
- 10 Neg Envelope Upper Admin. (UA)
- 12 Neg Envelope Lower Admin. (LA)
- 14 Neg Envelope Lobby (UL)
Normalized Envelope Leakage - Individual Zones
Door Leakage – Upper North Stairwell

**Negative Pressurization**

- 17 Neg North Stairwell (NC)
- 17A Neg N. Stairwell - door undercut unsealed
- 17B Neg N. Stairwell - entire door unsealed

**Positive Pressurization**

- 17 Pos North Stairwell (NS)
- 17A Pos N. Stairwell - door undercut unsealed
- 17B Pos N. Stairwell - entire door unsealed

Door opens into Stairwell
Leakage Parameters

Delta P Measurements

• Baseline Conditions for CFD Model
  – Environmental
  – HVAC
  – Door/Window Status
• Measurement Locations
  – Interior (at plenum returns)
    4’ above floor
    2’ below underside of roof deck (center ht. of plenum
  – Exterior
    • 4’ above ground level
Leakage Parameters

Assumptions

- **Envelope Leakage**
  - 5540 cfm (baseline conditions)
  - 90% at roof-wall interface
  - 10% at floor-wall interface
  - Negligible leakage at windows
- **Isolated Plenum Areas** (no intentional air path)
  - Air flow uniform through drop-down ceiling tile
- **Interior Partition Leakage**
  - Negligible (interior doors open)
## Model Envelope Leakage Parameters

<table>
<thead>
<tr>
<th></th>
<th>Q (cfm)</th>
<th>( \Delta P )</th>
<th>L</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Lower Classroom B105</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Roof-Wall</td>
<td>Q/ft = 2.77</td>
<td>( 19.0 ) Pa</td>
<td>53’</td>
</tr>
<tr>
<td>Floor-Wall</td>
<td>Q/ft = 0.30</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Lower Classroom B104</strong></td>
<td></td>
<td>( 11.8 ) Pa</td>
<td></td>
</tr>
<tr>
<td>Roof-Wall</td>
<td>Q/ft = 7.26</td>
<td></td>
<td>111’</td>
</tr>
<tr>
<td>Floor-Wall</td>
<td>Q/ft = 0.81</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Upper Classroom Wing</strong></td>
<td></td>
<td>( 16.7 ) Pa</td>
<td></td>
</tr>
<tr>
<td>Roof-Wall</td>
<td>Q/ft = 3.25</td>
<td></td>
<td>220’</td>
</tr>
<tr>
<td>Floor-Wall</td>
<td>Q/ft = 0.36</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Lower Admin Wing</strong></td>
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<td>( 12.2 ) Pa</td>
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<tr>
<td>Roof-Wall</td>
<td>Q/ft = 2.37</td>
<td></td>
<td>259’</td>
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<tr>
<td>Floor-Wall</td>
<td>Q/ft = 0.26</td>
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<tr>
<td><strong>Upper Admin Wing</strong></td>
<td></td>
<td>( 12.1 ) Pa</td>
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<tr>
<td>Roof-Wall</td>
<td>Q/ft = 4.88</td>
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<td>189’</td>
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<tr>
<td>Floor-Wall</td>
<td>Q/ft = 0.49</td>
<td></td>
<td>211’</td>
</tr>
</tbody>
</table>

\( \Delta P \) is pressure difference across envelope
L is envelope perimeter length
Observations

• Selected field measurement methods are highly dependant on building characteristics
  – configuration/layout
  – HVAC Systems
• Sensitivity analyses will provide level of measurement accuracy
• Dynamics of HVAC system & environment need to be considered