Fire Modeling for Smoke Control Design

Presented by:

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2011
Overview

- Smoke Control Requirements
- Smoke Control Design Considerations
- Fire Model Types
- Case Study
- Questions

Smoke Control Requirements

- Early Prescriptive Requirements (up to early 1990’s)
  - Air Changes
  - Operable Windows
- Current Prescriptive Requirements
  - Passive or active smoke control
  - Based on design fire and specific guidelines for feature being protected
- Performance Requirements
  - Establish Performance Goals
  - Outline Design Method
    - Acceptance Testing Requirements
IBC Smoke Control

• Prescriptive requirements based on specific objectives
• Design Guidelines - Section 909
• Specific requirements based on building feature being protected

Building Features with Smoke Control Provisions:

• Covered Mall Buildings (Section 402)
• Atriums (Section 404)
• Underground Buildings (Section 405)
• Stages (Section 410.3.7)
• Stair Protection (Section 1005.3.2.5)
• Smoke Protected Assembly Seating (Section 1008.5.2)
• Pedestrian Bridges/Tunnels (Section 3104)
Atria/Covered Malls

- Atrium is typical feature for smoke control considerations
- Refers to IBC Section 909, Smoke Control Systems
  - Pressurization Method
  - Airflow Method
  - Exhaust Method
- Exhaust Method considered most applicable to atria/covered malls

IBC Smoke Control Methodologies

- Pressurization Method ("zoned approach")
  - Need a barrier for pressure differential such as smoke barrier
- Airflow Method
  - Most often used in combination with another method
- Exhaust Method
  - Most common
- Analysis
  - Stack Effect
  - Temperature Effect
  - Wind Effect
  - HVAC Systems
  - Climate
  - Duration of Operation
Pressurization Method

• Maintain pressure difference across smoke barriers
  – Minimum 0.05 inch water gage
  – Maximum based on door opening/closing forces

• Problems
  – Building may be tighter or looser than calculated
  – Oversizing fans means door opening problems
  – Balancing with stairs

Airflow Method

• Can be used for unprotected vertical openings between zones

• Velocity required through opening (fpm):
  \[ v = 217.2 \left( \frac{h (T_r - T_o)}{T_r + 460} \right)^{1/2} \]

  Where:
  \( h \) = height of opening - ft.
  \( T_r \) = Temperature of smoke - °F
  \( T_o \) = Ambient temperature - °F

• Airflow cannot exceed 200 fpm.
Exhaust Method

• Used for large enclosed volumes
• Maintain smoke 10 ft. or 6 ft. above highest walking surface used for egress
• Make up air by natural or mechanical means is required
• Maximum make up air velocity -- 200 fpm
• Exhaust high and supply low
• Plugholing
• Analyze balcony conditions

Exhaust Method

• Based on plume type
  – Axisymmetric
  – Balcony spill
  – Window
Axisymmetric Plume

- Prototypical plume
- Cone with tip at bottom
- Air entrained on all sides

\[ z_1 = 0.533 \ Q_c^{2/5} \]

where \( z_1 \) = flame height
\( Q_c \) = convective heat release - usually 70% of fire size

Axisymmetric Plume

- Used when no obstructions to the plume

- Determine Flame Height
Axisymmetric Plume

• Determine Formula to Use
  – Smoke layer must be at least 6 feet above highest walking surface (z)
  – 3 formulas depending on flame height vs required smoke layer height

\[
\begin{align*}
  \text{If } z < z_1 & \quad m_p = 0.0208 Q_c^{3/5} z \\
  \text{If } z = z_1 & \quad m_p = 0.0011 Q_c \\
  \text{If } z > z_1 & \quad m_p = 0.022 Q_c^{1/3} z^{5/3} + 0.0042 Q_c
\end{align*}
\]

- Note impact of z where clear height is greater than flame height

Axisymmetric Plume

• Convert \( m_p \) (mass flow rate) to \( V \) (volumetric flow rate)
\[
  v = 60 \frac{m_p}{\rho}
\]

where
\[
\begin{align*}
  v & = \text{volume in cfm} \\
  m_p & = \text{mass in lbs/sec} \\
  \rho & = \text{density at smoke temp. in lbs/ft}^3
\end{align*}
\]
Axisymmetric Plume

- Result shows exhaust rate (fan size)
- Problems:
  - must know fire size
  - very dependent on height
  - does not address large area spaces
  - does not address dilution
  - Conservative for tall, small spaces

Balcony Spill Plume
Balcony Spill Plume

• Used where smoke may spread across ceiling before reaching open area
• Determine fire size and dimensions of space
  – $H = \text{height from fire to underside of balcony}$
  – $W = \text{width of spill between architectural projections}$
  – $z_b = \text{height from balcony to bottom of clear layer}$

Results in very high numbers

– What is a realistic plume width?
– Controversy about whether results are realistic for sprinkler protected spaces
– Much discussion regarding balcony spill plume correlations
Window Plume

- Least used plume correlation
- Application is limited
  - Fire confined to room
  - Effect of sprinklers in room
  - May be used if separation is glass or unrated construction
Other Considerations

- Plume Contact with Wall
  - Plume contact affects entrainment
  - Formula provided to estimate plume width
  - Plume flow rate can be considered constant once it hits the wall

Exhaust Method

- Plugholing
An Example Atrium

- Axisymmetric vs. Balcony Spill Plume
  - 50-foot tall atrium
- Axisymmetric Plume
  - 5,000 Btu/s design fire
  - ~148,000 cfm
- Balcony Spill Plume 1
  - 5,000 Btu/s fire
  - 12-foot spill width
  - ~372,000 cfm
- Balcony Spill Plume 2
  - 2,000 Btu/s fire (sprinkler control)
  - 12-foot spill width
  - ~274,000 cfm

Design Fire

- Code guidance
  - 2003 IBC
    - 5,000 Btu/sec (5,275 kW) minimum
    - May be modified with rational analysis
    - System duration:
      - 20 minute minimum
  - 2006 IBC
    - Based on a rational analysis
    - System duration (the least):
      - 20 minutes, or
      - 1.5 times the calculated egress time
  - NFPA 92B
    - Performance based design
Design Fire

• Fire Test Results

2 Panel Workstation Fire

- 0min, 10kW
- 1min, 10kW
- 2min, 70kW
- 3min, 215kW
- 4min, 680kW
- 5min, 1.7MW
- 8min, 1.3MW
- 10min, 1.1 MW
- 12min, 960kW
- 14min, 880kW
- 20min, 750kW
- 28min, 480kW
NIST Design Fire Data

Typical Design Fire Curve
Typical Design Fire Curve

Fire Model Types

- Algebraic Equations
- Zone models
  - One zone
  - Two zones
- Field models
  - Computational fluid dynamics (CFD)
Algebraic Equations

- Equations
  - Specific phenomenon
  - Finite applicability
  - Simple algebra
    - Identify variables
    - Solve equation
  - Calculator or spreadsheet

Algebraic Equations

- Alpert’s ceiling jet correlations
  - Temperature
  - Velocity
  - Variables
    - Ceiling height (H)
    - Radial distance from fire to point of interest (r)
    - Fire size (Q)
Algebraic Equations

• Alpert’s equations for ceiling jet temperature and velocity

\[ T - T_{amb} = \frac{5.38(Q/r)^{3/2}}{H} \]

\[ U = \frac{0.195Q^{1/3}H^{1/2}}{r^{1/6}} \]

r/H > 0.18

r/H > 0.15

Fig 3.4.1. Ceiling jet flow beneath an unconfined ceiling.
Algebraic Equations

- Alpert’s ceiling jet correlations
  - Limits of applicability
    - Geometry
      - Unconfined smooth ceiling
      - Ratio of r/H
    - Fire size
      - 668 kW < Q < 98 MW

Zone Models

Figure 1. Zone model terms.
Zone Models

- Conservation of mass
- Conservation of energy
- Ideal gas law
- Solution
  - Ordinary differential equations
  - Algebraic equations
  - 2 dimensions

Figure 2. Schematic of control volumes in a two-layer zone model.
Zone Models

- Dedicated computer program
- Spreadsheet approximations
- NIST CFAST
  - Technical Reference
    - Validation
    - Sensitivity
    - Robustness

Field Models
Field Models

- Conservation of mass
- Conservation of energy
- Conservation of momentum
- Ideal gas law
- Solution
  - Partial differential equations
  - 3 dimensions

Field Models

- Dedicated computer program
- Spreadsheets not possible
- NIST Fire Dynamics Simulator (FDS)
  - Technical Reference (3 volumes)
    - Mathematical model & numerical method
    - Validation
    - Verification
Case Study

- Two (7)-story university buildings
- Five-story atrium connecting the north and south towers
Design Parameters

• Axisymmetric Plume Scenario
  – Furniture Group
  – 177 second characteristic growth time
  – Peaks at 350 seconds
  – 4,115 kW fire
Design Parameters

• Balcony Spill Plume Scenario
  – Single piece of upholstered furniture
  – 150 second characteristic growth time
  – Automatic sprinkler activation at 130 seconds
  – 799 kW fire

Design Parameters

• Failure Criteria
  – Visibility
    • Greater than 33 feet (10 meters)
  – Upper Layer Temperature
    • Less than 120 °F (49°C) (single point)
  – Carbon Monoxide
    • Less than 3,000 ppm (single point)
FDS Model Elevations

Axisymmetric Plume Analysis

- IBC 909 calculations
  - 5 stories open
    - 5,275 kW (5,000 Btu/sec) fire
    - 230,000 cfm at the top of the atrium
  - 3 stories open
    - 5,275 kW (5,000 Btu/sec) fire
    - 130,000 cfm at the top of the atrium

- CFAST Simulation
  - 3 stories open
    - 4,115 kW fire
    - 200,000 cfm at the top of the atrium
Axisymmetric Plume Analysis

- FDS Simulation
  - 3 stories open
    - 4,115 kW fire
    - 70,000 cfm at the top of the atrium
Balcony Spill Plume Analysis

- IBC 909 calculations
  - 5 stories open
    - 768 kW (728 Btu/sec) fire
    - 216,000 cfm at the top of the atrium
  - 3 stories open
    - 768 kW (728 Btu/sec) fire
    - 130,000 cfm at the top of the atrium

- FDS Simulation
  - 3 stories open
    - 799 kW (757 Btu/sec) fire
    - 140,000 total exhaust
      » 100,000 cfm at the top of the atrium
      » 20,000 cfm above the 2nd and 3rd floor balconies
Summary

• Unexpected phenomena due to geometry
• IBC/NFPA 92B equations don’t address inlet locations
• Engineered analysis doesn’t always reduce the exhaust quantity

Thank You For Your Time!

Questions?

This concludes the Continuing Education Program

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Roles of AEC Team Members in Smoke Control System Design

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Objectives

• Understand each team members role in the successful implementation of a smoke control system
• Identify ways each member can improve the process
Overview

• Introduce the usual suspects
• Identify broad responsibilities
• Walk through a timeline of the process
• Highlight key aspects of the process with emphasis on roles and responsibilities
Team Org Chart

- AHJ
  - Owner/Developer
    - General Contractor
      - Architect
        - Sub-Contractors
          - A/E Team Members
  - CxA / 3rd Party / Special Inspector
Who are the Players?

• Owner/Developer
• Architect
• General Contractor
• Fire Protection Engineer
• AHJ
  – Building/Fire Official
  – Insurance Carrier
Who else is involved?

• MEP Engineer – Works in conjunction with the Architect and FPE to select, or assist in selection of products and design of the system.
Who else is involved?

- Testing and Balancing Contractor – Works in conjunction with Special Inspector to commission the system.
- Fire Alarm Contractor – Primary system controls.
- Sprinkler Contractor – Interface with system controls.
Who else is involved?

• HVAC Contractor – Major system components.
• Interior Designer – Furniture selection.
• Specialties Contractor – Special system components.
Who else is involved?

• That’s at least 14 different entities!!!
What does the Code say?

• The **Building Official** (AHJ) shall:
  – Receive, review, and issue permits for construction (IBC 104.2)
  – Render interpretations of the Code (IBC 104.1)
  – Make all required inspections or accept reports of inspection (IBC 104.4)
What does the Code say?

• The **Owner** (or authorized agent) shall:
  – Apply for and obtain all required permits (IBC 105.1)
  – Engage and designate a Registered Design Professional in Responsible Charge (RDPiRC) (IBC 107.3.4)
  – Engage the Special Inspector (IBC 1703.1.1)
What does the Code say?

- The **Architect** (RDPiRC) shall:
  - Review and coordinate submittal documents prepared by others for compatibility with the design of the building (IBC 107.3.4)
  - Prepare a statement of special inspections (IBC 1704.3)
What does the Code say?

• The **FPE / ME**(Registered Design Professional) shall:
  
  – Prepare Construction Documents. (IBC 107.1)
  
  – Prepare a rational analysis supporting the types of smoke control systems to be employed and their methods of operation. (IBC 909.4)
  
  – Sign, seal, and date the final complete report of testing by the Special Inspector. (IBC 909.18.8.3)
What does the Code say?

• The Special Inspector shall:
  – Be objective, competent and independent from the contractor responsible for the work being inspected. (IBC 1703.1.1)
  – Keep records of special inspections and furnish reports to the Building Official and RDPiRC. (1704.2.4)
  – Have expertise in fire protection engineering, mechanical engineering, and certification as air balancers. (IBC 909.18.8.2)
What does the Code say?

• The **Contractor** shall:
  – IBC has no defined role for the Contractor as it relates to smoke control systems.
  – Submit Statement of Compliance for fire protection system installations prior to final inspections (IFC 901.2.1)
  – Local requirements may define the role further:
    • Coordinate subs, provide access to site, notify Special Inspector, etc.
# Timeline of Events

<table>
<thead>
<tr>
<th>Pre-Design Phase</th>
<th>Design Phase</th>
<th>Bidding and Pre-Construction Phase</th>
<th>Construction Phase</th>
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</table>
Change Cost Multiplier Affect vs. Time

Actual $$$ vs. Time

Construction Begins

Base Cost
Pre-Design Phase

Identification of Atrium properties (complexity)

Select the RDIPC

Select the FPE

Work through major design challenges by answering key questions

Pre-Design Phase

Finalize building design concept.
Pre-Design Phase

• Owner and Architect are heavily involved during this phase.
• A/E team members could/should be involved in planning
  – Define role of ME and FPE
• GC or cost estimator could be brought on
Define role of ME and FPE – Option 1

• FPE
  – Select design fire and system design methodology
  – Identify the required exhaust volume
  – Document the rational analysis
  – Select control system and activation method

• ME
  – Specify ductwork, fans, louvers, dampers, etc. to meet the FPE defined requirements
Define role of ME and FPE – Option 2

• ME
  – Select design fire and system design methodology
  – Identify the required exhaust volume
  – Specify ductwork, fans, louvers, dampers, etc. to meet the FPE defined requirements

• FPE (as quasi 3rd Party)
  – Review design to document the rational analysis
  – Select control system and activation method
Pre-Design Phase

• Greatest Influence by:
  – Owner
  – Architect

• Try to answer the following questions in this Phase:
  – Will the Atrium take a “complex geometry”?
  – Where will make-up air be provided from?
  – Will the Atrium be furnished (heavy or light)?
Pre-Design Phase

• Simple vs. Complex Geometry
Pre-Design Phase

• Simple vs. Complex Geometry
• Air inlet and exhaust locations
Pre-Design Phase

• Furnishings
Pre-Design Phase

• Furnishings
Pre-Design Phase

• Furnishings
Pre-Design Phase

• Furnishings
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Design Phase

- Complete Atrium Design Configuration
- Discuss Specifics with the AHJ, Development of Budget
- Atrium Smoke Control Design Accepted by AHJ
- Cost estimation with GC/subs or consultant

**Design Phase**

Detailed building design, Plan review and permitting, cost estimation, and finalize project budget.
Design Phase

• Greatest Influence by:
  – FPE and AHJ
  – Architect and MEP
  – Owner

• Accomplish the following in this Phase:
  – AHJ engaged as a part of the design team.
  – Specify as much equipment as possible.
  – Engage the CxA
  – Identify costs
Design Phase

• FPE and AHJ
  – FPE must engage the AHJ to be a part of the design.
    • Design fire
    • Communicating spaces
    • Tenability criteria
  – Handbook by ICC, SFPE, etc.
Design Phase

• FPE and AHJ
  – AHJ must review and respond to questions of interpretation in a timely manner to aid success.
  • IFC Section 104.7.2 – the Fire Code Official is authorized to required the Owner or agent to provide, with out charge to the jurisdiction, a technical opinion and report.
Design Phase

• FPE and AHJ
  – Work together to resolve concerns
Design Phase

• Architect, MEP, and FPE
  – Specify as much equipment as possible.
Design Phase

• Architect, MEP, and FPE
  – Specify as much equipment as possible.
Design Phase

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Design Phase

- Architect, MEP, and FPE
  - Specify as much equipment as possible.
Design Phase

- Owner
  - Engage the CxA
  - Identify costs
Change Cost Multiplier Affect vs. Time

Time

Construction Begins

Actual $$

Base Cost
## Timeline of Events

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Bidding and Pre-Construction Phase

- Bidding, bid review, and award construction contract. 
- Hire subcontractors. 
- Submittal review and approval by A/E Team. 
- *Begin sprinkler and fire alarm shop drawings, trade permit plan review by AHJ, and finalize the CxA Plan.
Bidding and Pre-Construction Phase

• Greatest Influence by:
  – Contractor/Sub-contractors

• Accomplish the following in this Phase:
  – Identify all items needing clarification
  – Select final products
Bidding and Pre-Construction Phase

- Contractor/Sub-contractors
  - Identify all items needing clarification
  - NFPA 92, 6.4.5.4.8 - Positive confirmation of fully open/closed damper position
Bidding and Pre-Construction Phase

• Contractor/Sub-contractors
  – Identify all items needing clarification
  – NFPA 92, 6.4.8.1 – positive confirmation required for all components.
Bidding and Pre-Construction Phase

- Contractor/Sub-contractors
  - Identify all items needing clarification
  - Avoid product substitutions and read all documentation carefully.

<table>
<thead>
<tr>
<th>Color</th>
<th>Temperature</th>
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<tbody>
<tr>
<td>Orange</td>
<td>57 °C (135 °F)</td>
</tr>
<tr>
<td>Red</td>
<td>68 °C (155 °F)</td>
</tr>
<tr>
<td>Yellow</td>
<td>79 °C (175 °F)</td>
</tr>
<tr>
<td>Green</td>
<td>93 °C (200 °F)</td>
</tr>
<tr>
<td>Blue</td>
<td>141 °C (286 °F)</td>
</tr>
</tbody>
</table>
Bidding and Pre-Construction Phase

• Contractor/Sub-contractors
  – Identify all items needing clarification
  – Avoid product substitutions and read all documentation carefully.
Bidding and Pre-Construction Phase

• Contractor/Sub-contractors
  – Identify all items needing clarification
  – IBC 909.12.1 – Detection and control wiring shall be enclosed in continuous raceway.
Bidding and Pre-Construction Phase

• Contractor/Sub-contractors
  – Identify all items needing clarification
  – IBC 909.16.1 – LED color requirements
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Construction Phase

Construction begins, trade permits issued, trades are installed, conduct construction progress inspections, RFI, PR, and CO process begins.

- Trades are installed
- Overcome unforeseen conditions and field conflicts
- Special Inspections begin
Construction Phase

• Greatest Influence by:
  – Contractor
  – CxA

• Accomplish the following in this Phase:
  – Quality installation practices
  – Resolve field conflicts through A/E team
  – Coordinate progress inspections
Bidding and Pre-Construction Phase

- CxA
  - Plans, procedures should follow NFPA 3
  - Required Documents and Equipment (RDEs)
  - Pre-Functional Checklist (PFCs)
  - Functional Performance Testing (FPTs)
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Testing and Acceptance Phase

- Contractor pre-testing followed by AHJ and A/E inspections
- CxA continues to completion
- Subcontractor coordination is critical for testing

Testing and Acceptance Phase
Preliminary testing, final testing, commissioning, building turn-over to Owner.
Testing and Acceptance Phase

• Greatest Influence by:
  – Contractor/Architect
  – CxA

• Accomplish the following in this Phase:
  – Coordinate efforts between construction and design team
  – This is where the hard work pays off!!
Summary

• Roles defined by Code
  – Building/Fire Official
    • Review plans, issue permits, conduct inspections
    • Interpret the Code
  – Owner
    • Assign the RDPiRC
  – Architect
    • Coordinate registered design professionals
    • Review and coordinate deferred submittals
    • Determination of Special Inspections
  – FPE
    • Design Rational Analysis
  – Special Inspector
    • Perform and document inspections
Summary

• How to improve the process
  – Owner
    • Assemble team members as early as possible in the design
    • Make influencing decisions early
  – Architect
    • Finalize critical Atrium properties early in design
    • Coordinate the specification of all products in design
    • Limit deferred submittals
  – FPE
    • Engage the AHJ as a design team member
    • Carefully select and review products with Architect and Owner
  – AHJ
    • Quickly review, interpret, and communicate requirements to design team
  – Special Inspector
    • Complete testing plan early in design in coordination with design team
Summary

• How to improve the process
  – Contractor
    • Work to clarify issues early in construction
    • Diligently coordinate construction with progress inspections
  – Fire Alarm Contractor
    • Carefully review the Design Rational Analysis
    • Only modify controls after approval of FPE
  – Sprinkler Contractor
    • Carefully review the Design Rational Analysis
    • Only modify materials, especially sprinkler head types, after approval of FPE
Questions
**Who to Contact**

**Fire Protection Engineering**

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