High Rise Building
Air Pressure, Infiltration & Stack Effect
Theory and Impact on Indoor Environment

CCHRB
CHICAGO COMMITTEE
ON HIGH RISE BUILDINGS

2012 Spring Seminar, June 14, 2012

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ESD

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

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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

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Basic Theory

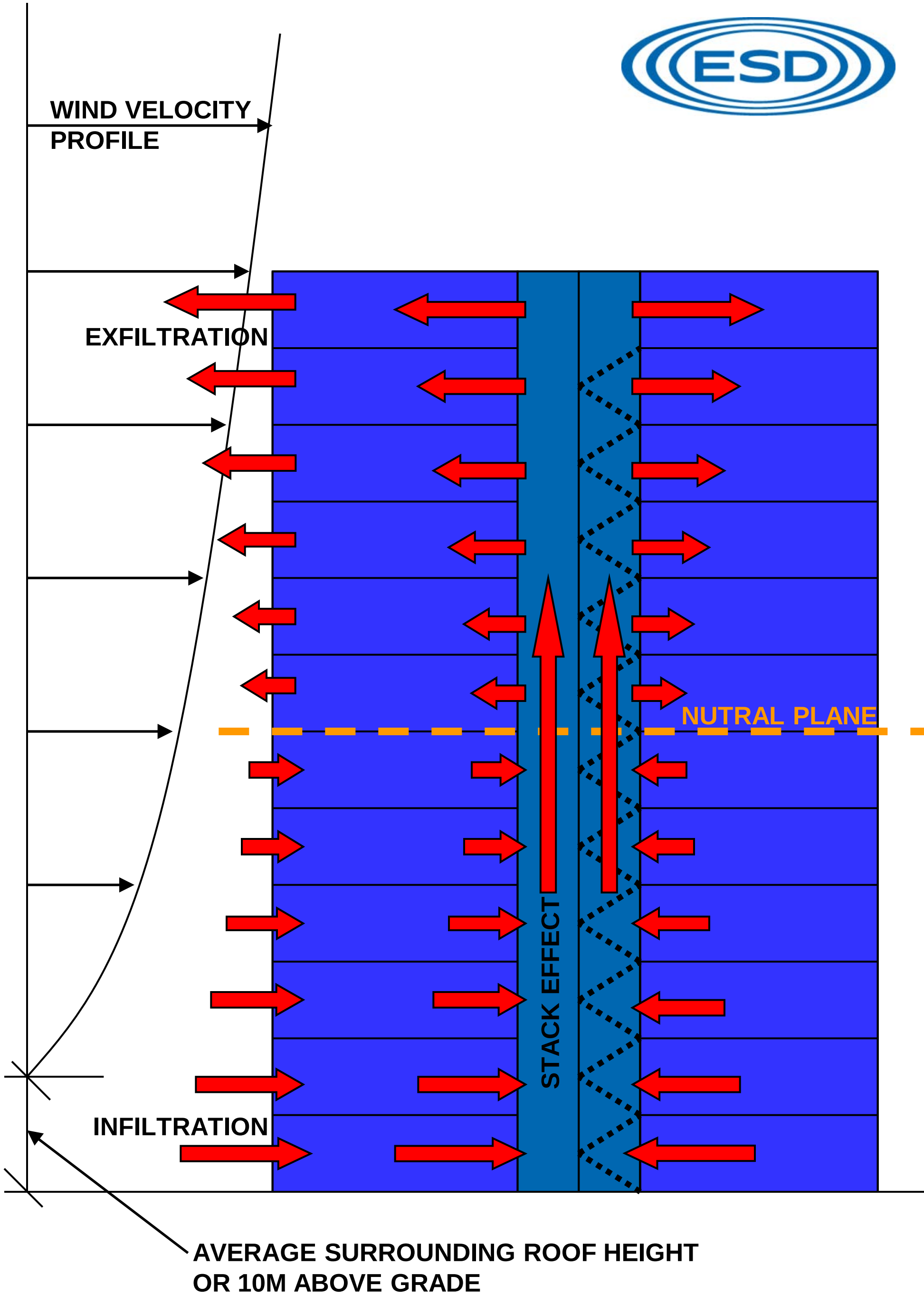
- Air movement into/out of a building is caused by wind pressure and stack effect pressure
- Wind pressure causes air to infiltrates into the building, or ex-filtrate out of the building
- Stack effect (air buoyancy) pressure causes air to rise or drop

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.



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Basic Theory – Air Flow Around Building

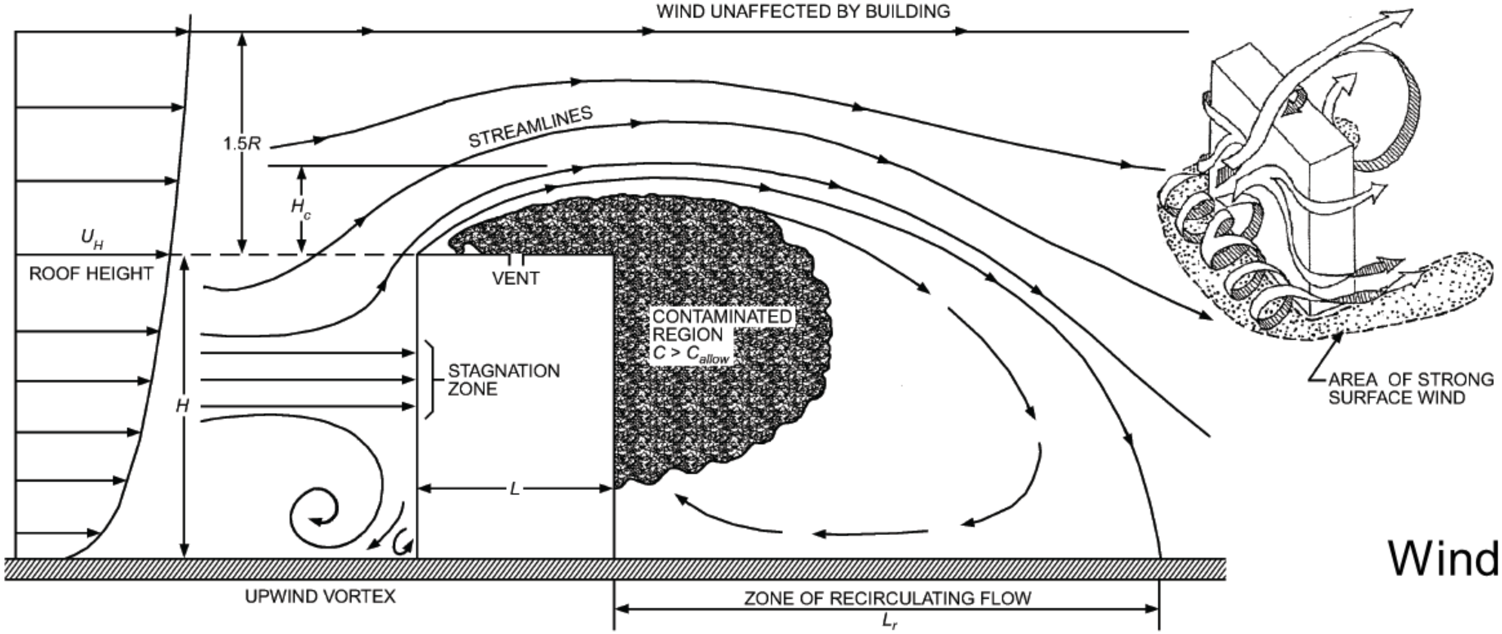
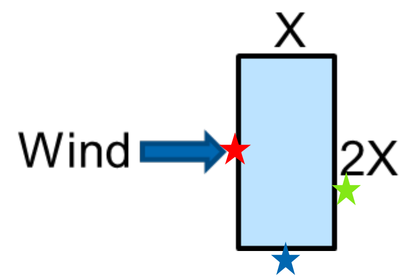


Fig. 1 Flow Patterns Around Rectangular Building



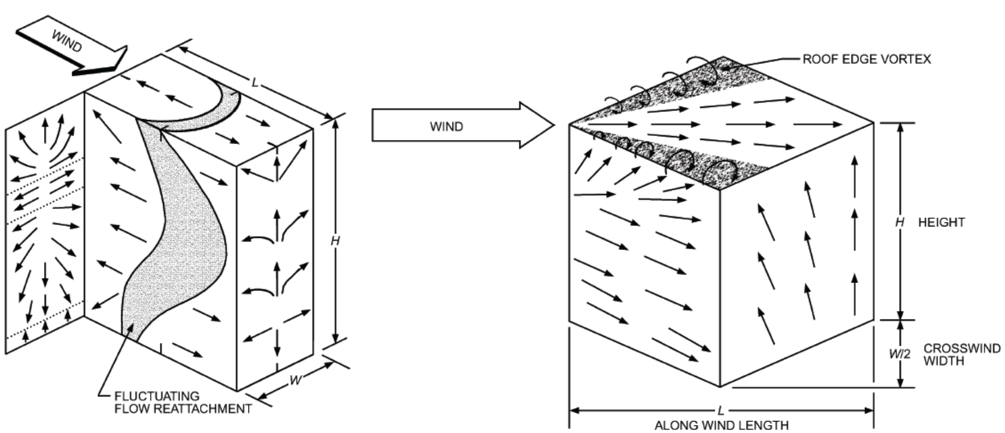


Fig. 2 Surface Flow Patterns for Normal and Oblique Winds
(Wilson 1979)

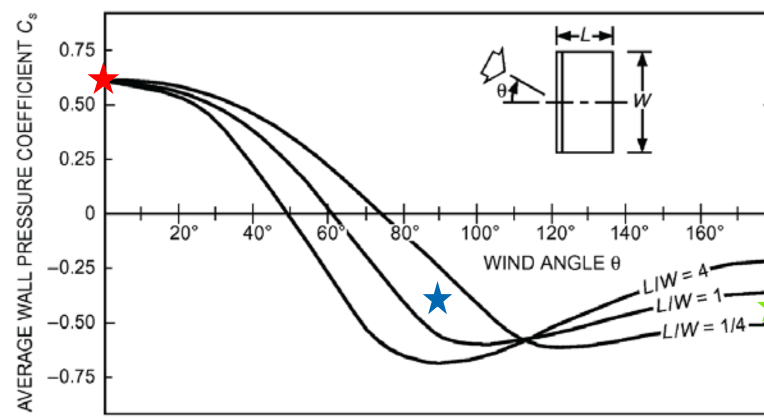


Fig. 7 Surface-Averaged Wall Pressure Coefficients for Tall Buildings
(Akins et al. 1979)

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Basic Theory - Wind Pressure

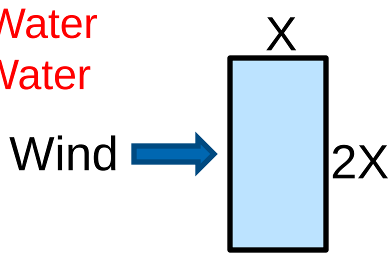
Wind creates a distribution of static pressure on the building envelope, which is dependent on wind direction and location on building envelope.

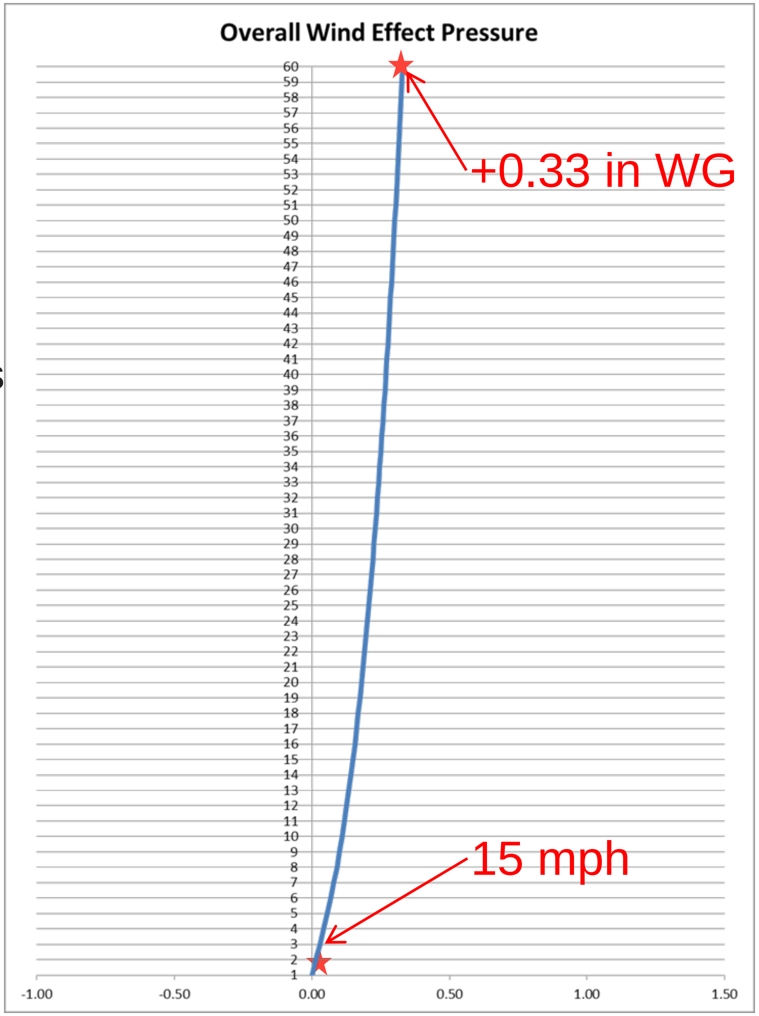
$$\Delta P_w = C\, C_p\, \rho\, v^2/2$$

- ΔP_w = wind pressure difference, inches of water
- C = unit conversion, 0.0129
- C_p = surface pressure coefficient, dimensionless
- ρ = 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





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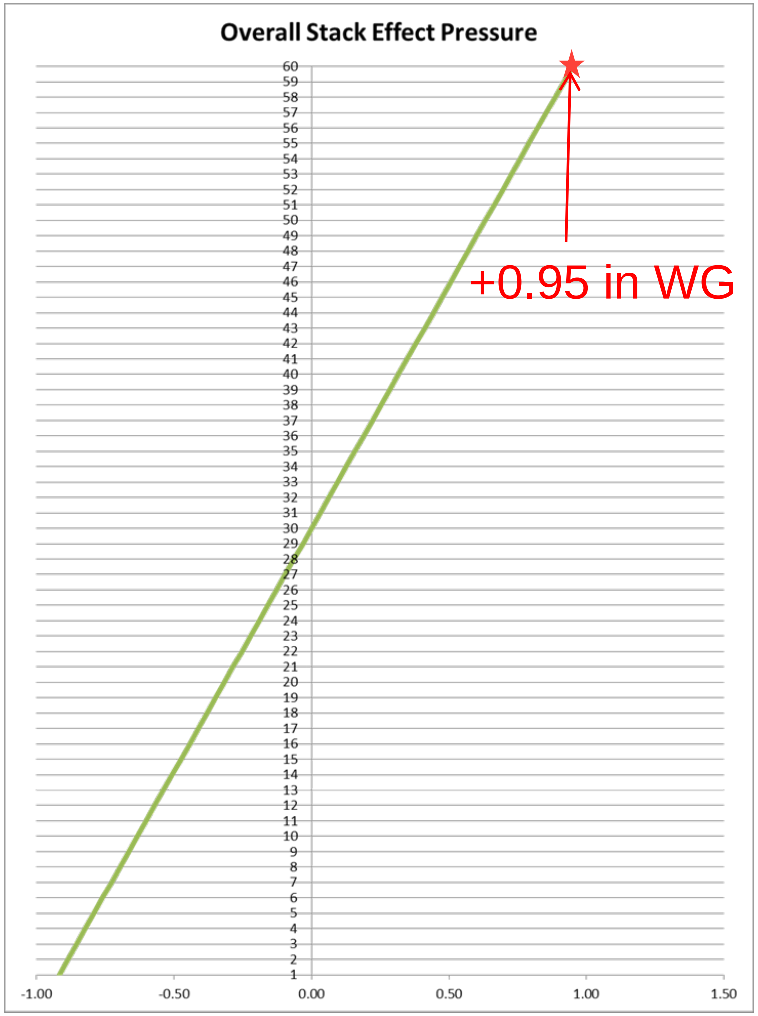
Basic Theory - Stack Effect Pressure

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

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

ΔP_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, ^oR
i & o	= inside & outside

Note: Stack Pressure is approximately 1 in. of water for a 60-story building and -10ºF outside T



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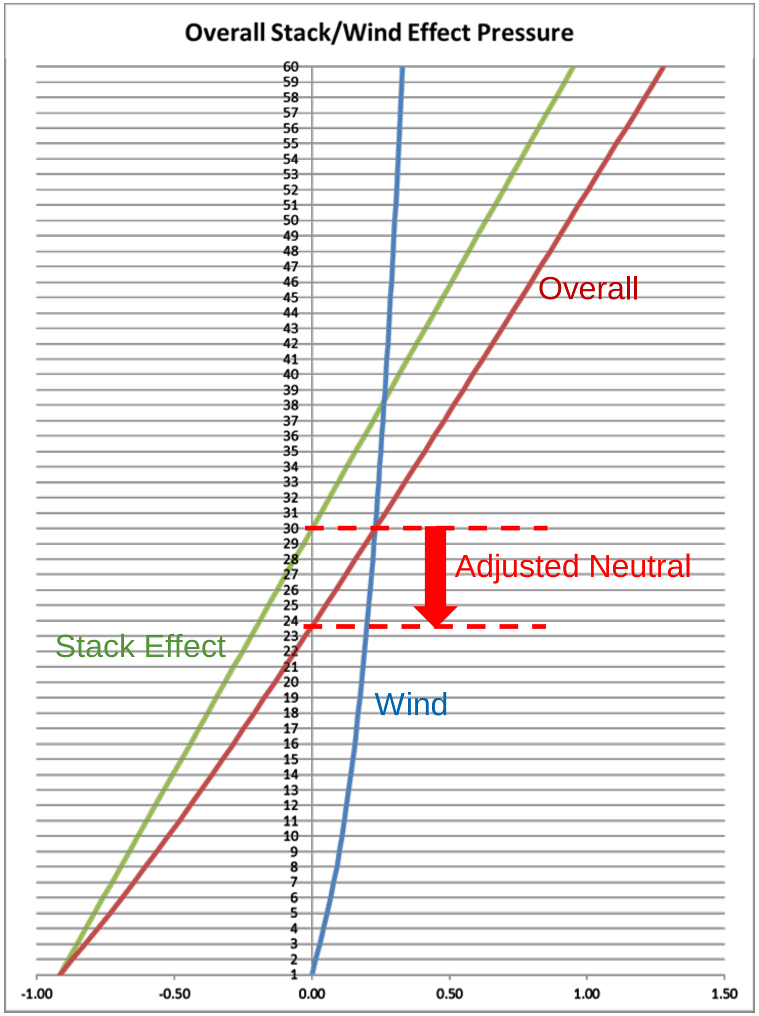
Basic Theory – Overall Pressure

Natural air movement in a building is due to pressure difference caused by wind and temperature difference between indoor and outdoor air (stack effect).

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

- ΔP = pressure difference
- P_o = outside static pressure
- P_i = interior static pressure
- ΔP_w = pressure difference due to wind (depends on orientation)
- ΔP_s = pressure difference due to stack effect



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Basic Theory – Air Flow Through Opening

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
- ΔP = pressure difference, inches of water
- ρ = 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

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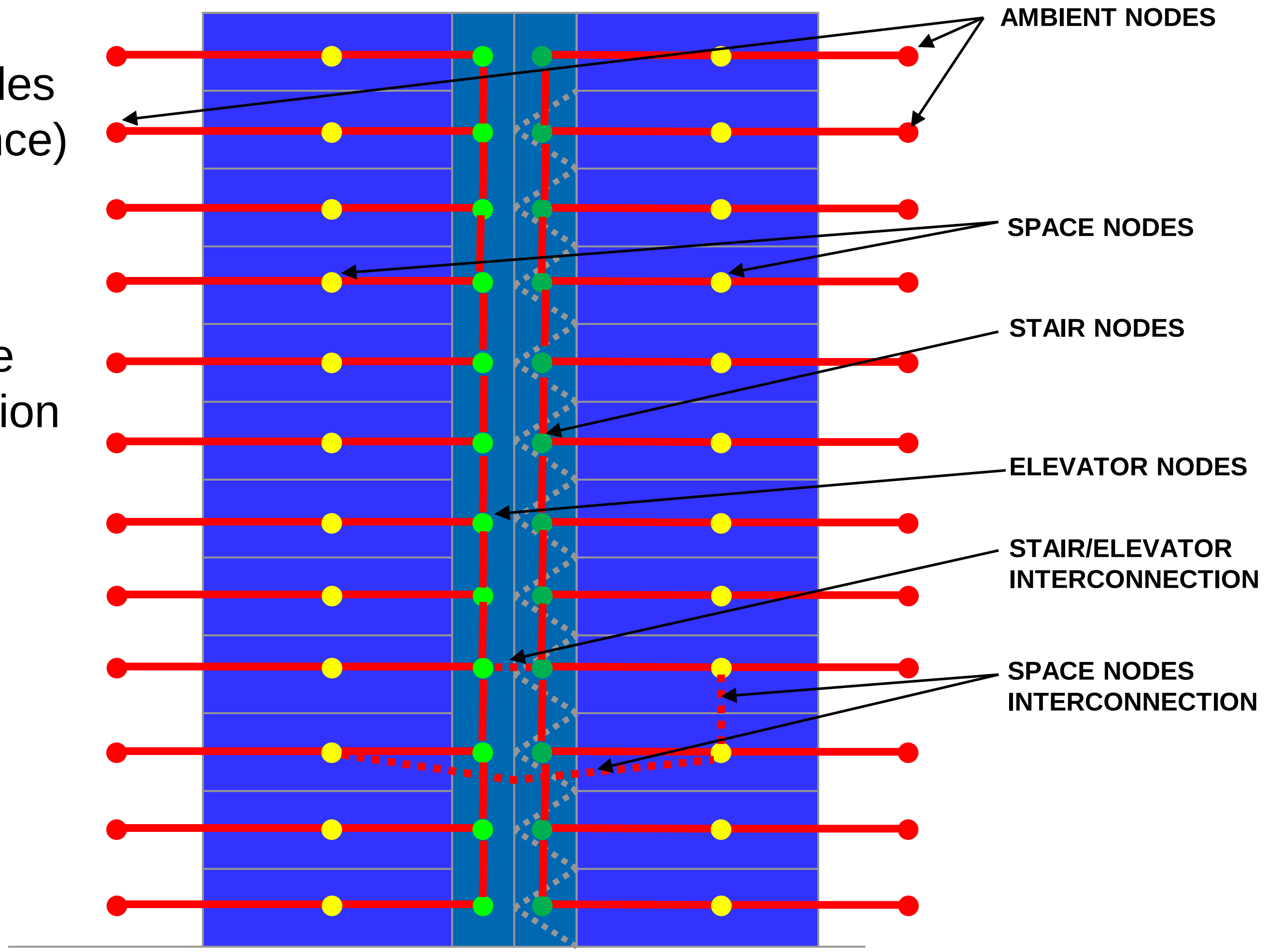
Basic Theory - Air Flow Network

Flow equations are developed between nodes (pressure & mass balance)

Q = C x A x √(2ΔP)/ρ

System of equations are solved for each calculation time period

Software:
NIST CONTAM
LBNL COMIS
e-Quest



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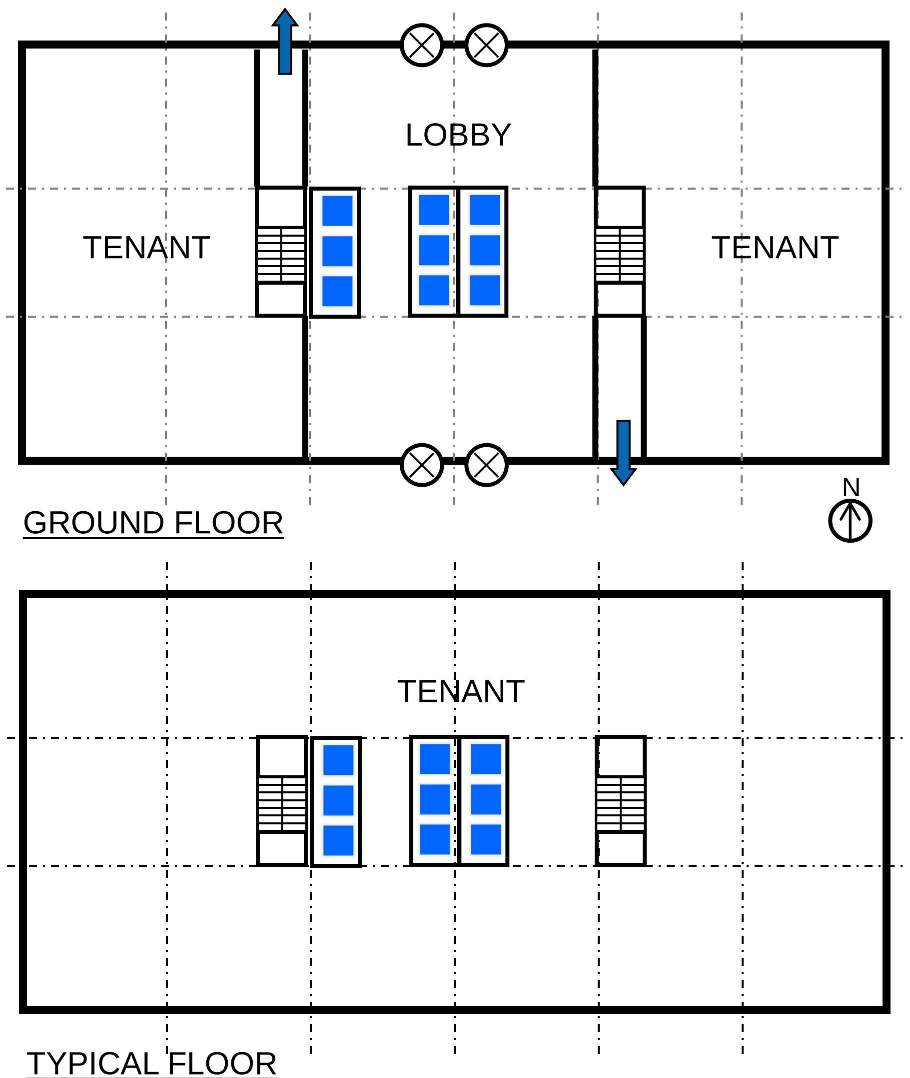
Example High Rise Building Air Infiltration

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 -10ºF
- Interior condition at 73ºF
- Wind direction from south (longer wall)
- Wind speed 15 mph (33 feet above grade)



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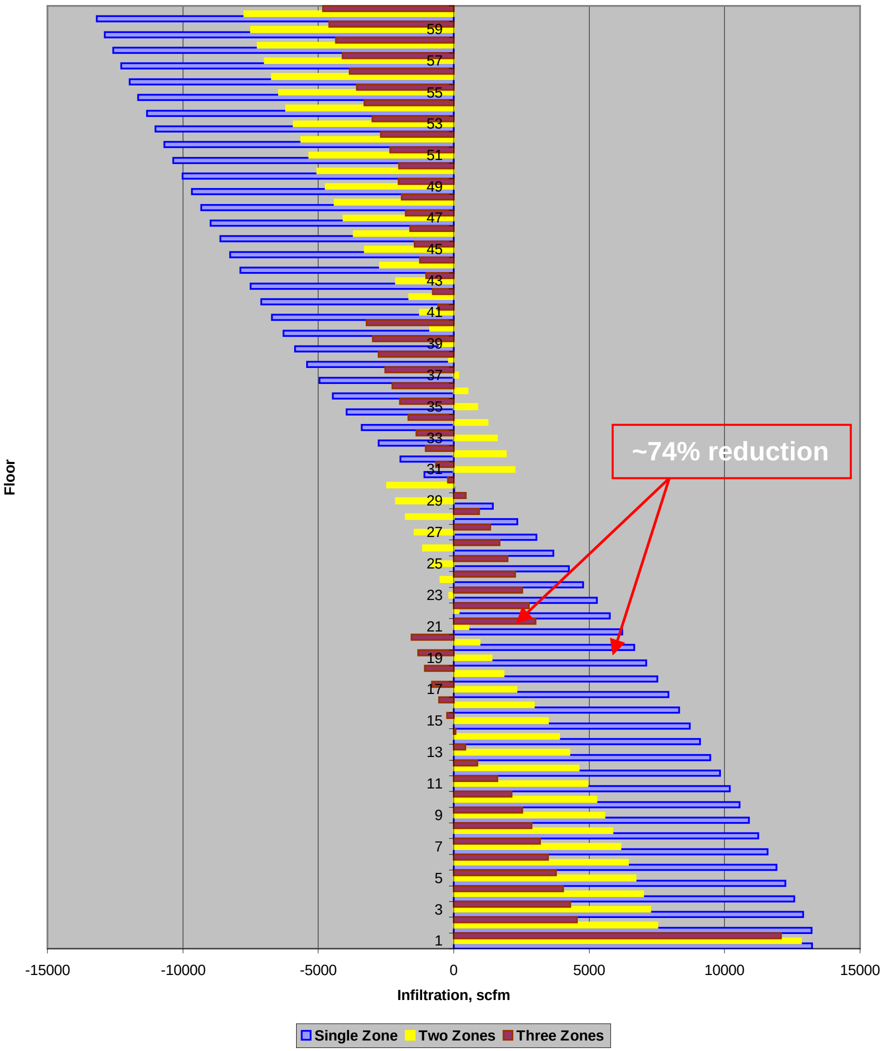
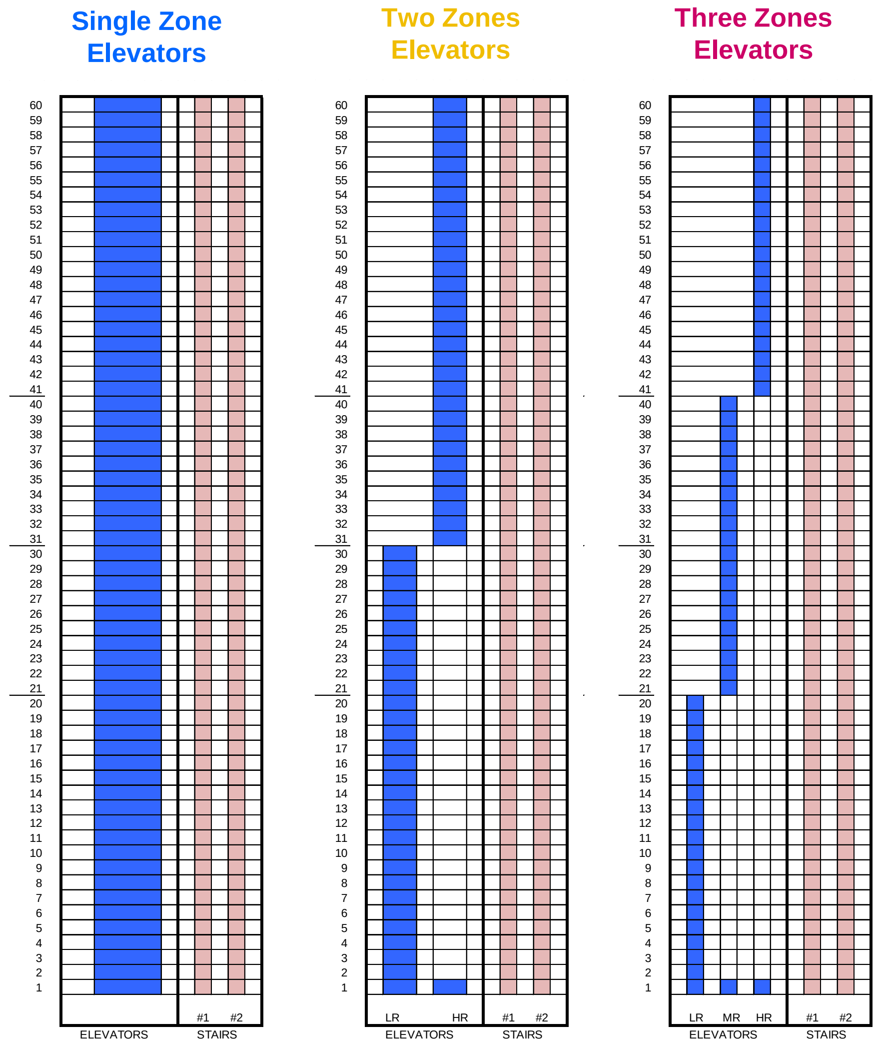
Building Air Infiltration – Effect of Elevators

60-Story Office Building
Effect of Elevator Zones





Total Infiltration Heat Load

Single Zone	Two Zones	Three Zones
6,357 KW	2,903 KW	1,652 KW
100%	45.7%	25.9%

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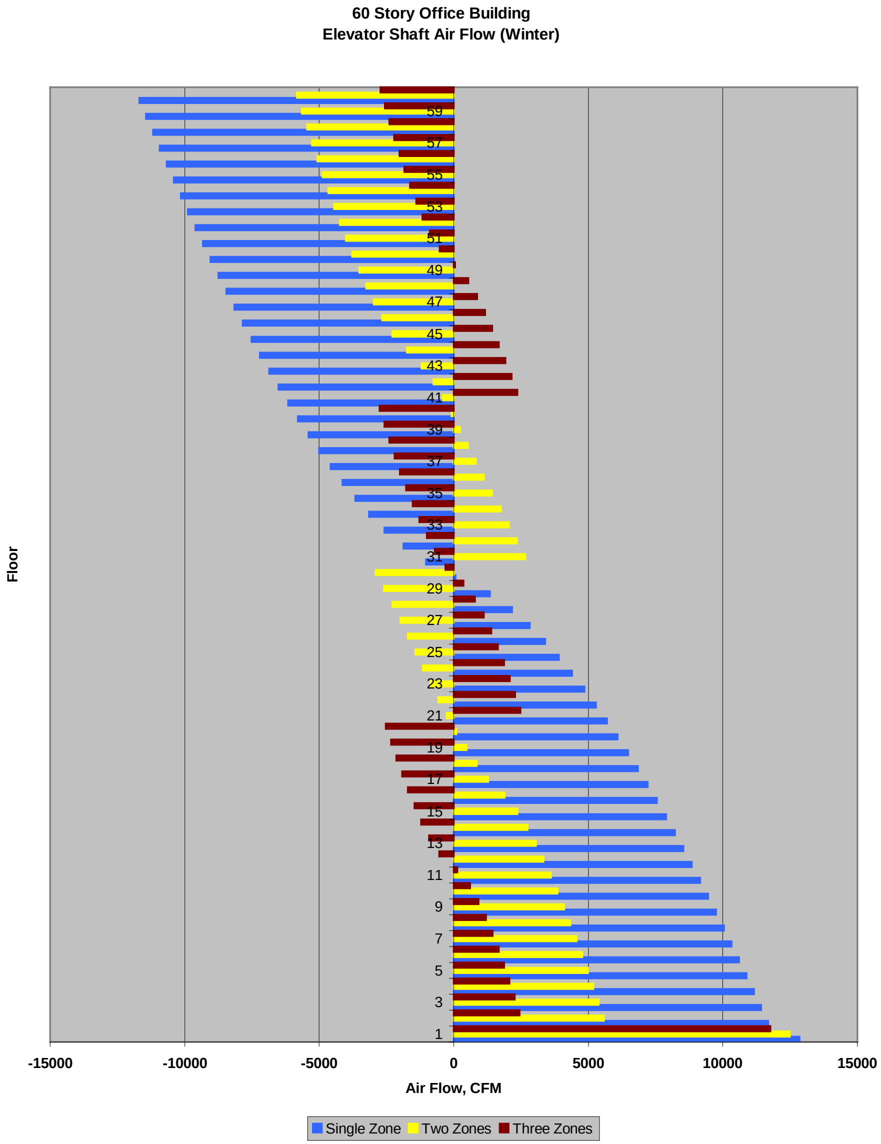
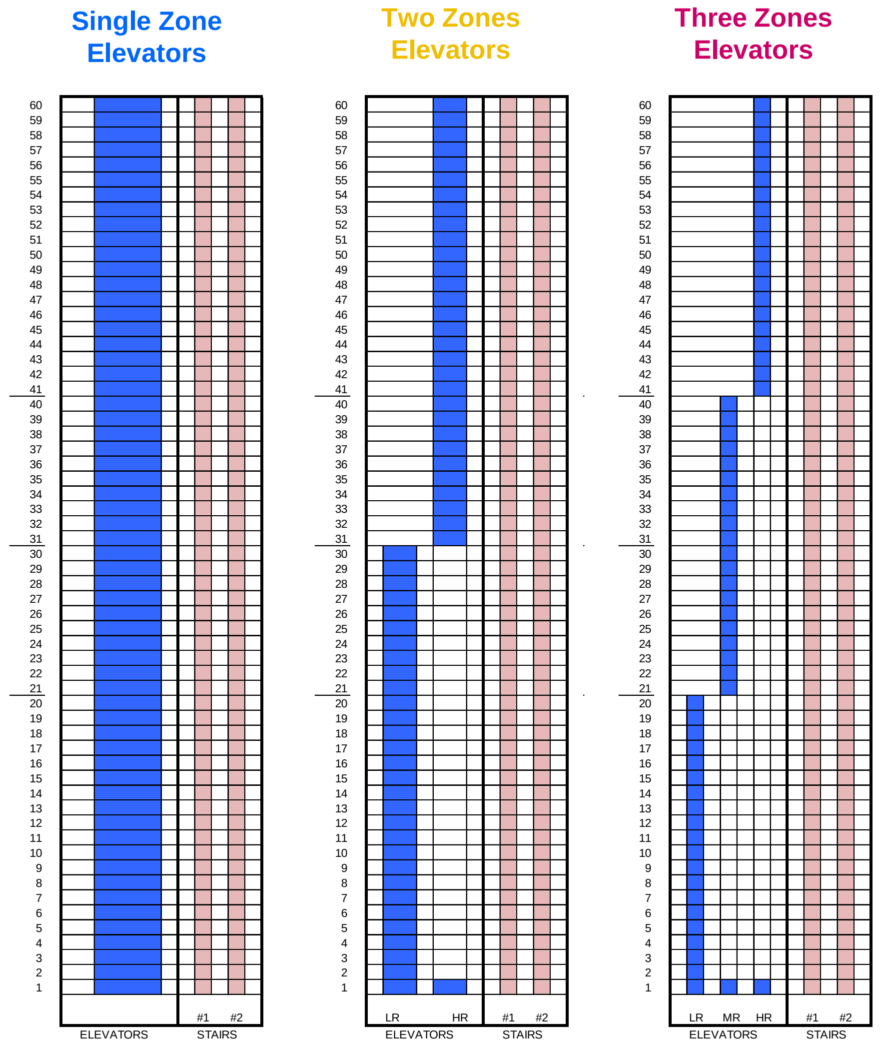
Elevator Shaft Air Flow





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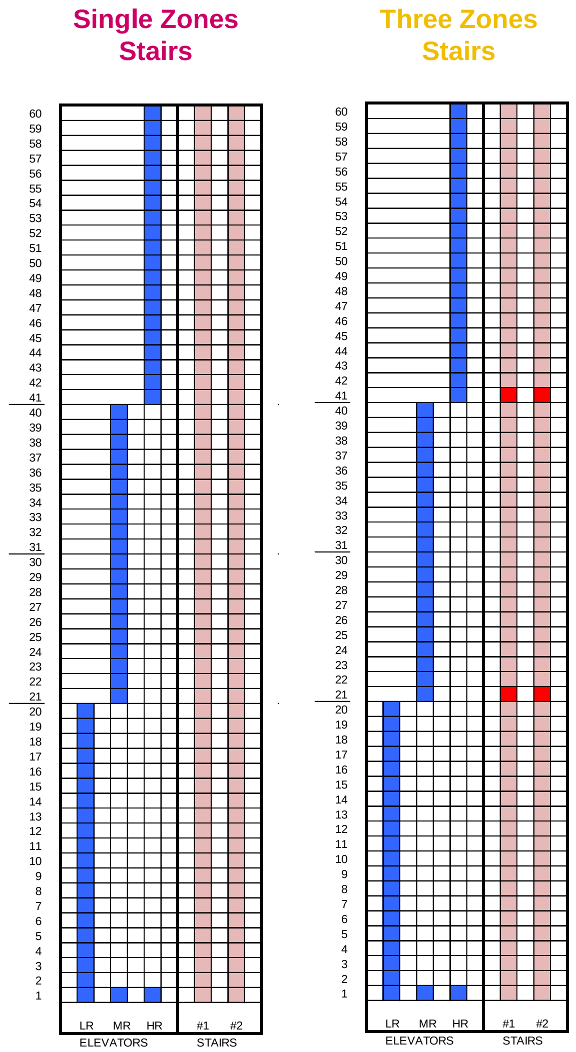
Building Air Infiltration – Effect of Stairs



Total Infiltration Heat Load

Single Zones Stairs	Three Zones Stairs
1,652 KW	909 KW
100%	55%

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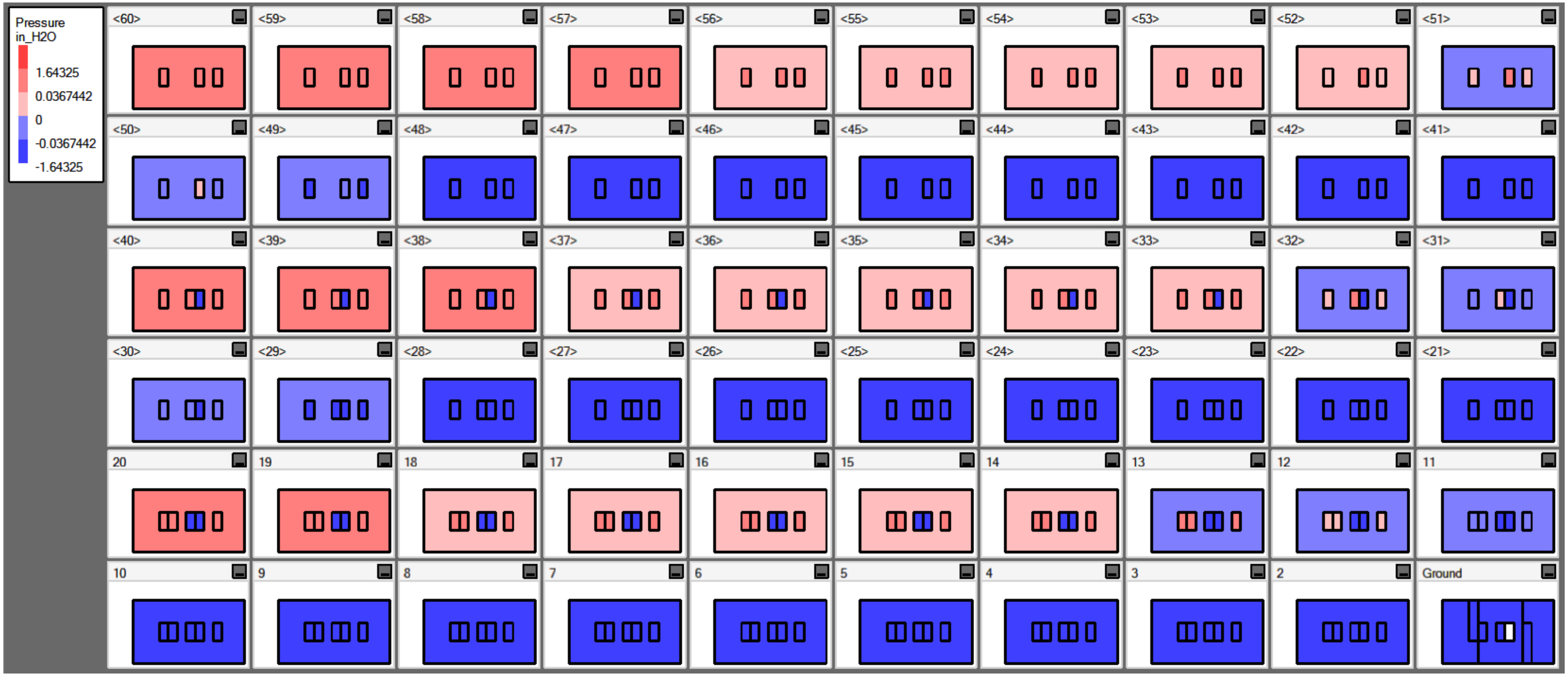
60 Story Building – Space Pressure



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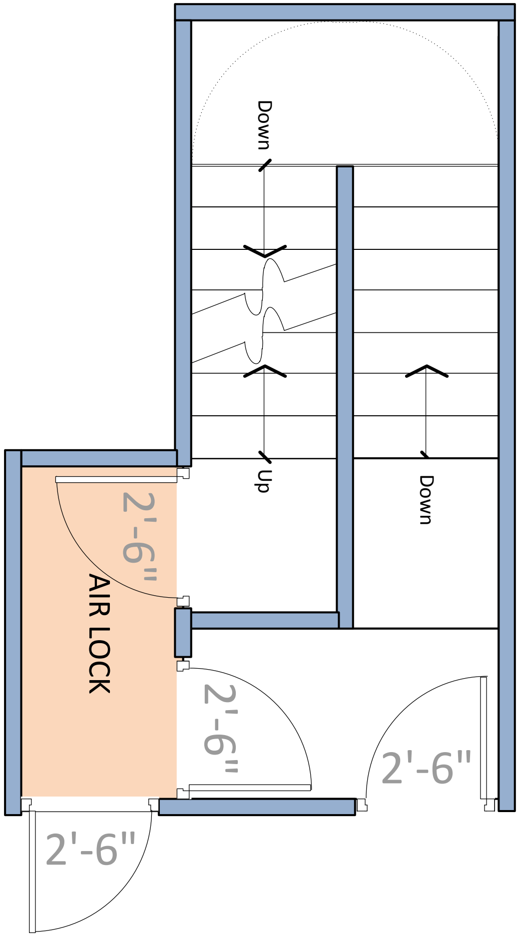
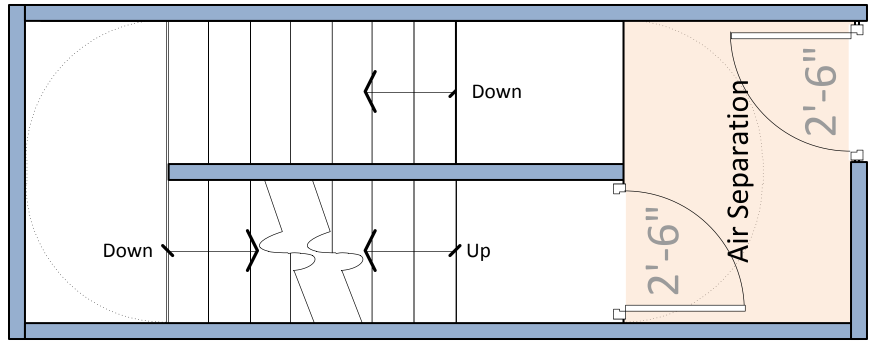
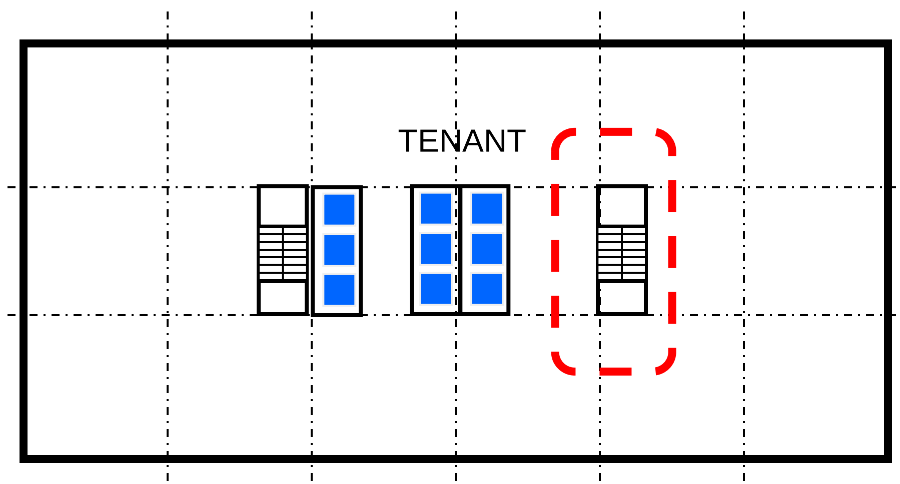
Typical Stair Air Separation/Lock



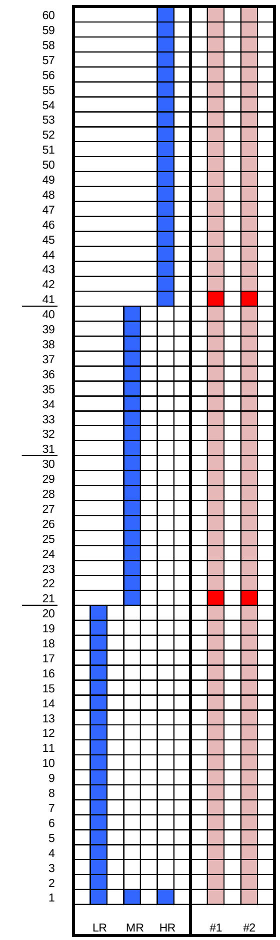
Alternate B



Alternate A



TYPICAL FLOOR



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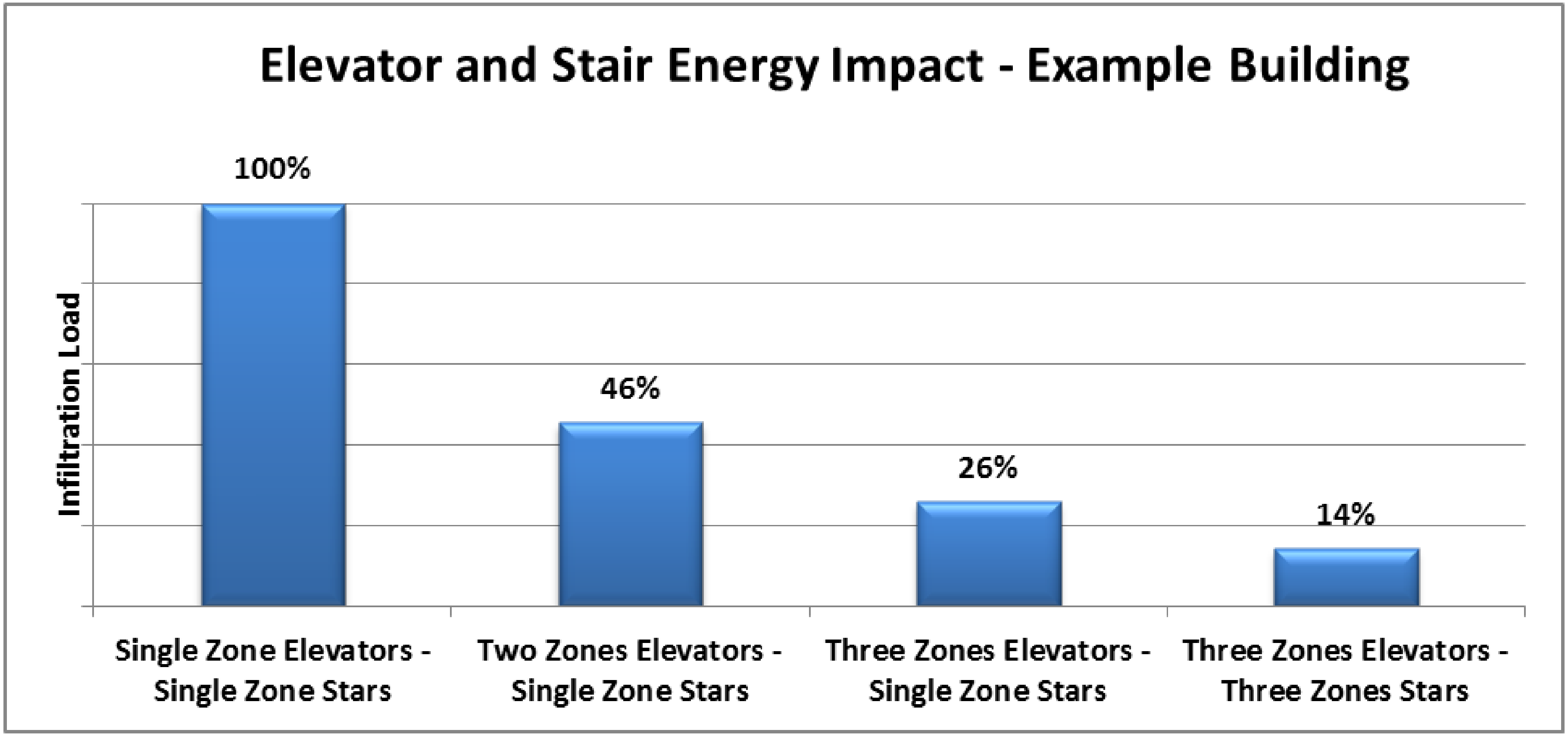
60 Story Building – Infiltration Load (Energy)



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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

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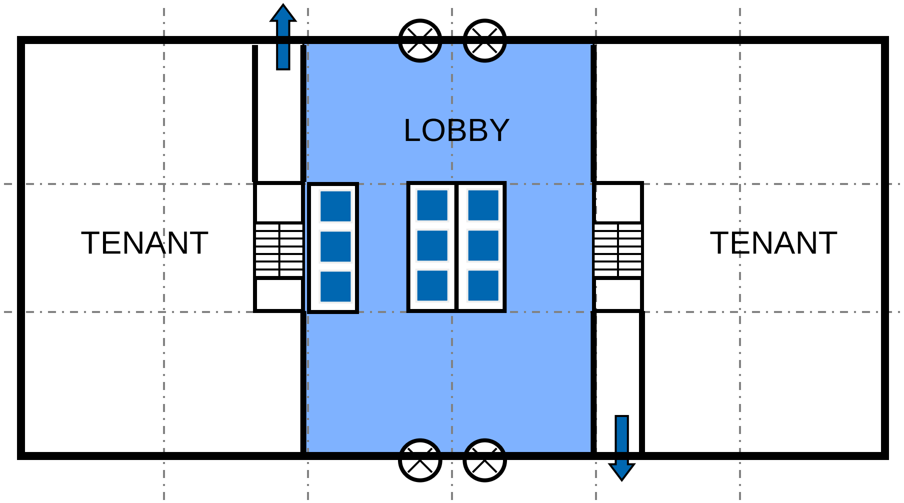
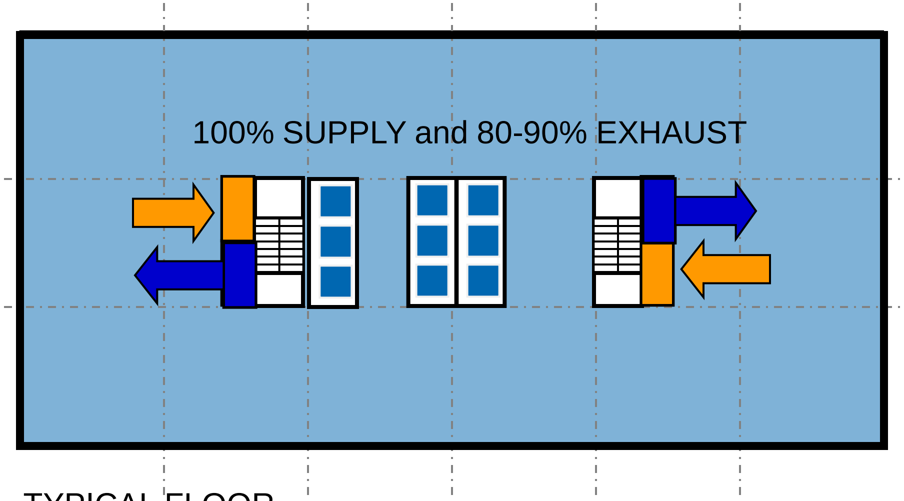
Pressurization – Normal Mode of Operation

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



GROUND FLOOR



TYPICAL FLOOR

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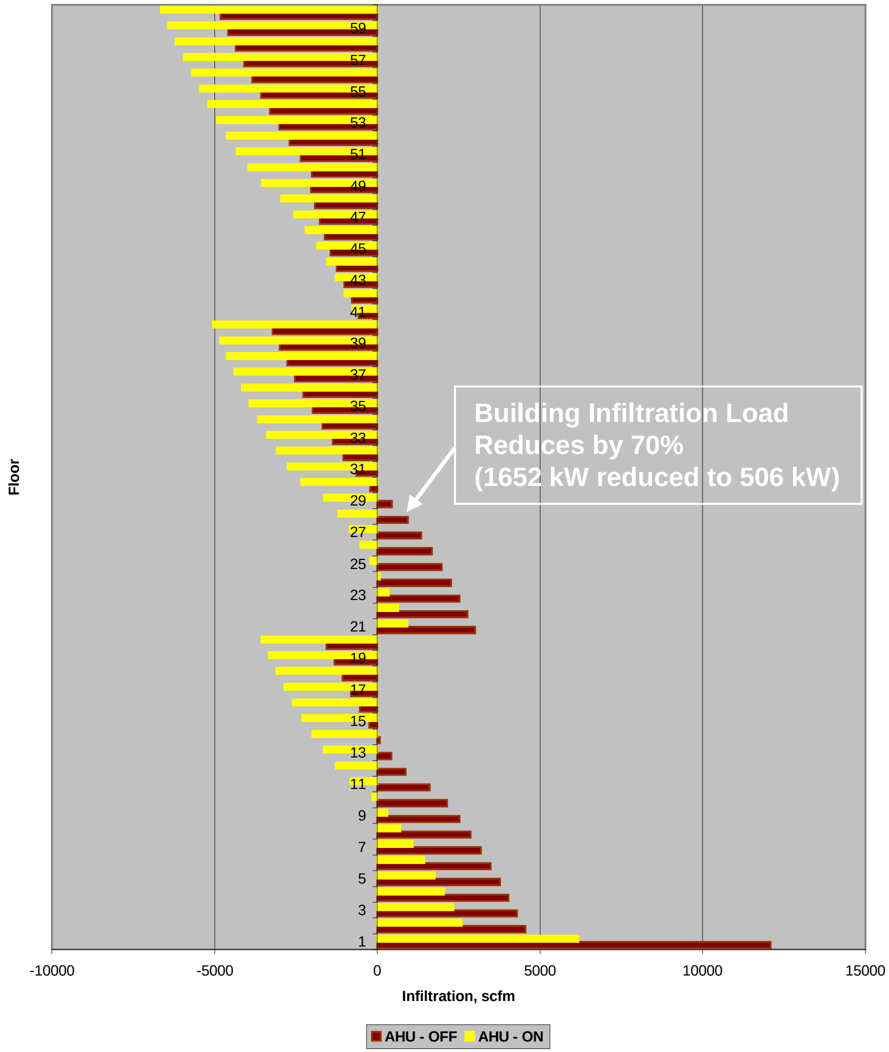
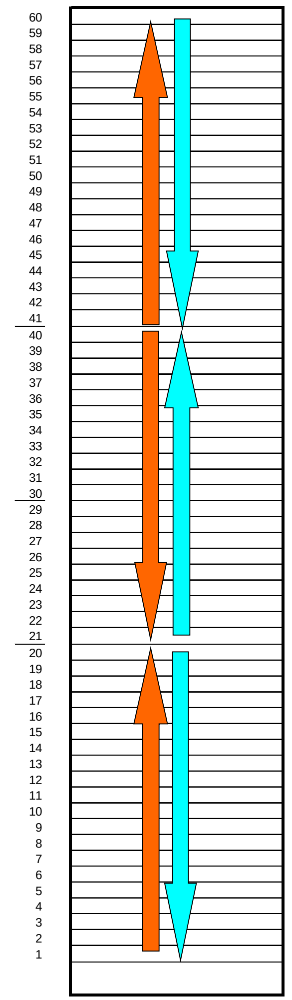
Pressurization – Normal Mode of Operation

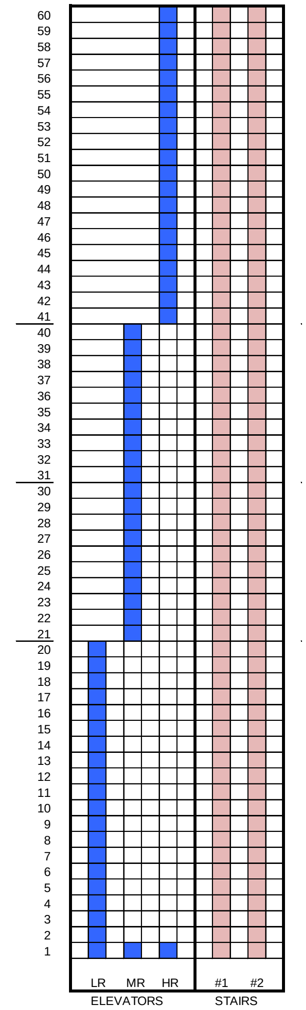
60-Story Office Building Infiltration
Effect of AHU Pressurization (Normal Mode)



Three Zones Central AHU



Three Zones Elevator Single Zone Stairs



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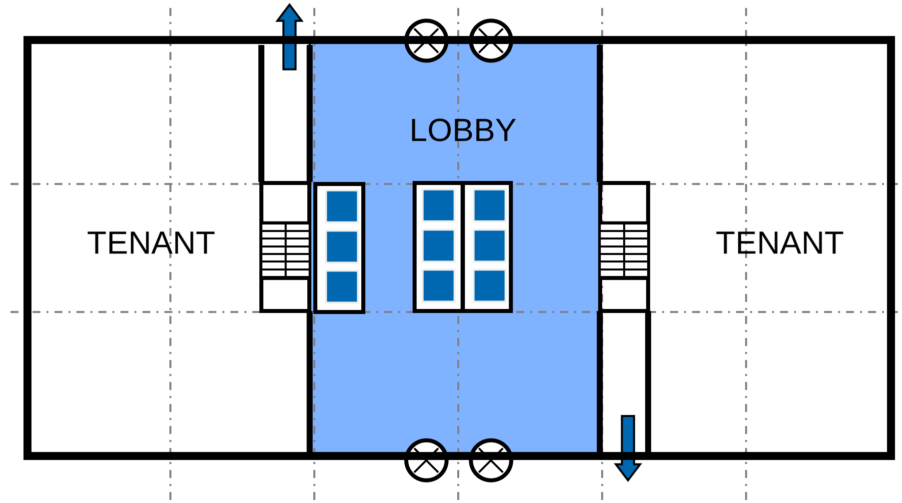
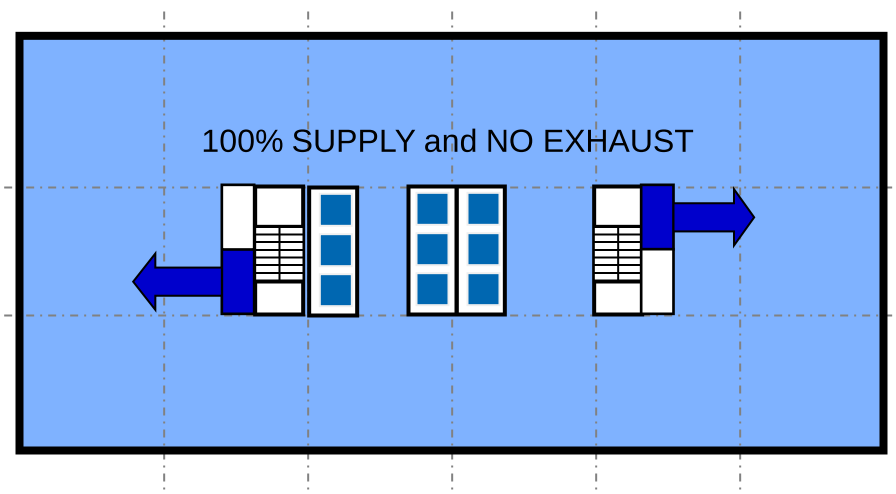
Pressurization – Fire Mode of Operation

Floor Pressurization

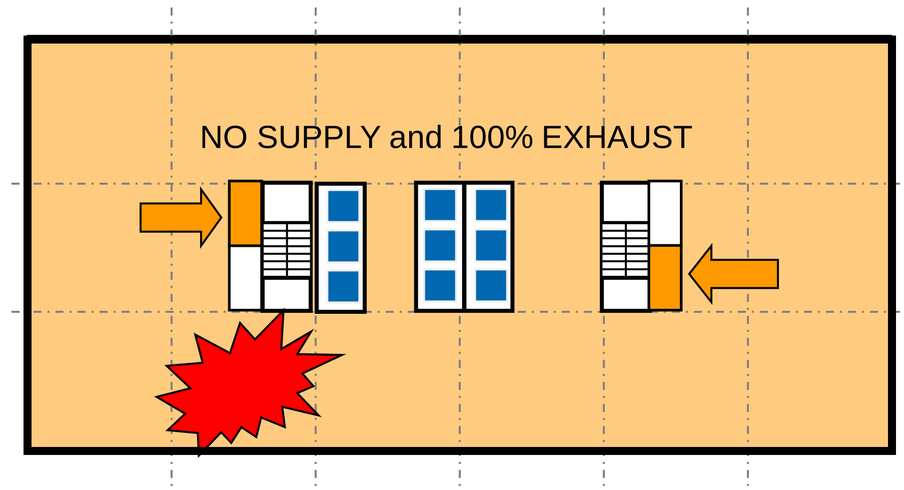
- Main building lobby is pressurized
- Fire Floor is provided with full exhaust
- Floors above and below fire floor is provided with full supply air
- All other floors operate normal mode
- Stairs not pressurized



GROUND FLOOR



ABOVE OR BELOW FIRE FLOOR



FIRE FLOOR

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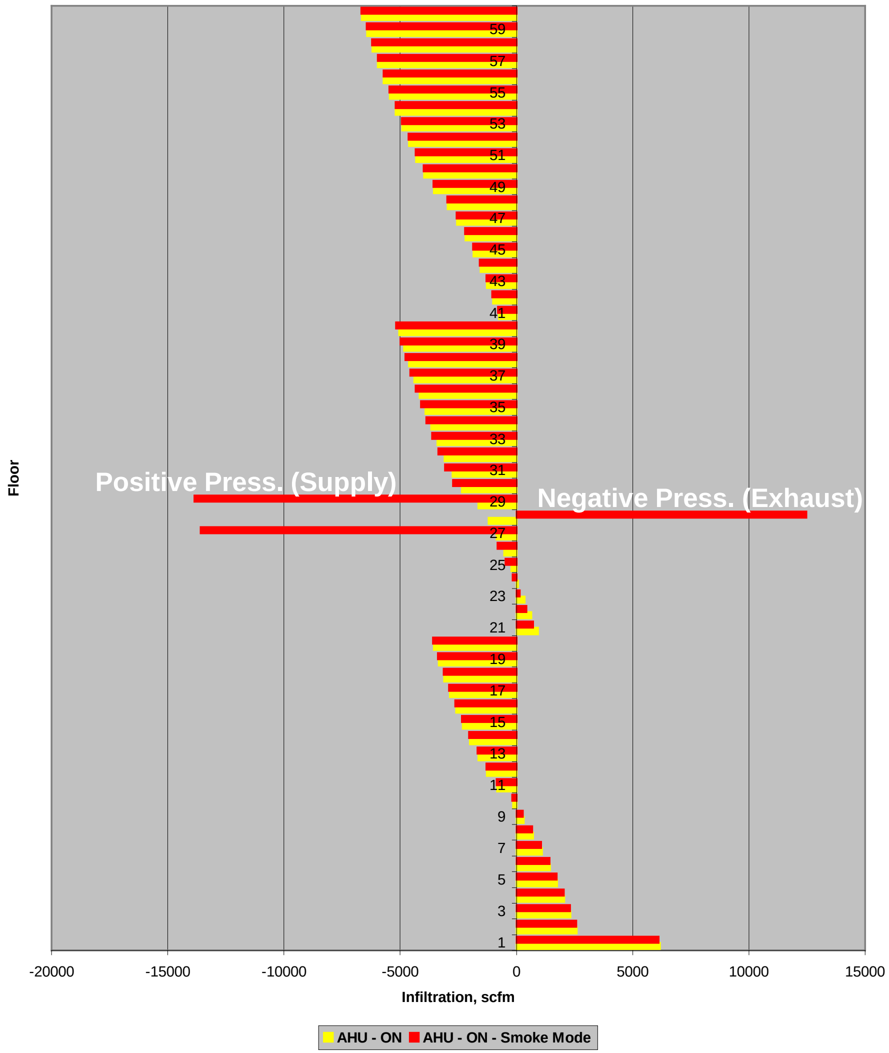
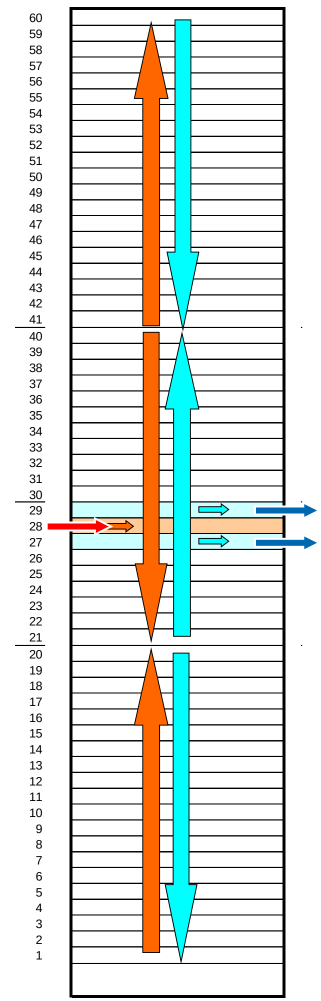
Pressurization – Fire Mode of Operation

No Stair Pressurization Provided

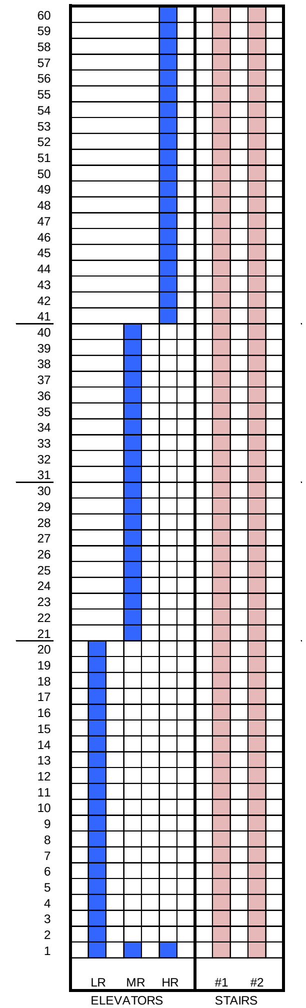
60-Story Office Building Infiltration
Smoke Condition (Level 28) - Fire Mode Pressurization



Exhaust on Fire Floor & Supply Above/Below



Single Zone Stairs Non-pressurized



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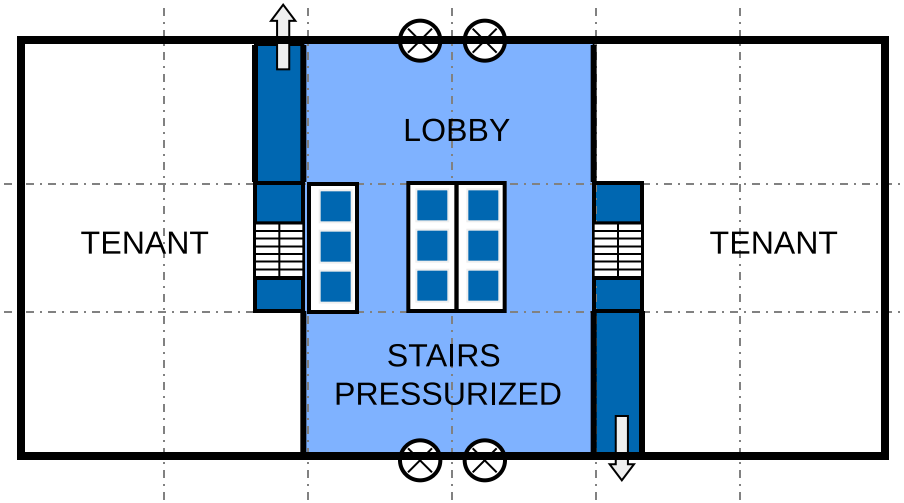
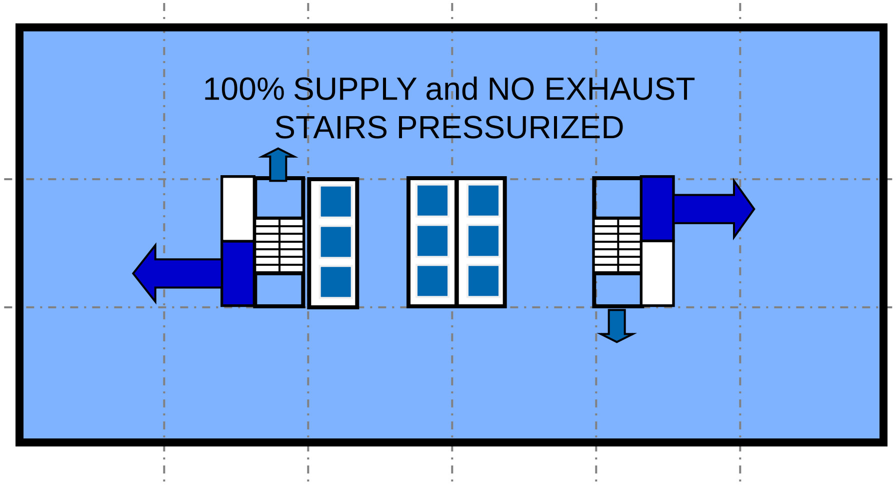
Pressurization – Fire Mode/Stair Impact

Floor and Stair Pressurization

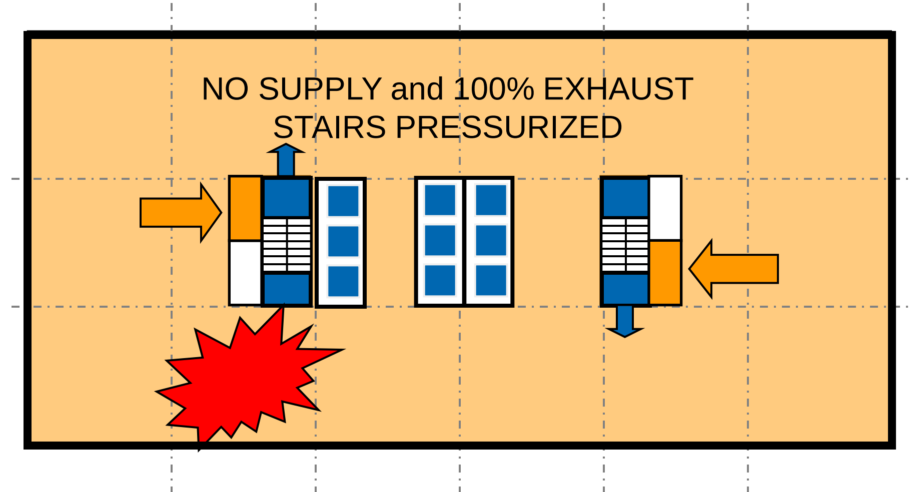
- Main building lobby is pressurized
- Fire Floor is provided with full exhaust
- Floors above and below fire floor is provided with full supply air
- All other floors operate normal mode
- Stairs are pressurized



GROUND FLOOR



ABOVE OR BELOW FIRE FLOOR



FIRE FLOOR

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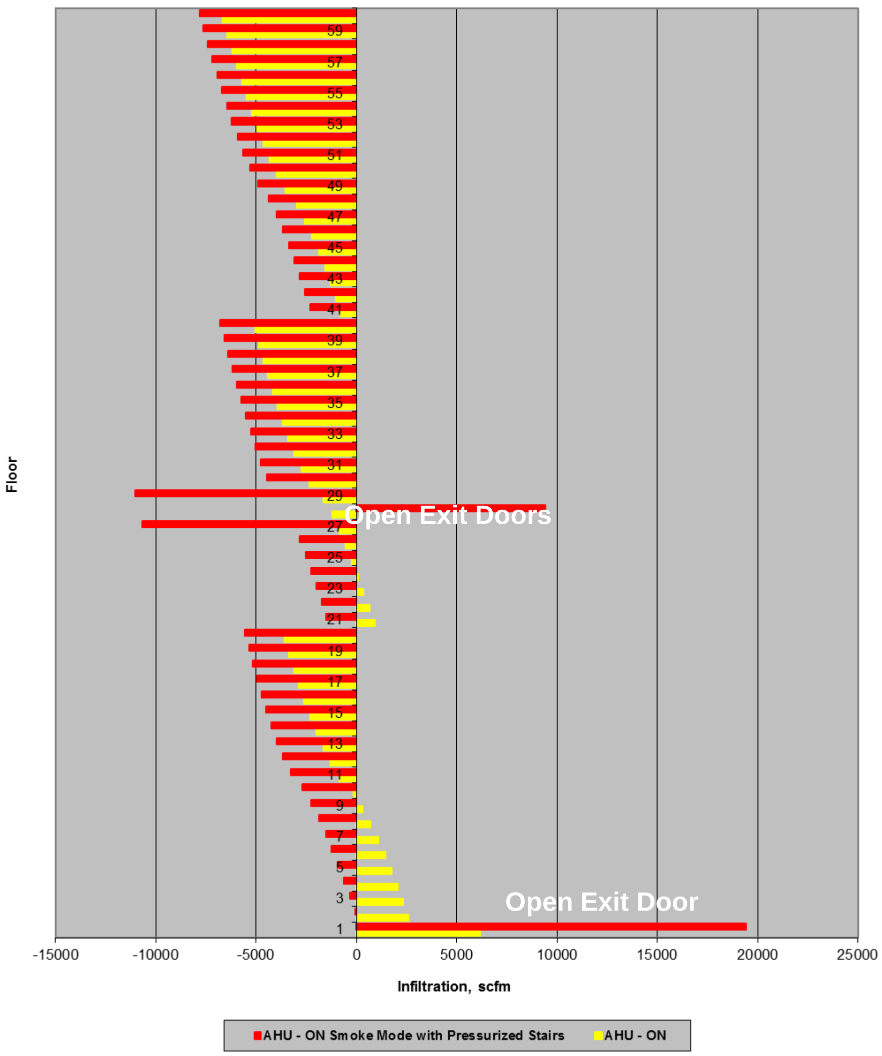
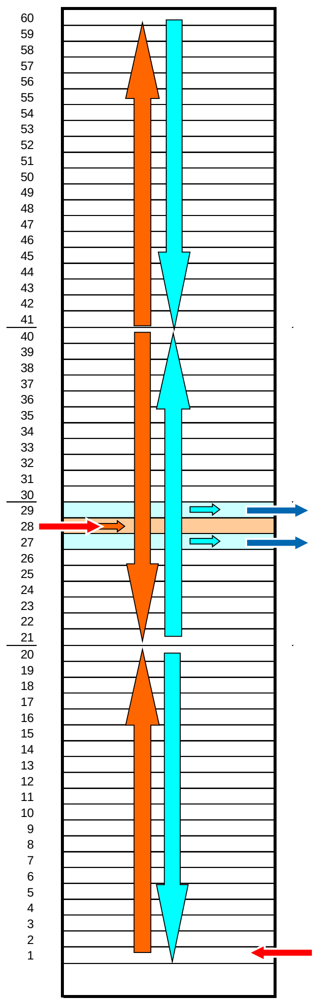
Pressurization – Fire Mode/Stair Impact

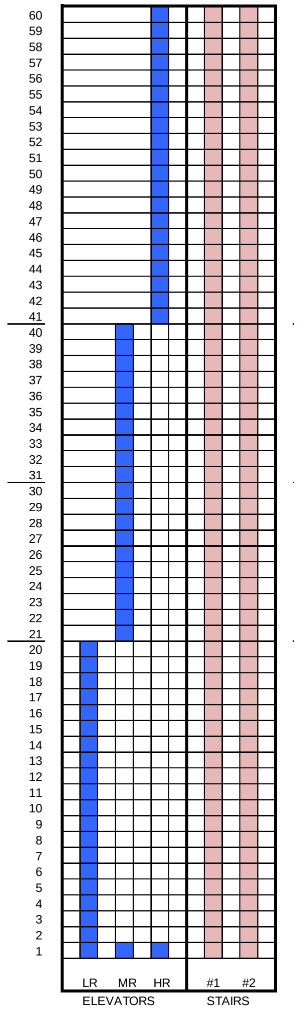
Stairs Are Pressurized



Exhaust on Fire Floor & Supply Above/Below



Single Zone Stairs Pressurized – doors open



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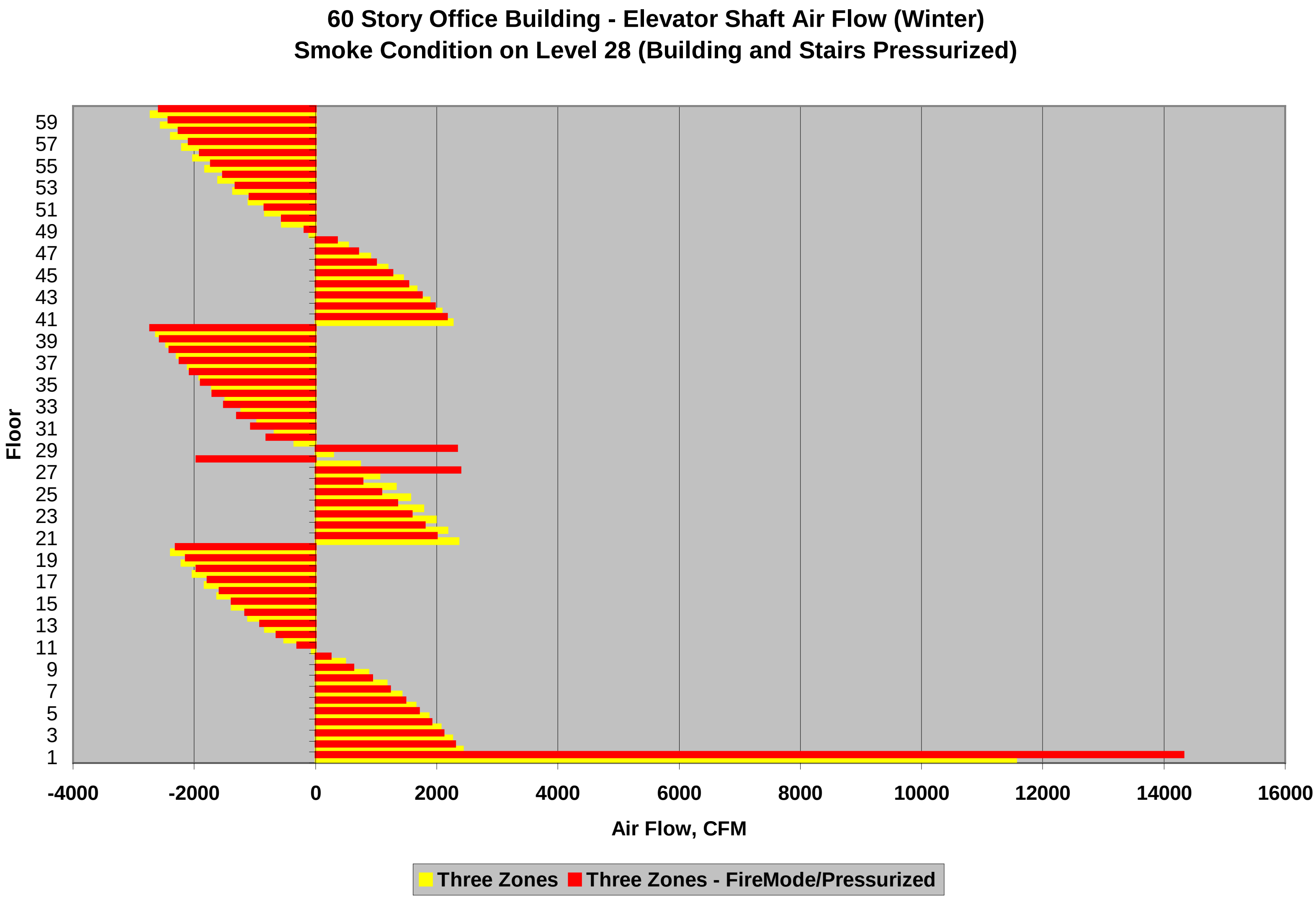
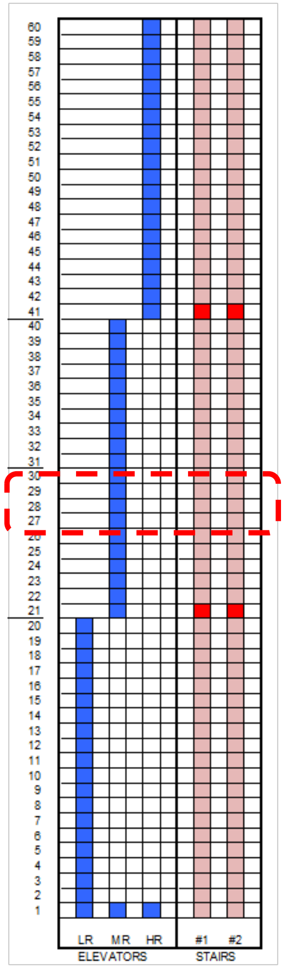
Elevator Shaft Air Flow – Fire Mode





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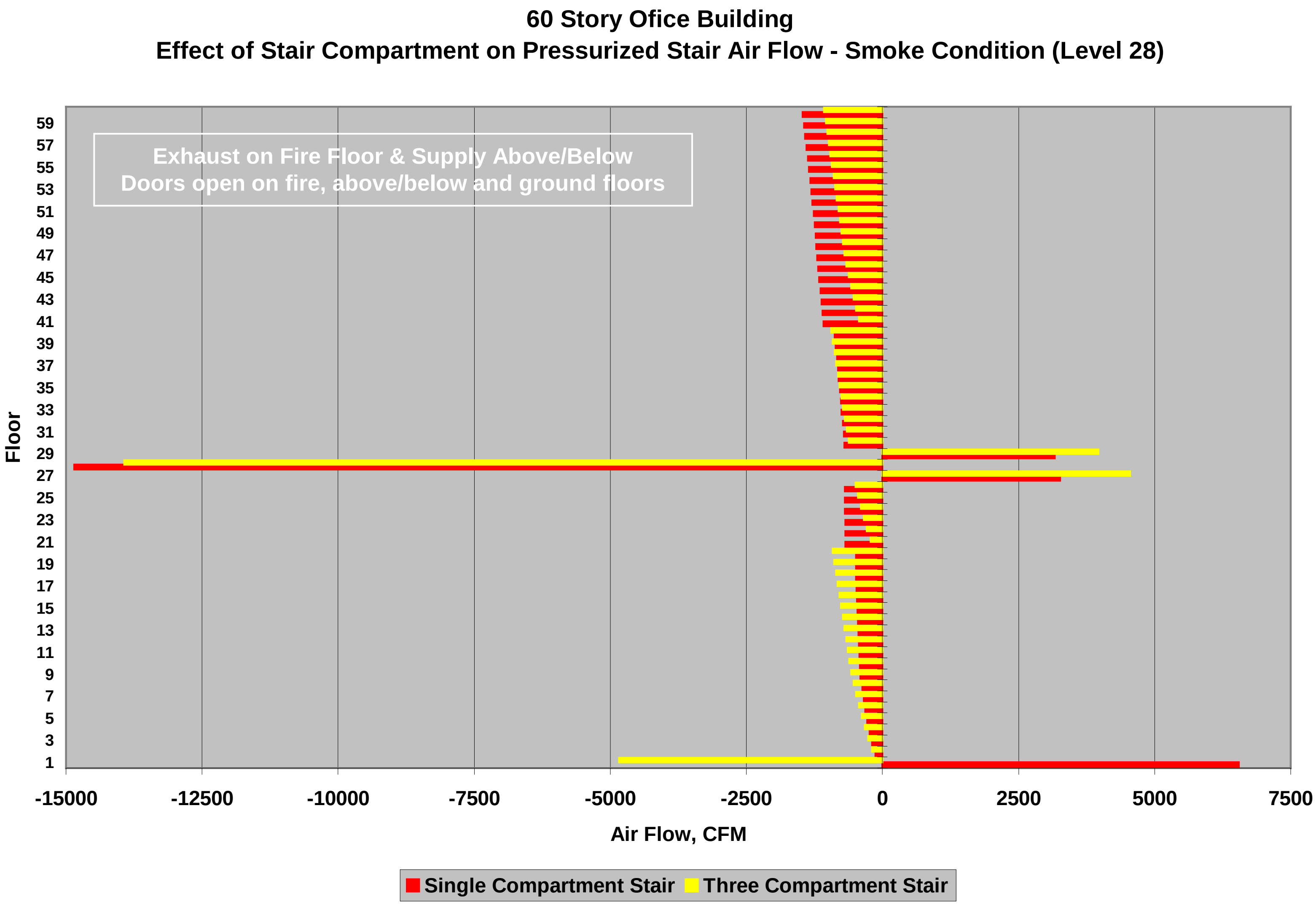
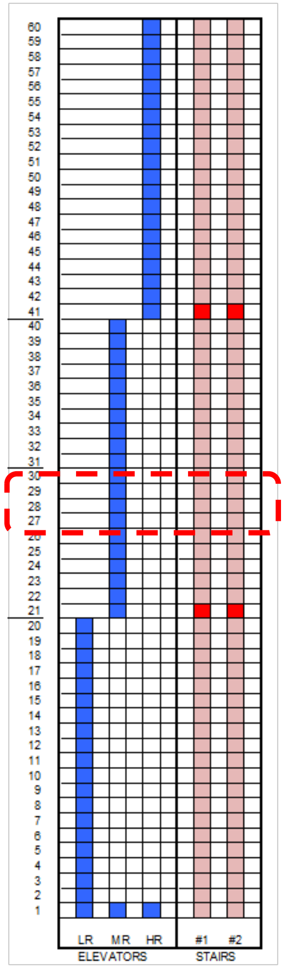
Stair Air Flow – Fire Mode





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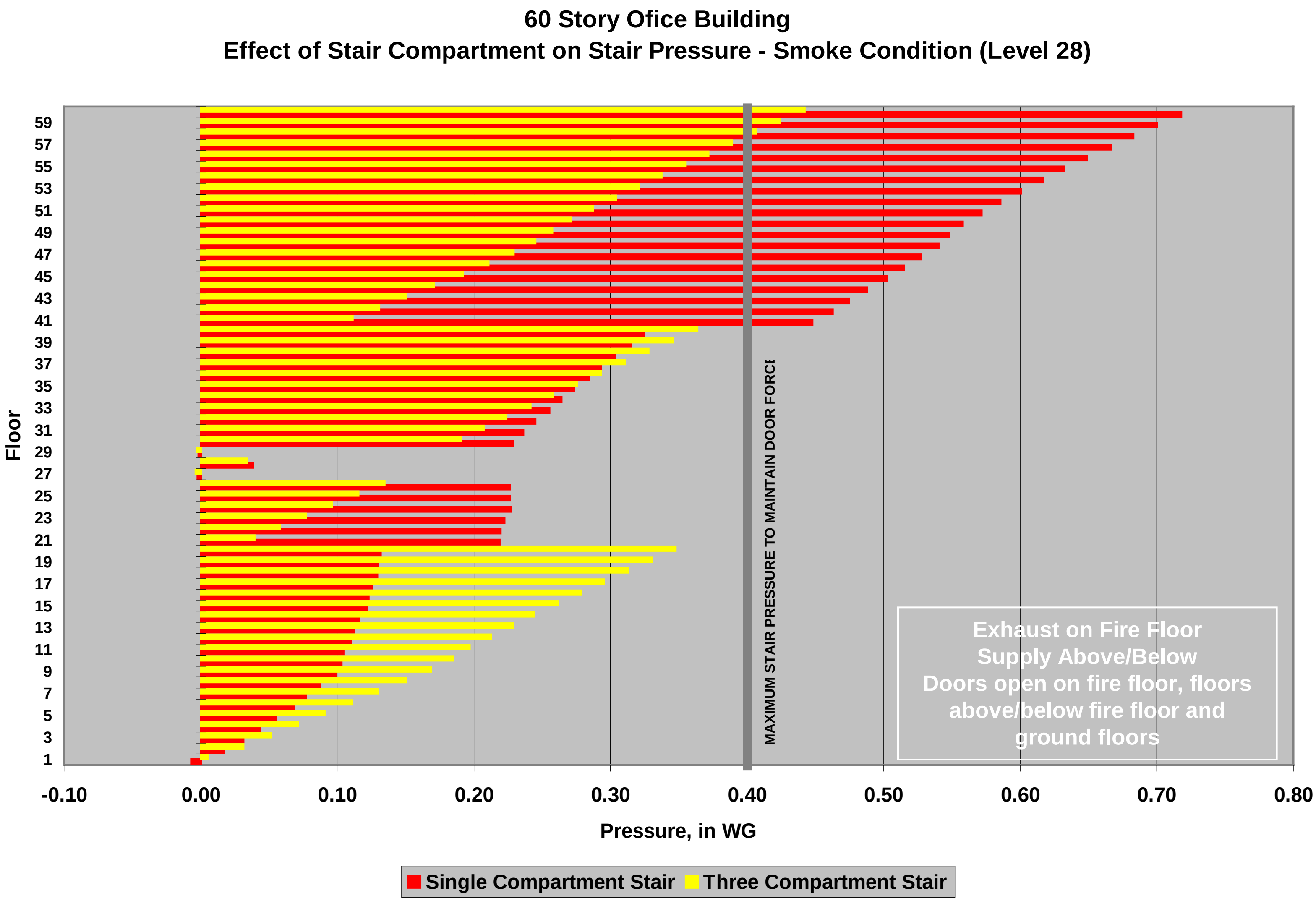
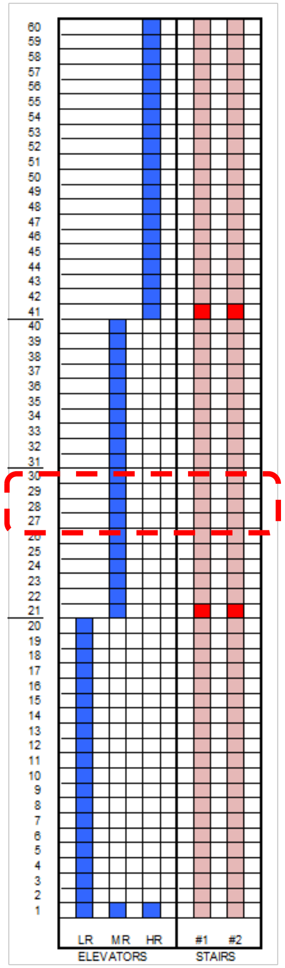
Stair Pressure – Fire Mode





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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)

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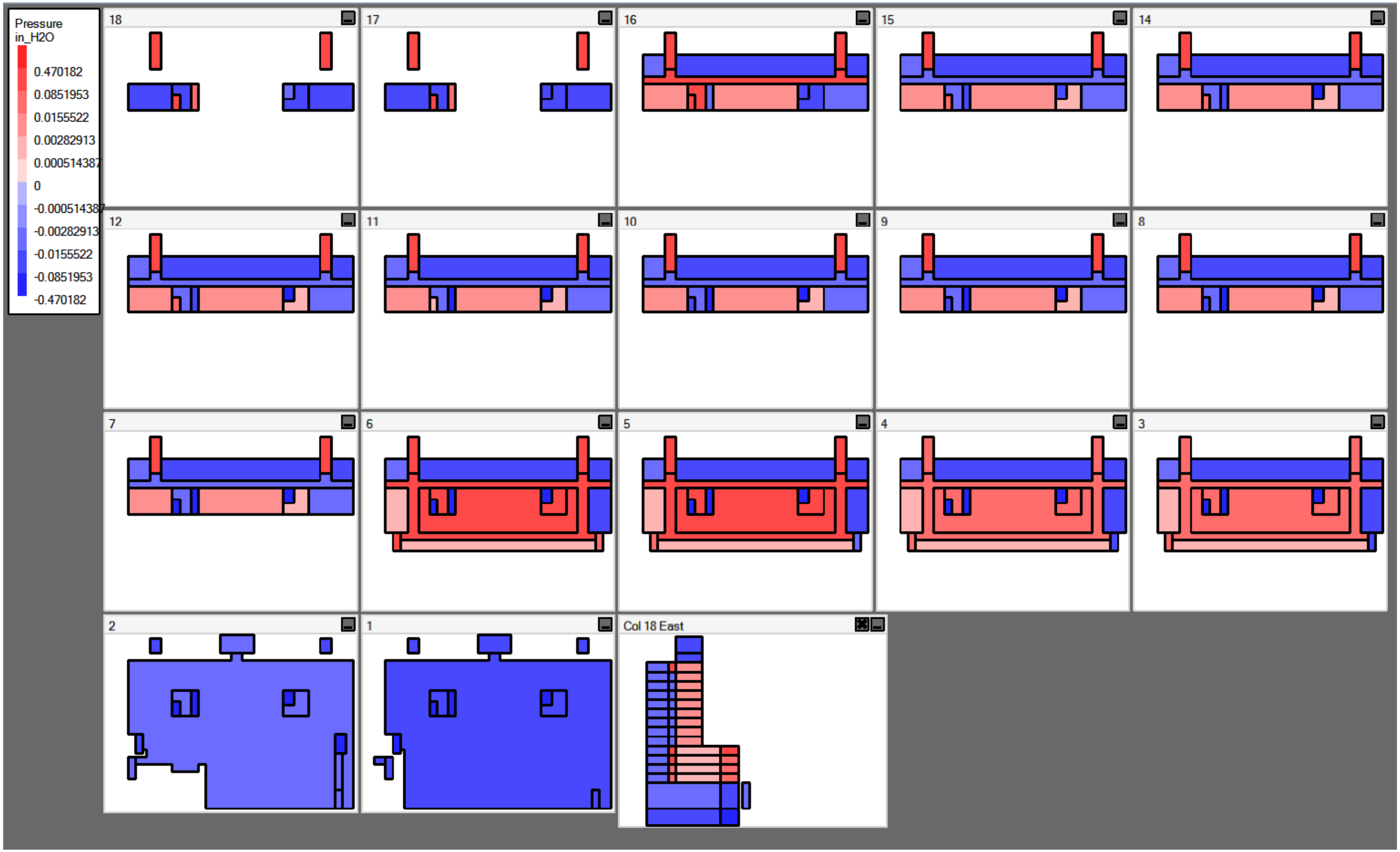
16 Story Hotel Example – Space Pressure



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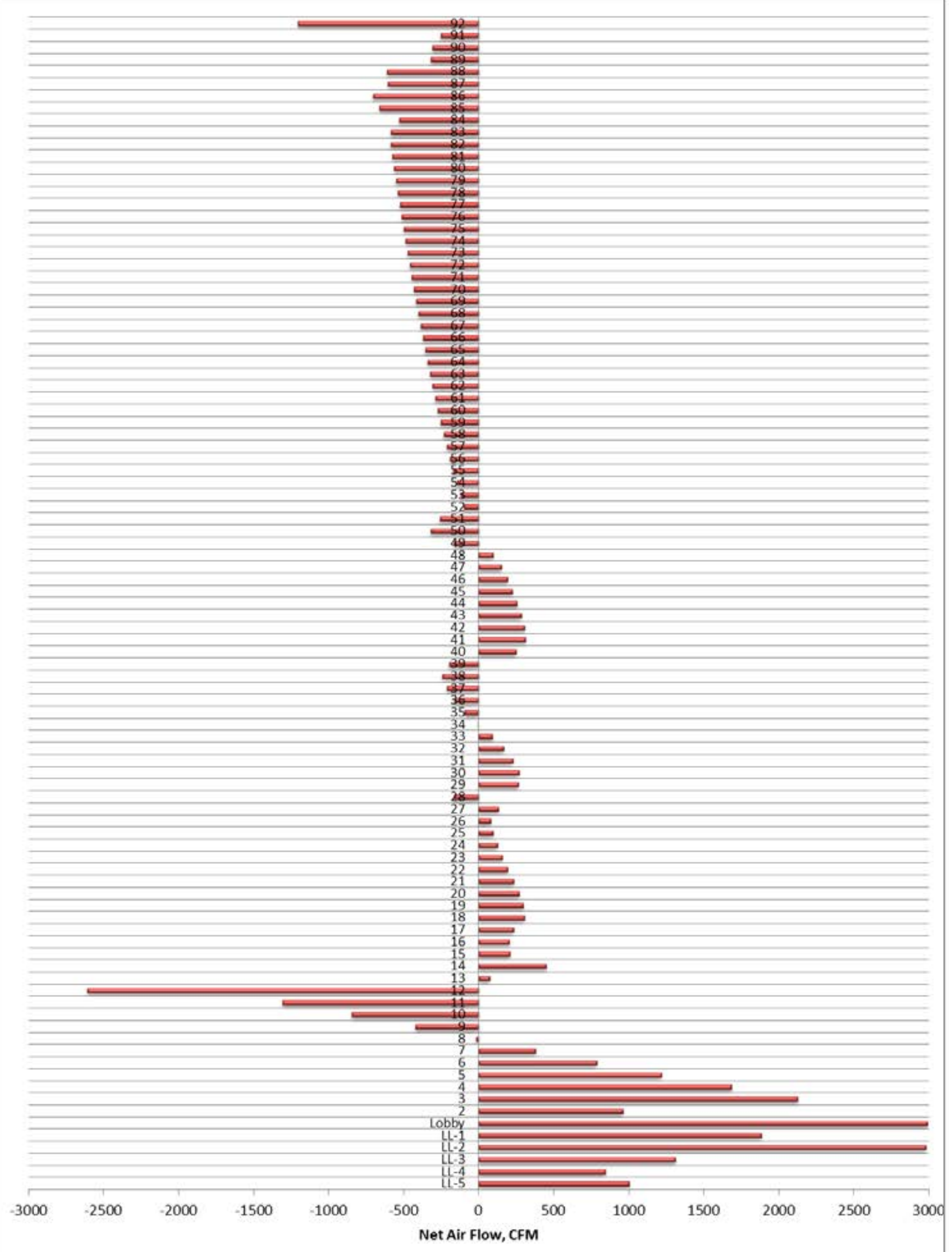
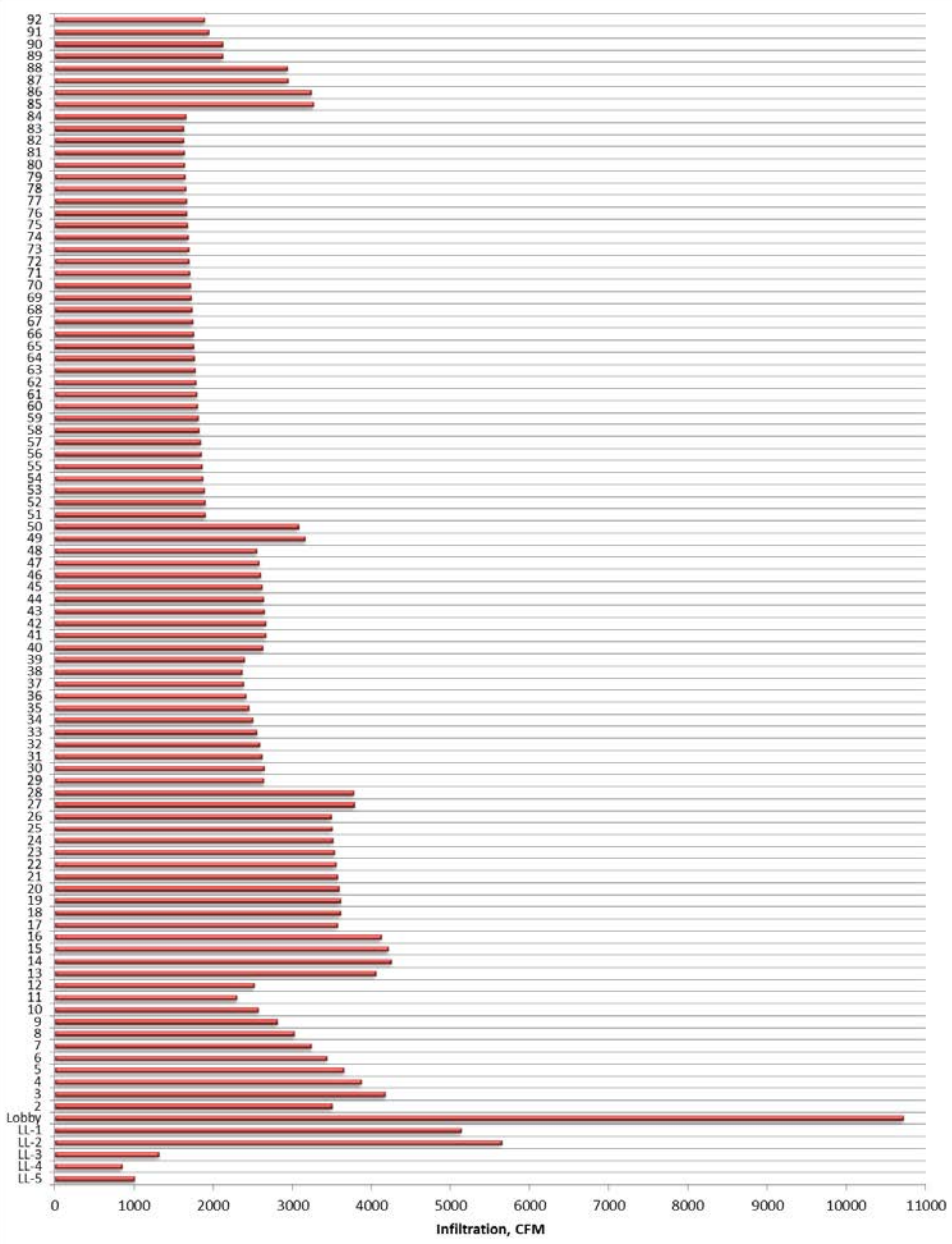
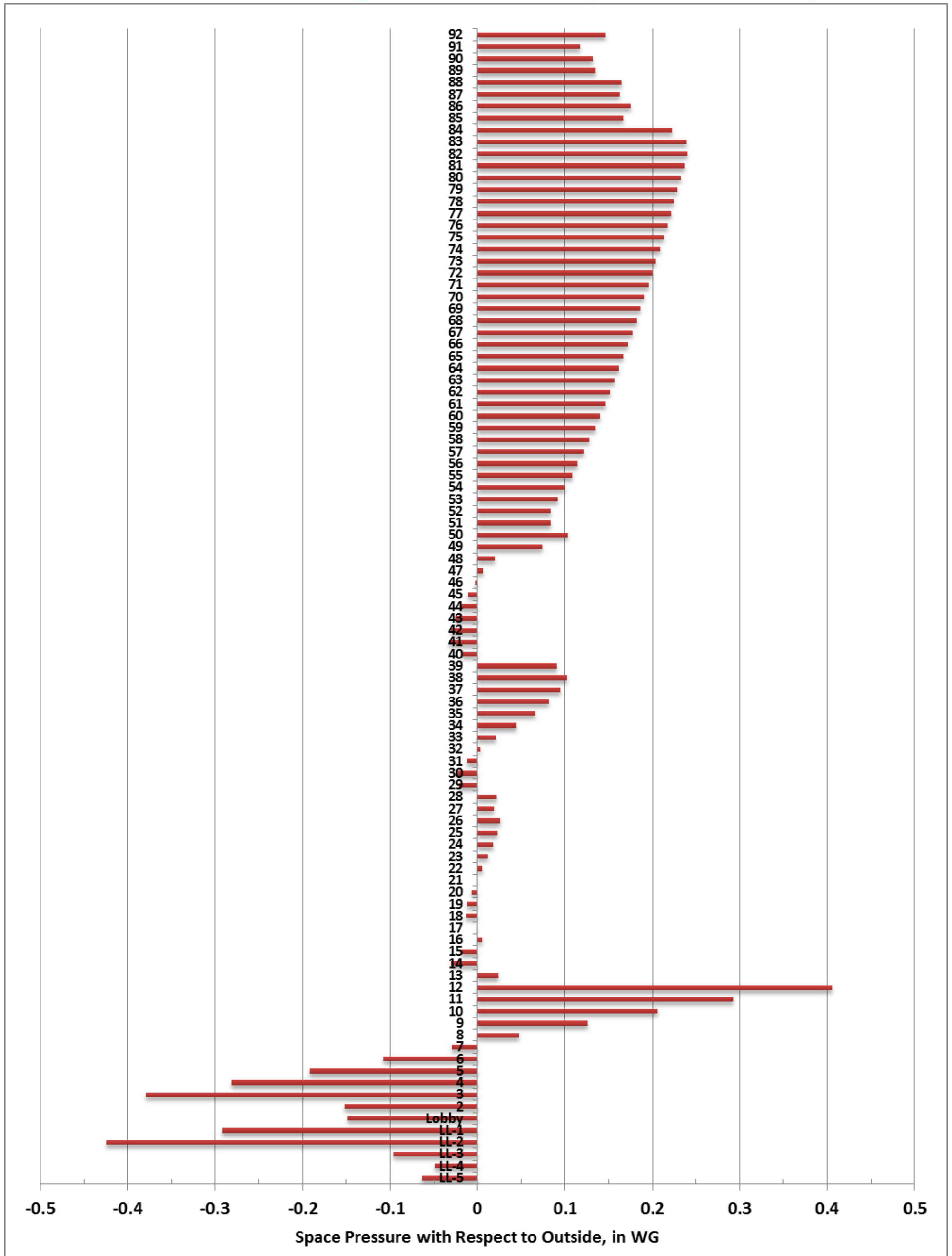
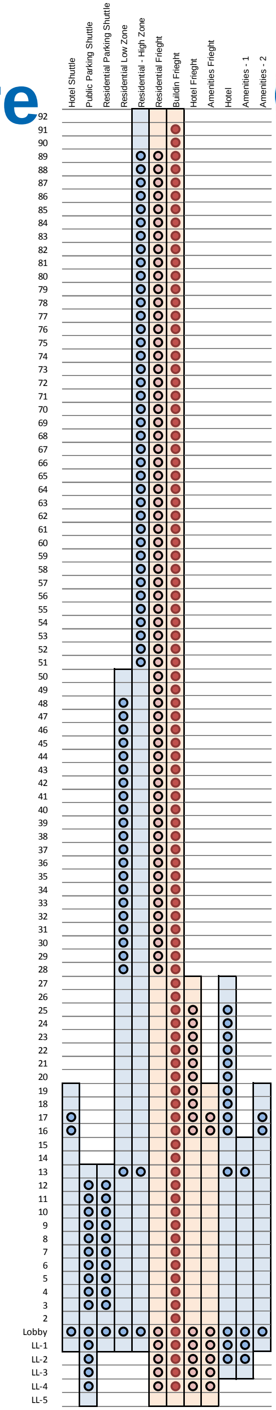
Tall Building Example – Infiltration Air Flow





Tall Building Example – Space Pressure





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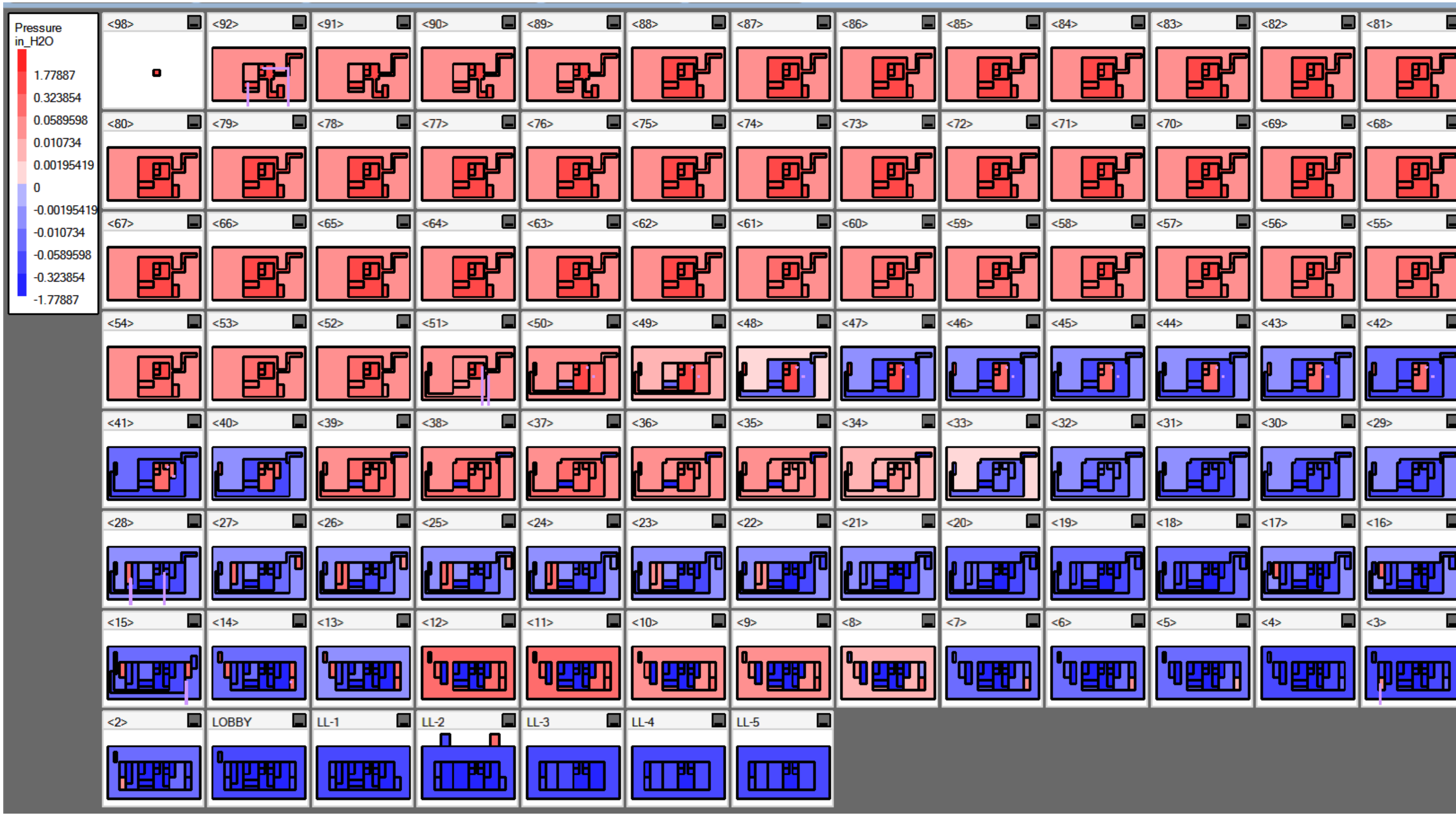
Tall Building Example – Space Pressure



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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)

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Thank you!

CCHRB

CHICAGO COMMITTEE ON HIGH RISE BUILDINGS

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