Learning Objectives

• Basic Theory of Air Flow Around and In High Rise Building
  – Wind
  – Stack-Effect

• Vertical Compartmentation
  – Elevators
  – Stairs
  – Impact on Energy
  – Impact on Pressure

• Smoke Management
  – Pressurization (Stairs/Space)
  – Smoke Control Considerations

• Example Building Air Movement/Pressure Analysis
  – 16 Story Hotel
  – Mixed-use Tall Building

• Summary Guidelines
Air Flow in High Rise Buildings

• Forced ventilation
  – Building supply/exhaust air systems
  – Fully controlled and distributed

• Natural ventilation
  – Pressure from wind and/or stack effect
  – Strategically placed intentional openings

• Infiltration
  – Uncontrolled air leakage
  – Unintentional openings in building envelope
  – Air leakage through floor/wall openings
  – Driven by wind force, temperature difference (buoyancy), and/or system/appliance induced

• Space Pressurization
  – Normal mode pressurization
  – Fire mode pressurization (fire floor and stairs) for smoke management
Basic Theory

- Air movement into/out of a building is caused by wind pressure and stack effect pressure
- Wind pressure causes air to infiltrate into the building, or ex-filtrate out of the building
- Stack effect (air buoyancy) pressure causes air to rise or drop

Cold Weather
- Air infiltrates into the lower half of the building, rises to upper floors due to stack effect and exfiltrates in the upper half of the building.

Hot Weather
- Air infiltrates into the upper half of the building, drops to lower floors due to stack effect and exfiltrates in the lower half of the building.
Basic Theory – Air Flow Around Building

Fig. 1 Flow Patterns Around Rectangular Building

Fig. 2 Surface Flow Patterns for Normal and Oblique Winds
(Wilson 1979)

Fig. 7 Surface-Averaged Wall Pressure Coefficients for Tall Buildings
(Akins et al. 1979)
Basic Theory - Wind Pressure

Wind creates a distribution of static pressure on the building envelope, which is dependent on wind direction and location on building envelope.

$$\Delta P_w = C \cdot C_p \cdot \rho \cdot \frac{v^2}{2}$$

- $\Delta P_w$ = wind pressure difference, inches of water
- $C$ = unit conversion, 0.0129
- $C_p$ = surface pressure coefficient, dimensionless
- $\rho$ = air density, lbm/ft$^3$ (about 0.075)
- $v$ = wind speed, mph

Note: Wind Pressure at top of 60 Story:
- Upwind    = +1.32 in. of Water
- Sides     = +0.61 in. of Water
- Downwind  = -0.61 in. of Water

Overall Wind Effect Pressure

- +0.33 in WG
- 15 mph
Basic Theory - Stack Effect Pressure

Air density varies with temperature. In cold weather, low density air infiltrated into a building rises and creates stack effect pressure.

$$\Delta P_s = C_2 \rho_i g (h-h_{NPL})(T_i - T_o)/T_o$$

- $\Delta P_s$ = pressure difference, inches of water
- $C_2 \rho_i g$ = density and gravity constant, 0.01444
- $h$ = height of observation, ft
- $NPL$ = building neutral pressure level
- $T$ = absolute temperature, °R
- $i$ & $o$ = inside & outside

Note: Stack Pressure is approximately 1 in. of water for a 60-story building and -10°F outside $T$
Natural air movement in a building is due to pressure difference caused by wind and temperature difference between indoor and outdoor air (stack effect).

\[ \Delta P = (P_o - P_i) + \Delta P_w + \Delta P_s \]

- $\Delta P$ = pressure difference
- $P_o$ = outside static pressure
- $P_i$ = interior static pressure
- $\Delta P_w$ = pressure difference due to wind (depends on orientation)
- $\Delta P_s$ = pressure difference due to stack effect
Dynamic air flow through an opening is proportional to square root of the pressure difference across the flow path.

\[ Q = C \times C_f \times A \times \sqrt{2\Delta P/\rho} \]

- \( Q \) = Air flow, CFM
- \( C \) = Unit Conversion, 776
- \( C_f \) = Flow Coefficient, typically = 0.6-0.7
- \( A \) = Opening Area, ft\(^2\)
- \( \Delta P \) = pressure difference, inches of water
- \( \rho \) = air density, lbm/ft\(^3\) (about 0.075 at standard conditions)

Operation of building appliances and mechanical ventilation systems impact natural air movement. The impact is included with outside/inside pressure difference.
Flow equations are developed between nodes (pressure & mass balance)

\[ Q = C \times A \times \sqrt{\frac{2\Delta P}{\rho}} \]

System of equations are solved for each calculation time period

Software:
NIST CONTAM
LBNL COMIS
e-Quest
Example High Rise Building Air Infiltration

Assumptions

- 60-Story Office
- 200 feet x 100 feet floor plate
- Average leakage curtain wall
- Weather-stripped exterior exist doors
- Revolving doors + swing exit doors at main lobby
- Standard door on typical floor stair
- Average leakage elevator doors
- Exterior condition at -10°F
- Interior condition at 73°F
- Wind direction from south (longer wall)
- Wind speed 15 mph (33 feet above grade)
Building Air Infiltration – Effect of Elevators

60-Story Office Building
Effect of Elevator Zones

Single Zone Elevators

Two Zones Elevators

Three Zones Elevators

Total Infiltration Heat Load

- 6,357 KW (100%)
- 2,903 KW (45.7%)
- 1,652 KW (25.9%)

Floor

Infiltration, scfm

- ~74% reduction

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Building Air Infiltration – Effect of Stairs

60-Story Office Building
Effect of Stair Zones (Three Elevator Zones)

- Total Infiltration Heat Load
  - Single Zones Stairs: 1,652 KW (100%)
  - Three Zones Stairs: 909 KW (55%)

- ~45% reduction

Infiltration, scfm

Floor

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60 Story Building – Space Pressure
Typical Stair Air Separation/Lock

Alternate A

Alternate B

TYPICAL FLOOR

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60 Story Building – Infiltration Load (Energy)

Elevator and Stair Energy Impact - Example Building

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Infiltration Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Zone Elevators - Single Zone Stars</td>
<td>100%</td>
</tr>
<tr>
<td>Two Zones Elevators - Single Zone Stars</td>
<td>46%</td>
</tr>
<tr>
<td>Three Zones Elevators - Single Zone Stars</td>
<td>26%</td>
</tr>
<tr>
<td>Three Zones Elevators - Three Zones Stars</td>
<td>14%</td>
</tr>
</tbody>
</table>
High Rise Building - Smoke Management

System Objectives

• Reduce occupant death and injuries
  – Delay smoke accumulation
  – Reduce smoke migration
  – Provide safe escape route
  – Provide safe refuge area

• Reduce property loss
  – Purge smoke
  – Manage fire impact

System Approach

• Design/operate system to prevent smoke entering the unaffected areas

• Integrate Smoke Control with Fire Protection System

• Allow for operational flexibility

• Use HVAC system for smoke control to improve system reliability

• Utilize compartmentation

• Pressurization
  – Horizontal
  – Vertical
  – Stairs
  – Lobbies
Pressurization – Normal Mode of Operation

Floor Pressurization
- Main building lobby is pressurized
- Each floor is provided with required supply and exhaust
- Each zone of building is pressurized by maintaining differential air flow between supply/exhaust to minimize infiltration
- Stair pressurization systems are off
Pressurization – Normal Mode of Operation

60-Story Office Building Infiltration
Effect of AHU Pressurization (Normal Mode)

Building Infiltration Load Reduces by 70%
(1652 kW reduced to 506 kW)

60-Story Office Building Infiltration
Effect of AHU Pressurization (Normal Mode)

Three Zones Central AHU

Three Zones Elevator Single Zone Stairs
Floor Pressurization
- Main building lobby is pressurized
- Fire Floor is provided with full exhaust
- Floors above and below fire floor is provided with full supply air
- All other floors operate normal mode
- Stairs not pressurized
No Stair Pressurization Provided

60-Story Office Building Infiltration
Smoke Condition (Level 28) - Fire Mode Pressurization

Exhaust on Fire Floor &
Supply Above/Below

Single Zone Stairs
Non-pressurized

Pressurization – Fire Mode of Operation
Floor and Stair Pressurization
• Main building lobby is pressurized
• Fire Floor is provided with full exhaust
• Floors above and below fire floor is provided with full supply air
• All other floors operate normal mode
• Stairs are pressurized
Pressurization – Fire Mode/Stair Impact

Stairs Are Pressurized

60-Story Office Building Infiltration
Smoke Condition (Level 28) - Fire Mode and Stair Pressurization

Open Exit Door

Exhaust on Fire Floor & Supply Above/Below

Single Zone Stairs Pressurized – doors open

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Elevator Shaft Air Flow – Fire Mode

60 Story Office Building - Elevator Shaft Air Flow (Winter)
Smoke Condition on Level 28 (Building and Stairs Pressurized)

Floor

Air Flow, CFM

Three Zones
Three Zones - FireMode/Pressurized
60 Story Office Building

Effect of Stair Compartment on Pressurized Stair Air Flow - Smoke Condition (Level 28)

Exhaust on Fire Floor & Supply Above/Below
Doors open on fire, above/below and ground floors

Air Flow, CFM

-15000 -12500 -10000 -7500 -5000 -2500 0 2500 5000 7500

Floor

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60 Story Office Building
Effect of Stair Compartment on Stair Pressure - Smoke Condition (Level 28)

Floor

Pressure, in WG

-0.10 0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80

MAXIMUM STAIR PRESSURE TO MAINTAIN DOOR FORCE

Exhaust on Fire Floor
Supply Above/Below
Doors open on fire floor, floors above/below fire floor and ground floors

Single Compartment Stair  Three Compartment Stair
Smoke Control Considerations

- Building envelope design
- Compartmentation
  - Building occupancy types
  - Zones
- Elevator shafts
  - Design/construction
- Stair shafts
  - Design/construction
- Air leakage paths (smoke movement)
- Local design temperatures
- Local wind velocities:
  - Site
  - Envelope (wind tunnel test)
- HVAC system:
  - System zoning
  - Components design
  - System Activation/Controls
- Fire protection, detection and alarm system
  - Integration/coordination
- Firefighters Access:
  - To site
  - To manual/remote control of system
- Exiting plan
  - Refuge areas
  - Exit duration
- Security and access control (door status/control)
16 Story Hotel Example – Space Pressure
Tall Building Example – Space Pressure
Summary

• High rise building infiltration can be significantly reduced by vertical compartmentation of building shafts (elevators, stairs, HVAC risers)

• Vertical compartmentation of building shafts creates more uniform pressure and air flow characteristics

• High rise building’s HVAC system will perform more effectively and more efficiently through a managed plan for stack effect

• Smoke control system configuration and performance must be carefully analyzed for various fire conditions and plan designs

• Integrated design process between architecture, structure and MEP assures an optimized building natural air flow

• High rise building’s natural air flow, air pressures characteristics and stack effect must be reviewed early in the design stage

• Minimum of two air barriers (walls, doors & vestibules) shall separate the internal building shafts (elevator, stairs) from the outside environment on each floor
  – main lobby, sky lobbies and loading dock levels may require additional layer of separation)
Thank you!