Smoke Management in High-Rise Buildings

Presented by: Kevin Geidel - CFPS, CET
Smoke Management

- Maintain tenable means of egress longer than the required safe egress time
- Reduce or control the flow of smoke from fire area to other spaces
- Assist emergency responders with S&R and suppression/control of fire
- Protection of life and property
- Assist in post-fire smoke removal
Objectives

- Review of Smoke
- Smoke Movement
- Smoke Management
- Smoke Control Systems
- Design Considerations
What is smoke?

Airborne solid and liquid particles and gases evolved when a material undergoes pyrolysis or combustion, along with the quantity of air that is entrained or otherwise mixed into the mass.
What is smoke?

Airborne solid and liquid particles and gases evolved when a material undergoes pyrolysis or combustion, along with the quantity of air that is entrained or otherwise mixed into the mass.

At 10’ above fire, 99.9% of smoke is entrained air.
Hazards of Smoke

- ¾ of all fire deaths are caused by smoke inhalation
- Approximately 57% of fire deaths occur outside room of fire origin
- 47% of fire survivors could not see more than 12’
- Smoke travels 120 – 240 ft/min
Smoke

- Smoke Production
- Flame Height
- Plume Temperature
- Plume Flow
Smoke Production

\[ \dot{m} = 0.071k^{2/3}Q_c^{1/3}z^{5/3} + 0.0018Q_c \]

\( \dot{m} \) = Mass flow in plume at height \( z \) (kg/sec)
\( k \) = Wall factor (1, \( \frac{3}{4}, \frac{1}{2}, \frac{1}{4} \))
\( Q_c \) = Convective heat release rate of fire (kW)
\( z \) = Height above top of fuel (m)
Flame Height

$$Z_f = 0.166(Q/k)^{0.4}$$

$Z_f$ = Mean flame height (m)
$Q$ = Heat release rate of fire (kW)
$k$ = Wall factor ($1, \frac{3}{4}, \frac{1}{2}, \frac{1}{4}$)
Plume Temperature

\[ T_p = \left[ \frac{Q_c}{(\dot{m} C_p)} \right] + T_o \]

- \( T_p \): Average plume temperature (°C)
- \( \dot{m} \): Mass flow in plume at height \( z \) (kg/sec)
- \( Q_c \): Convective heat release rate of fire (kW)
- \( C_p \): Specific heat of plume gases, 1.00 kJ/kg°C
- \( T_o \): Ambient temperature (°C)
Volumetric Plume Flow

\[
\dot{V} = 1.51 \dot{m} (T_p + 460)
\]

\(\dot{V}\) = Volumetric flow rate of plume at height \(z\) (ft\(^3\)/min)

\(\dot{m}\) = Mass flow in plume at height \(z\) (kg/sec)

\(T_p\) = Average temperature of plume gases at height \(z\) (°F)
Smoke Flow

• 20’ x 20’ x 20’ Room
  – Assume minimal leakage and even smoke movement
  – Pencil sized hole to fire room

• How long until the room is filled with smoke preventing you from seeing your hand 18” in front of you?
Smoke Flow

• 20’ x 20’ x 20’ Room
  – Assume minimal leakage and even smoke movement
  – Pencil sized hole to fire room

• How long until the room is filled with smoke preventing you from seeing your hand 18” in front of you?

3 minutes 40 seconds
Objectives

• Review of Smoke
• **Smoke Movement**
• Smoke Management
• Smoke Control Systems
• Design Considerations
Smoke Movement

- REGISTER
- BUILDING SPACE
- CORRIDOR
- STAIRCASE
- MECHANICAL HVAC SYSTEM
- BUOYANT SMOKE
- GAS EXPANDS
- WIND

SFPE
Forces that Affect Smoke Movement

- **Buoyancy of Combustible Gas**
  - Temperature of smoke
  - Temperature derived density difference between two spaces “Stack Effect”

- **Expansion of Combustible Gas**
  - Volume of smoke

- **Wind Effect**
  - External factors

- **Building Systems**
  - Elevator Piston Effect
  - HVAC
  - Sprinklers
Buoyancy of Combustible Gas

$$\Delta P = K_s \left[ (1/T_o) - (1/T_f) \right] h$$

- $\Delta P$ = Pressure difference (in. H$_2$O [Pa])
- $T_o$ = Absolute temperature of surrounding (R [K])
- $T_f$ = Absolute temperature of compartment (R [K])
- $h$ = Distance above the neutral plane (ft. [m])
- $K_s$ = coefficient (7.64 [3460])
Buoyancy of Combustible Gas

\[ \Delta P = K_s \left[ \left(\frac{1}{T_o}\right) - \left(\frac{1}{T_f}\right) \right] h \]

\[ h = 3 \text{ m} \]
\[ T_o = 20 \, ^\circ \text{C} \]
\[ T_f = 700 \, ^\circ \text{C} \]
\[ \Delta P = ? \]
Buoyancy of Combustible Gas

$$\Delta P = K_s \left[ \left( \frac{1}{T_o} \right) - \left( \frac{1}{T_f} \right) \right] h$$

$h = 3$ m
$T_o = 20 \, ^\circ$C
$T_f = 700 \, ^\circ$C
$\Delta P = 25 \, \text{Pa}$
Stack Effect

\[ \Delta P = K_s \left[ \left( \frac{1}{T_o} \right) - \left( \frac{1}{T_i} \right) \right] h \]

\( \Delta P \) = Pressure difference (in. H\(_2\)O [Pa])
\( T_o \) = Absolute temperature of outside air (R [K])
\( T_i \) = Absolute temperature of inside air (R [K])
\( h \) = Distance above the neutral plane (ft. [m])
\( K_s \) = coefficient (7.64 [3460])
Stack Effect

- Buoyancy via temperature gradient between inside and outside
- Building is not a balloon
- Buildings leakage, there are no air tight buildings
- Neutral plane is between 49% and 51% of building height
Stack Effect

$$\Delta P = K_s \left[ \left( \frac{1}{T_o} \right) - \left( \frac{1}{T_i} \right) \right] h$$

$\Delta P =$ Pressure difference (in. H$_2$O [Pa])

$T_o =$ Absolute temperature of outside air (R [K])

$T_i =$ Absolute temperature of inside air (R [K])

$h =$ Distance above the neutral plane (ft. [m])

$K_s =$ coefficient (7.64 [3460])
Stack Effect

$$\Delta P = K_s \left[ \left( \frac{1}{T_o} \right) - \left( \frac{1}{T_i} \right) \right] h$$

h = 30 m

$T_o = 0^\circ C$

$T_i = 20^\circ C$

$\Delta P = 25 \text{ Pa}$
Expansion of Combustible Gas

\[
\frac{Q_{\text{out}}}{Q_{\text{in}}} = \frac{T_{\text{out}}}{T_{\text{in}}}
\]

- \(Q_{\text{out}}\) = Volumetric flow rate of smoke out of fire compartment (ft\(^3\)[m\(^3\)]/min)
- \(Q_{\text{in}}\) = Volumetric flow rate of smoke into fire compartment (ft\(^3\)[m\(^3\)]/min)
- \(T_{\text{out}}\) = Absolute temperature of smoke leaving fire compartment (R [K])
- \(T_{\text{in}}\) = Absolute temperature of air into fire compartment (R [K])
Expansion of Combustible Gas

\[
\frac{Q_{\text{out}}}{Q_{\text{in}}} = \frac{T_{\text{out}}}{T_{\text{in}}}
\]

\( T_{\text{in}} = 20 \, \text{K} \)
\( T_{\text{out}} = 700 \, \text{K} \)
\( Q_{\text{in}} = 1.5 \, \text{m}^3/\text{s} \)
\( Q_{\text{out}} = ? \)
Expansion of Combustible Gas

\[
\left( \frac{Q_{out}}{Q_{in}} \right) = \left( \frac{T_{out}}{T_{in}} \right)
\]

\[
T_{in} = 20 \text{ K}
\]
\[
T_{out} = 700 \text{ K}
\]
\[
Q_{in} = 1.5 \text{ m}^3/\text{s}
\]
\[
Q_{out} = 5.0 \text{ m}^3/\text{s}
\]
Wind Effect

- Slanted or stepped neutral plane
- Wind coefficient to determine true effect
  - Need wind tunnel test of building/surrounding to determine
- Structural (wind load) typical have information
- FDS modeling is a possibility
Elevator Piston Effect

- Transient pressure from elevator movement
- Pull smoke into pressurized shaft way
- Critical pressure reduces/eliminates effect
Elevator Piston Effect

$$\Delta P_{\text{crit}} = \left[\frac{(K_{\text{pe}} \rho)}{2}\right] \left[\frac{(A_s A_e V)}{(A_a A_{si} C_c)}\right]^2$$

$$\Delta P_{\text{crit}} = \text{Critical pressure difference (in. H}_2\text{O [Pa])}$$
$$\rho = \text{air density in elevator shaft (lb/ft}^3 \text{ [kg/m}^3\text{])}$$
$$A_s = \text{Cross-sectional area of the elevator shaft (ft}^2 \text{ [m}^2\text{])}$$
$$A_{si} = \text{Leakage area between lobby and building (ft}^2 \text{ [m}^2\text{])}$$
$$A_a = \text{Free area around the elevator car (ft}^2 \text{ [m}^2\text{])}$$
$$A_e = \text{Effective area between elevator shaft and outside (ft}^2 \text{ [m}^2\text{])}$$
$$V = \text{Elevator car velocity (ft/\text{min [m/s])}$$
$$C_c = \text{Flow coefficient for flow around car (single: 0.92, multiple: 0.83)}$$
$$K_{\text{pe}} = \text{Coefficient, 1.66 x 10-6 (1.00)}$$
Elevator Piston Effect

(non-enclosed lobby)

\[ \mathbf{A}_e = \left( \frac{1}{\mathbf{A}_{si}^2} + \frac{1}{\mathbf{A}_{io}^2} \right)^{-\frac{1}{2}} \]

\( A_e \) = Effective area between elevator shaft and outside (ft\(^2\) [m\(^2\)])
\( A_{si} \) = Leakage area between lobby and building (ft\(^2\) [m\(^2\)])
\( A_{io} \) = Leakage area between outside and building (ft\(^2\) [m\(^2\)])

(enclosed lobby)

\[ \mathbf{A}_e = \left( \frac{1}{\mathbf{A}_{sr}^2} + \frac{1}{\mathbf{A}_{ir}^2} + \frac{1}{\mathbf{A}_{io}^2} \right)^{-\frac{1}{2}} \]

\( A_e \) = Effective area between elevator shaft and outside (ft\(^2\) [m\(^2\)])
\( A_{sr} \) = Leakage area between shaft and lobby (ft\(^2\) [m\(^2\)])
\( A_{ir} \) = Leakage area between building and lobby (ft\(^2\) [m\(^2\)])
\( A_{io} \) = Leakage area between outside and building (ft\(^2\) [m\(^2\)])
Elevator Piston Effect

Notes:
1. The point of this figure is to show that with the basic system the pressure differences at the ground floor can be very large with leaky and average exterior walls. However, with very leaky exterior walls, the basic system meets the pressure difference criteria. It is not shown on this figure, but even larger pressure differences happen with tight exterior walls.
2. The shaded space is the pressure difference criteria of 25 to 62 Pa (0.10 to 0.25 in. H₂O).

Exterior Wall Leakage:
- Very Leaky
- Leaky
- Average

Pressure Difference (in H₂O)

Floor
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14

Pressure Difference (Pa)
0 100 200 300 400 500

See Note 1.
See Note 2.
Mechanical Ventilation

Good or Bad?

- May aid detection
- Assist with smoke removal
- Spread smoke
- Supplies air to fire
Mechanical Ventilation

- NBFU 1939 – National Board of Fire Underwriters
- Report on 25 fires from 1936 to 1938
- 19 – Fire involved HVAC system
- 5 – No fire in HVAC but distributed smoke
- Modern HVAC material fire resistant
- HVAC shutdown or go into smoke control mode
Objectives

• Review of Smoke
• Smoke Movement

• Smoke Management
• Smoke Control Systems
• Design Considerations
Smoke Management

• **Smoke Management:**
  – A smoke control method that utilizes natural or mechanical systems to maintain a tenable environment in the means of egress from a large-volume space or to control and reduce the migration of smoke between the fire area and communicating spaces

• **Smoke Control System:**
  – An engineered system that includes all methods that can be used singly or in combination to modify smoke movement.
Smoke Management

- Prevent smoke from entering means of egress, stairwells, elevator shafts, etc.
- Maintain tenable conditions in means of egress and areas of refuge
- Prevent smoke from migrating from smoke zone
- Maintain acceptable conditions outside of smoke zone to allow emergency response operations
- Protect life and property
Smoke Management

• **Passive Management**
  – Compartmentation
  – Smoke barriers
  – Smoke vents
  – Smoke shafts

• **Active Management**
  – Dedicated Systems
  – Non-Dedicated Systems
Smoke Management

- Buoyancy
- Compartmentation
- Dilution
- Airflow
- Pressurization
Buoyancy

• Smoke Filling
  – Large-volume areas (typical atrium)
  – Dependent upon egress models
• Unsteady Clear Height with Upper Layer Exhaust
  – Delaying smoke fill
• Steady Clear Height with Upper Layer Exhaust
  – Prevent smoke fill
• Activation of fire suppression system may affect
Compartmentation

- Fire walls, partitions, floors, doors, dampers, etc.
- Smoke leakage typically occurs
  - Approximate using and orifice equation:
    \[ \dot{V} = CA \sqrt{\frac{(2 \Delta P)}{\rho}} \]
- Better understanding using computer modeling
  - CFAST
  - FDS
  - SmokeView
Dilution

- Smoke purging, removal, exhaust, extraction
- Concern for toxicity versus visibility
  - Toxicity difficult to analyze
  - Estimation of smoke obscuration often used
- Required air exchanges can be calculated:
  \[ \alpha = \frac{1}{t} \log_e \left( \frac{C_o}{C} \right) \]
- HVAC not typically practical for dilution
- Smoke purge systems
Post-Fire Smoke Removal

- Fire produces large quantity of smoke
- Mechanically purge smoke
- Decreases level of obscuration
- Allows firefighters to verify extinguishment
- Reduces collateral structural damage
- Reduces fire service labor/exertion
Post-Fire Smoke Removal

\[ C = C_0 \, e^{\alpha t} \]

- \( C \) = Concentration of contaminant at time, \( t \)
- \( C_0 \) = Initial concentration of contaminant
- \( \alpha \) = Dilution rate in number of air changes per minute
- \( t \) = Time after doors close in minutes
- \( e \) = Constant, approximately 2.718
Airflow

- Utilizing flow rates of air to control smoke movement
- Not typically used in High-rise buildings:
  - Large flow rates needed
  - Supply additional oxygen to fire
  - Flow adjustment for open/closed doors
Pressurization

- Airflow into small gaps around closed doors and construction cracks
- Typical:
  - Stairwells
  - Elevator Hoistways
  - Zoned Smoke Control
Pressurization – NFPA 92 (2012)

- 5.2.1 – Pressure differential across smoke barrier shall be 12.5 Pa for fully sprinklered buildings
- 5.2.2 – Pressure differential across doors shall not cause the force required to open the doors to exceed 133 N.
- 5.3 – Stairways are to be pressurized to a minimum of 12.5 Pa and a maximum level that causes the door opening forces to be less than 133 N.
- 5.4 – Elevators shall be considered a separate smoke zone when smoke control is required.
- 5.3.5.1 – Vestibules shall not be required, but shall be permitted as part of a building smoke management system.
Objectives

- Review of Smoke
- Smoke Movement
- Smoke Management
- Smoke Control Systems
- Design Considerations
Smoke Control Systems

- Zone Smoke control
  - Designed Pressure Differences
- Stair pressurization
- Pressurized Elevator Hoistways
Zoned Smoke Control

• Limit smoke movement through zones
• Typically zoned by floor in high-rise buildings
  – Can be partial or multiple floors
• Basement(s) are separate zones
• Mechanical fans provide air flow and pressurization
  – Supply outside air to non-smoke zones
  – Vent smoke from smoke zone
  – Combination of both
Zone Smoke Control

- Partial floor smoke zone
  - Smoke zone not protected
Zone Smoke Control

• Designed pressure difference
  – All zones except smoke zone are pressurized

• Pressure Sandwich
  – Only zones adjacent to smoke zone are pressurized
Stairwell Pressurization

• Stairwells shall be pressurized to maintain 0.10 in. H₂O (25 Pa) to 0.35 in. H₂O (88 Pa) across any (closed) stairwell door when used in conjunction with an automatic sprinkler system. In both systems, minimum pressure differences are imposed to prevent smoke from entering the shaft, whereas maximum values are specified to maintain proper door functioning.
Stairwell Pressurization

- Single Point injection
- Multi-point injection
- Single-zone stair
- Multi-zone stair

Figure 1. Fixed Pressurization System

Source for illustrations: National Institute of Standards and Technology.
Pressurization Design Criteria

Minimum Pressure
• Prevent smoke migration into stairwell
• Depends on pressure from fire

Maximum Pressure
• Established to allow doors to still open
• Maximum allowable force is 30 lbs. (NYSBC & NFPA 101)
Minimum Design Pressure

\[ \Delta P_{\text{min}} = \Delta P_{sf} + Ch \left[ \left( \frac{1}{T_o} \right) - \left( \frac{1}{T_f} \right) \right] \]

\( \Delta P_{\text{min}} \) = Minimum design pressure difference (in. H\(_2\)O [Pa])
\( \Delta P_{sf} \) = Pressure difference safety factor (in. H\(_2\)O [Pa])
\( C \) = Coefficient (3460 [7.64])
\( h \) = distance above neutral plane (ft [m])
\( T_o \) = Absolute temperature of surroundings (R [K])
\( T_f \) = Absolute temperature of smoke (R [K])
# Suggested Minimum Pressure Design Differences

<table>
<thead>
<tr>
<th>Building Type</th>
<th>Ceiling Height</th>
<th>Design Pressure Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sprinklered</td>
<td>Any Height</td>
<td>0.05 in. H₂O, 12.4 Pa</td>
</tr>
<tr>
<td>Not Sprinklered</td>
<td>9 ft. 2.7 m</td>
<td>0.10 in. H₂O, 24.9 Pa</td>
</tr>
<tr>
<td>Not Sprinklered</td>
<td>15 ft. 4.6 m</td>
<td>0.14 in. H₂O, 34.8 Pa</td>
</tr>
<tr>
<td>Not Sprinklered</td>
<td>21 ft. 6.4 m</td>
<td>0.18 in. H₂O, 44.8 Pa</td>
</tr>
</tbody>
</table>
Maximum Design Pressure

$$\Delta P_{\text{max}} = \left[ 2(W - d)(F - F_{\text{dc}}) \right] / \text{CWA}$$

$$\Delta P_{\text{max}} = \text{Maximum design pressure difference (in. H}_2\text{O [Pa])}$$
$$W = \text{Door width (ft. [m])}$$
$$d = \text{Distance from doorknob to knob side of door (ft. [m])}$$
$$F = \text{Total door-opening force (lb. [N])}$$
$$F_{\text{dc}} = \text{Door closer force (lb. [N])}$$
$$C = \text{Coefficient (1 [5.2])}$$
$$A = \text{Door area (ft}^2\text{ [m}^2\text{])}$$
Maximum Design Pressure

• Side-Hinged Swinging Doors
  – 30 lbs. (133 N)

\[ \Delta P_{\text{max}} = \frac{2(W - d)(F - F_{dc})}{CWA} \]

• Elevator Doors
  – 0.25 in. H\textsubscript{2}O (62.2 Pa)
### Maximum Pressure Design Differences

<table>
<thead>
<tr>
<th>Door Closer Force</th>
<th>32” (0.81m) Door</th>
<th>36” (0.91) Door</th>
<th>40” (1.02m) Door</th>
<th>44” (1.12 m) Door</th>
<th>48” (1.22m) Door</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 lb. (25 N)</td>
<td>0.45 (113)</td>
<td>0.40 (102)</td>
<td>0.37 (92)</td>
<td>0.34 (84)</td>
<td>0.31 (78)</td>
</tr>
<tr>
<td>7 lb. (30 N)</td>
<td>0.43 (108)</td>
<td>0.39 (97)</td>
<td>0.35 (88)</td>
<td>0.32 (80)</td>
<td>0.30 (74)</td>
</tr>
<tr>
<td>8 lb. (35 N)</td>
<td>0.41 (103)</td>
<td>0.37 (93)</td>
<td>0.34 (83)</td>
<td>0.31 (77)</td>
<td>0.28 (71)</td>
</tr>
<tr>
<td>9 lb. (40 N)</td>
<td>0.39 (98)</td>
<td>0.35 (88)</td>
<td>0.32 (79)</td>
<td>0.29 (73)</td>
<td>0.27 (67)</td>
</tr>
<tr>
<td>10 lb. (45 N)</td>
<td>0.37 (92)</td>
<td>0.34 (83)</td>
<td>0.30 (75)</td>
<td>0.28 (69)</td>
<td>0.26 (64)</td>
</tr>
<tr>
<td>11 lb. (50 N)</td>
<td>0.35 (87)</td>
<td>0.32 (78)</td>
<td>0.29 (71)</td>
<td>0.27 (65)</td>
<td>0.24 (60)</td>
</tr>
<tr>
<td>12 lb. (55N)</td>
<td>0.34 (82)</td>
<td>0.30 (74)</td>
<td>0.27 (66)</td>
<td>0.25 (61)</td>
<td>0.23 (56)</td>
</tr>
<tr>
<td>13 lb. (60 N)</td>
<td>0.32 (77)</td>
<td>0.29 (69)</td>
<td>0.26 (62)</td>
<td>0.24 (57)</td>
<td>0.22 (53)</td>
</tr>
<tr>
<td>14 lb. (65 N)</td>
<td>0.30 (71)</td>
<td>0.27 (64)</td>
<td>0.24 (58)</td>
<td>0.22 (53)</td>
<td>0.21 (49)</td>
</tr>
</tbody>
</table>

* Pressure design differences shown as in. H₂O (Pa)
Top vs. Bottom Injection

**Top Injection**
- Fan at top of stair
- Security less issue
- Smoke recirculation
- Minimal footprint
- Higher pressure at top of stair
- Lower pressure at bottom

**Bottom Injection**
- Fan at bottom of stair
- Security of air is concern
- No smoke circulation issue
- Takes up valuable real-estate
- Lower pressure at top of stair
- Higher pressure at bottom
Compartmented Stairwell

- Single point/multi-point source
- Separate shaft (integrity is a concern)
- Damper control
- Pressure sensors
- May need intermediate stair/transverse corridor
Multiple Injection System

- Multiple sources
- Typical fans to exterior
- One shaft
- Damper control
- Pressure sensors
Vestibules

• Buffer zone between stair and building
• Pressurizations?
  – Vestibule only
  – Stair only
  – Vestibule and stairwell
Vestibules

• Buffer zone between stair and building

• Pressurizations?
  – Vestibule only
  – Stair only
  – Vestibule and stairwell
Pressurized Elevator Hoistways

• Elevator hoistways shall be pressurized to maintain a minimum positive pressure of 0.10 in. H2O (25 Pa) and a maximum of 0.25 in. H2O (62 Pa) with respect to adjacent space on all floors. This pressure shall be measured with all elevator cars at floor of recall and all hoistway doors on the floor of recall open.
Objectives

- Review of Smoke
- Smoke Movement
- Smoke Management
- Smoke Control Systems
- Design Considerations
Design Considerations

- NYS Code Requirements
- Door opening/closing force
- Venting
- Component Failure (Redundancy)
- Commissioning
- Inspection/Testing/Maintenance
Closing

- Questions
- Comments
- Open Discussion

- Thanks You!
Smoke Management in High-Rise Buildings

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