Fire Dynamics in Structures: 
Size-up, Ventilation, Flow Paths and 
Softening the Target

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Fire Dynamics

• Study of how fires start, spread and develop.  
• Fire Dynamics – detailed study of how chemistry, fire science, material science and the engineering disciplines of fluid mechanics and heat transfer interact to influence fire behavior.  
• Critical to the interactions of the fire with structures, materials and people.
What is a fire?

• A fire is a gas phase, chemical reaction that emits heat and light
• A rapid oxidation process, which is a chemical reaction resulting in the evolution of light and heat in varying intensities
• Fire Tetrahedron
  Fuel
  Oxidizing Agent
  Heat
  Uninhibited Chemical Reactions

The Firefighters’ Work Place

• Houses are getting larger
  — 1973: 1,600 sq. ft.  2008: 2,500 sq. ft.
• Housing lots are getting smaller
  — 1976: 10,100 sq. ft.  2008: 8,800 sq. ft.
• During the past 50 years fuel loads have in homes have changed
  — Resulting in fuel rich fire conditions within homes
• Home designs have become more open (less compartmentation, engineered structural members) and more energy efficient (multi-pane windows, wrapped in plastic, alternate energy sources)
• Have staffing and tactics changed to adapt to these changes?
### Chemical Products of Combustion

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Yields (g product per g mass loss)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>free burn conditions</td>
<td>CO₂</td>
<td>CO</td>
<td>Soot</td>
</tr>
<tr>
<td>Methane</td>
<td>2.72</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Propane</td>
<td>2.85</td>
<td>0.005</td>
<td>0.024</td>
<td>0.003</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>2.79</td>
<td>0.024</td>
<td>0.059</td>
<td>0.006</td>
</tr>
<tr>
<td>Polystyrene</td>
<td>2.30</td>
<td>0.060</td>
<td>0.180</td>
<td>0.014</td>
</tr>
<tr>
<td>Polyurethane</td>
<td>1.50</td>
<td>0.031</td>
<td>0.227</td>
<td>0.005</td>
</tr>
<tr>
<td>Red oak</td>
<td>1.27</td>
<td>0.004</td>
<td>0.015</td>
<td>0.001</td>
</tr>
</tbody>
</table>

Ref: SFPE Handbook of Fire Protection Engineering, 4th ed., Table 3-4.16

### Fuels are Different

**Wood**

**Polystyrene**
Diffusion vs Pre-mixed Flame

Fuel Rich

Oxygen Added

Oxygen – No Heat without it!
For each kg of O₂ consumed in a fire,
13 MJ of heat is released.

A Disturbing Trend

• Rate of FF deaths due to traumatic injuries
  – Late 1970s – 1.8 deaths per 100,000 fires
  – Late 2000s - 3.0 deaths per 100,000 fires
• During this same period the annual number of structures fires decreased by 53%
• Since the number of structure fires is decreasing, how do firefighters and fire officers gain the experience to understand fire progression, fire behavior, and what happens to the structural integrity of a building under fire conditions?

Tradition vs Research

- Changes in fire environment
- Limited fire behavior training in the academy
- Fewer fires = less experience
- New FF protective equipment standards working to catch up to advances in technology and increased hazard

Traditional Tactics

- Whenever possible, attack from the unburned to the burned side.
- Ventilation – systematic removal and replacement of heated air, smoke and gases from a structure with cooler air.
- The most effective and efficient fire attack is from the interior.
- Don’t flow water from the outside – you will push fire.

Are these tactics working for you? The research results are providing options.
Radiation

Convection
Conduction

Fire Fighting Thermal Environments

Traditional Fire Behavior
Fuel Controlled

Temperature

Time

Ignition
Growth
Fully Developed
Decay begins as fuel is depleted
Decay
Sofa Fire

Sofa – 75 in x 35 in x 30 in high
105 lbs
Single Compartment – Open Doorway

Peak HRR approximately 6 MW at 70 s
Heat Flux Outside the Room
6.5 ft away from doorway and 3.3 ft above the floor

Typical Structural Fire Behavior?
Ventilation Controlled
Temperature – Center of the Room

![Graph showing temperature over time with various markers for different distances from ignition to suppression.](Image)
Total and Radiant Heat Flux

[Graph showing Total HF and Rad HF over time with key events: ignition, door open, rollover, suppression]

PPE Temperatures

[Graph showing TC Outer Shell and TC Face Cloth temperatures over time with key events: ignition, door open, rollover, suppression]
Heat Flux inside PPE

![Graph showing heat flux over time with specific events labeled: ignition, door open, rollover, suppression.]

- Heat Flux (kW/m²)
- Time (sec)

Legend:
- HF FFPE without PCM
- Total HF @ Samples
PPE Temperatures

Time (sec)
0 100 200 300 400 500
0 200 400 600 800 1000
32 392 752 1112 1472 1832

Temperature (°C)

TC Outer Shell
TC Face Cloth

Simulation of the Fire at 1100 Prospect Place
12-19-2011
Can You Vent Enough?

Adam Barowy
Daniel Madrzykowski
NIST- Fire Research
0904: 911 call received

0911: Flames observed extending from Two rear window on the top floor Front Window , top floor, exp 2 side, Vented Stairwell skylight vented Scuttle opened

0912: Front Window , top floor, center, vented. Bathroom skylight vented Bedroom skylight vented

0913: Firefighter bailing out of front Window, top floor, exp 4 side.

Prospect Place
Floor plan

Rear Bed Room
(fire origin)

Front Bed Room

Rear Room
(Room of fire origin)
Front Room
(Room where firefighters were burned)
Model Timeline
(min:sec)

- 3:40 – Front Door Open
- 5:50 – Rear windows start to fail
- 11:40 – Luan Door opened
- 12:40 – Front Window, Bottom Pane – Exp 2 side
- 12:55 – Stairwell Skylight
- 13:05 – Front Window Top Pane – Exp 2 side
- 13:20 – Scuttle opened
- 13:50 – Center Window, Bottom pane opened
- 13:50 - Bedroom skylight
- 14:10 – Center Window, Top pane opened
- 14:10 – Bathroom Skylight opened
- 14:35 – Front Window, Exp 4 side opened
Before Tactical Roof and Window Ventilation

Front  
Bed Room Side  
Stair Side

Adam Barowy, Daniel Madrzykowski, NIST- Fire Research

After Roof (44 sq ft) and Window (3 in Front, 2 in Rear ) Ventilation

Front  
Bed Room Side  
Stair Side

Adam Barowy, Daniel Madrzykowski, NIST- Fire Research
The flow path is the volume between an inlet and an outlet that allows the movement of heat and smoke from the higher pressure within the fire area towards the lower pressure areas accessible via doors and window openings.

Based on varying building configurations, there may be several flow paths within a structure.

Operations conducted in the flow path, between the fire and the where the fire wants to go, will place members at significant risk due to the increased flow of fire, heat and smoke toward their position.

Fuel Load
# Heat Release Rates

<table>
<thead>
<tr>
<th>Item</th>
<th>Avg. Peak HRR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trash Container</td>
<td>30 kW</td>
</tr>
<tr>
<td>Chair</td>
<td>1.8 MW</td>
</tr>
<tr>
<td>Sofa</td>
<td>2.5 MW</td>
</tr>
<tr>
<td>Bed</td>
<td>4.3 MW</td>
</tr>
</tbody>
</table>
Impact of Ventilation on HRR
No Wind

Impact of Ventilation Bedroom Temperatures
Impact of Ventilation on Living Room Temperatures

Velocity in the Hallway
This is a fire induced flow between the bedroom (room of origin) and the living room (downstream in the fire's flow path to the outlet)
Impact of Ventilation on Total Unburned Hydrocarbon Generation

Gas Concentration (% Volume)

Time (s)

LR Upper THC
BR Upper THC

Window vented  Begin Suppression

2:25
Single Family Home – Houston Wind Driven Fire


FDS Model
Flow reversal at the front door

10 s before glass failure

10 s after glass failure
Impact of Closing Door During VEIS

Impact of flow path through Open Bedroom due to Window Ventilation
Flow Path from Open Front Door and exits through Open 2nd Floor Bedroom Window
DC2 (642B)
You MUST Control the Flow Path to Improve Victim Survivability

Top of Stairs 350°F → 950°F
Bottom of Stairs 800°F → 1800°F
Closed Bedroom 120°F → 160°F
Open Bedroom 350°F → 600°F
15 mph
170°F → 290°F
Living Room Rear 800°F → 1600°F
Living Room Front 800°F → 1800°F
Impact of Closing Door During VEIS
Flow Path from Open Front Door and exits through Open 2nd Floor Bedroom Window
DC3 (640C)
You MUST Control the Flow Path to Improve Firefighter Safety

Impact of Water through Open Front Door on Living Room Fire
DC 2 (6428) – 28 seconds of water
You Don’t Have to be on top of the fire to flow water
Impact of Door Control

Flow Path control of the Front Door by Opening and Closing it

DC4 (640E)

Control of the Front Door Controls the Fire, Less Oxygen equals Lower Temperatures

Top of Stairs
- 500°F → 250°F Closed
- 250°F → 750°F Open
- 750°F → 450°F Closed
- 450°F → 900°F Open
- 900°F → 500°F Closed

Open Bedroom
- 400°F → 250°F Closed
- 250°F → 650°F Open
- 650°F → 450°F Closed
- 450°F → 700°F Open
- 700°F → 600°F Closed

Living Room Rear
- 850°F → 400°F Closed
- 400°F → 1200°F Open
- 1200°F → 600°F Closed
- 600°F → 1300°F Open
- 1300°F → 650°F Closed

Living Room Front
- 1700°F → 550°F Closed
- 550°F → 2000°F Open
- 2000°F → 600°F Closed
- 600°F → 1300°F Open
- 1300°F → 700°F Closed

Inlet

Outlet

EXPOSURE 1

EXPOSURE 2

EXPOSURE 3

EXPOSURE 4

Basement Fire – Only vent on 1st Floor
Learning Objectives: 1) Ventilation Induced Flashover 2) Need for proper venting 3) Speed of transition to flashover
Protecting the Stairs

Front

Top of Stairs IR

11:00

Bmt
Protecting the Stairs

Flow Path from Open Front Door and exits through Open Front Door
Basement 3 (644C) – 25 seconds of water
Flowing Water into the 1st Floor Basement Door Has Little Effect

Watch Your Back, Fire Extended Through the Kitchen Pipe Chases, Not the Interior Stairwell And Collapse Occurred in the Kitchen
Protecting the Stairs

Flow Path from Open Front Door and exits through Open Front Door
Basement Fires (644C, 644A, 642F, 640F)

Watch Your Back, Fire Extended Through the Kitchen Pipe Chases, Not the Interior Stairwell
And Collapse Occurred in the Kitchen
Water through the Basement Window

Flow Path from Open Basement Window and Bilco Door, exits through Open Front Door
Basement 3 (644C) – 60 seconds of water
Flowing Water on the Fire Improves Conditions Everywhere in the Structure

Outlet
Exterior Water Application
Base of Stairs
1200°F → 400°F

Inlet
Exterior Water Application
Base of Stairs
1200°F → 400°F

Top of Stairs
600°F → 200°F
14kW/m² → 0kW/m²

Closed Bedroom
110°F → 110°F

Open Bedroom
225°F → 190°F

Baseline Rear
800°F → 300°F

Base of Stairs
1700°F → 300°F

Front Door
250°F → 200°F

Flow Path from Open Basement Window and Bilco Door, exits through Open Front Door
Basement 3 (644C) – 60 seconds of water
Flowing Water on the Fire Improves Conditions Everywhere in the Structure

Outlet
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14kW/m² → 0kW/m²

Closed Bedroom
110°F → 110°F

Open Bedroom
225°F → 190°F

Baseline Rear
800°F → 300°F

Base of Stairs
1700°F → 300°F

Front Door
250°F → 200°F
Exterior Water into 2\textsuperscript{nd} Floor
Flow Path from Bedroom Window and 1\textsuperscript{st} Floor
Can Test 2 (644D) – 22 Seconds of Water

Hallway
- 900°F → 250°F (7 ft.)
- 400°F → 200°F (3 ft.)
- 100°F → 120°F (1 ft.)

Bedroom
- 1000°F → 200°F (7 ft.)
- 900°F → 150°F (3 ft.)
- 400°F → 150°F (1 ft.)

Water Application

Impact of Door Control and Suppression During Scuttle Test

Front | Front IR | Living Room

Front Door Opened

NIST 05:00
Impact of Water through Open Front Door With Vertical Vent

Scuttle (640A) – 25 seconds of water

Conditions improve everywhere from water on fire

- **Closed Bedroom**: 1500°F → 100°F
- **Open Bedroom**: 1500°F → 100°F
- **Living Room Rear**: 1550°F → 250°F
- **Living Room Front**: 850°F → 400°F
- **Top of Stairs**: 1200°F → 400°F
- **Bottom of Stairs**: 1700°F → 650°F

**Water Application**

**Inlet**

**Outlet**

*Spartanburg, SC January 2013*
Impact of Venting the Living Room Window
214 Folsom St. Experiment 1

Bidirectional Flow (Both Inlet and Outlet)

Rear Bedroom
At 7 ft: 300°F → 300°F
At 1 ft: 100°F → 100°F

Middle Bedroom
At 7 ft: 300°F → 300°F
At 1 ft: 100°F → 100°F
7 kW/m² → 5 kW/m²

Front Bedroom
At 7 ft: 120°F → 120°F
At 1 ft: 70°F → 70°F
At 3 ft: 20% O₂ → 20% O₂
1% CO₂ → 1% CO₂
0% CO → 0% CO
0 kW/m² → 0 kW/m²

Kitchen
At 7 ft: 400°F → 450°F
At 1 ft: 100°F → 100°F

Living Room
At 7 ft: 600°F → 700°F
At 1 ft: 200°F → 200°F

Impact of Exterior Attack through Living Room Window with no other Ventilation
214 Folsom St. Experiment 1

Bidirectional Flow (Both Inlet and Outlet)

Rear Bedroom
At 7 ft: 300°F → 250°F
At 1 ft: 100°F → 100°F

Middle Bedroom
At 7 ft: 300°F → 250°F
At 1 ft: 100°F → 100°F
5 kW/m² → 4 kW/m²

Front Bedroom
At 7 ft: 120°F → 120°F
At 1 ft: 70°F → 70°F
At 3 ft: 20% O₂ → 20% O₂
1% CO₂ → 1% CO₂
0% CO → 0% CO
0 kW/m² → 0 kW/m²

Kitchen
At 7 ft: 450°F → 300°F
At 1 ft: 100°F → 100°F

Living Room
At 7 ft: 700°F → 100°F
At 1 ft: 200°F → 200°F
Impact of Opening the Front Door

215 Folsom St. Experiment 1

Rear Bedroom
At 7 ft: 70 °F → 75 °F
At 1 ft: 50 °F → 50 °F

Middle Bedroom
At 7 ft: 600 °F → 700 °F
At 1 ft: 200 °F → 300 °F
At 3 ft: 4 kW/m² → 4 kW/m²

Front Bedroom
At 7 ft: 80 °F → 90 °F
At 1 ft: 50 °F → 50 °F
At 3 ft: 20% O₂ → 20% O₂
0% CO₂ → 0% CO₂
0% CO → 0% CO
3 kW/m² → 3 kW/m²

Kitchen
At 7 ft: 500 °F → 700 °F
At 1 ft: 200 °F → 300 °F

Living Room
At 7 ft: 1100 °F → 1400 °F
At 1 ft: 400 °F → 300 °F

Door Knob Inside Room:
100 °F → 200 °F

Door Knob Exposed to Fire:
700 °F → 1200 °F
Impact of Exterior Water through the Front Door

215 Folsom St. Experiment 1
~ 75 seconds of water

Rear Bedroom
At 7 ft: 75 °F → 75 °F
At 1 ft: 50 °F → 50 °F

Middle Bedroom
At 7 ft: 700 °F → 200 °F
At 1 ft: 300 °F → 100 °F
At 3 ft: 4 kW/m² → 1 kW/m²

Front Bedroom
At 7 ft: 90 °F → 80 °F
At 1 ft: 50 °F → 50 °F
At 3 ft: 20% O₂ → 20% O₂
0% CO₂ → 0% CO₂
0% CO → 0% CO
3 kW/m² → 1 kW/m²

Kitchen
At 7 ft: 700 °F → 200 °F
At 1 ft: 300 °F → 100 °F

Living Room
At 7 ft: 1400 °F → 200 °F
At 1 ft: 300 °F → 70 °F

Exterior Water Application

Door Knob Inside Room: 200 °F → 100 °F
Door Knob Exposed to Fire: 1200 °F → 300 °F
Impact of Exterior Attack through Basement Door

227 Folsom St. Experiment

~ 60 seconds of water

BC Bedroom
At 7 ft: 400°F → 200°F
At 1 ft: 200°F → 150°F

CD Bedroom
At 7 ft: 350°F → 200°F
At 1 ft: 250°F → 150°F

Kitchen
At 7 ft: 400°F → 200°F
At 1 ft: 250°F → 150°F

Living Room
At 7 ft: 400°F → 200°F
At 1 ft: 150°F → 100°F

Turnout Gear
At 3 ft: 300°F → 200°F
3 kW/m² → 2 kW/m²

Basement
At 7 ft: 1800°F → 400°F
At 1 ft: 1800°F → 400°F

Exterior Water Application
Inlets
Outlet
Thermal Imager is not a reliable thermometer
Thermal Conditions of a Wood Floor Assembly above a Compartment Fire

A TI is not an X-ray device
Research Summary

• The hazard from a residential fire has increased due to:
  – Synthetic fuel loads
  – Reduced compartmentation
  – Light-weight construction techniques
  – Energy efficiency/alternate energy measures

• Fire conditions can exceed PPE limits
• Tactics may need to be revised
• Early water may be the best approach
• “Softening the target”
Fire Service Knowledge

• Be aware of the capabilities and limitations of PPE
• Smoke is fuel
• Venting does not equal cooling
• Most structure fires are ventilation limited (fuel rich)
• Size up – reassess as ventilation changes
• Locate the fire
• Account for wind conditions (keep the upwind of the fire)
• Identify and stay out of the fire’s flow path (exhaust)
• Consider alternate approaches to basement fire
• Unburned to burned may not be the best attack
• Current understanding, education, training and SOPs/SOGs must be in sync.

Technology Transfer - Online Training Programs

http://learn.isfsi.org/

www.ULfirefightersonsafety.com  www.cfitrainer.net
ALIVE : Web-Based and Mobile Applications
Wind Driven High Rise Fires, Modern Residential Fires, and Fire Dynamics (coming soon) www.poly.edu/fire

F-STAR
Firefighter Safety Through Advanced Research
Web Portal Under Development

iPhone  iPad  Android

http://www.lacofdturnout.com/

IFSTA 200, 1977 Figure 6.20

<table>
<thead>
<tr>
<th>PHASE</th>
<th>CONDITIONS</th>
<th>REQUIREMENTS TO EXTINGUISH</th>
<th>METHOD</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>Igniting fire.  20% oxygen content of atmosphere. Accelerating heat generation according to development of fire. Considerable smoke in reverse proportion to heat generation. Destruction limited to immediate fire area.</td>
<td>Entrance and direct application of extinguishing agent. Personal protection if needed.</td>
<td>Make entrance. Locate fire. Apply extinguishing agent at base of fire. Protect self with protective breathing equipment. Ventilate at natural openings if needed.</td>
</tr>
<tr>
<td>2nd</td>
<td>Flame production. Major involvement. Entrance difficult because of heat. Oxygen reduction 10% - 15% or less. Rapid heat generation with highest temperature at ceiling. High convection of heated gases and air. Limited smoke production, increasing as flame decreases. Increasing atmospheric pressure within space. Rapid destruction.</td>
<td>Reduction of room temperature to 300°F or less. Entrance and direct application of extinguishing agent to remaining fire. Personal protection if needed.</td>
<td>1. Limit area of major involvement. 2. Determine point or points at which application is to be made. 3. Make opening, if needed, small as possible for application of water fog. 4. Assume precision so that water stream will not be involved with hot smoke and condensing steam. 5. Apply fog into upper level to meet space requirements. —If applied at upper level use short-throw fog. —If applied at lower level use long-throw fog and direct into upper level. The order of expudation due to displacement will be: 1st Smoke 2nd S青睐 and condensing steam 3nd Condensing steam 6. Continue application of fog without interruption until decrease of condensing steam is noticed. 7. Enter and extinguish remaining fire and spot fires. 8. Protect self if necessary with breathing equipment and heavy clothing.</td>
</tr>
</tbody>
</table>
More Information

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