“It isn’t what we don’t know that gives us trouble, it’s what we know that ain’t so”

Will Rogers

“There are known knowns. These are things we know. There are known unknowns. There are things that we know we don’t know. But there are also unknown unknowns. There are things we don’t know we don’t know.

Donald Rumsfeld
Faking the Physics.....
Flow Through Orifices

Turbulent Flow - “inertial effects”

Flow Through Porous Media

Laminar Flow - “viscosity effects”
Flow Through Orifices
  Turbulent Flow - “inertial effects”

Flow Through Porous Media
  Laminar Flow - “viscosity effects”

  “true but not useful”
\[ Q = A \cdot C_D \left[ \frac{2}{\rho} (\Delta P) \right]^{\frac{1}{2}} \quad \text{Bernoulli} \]

\[ Q = C_K \frac{\rho}{\mu} (\Delta P) \quad \text{Darcy} \]
\[ Q = A \cdot C_D \left[ \frac{2}{\rho} (\Delta P) \right]^{\frac{1}{2}} \quad \text{Bernoulli} \]

\[ Q = C_K \frac{\rho}{\mu} (\Delta P) \quad \text{Darcy} \]

\[ Q = A \cdot C (\Delta P)^{\frac{1}{2}} \]

\[ Q = C (\Delta P) \]
\[ Q = A \cdot C_D \left[ \frac{2}{\rho} (\Delta P) \right]^{\frac{1}{2}} \]  
Bernoulli

\[ Q = C_K \frac{\rho}{\mu} (\Delta P) \]  
Darcy

\[ Q = A \cdot C (\Delta P)^{\frac{1}{2}} \]  

\[ Q = C (\Delta P) \]  

\[ Q = A \cdot C (\Delta P)^n \]  
Kronval “an engineer”
$ELA = C \times \frac{\text{Rate of flow}}{\sqrt{\text{Pressure difference}}}$

$(\text{Meters})^2 \approx \frac{1}{780} \times \frac{\text{Litres per second}}{\sqrt{\text{Pascals}}}$
Possible air flows around sill of a wood-framed house modelled as a resistance network.

Figure 2.10
Resistance Network
(from Kronvall, 1980)

1. Air permeating the wood-panel cladding
2. Air flow between floor slab and panel
3. Air flow between floor slab and wind protection
4. Air permeating the caulking
5. Air flow between wind protection and sill
6. Air flow between insulation material and sill
7. Air flow between inner lining and sill
8. Air flow between inner lining and floor slab
9. Air flow between fillet and inner lining
10. Air flow between fillet and floor slab
Figure 2.5
Modes of Air Flow
(from Bumbaru, Jutras and Patenaude, 1988)
Figure 2.5

Modes of Air Flow
(from Bumbaru, Jutras and Patenaude, 1988)
\[ Q = f(Dp) \propto k(Dp)^b \]

- **Q** = air flow, volume/unit of time
- **Dp** = pressure difference
- **k** = coefficient
- **b** = exponent in approximate leakage function

**Figure 2.6**

**Characteristic Curve of Leakage Flow as a Function of Pressure Difference**
(from Nylund, 1980)
\[ Q = f(Dp) \approx k(Dp)^b \]

- **Q** = air flow, volume/unit of time
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**Figure 2.6**

**Characteristic Curve of Leakage Flow as a Function of Pressure Difference**
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**Figure 2.6**

**Characteristic Curve of Leakage Flow as a Function of Pressure Difference**
(from Nylund, 1980)
Air Flow

- Air flow depends on size of hole
- Air flow depends on pressure difference
  \[ \text{Flow} = \text{Area} \times \sqrt{\Delta P} \times \text{Coefficient} \]
- Air flows from higher pressure to lower pressure
The Cult of The Blower Door
Blower Door Can’t Get You The True ACH On A Short Term Basis – Hour, Day, Week
Don’t Know Where The Holes Are
Don’t Know The Type of Holes
Don’t Know The Pressure Across The Holes
Why Do We Suck and Not Blow?
Figure 2.11
Three Dimensional Multi-Layer Multi-Cell Analogue

Figure 2.12
Three Dimensional Multi-Layer Multi-Cell Non-Contiguous Analogue
Figure 3.1
**Exterior Air Pressure Field**
(from Hutchison & Handegard, 1983)

Distribution of pressures (+) and suctions (-) on a house with a low-sloped roof with wind perpendicular to eave

Figure 3.2
**Exterior Air Pressure Field Extending Below Grade**
Pressure coefficients on walls and roof of rectangular buildings without parapets.
Figure 3.3
**Interior Air Pressure Field**

Figure 3.4
**Interstitial Air Pressure Field**
Figure 3.5

Air Conveyance System Air Pressure Field
(from Sauer & Howell, 1990)
People
Pollutant (hot, wet, UV, ozone)
Path
Pressure
Supply air into occupied zone returns to AHU by passing through deliberately porous dropped ceiling or through return grilles installed in dropped ceiling.

Air handling unit extracts air from dropped ceiling, conditions it and injects it into the occupied zones via supply ductwork.

Dropped ceiling depressurized by air handling units extracting air from dropped ceiling.
Air barrier system not present to prevent air from being extracted from roof assembly.

- Corrugated metal roof deck
- Membrane roof
- Rigid insulation

1. Return plenum operates under negative pressure relative to occupied space and exterior.
2. Exterior sheathing
3. Metal stud wall
4. Cavity insulation

Brick veneer
Building paper
Interior gypsum should extend to underside of roof deck and be sealed
Suspended ceiling
Top chord bearing roof truss
Interior gypsum
Figure 3.8

**Hotel HVAC System**

- Air exhausted from bathrooms via central rooftop exhaust fans
- Air supplied from corridors via undercut doors
Interior gypsum board

Metal studs are perforated permitting air to be drawn through wall cavity

Interconnected hollow wall cavity constructed from metal studs with punched openings acting as an air duct

Interior spaces are at a positive pressure relative to the exterior

Brick veneer

Air space

Building paper

Gypsum sheathing

Fiberglass cavity insulation
Figure 3.10
**Pressure Field Due to Fan-Coil Unit**
**Plan View**
- Room is at positive air pressure relative to exterior-driven air from corridor and air supplied to room from fan-coil unit pulling air from exterior through the demising wall
- Fan-coil unit depressurizes dropped ceiling assembly due to return plenum design
- Demising wall cavity pulled negative due to connection to dropped ceiling return plenum

Figure 3.11
**Pressure Field Due to Central Exhaust**
**Plan View**
- Leakage of central exhaust duct pulls air out of service shaft depressurizing shaft and demising walls
Lapse Rate
U.S. Standard Atmosphere (1976)

Temperature (K)

160 180 200 220 240 260 280

100

Thermosphere
(heated by oxygen absorption of solar UV)

Mesopause

Mesosphere

Stratopause

Stratosphere
(heated by ozone absorption of solar UV)

Tropopause

Troposphere
(heated by surface absorption of solar visible)

Height (km)

Pressure (hPa)

$10^{-6}$ $10^{-4}$ $10^{-2}$ $10^{0}$ $10^{2}$ $10^{4}$
Figure 11.1: Building with no internal separations with opening at the bottom (Adapted from G.O. Handegord, 1998)
Figure 11.2: Building with no internal separations with opening at the top (Adapted from G.O. Handegord, 1998)
Figure 11.3: Building with no internal separations with openings at top and bottom (Adapted from G.O. Handegord, 1998)
Figure 11.4: Basic two storey house with vented attic
(Adapted from G.O. Handegord, 1998)
Figure 11.5: Two storey house with non-operating chimney and exhaust fan
(Adapted from G.O. Handegord, 1998)
Figure 11.6: Two storey house with operating chimney
(Adapted from G.O. Handegord, 1998)
Wind
Stack effect and wind
Chimney effect
Leakage opening (72 in²)

Total “measured” leakage 144 in²

Neutral pressure plane

Leakage opening (72 in²)

Total “measured” leakage 144 in²

Leakage openings (each 72 in²)

Neutral pressure plane

Leakage area
Stack Effect Flow Out (Exfiltration)

\( P_{\text{inside}} \) drops with height slower than \( P_{\text{outside}} \)

\( P_{\text{outside}} \) drops with height faster than \( P_{\text{inside}} \)

Neutral Pressure Plane

Stack Effect Flow In (Infiltration)
Figure 11.8: Stack effect pressures in high rise office building
(Adapted from G.O. Handegord, 1998)
Figure 11.9: Multi-storey building with floor spaces isolated from vertical shafts (Adapted from G.O. Handegord, 1998)
Figure 11.12: Apartment building with tighter apartment entry doors (Adapted from G.O. Handegord, 1998)
Flow and pressure key:
- **flow:** 6e+004 scfm
- **ΔP:** 21 Pa

- **Penthouse**
- **Fourth Floor**
- **Seventh Floor**
- **Third Floor**
- **Sixth Floor**
- **Second Floor**
- **Fifth Floor**
- **Ground Floor**

- **Zone identification icon**
- **Animal lab**
- **Main exhaust fan**
- **Leaks through floor set at 200 sf equivalent area**
- **Leaks to exterior apportioned by exposed surface area**

AHU Units
Air Barrier Metrics

Material  0.02 l/(s-m²) @ 75 Pa
Assembly  0.20 l/(s-m²) @ 75 Pa
Enclosure 2.00 l/(s-m²) @ 75 Pa

0.25 cfm/ft² @ 50 Pa
<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Getting rid of big holes</td>
<td>3 ach@50</td>
</tr>
<tr>
<td>Getting rid of smaller holes</td>
<td>1.5 ach@50</td>
</tr>
<tr>
<td>Getting German</td>
<td>0.6 ach@50</td>
</tr>
</tbody>
</table>
Figure 5.10

**HVAC System as Designed**
Figure 5.11

Unintended Pressurization of Interstitial Cavity

- 10 Pa with respect to exterior
- 8 Pa with respect to exterior
- 18 Pa with respect to exterior
- 8 Pa with respect to exterior
- 7 Pa with respect to exterior
- 14 Pa with respect to exterior
Figure 5.12
Modified Pressure Relationship
Fan pressurizes roof cavity

Ridge vent sealed

Distribution "manifold"

Gypsum board removed

Rigid insulation added

Soffit vent sealed

Soffit vent sealed