FIRE PATTERN ANALYSIS

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OBJECTIVES

- Recognize the importance of fire pattern analysis in determining the origin of fires (NFPA 921)
- Provide basic calculation methodology for use in conducting fire engineering analysis
- Use fire hazard analysis (FHA) methodology for credible fire scenarios
- Encourage the use of FDTs spreadsheets to supplement correlations and mathematical calculations based upon fundamental fire dynamics principles
3.1 Fire Plumes
3.2 Types of Fire Plumes
3.3 Fire Plume Calculations
3.4 Fire Patterns
3.5 Interpreting Fire Plume Behavior
3.6 Fire Burn Pattern Tests
3.7 Summary and Conclusions
OBJECTIVES

The Analysis of Fire Patterns

- Is useful in documenting fire plume damage to areas/points of fire origin
- Documents surfaces on materials that change their appearance when exposed to heat, flames, and products of combustion
- Can document fire movement and intensity
- Forms the basis for forensic fire scene reconstructions
3.1 FIRE PLUMES

- V Patterns
- Hourglass Patterns
- Fire Plume Damage Correlations
3.1 FIRE PLUMES

- **Fire Plume** – A simple flaming fuel source emitting a vertical column of flames and hot products of combustion

- Fire plume behavior of burning pools producing fire plumes depend upon geometry, substrate, and wind

- Fire plumes produce “V” patterns
Fire Plumes – Single most significant contributor of fire pattern damage
“V” patterns are formed when fire plumes come into contact with and damage exposed wall surfaces.
- Fire plumes contain both flames and buoyant smoke.
- Temperature distribution of the gases in the buoyant plume is changed when restricted under ceilings.
Features of the Fire Plume

- Damage patterns *(NFPA 921-6, 2008)*
There is a direct correlation between the critical heat flux boundary and lines of demarcation.
3.2 TYPES OF FIRE PLUMES

- Axisymmetric plumes
- Window plumes
- Balcony plumes
- Line plumes
Axisymmetric Plumes

- Uniform radial distribution
- Generally occur in open areas or centers of rooms
- Much research concerns the flame heights
Example: Axisymmetric Plume
Window Plumes

- Flames that emerge from doors and windows in large spaces
- The fire is generally ventilation controlled
- Often associated with post-ventilation fires
Balcony Spill Plumes

- Fire plumes that emerge under overhangs from doors
- Characteristic of fires in enclosed rooms and spreading through patio doors or window to covered porches, patios, or balconies
Line Plumes

- Elongated shapes producing narrow, thin, shallow plumes
- Scenarios include fires in trenches, sofas, flame front from a forest fire
3.3 FIRE PLUME CALCULATIONS
What is the equivalent diameter and area of this irregular spill?

What graphical techniques would you recommend to estimate the area?
For spills on non-porous surfaces, a standing pool of 1 liter ($10^{-3} \text{ m}^3$) gasoline is about 1 mm ($1 \times 10^{-3} \text{ m}$) thick.

Area = Volume/depth
Virtual Origin and Flame Height Relationships

- Heat detector activation
- Smoke detector activation
- Sprinkler head activation
- Plume centerline temperature and velocities
- Smoke filling rate
Virtual Origin and Flame Height
Heskestad Equation

- Shows the relationship between average flame height and heat release rate
- Useful for fires away from walls (circular perimeter) and having a broad fuel base

\[
\dot{Q} = \text{Heat release rate (kW)}
\]
\[
Z_f = \text{Average flame height (meters)}
\]
\[
D = \text{Equivalent diameter (meters)}
\]

\[
Z_f = 0.23\dot{Q}^{0.4} - 1.02D
\]
Can be used for fires against walls \((k=2)\)
or in corners \((k=4)\) where walls are not combustible

\[ Z = 0.17 \left( k \frac{\dot{Q}}{\dot{Q}} \right)^{0.4} \]

\( \dot{Q} \) = Heat release rate (kW)

\( Z \) = Average flame height (meters)
Practical Applications of Fire
Plume Calculations

- **Flame height** – did the flames reach the ceiling?
- **Radiant heat** – how credible is the witness? - Why didn’t he get burned?
- **Smoke filling** – was there enough smoke generated to fill the room?
Enclosure Fires

- Once a fire is confined in a room, this constrains the flow of smoke, hot gasses, and fire growth.
- Several confining variables include the ceiling height, ventilation openings formed by windows and doors, room volume, and location of the fire in the room or compartment.
- While this ventilation is constrained, a condition called *flashover* may occur, depending upon the heat release rate.
Addresses methods for evaluating the potential for room flashover:
- Prevention of ignition
- Installation of automatic fire suppression systems
- Control of ventilation factors
- Limitation of the heat release rate of room contents, furnishings, and interior finish

Accuracy, precision, and relevance are a function of the data from the test methods and calculations used.

These techniques can help minimize the probability of flashover or delay its occurrence, but might not prevent it.
Flashover: Inferred from **one or more factors** (ASTM E 603-07):

- **(1)** An average air temperature of 500 to 600°C measured 100 mm below the ceiling, or above 600°C measured at the top of the doorway.
- **(2)** A level of 20 kW/m² at the center of the floor is indicative of incipient flashover in the room.
- **(3)** The emergence of flames from the doorway (for some products), or
- **(4)** The ignition of cotton indicators or a ball of crumpled newsprint on the floor.
Flashover conditions may mask pre-existing fire burn patterns

Flashover may produce burn patterns consistent with suspected accelerated fires (irregular floor patterns, floor penetrations)

Eliminates the confusion of eyewitness reports of “roll-over” and “flame over”
What observations are needed to determine if *flashover* has occurred in the room of fire origin?
What observations are needed to determine if flashover has occurred in the room of fire origin?

- Fairly uniform damage floor to ceiling
- Widespread damage to floor covering
- Plume damage observed outside doors and windows
ENCLOSURE FIRES - Minimum Heat Release Rate for Flashover

\[
\dot{Q}_{fo} = (378A_o)(h_o)^{0.5} + 7.8A_w
\]

- \(A_o\) = area of the opening to the compartment in square meters \((m^2)\) = \((2.5 \, m) \times (1 \, m) = 2.5 \, m^2\)
- \(h_o\) = height of the opening in meters \((m)\) = 2.5 \, m
- \(A_w\) = area of the walls, ceiling, and floors in square meters \((m^2)\) minus the total area of openings
Problem: Given a 10 by 10 meter room, a 3 meter ceiling, and 2.5 meter high by 1 meter wide opening

Question: Determine the minimum heat release rate needed to cause flashover
ENCLOSURE FIRES - Minimum Heat Release Rate for Flashover

- $A_w = \text{area of the walls, ceiling, and floors in square meters (m}^2\text{)} \text{ minus the area of the openings}$
  - 1 floor = $(10 \text{ m})(10 \text{ m}) = 100 \text{ m}^2$
  - 4 walls = $(4)(10 \text{ m})(3 \text{ m}) = 120 \text{ m}^2$
  - 1 ceiling = $(10 \text{ m})(10 \text{ m}) = 100 \text{ m}^2$
  - 1 opening = $2.5 \text{ m}^2$

- $\dot{Q}_{fo} = (378 A_o)(h_o)^{0.5} + 7.8 A_w$
  $= (378)(2.5)(2.5)^{0.5} + (7.8)(317.5)$
  $= 1494 + 2477$
  $= 3971 \text{ kW}$
  $= 4 \text{ MW approximately}$
First line computer model contained in spreadsheet calculation format

Developed by and can be obtained from the Nuclear Regulatory Commission (NRC) see website: (http://www.nrc.gov/)

NRC website contains both on-line manual and latest spreadsheets
Example Problem Using FDTs

- **Given:** a 3.5 x 4.3 x 2.5 m room containing one door measuring 0.81 x 2 meter. Room constructed using 16 mm (5/8 in) gypsum wall covering.

- **Solve for:** HRR necessary to cause flashover using the Fire Dynamics Tools
# Flashover Calculations - FDTs

## CHAPTER 13. PREDICTING COMPARTMENT FLASHOVER HEAT RELEASE RATE

**Version 1805.0 (SI Units)**

The following calculations estimate the minimum heat release rate required to compartment flashover.

**Parameters in YELLOW CELLS are Entered by the User.**

**Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Material Selected.**

All subsequent output values are calculated by the spreadsheet and based on values specified in the input parameters. This spreadsheet is protected and secure to avoid errors due to a wrong entry in a cell(s).

The chapter in the NUREG should be read before an analysis is made.

### INPUT PARAMETERS

<table>
<thead>
<tr>
<th>COMPARTMENT INFORMATION</th>
<th>SI UNITS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compartement Width ($w_c$)</td>
<td>3.60 m</td>
</tr>
<tr>
<td>Compartement Length ($l_c$)</td>
<td>4.30 m</td>
</tr>
<tr>
<td>Compartement Height ($h_c$)</td>
<td>2.50 m</td>
</tr>
<tr>
<td>Vent Width ($w_v$)</td>
<td>0.81 m</td>
</tr>
<tr>
<td>Vent Height ($h_v$)</td>
<td>2.00 m</td>
</tr>
<tr>
<td>Interior Lining Thickness ($\delta$)</td>
<td>16.00 mm</td>
</tr>
<tr>
<td>Interior Lining Thermal Conductivity ($\kappa$)</td>
<td>0.00017 kW/m-K</td>
</tr>
</tbody>
</table>

**Calculate**
# Flashover Calculations - FDTs

## Predicting Flashover Heat Release Rate

**Method of McCaffrey, Quintiere, and Harkleroad (MQH)**


\[ Q_{f,0} = 510 \cdot \left( h_a A_v A_r (h_v) \right) \]

Where:
- \( Q_{f,0} \) = heat release rate necessary for flashover (kW)
- \( h_a \) = effective heat transfer coefficient (kW/m²-K)
- \( A_v \) = total area of the compartment enclosing surface boundaries excluding area of vent openings (m²)
- \( A_r \) = area of ventilation opening (m²)
- \( h_v \) = height of ventilation opening (m)

### Heat Transfer Coefficient Calculation

\[ h_a = \frac{k}{\delta} \]

Assuming that compartment has been heated thoroughly before flashover, i.e., \( t > t_c \).

Where:
- \( h_a \) = effective heat transfer coefficient (kW/m²-K)
- \( k \) = interior lining thermal conductivity (kW/m-K)
- \( \delta \) = interior lining thickness (m)

\[ h_a = 0.011 \text{ (kW/m²-K)} \]

### Area of Ventilation Opening Calculation

\[ A_v = (w_v) (h_v) \]

Where:
- \( A_v \) = area of ventilation opening (m²)
- \( w_v \) = vent width (m)
- \( h_v \) = vent height (m)

\[ A_v = 1.62 \text{ m}^2 \]

### Area of Compartment Enclosing Surface Boundaries

\[ A_r = \left[ 12 (w_c + l) + 2 (l_h + w_c) + 2 b_c \right] - A_v \]

Where:
- \( A_r \) = total area of the compartment enclosing surface boundaries excluding area of vent openings (m²)
- \( w_c \) = compartment width (m)
- \( l_h \) = compartment height (m)
- \( b_c \) = compartment height (m)
- \( A_v \) = area of ventilation opening (m²)

\[ A_r = 67.48 \text{ m}^2 \]

### Minimum Heat Release Rate for Flashover

\[ Q_{f,0} = 510 \cdot \left( h_a A_v A_r (h_v) \right) \]

\[ Q_{f,0} = 781.98 \text{ kW} \]

**Answer**
### Flashover Calculations - FDTs

#### Method of Babrauskas


\[
Q_{fo} = 750 A_v (\sqrt{h_v})
\]

Where:
- \(Q_{fo}\) = heat release rate necessary for flashover (kW)
- \(A_v\) = area of ventilation opening (m²)
- \(h_v\) = height of ventilation opening (m)

Minimum Heat Release Rate for Flashover:

\[
Q_{fo} = 750 A_v (\sqrt{h_v})
\]

\(Q_{fo}\) = 1718.27 kW

#### Method of Thomas


\[
Q_{fo} = 7.8 A_T + 378 A_v (\sqrt{h_v})
\]

Where:
- \(Q_{fo}\) = heat release rate necessary for flashover (kW)
- \(A_T\) = total area of the compartment enclosing surface boundaries excluding area of vent openings (m²)
- \(A_v\) = area of ventilation opening (m²)
- \(h_v\) = height of ventilation opening (m)

Minimum Heat Release Rate for Flashover:

\[
Q_{fo} = 7.8 A_T + 378 A_v (\sqrt{h_v})
\]

\(Q_{fo}\) = 1392.35 kW

#### Summary of Results

<table>
<thead>
<tr>
<th>Calculation Method</th>
<th>Flashover HRR (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method of MoH</td>
<td>782</td>
</tr>
<tr>
<td>Method of Babrauskas</td>
<td>1718</td>
</tr>
<tr>
<td>Method of Thomas</td>
<td>1392</td>
</tr>
</tbody>
</table>
Importance of Multiple HRR Calculations for Flashover

- Each method has different data and variables
- Supports validation of hypothesis testing
- Illustrates the variability of mathematical models
Other Enclosure Relationships

- Estimated radiant heat transfer
- Burn injuries, exposure to other targets
- Estimated heat/smoke detector and sprinkler response time
- Time line analysis from incipient fire to activation of fire protection systems
- Pre-flashover compartment fire temperatures
- Habitability analysis
- Smoke filling rate
- Estimation of visibility
3.4 FIRE PATTERNS

- Fire Patterns
- Fire Pattern Testing
- Fire Pattern Examples
### 3.4 FIRE PATTERNS

- **Demarcations** - Intersection of affected and unaffected borders of materials ("V" patterns)
- **Surface Deposits** – Non-thermal deposits (smoke stains, fire hose streams)
- **Surface Effects** - Surface type determines the shape of lines and area of demarcation (scorching, melting, clean burn, spalling, calcination)
- **Penetrations** - Breaching of horizontal and vertical surfaces (Saddle burns, failures, internal damage)
- **Loss of Material** - Combustible surfaces with loss of material and mass (Tops of studs, fall-down, heat shadowing)
- **Victim Injuries** - Areas and degrees of burns on the victim’s body and clothing (Degrees, heat shadowing)
Fire Pattern Testing

- Testing confirms correlations of visible burn patterns to observed fires
- Initial Calculations
  - Estimated heat release rate
  - Virtual origin
  - Flame height
  - Fire duration
  - Regression rates
- Adjustments due to evaporation rates
Fire Pattern Examples

FIRE PATTERN ANALYSIS

- **DEMARCATIONS**
  - 1. “V” patterns
  - 2. Calcination

- **SURFACE EFFECTS**
  - 3. Charring
  - 4. Cracked glass
  - 5. Flammable liquid burn pattern

- **PENETRATIONS**
  - 6. Damage to ceiling

- **LOSS OF MATERIAL**
  - 7. Combustible surface
Fire Pattern Examples

- **Surface Deposits**
  - Non-thermal effects
    (examples: smoke stains, fire hose streams)
  - Smoke/soot stains
Glass Breakage

- Data shows that when the exposed surfaces of standard tempered glass exceed continuous temperatures in excess of 500 °F (260 °C), glass breakage results.

- Tempered glass, however, is very brittle and when broken, it shatters into small oval-shaped pieces, failing as a whole unit.

- “Extinguishing the Myths of Fires, Sprinklers and Glass,” See website: http://www.glassonweb.com/articles/article/505/
Glass Breakage

- Single-glazed glass requires a much higher temperature to cause breakage. This prediction is based upon results concerning glass exposed to a uniform hot temperature come from the Building Research Institute (BRI) of Japan.

- Although only single-glazed, 3 mm thick window glass was studied, tests developed a probability graph could be plotted as a function of temperature rise above ambient.
The data shows that the Gaussian fit that can correlate this data corresponds to a mean temperature rise of 644 °F (340 °C) corresponding to 50 percent probability of breakage, along with a standard deviation of 122 °F (50 °C).


V. Babrauskas, “Glass Breakage,” Fire Science and Technology, Inc. , see website: www.doctorfire.com/glass.html
Probability of single-glazed glass breakage

![Graph showing the probability of breaking glass as a function of temperature rise. The graph includes data points for experiments and a Gaussian fit curve.](image)
Crazed glass should not be used as a reliable fire growth indicator.

Crazed glass is a result usually of rapid cooling, often associated with fire suppression.
- Explanation for “hourglass” burn patterns
- Demonstration of virtual origin above the fuel package
- Illustration of fire vector analysis
Fire Pattern Testing

Generation of Misleading “V” Patterns

- Penetration of fire through ceiling directly above area of fire origin
- Formation of false lines of demarcation
- Fire pattern vectors on structural members, walls, and surfaces point back to area of fire origin
3.5 INTERPRETING FIRE PLUME BEHAVIOR

“TRACING THE FIRE”

- Upward and Downward Burning
- Fire Intensity
- Compartment Fires
- Fuel Load
- Fire Spread
- Enhanced Vertical Fire Spread
- Enhanced Downward and Outward Fire Spread

- Impact of Radiation
- Impact of Fire Suppression
- Heat and Smoke Flow
- Fire Intensity and Duration
- Surface Temperature Impact
- Impact of Fire Placement
**Upward and Downward Burning**
(Buoyancy and Momentum Flow)

- **Rising gases** – A fire plume's hot gases (including flames and products of combustion) are much lighter than the surrounding air and therefore will rise.

- **Upward burning** – A fire tends to burn upward (in the absence of strong winds or physical barriers such as noncombustible ceilings) which divert flames.

- **Downward burning** – Radiation from the plume will cause some downward and outward travel.
Fire Intensity

- **Increasing Heat Release Rates** – Combustible materials in the path of the plume's flames will be ignited, increasing the extent and intensity of the fire by increasing the heat release rate.

- **Fire Intensity** – The more intense the fire grows, the faster it will rise and spread.

- **Heat Transfer** – Heat transfer by radiation and convection combine in direct flame impingement.
Flashover Conditions — A flame plume that is large enough to reach the ceiling of a compartment is likely to trigger full involvement of a room and increase chances for flashover.

Production of Self-Limiting Conditions —

1. If there is not more fuel above or beside the initial plume's flame to be ignited by convected or radiated heat transfer, or

2. if the initial fire is too small to create the necessary heat flux on those fuels, then the fire will be self-limiting and often will burn itself out.
Fuel Load

- **Fuel Location** — In evaluating a fire's progress through a room, the investigator must establish what fuels were present and where they were located.

- **Total Fuel Load** — This fuel load includes not only the structure itself, but its furnishings, contents and wall, floor, and ceiling coverings (as well as combustible roofing materials) that feed a fire and offer it paths and directions of travel.
Fire Spread

- **Upward Fire Spread** — Variations on the upward spread of the fire plume will occur when air currents deflect the flame, when horizontal surfaces block the vertical travel, or when radiation from established flames ignite nearby surfaces.

- **Exposed Fuel Packages** — If fuel is present in these new areas, it will ignite and spread the flames laterally.
Heat and Smoke Flow

- **Direction of Flow** — Heat and smoke plumes tend to flow through a room or structure much like a liquid, (1) *upward* in relatively straight paths, (2) *outward* around barriers, (3) forms acute angle between the flame front and the horizontal surface.
- **Vertical Spread** – Upward, vertical spread is enhanced when the fire plume finds chimney-like configurations.

- **Openings** – Stairways, elevators, utility shafts and chases, air ducts, and interiors of walls all offer openings for carrying flames generated elsewhere.

- **Enhanced Burning** – Fires may burn more intensely because of the enhanced draft.
Enhanced Downward and Outward Fire Spread

- **Spread via Buoyancy and Momentum Flow**
  - Downward flame spread of the fire may be encouraged whenever suitable fuel is in the area (e.g. combustible wall coverings, paneling)

- **Falldown** — Fire plumes may ignite portions of ceilings, roof coverings, draperies, and lighting fixtures that can fall onto ignitable fuels below and start new fires that quickly join the main fire overhead

- **Ceiling Jets** — Fire plumes that are large enough to intersect with ceilings form ceiling jets that radially extend along the ceiling surface
Impact of Radiation

- **Ignition by Radiation** – Radiation from overhead ceiling jets or hot gas layers can ignite floor coverings, furniture, and walls even at some distance, creating new points of fire origin.

- **Caution** – The investigator is cautioned to take into account what fuel packages were present in the room from the standpoint of their potential ignitability and heat release rate contributions.
**Impact of Fire Suppression**

- **Fire Spread** – Suppression efforts can also greatly influence fire spread and the investigator must remember to check with the fire suppression personnel present as to their actions in extinguishing the fire.

- **Pushing the Fire** – Positive pressure ventilation or an active attack on one face of a fire may force it back into other areas that may or may not have already been involved, and push fire down and even under obstructions such as doors and cabinets.
**Fire Intensity versus Duration**

- **Intensity/Duration** – The total fire damage to an object observed after a fire is the result of both the intensity of the heat applied to that object and the duration of that exposure.

- **Time-Varying Conditions** – Both the intensity and exposure of that heat may vary considerably during the fire.
Surface Temperature Impact

- **Differentials** – The highest temperature area of a plume will produce the highest radiant heat flux and, therefore, affect a surface faster and more deeply than cooler areas.

- **Direction of flame plume** – Shows where a flame plume contacted a surface or which direction it was moving (since it will lose heat to the surface and cool as it moves across).
Location of Fuel — The contribution a fire makes to the growth process in a room depends on its:

- Size (heat release rate)
- Direction of travel
- Location in the room:
  - Center, against a wall, rear corner away from ventilation sources,
  - Closeness to a ventilation opening.
Fire investigation and reconstruction of a fire's growth pattern back to its origin are based on the fact that fire plumes form patterns of damage that are, to a large extent, predictable.

As with the application of the scientific method, each indicator is an independent test for direction of travel, intensity, duration of heat application, or point of origin and must be documented separately.
The investigator should remember that there is no one indicator that proves the origin or cause of a fire. They must be evaluated together and yet they may not all agree.

The application of fire vectoring can also enrich and document the opinion rendered as to the original location of the fire plume.

As long as there is not too much damage, ample fire pattern indicators may exist and can be documented at post-flashover.
SUMMARY

- **Fire plumes contribute** to evidence of fire pattern damage, area/point of origin, and direction of travel.

- Do not overlook signs of physical evidence involving *human* activities.

- Rely on *fire dynamics* for insights.