Fire Investigation: Fire Dynamics and Modeling

FI: FDM-Student Manual

2nd Edition, 1st Printing-July 2016

FEMA

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TABLE OF CONTENTS

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ACKNOWLEDGMENTS

The development of any National Fire Academy (NFA) course is a complex process aimed at providing students with the best possible learning opportunity we can deliver.

There are many players in course development, each of whom plays an equally important part in its success. We want to acknowledge their participation and contribution to this effort and extend our heartfelt thanks for making this quality product.

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COURSE GOAL

The goal of this course is to empower students with the knowledge to identify and define key concepts of fire dynamics and fire modeling. Students will also develop the ability to apply the available tools to fire investigation and prevention in order to support conclusions using scientific principles.

AUDIENCE, SCOPE AND COURSE PURPOSE

The target audiences for this course are investigators and code enforcement personnel. Priority will be reserved for full-time personnel with fire/arson investigation responsibility and/or full-time code enforcement responsibility. These personnel include fire/arson investigators, law enforcement personnel, and fire prevention staff/code enforcement officials.

The scope of this course encompasses five topics in fire dynamics and modeling. Included among these are identifying and defining the key concepts, locating and selecting appropriate data sources, identifying and using basic mathematical models, describing and analyzing the behavior of fire in compartment conditions, and critically evaluating the uses and limitations of computer modeling in fire prevention and investigation.

The purpose of this course is to provide students with the ability to identify and define key concepts of fire dynamics and fire modeling. Students will also develop the ability to apply the available tools to fire investigation and prevention in order to support conclusions using scientific principles.

GRADING METHODOLOGY

Each student will be assessed on the last day of class with one of two versions of the final examination. Each examination will consist of a minimum of 30 questions, including multiple choice, multiple answers, and/or true or false questions. There will not be more than two true/false questions per test.

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SCHEDULE

TIME	DAY 1	DAY 2
8:00-9:00	Introduction, Welcome and Administrative	Group Discussion of Howard County Assignment
9:00-9:15	*Break*	*Break*
9:15-10:15	Unit 1: Introduction to Fire Dynamics Activity 1.1: Candle Experiment	Unit 2: Compartment Fire Dynamics
10:15-10:30	*Break*	*Break*
10:30-11:30	Unit 1: Introduction to Fire Dynamics (cont'd)	Unit 2: Compartment Fire Dynamics (cont'd)
11:30-11:45	Unit 1: Introduction to Fire Dynamics (cont'd)	*Lunch Break*
11:45-12:30	*Lunch Break*	*Lunch Break (cont'd)*
12:30-12:45	*Lunch Break (cont'd)*	Activity 2.1: Live Burn Experiment
12:45-2:15	Unit 1: Introduction to Fire Dynamics (cont'd) Activity 1.2: Howard County, Maryland, Fire Unit 1: Introduction to Fire Dynamics (cont'd)	Activity 2.1: Live Burn Experiment (cont'd)
2:15-2:30	*Break*	Activity 2.1: Live Burn Experiment (cont'd)
2:30-3:00	Unit 1: Introduction to Fire Dynamics (cont'd)	*Break*
3:00-3:45	Unit 1: Introduction to Fire Dynamics (cont'd)	Activity 2.2: Baltimore County LODD, Live Fire Experiment
3:45-4:00	*Break*	Activity 2.2: Baltimore County LODD, Live Fire Experiment (cont'd)
4:00-5:00	Unit 1: Introduction to Fire Dynamics (cont'd)	Activity 2.2: Baltimore County LODD, Live Fire Experiment (cont'd)

TIME	DAY 3	DAY 4
8:00-9:00	Review of Previous Day	Review of Previous Day
9:00-9:15	*Break*	*Break*
9:15-10:15	Unit 3: Test Methods	Unit 4: Mathematical Modeling (cont'd)
10:15-10:30	*Break*	*Break*
10:30-12:00	Unit 3: Test Methods (cont'd) Unit 4: Mathematical Modeling	Unit 4: Mathematical Modeling (cont'd)
12:00-1:00	*Lunch Break*	*Lunch Break*
1:00-2:00	Unit 4: Mathematical Modeling (cont'd)	Activity 4.1: Howard County, Maryland, Fire: Mathematical Modeling
2:00-2:15	Unit 4: Mathematical Modeling (cont'd)	*Break*
2:15-2:30	*Break*	Activity 4.2: Case Study: Commonwealth of PA v. Paul Camiolo
2:30-3:00	Unit 4: Mathematical Modeling (cont'd)	Activity 4.2: Case Study: Commonwealth of PA v. Paul Camiolo (cont’d)
3:00-3:45	Unit 4: Mathematical Modeling (cont'd)	Review of Day
3:45-4:00	*Break*	*Break*
4:00-5:00	Unit 4: Mathematical Modeling (cont'd)	Unit 5: Computer Modeling

TIME	DAY 5	DAY 6
8:00-8:45	Activity 5.1: Build Ventilation Model for Burn Cell in CFAST	Unit 5: Computer Modeling (cont'd)
8:45-9:00	Activity 5.1: Build Ventilation Model for Burn Cell in CFAST (cont’d)	*Break*
9:00-9:30	Activity 5.1: Build Ventilation Model for Burn Cell in CFAST (cont’d)	Group Presentations of Howard County Fire Results
9:30-9:45	*Break*	Group Presentations of Howard County Fire Results (cont’d)
9:45-10:00	Unit 5: Computer Modeling (cont'd)	Group Presentations of Howard County Fire Results (cont’d)
10:00-10:15	Unit 5: Computer Modeling (cont'd)	*Break*
10:15-10:30	*Break*	Final Exam
10:30-12:00	Activity 5.2: CFAST Model for Howard County	Final Exam (cont’d)
12:00-12:15	*Lunch Break*	Final Exam (cont’d)
12:15-12:45	*Lunch Break (cont’d)*	
12:45-1:30	Unit 5: Computer Modeling (cont'd)	
1:30-1:45	*Break*	
1:45-3:15	Activity 5.3: Build Ventilation Model for Burn Cell in FDS Using PyroSim	
3:15-3:30	*Break*	
3:30-5:00	Activity 5.4: Analyze Output From FDS Model for Living Room and Hallway for Howard County, Maryland, Investigation Project	

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FIREFIGHTER CODE OF ETHICS

Background

The Fire Service is a noble calling, one which is founded on mutual respect and trust between firefighters and the citizens they serve. To ensure the continuing integrity of the Fire Service, the highest standards of ethical conduct must be maintained at all times.

Developed in response to the publication of the Fire Service Reputation Management White Paper, the purpose of this National Firefighter Code of Ethics is to establish criteria that encourages fire service personnel to promote a culture of ethical integrity and high standards of professionalism in our field. The broad scope of this recommended Code of Ethics is intended to mitigate and negate situations that may result in embarrassment and waning of public support for what has historically been a highly respected profession.

Ethics comes from the Greek word ethos, meaning character. Character is not necessarily defined by how a person behaves when conditions are optimal and life is good. It is easy to take the high road when the path is paved and obstacles are few or non-existent. Character is also defined by decisions made under pressure, when no one is looking, when the road contains land mines, and the way is obscured. As members of the Fire Service, we share a responsibility to project an ethical character of professionalism, integrity, compassion, loyalty and honesty in all that we do, all of the time.

We need to accept this ethics challenge and be truly willing to maintain a culture that is consistent with the expectations outlined in this document. By doing so, we can create a legacy that validates and sustains the distinguished Fire Service institution, and at the same time ensure that we leave the Fire Service in better condition than when we arrived.

FIREFIGHTER CODE OF ETHICS

I understand that I have the responsibility to conduct myself in a manner that reflects proper ethical behavior and integrity. In so doing, I will help foster a continuing positive public perception of the fire service. Therefore, I pledge the following…

- Always conduct myself, on and off duty, in a manner that reflects positively on myself, my department and the fire service in general.
- Accept responsibility for my actions and for the consequences of my actions.
- Support the concept of fairness and the value of diverse thoughts and opinions.
- Avoid situations that would adversely affect the credibility or public perception of the fire service profession.
- Be truthful and honest at all times and report instances of cheating or other dishonest acts that compromise the integrity of the fire service.
- Conduct my personal affairs in a manner that does not improperly influence the performance of my duties, or bring discredit to my organization.
- Be respectful and conscious of each member's safety and welfare.
- Recognize that I serve in a position of public trust that requires stewardship in the honest and efficient use of publicly owned resources, including uniforms, facilities, vehicles and equipment and that these are protected from misuse and theft.
- Exercise professionalism, competence, respect and loyalty in the performance of my duties and use information, confidential or otherwise, gained by virtue of my position, only to benefit those I am entrusted to serve.
- Avoid financial investments, outside employment, outside business interests or activities that conflict with or are enhanced by my official position or have the potential to create the perception of impropriety.
- Never propose or accept personal rewards, special privileges, benefits, advancement, honors or gifts that may create a conflict of interest, or the appearance thereof.
- Never engage in activities involving alcohol or other substance use or abuse that can impair my mental state or the performance of my duties and compromise safety.
- Never discriminate on the basis of race, religion, color, creed, age, marital status, national origin, ancestry, gender, sexual preference, medical condition or handicap.
- Never harass, intimidate or threaten fellow members of the service or the public and stop or report the actions of other firefighters who engage in such behaviors.
- Responsibly use social networking, electronic communications, or other media technology opportunities in a manner that does not discredit, dishonor or embarrass my organization, the fire service and the public. I also understand that failure to resolve or report inappropriate use of this media equates to condoning this behavior.

Developed by the National Society of Executive Fire Officers

A Student Guide to End-of-course Evaluations

Say What You Mean ...

Ten Things You Can Do to Improve the National Fire Academy

The National Fire Academy takes its course evaluations very seriously. Your comments and suggestions enable us to improve your learning experience.

Unfortunately, we often get end-of-course comments like these that are vague and, therefore, not actionable. We know you are trying to keep your answers short, but the more specific you can be, the better we can respond.

Actual quotes from student evaluations:	Examples of specific, actionable comments that would help us improve the course:
1 "Update the materials."	• The (ABC) fire video is out-of-date because of the dangerous tactics it demonstrates. The available (XYZ) video shows current practices. • The student manual references building codes that are 12 years old.
2 "We want an advanced class in (fill in the blank)."	• We would like a class that enables us to calculate energy transfer rates resulting from exposure fires. • We would like a class that provides one-on-one workplace harassment counseling practice exercises.
3 "More activities."	• An activity where students can physically measure the area of sprinkler coverage would improve understanding of the concept. • Not all students were able to fill all ICS positions in the exercises. Add more exercises so all students can participate.
4 "A longer course."	• The class should be increased by one hour per day to enable all students to participate in exercises. • The class should be increased by two days so that all group presentations can be peer evaluated and have written abstracts.
5 "Readable plans."	• The plans should be enlarged to 11 by 17 and provided with an accurate scale. • My plan set was blurry, which caused the dotted lines to be interpreted as solid lines.
6 "Better student guide organization," "manual did not coincide with slides."	• The slide sequence in Unit 4 did not align with the content in the student manual from slides 4-16 through 4-21. • The instructor added slides in Unit 4 that were not in my student manual.
7 "Dry in spots."	• The instructor/activity should have used student group activities rather than lecture to explain Maslow's Hierarchy. • Create a pre-course reading on symbiotic personal relationships rather than trying to lecture on them in class.
8 "More visual aids."	• The text description of V-patterns did not provide three-dimensional views. More photographs or drawings would help me imagine the pattern. • There was a video clip on NBC News (date) that summarized the topic very well.
9 "Re-evaluate pre-course assignments."	• The pre-course assignments were not discussed or referenced in class. Either connect them to the course content or delete them. • The pre-course assignments on ICS could be reduced to a one-page job aid rather than a 25-page reading.
10 "A better understanding of NIMS."	• The instructor did not explain the connection between NIMS and ICS. • The student manual needs an illustrated guide to NIMS.

UNIT 1: INTRODUCTION TO FIRE DYNAMICS

TERMINAL OBJECTIVE

The students will be able to:

1.1 Identify and define the key concepts of fire dynamics and fire modeling.

ENABLING OBJECTIVES

The students will be able to:

1.1 Identify the elements of the fire triangle and fire tetrahedron.

1.2 Describe the three modes of heat transfer.

1.3 Define heat release rate (HRR), ignition and flame spread.

1.4 Describe the mechanisms of burning in solids, liquids and gases.

1.5 Describe compartment fire growth from ignition through fully developed burning.

1.6 Differentiate between various types of computer models.

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UNIT 1: INTRODUCTION TO FIRE DYNAMICS

Slide 1-1

ENABLING OBJECTIVES

- Identify the elements of the fire triangle and fire tetrahedron.
- Describe the three modes of heat transfer.
- Define heat release rate (HRR), ignition and flame spread.

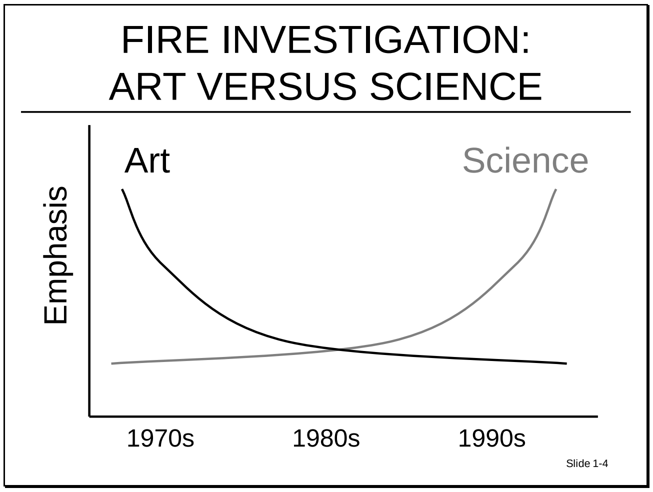
Slide 1-2

ENABLING OBJECTIVES (cont'd)

- Describe the mechanisms of burning in solids, liquids and gases.
- Describe compartment fire growth from ignition through fully developed burning.
- Differentiate between various types of computer models.

Slide 1-3

I. THE SCIENTIFIC METHOD

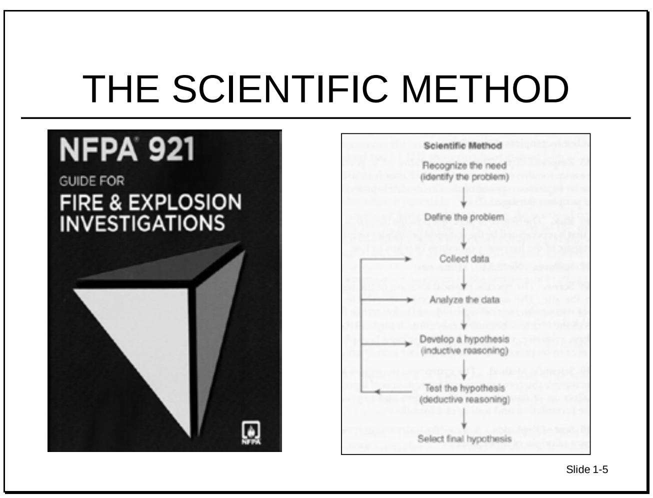


A. Fire investigation has evolved from an art-based field to a science-based discipline in the past 20 years for the following reasons:

1. Initiatives by the federal government in the 1970s to reduce loss of life by fire, which led to the funding of more fire research through National Institute of Standards and Technology (NIST).

2. The eventual dissemination and application of this type of fundamental research into the fire investigation field.

3. The introduction of the first edition of National Fire Protection Association (NFPA) 921 in 1992.



B. The investigation of fire is a scientific process.

1. All scientific processes have a basic methodology which one can follow to aid them in the analysis of problems and development of scientifically valid opinions.

2. The application of the scientific method in fire investigation is intended to ensure that investigators have considered all viable hypotheses and established one hypothesis that is most probable.

3. The scientific method is also intended to prevent the introduction of bias and presumption by weighing each potential hypothesis against all the known facts of the case and putting less emphasis on subjective data.

4. The scientific method is an iterative process, and it is the recognized methodology for use in fire origin and cause investigation.

5. This course will focus on the data collection and analysis steps of the scientific method.

    a. The students will learn about the types of data needed to perform analyses.

    b. They will learn how to perform these analyses during the course.

        - Define the problem.
        - Collect the background information.
        - Formulate a hypothesis.
        - Propose an experiment.
        - Gather materials.
        - Set-up documents.
        - Perform the tests.
        - Analyze data.
        - Derive results and conclusions.

II. FIRE CHEMISTRY AND FLAME ANATOMY

WHAT IS A FIRE?

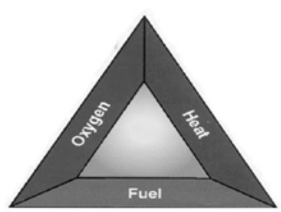
- A rapid chemical **oxidation** process that results in the evolution of **heat** and **light** in varying intensities.
- Fire is a gas phase chemical reaction.

Slide 1-6

A. Fire is a rapid chemical oxidation process that results in the evolution of heat and light in varying intensities.

FIRE TRIANGLE

- Fuel, oxygen and heat are required for combustion.
- Combustion will cease if any of the three components are removed from the reaction.



Slide 1-7

B. The fire triangle.

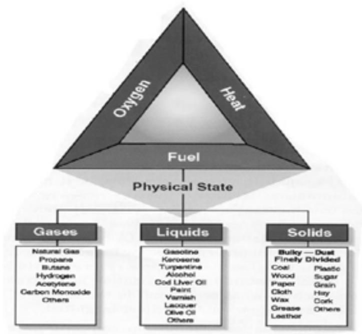
1. The three components of the fire triangle are fuel, oxygen and heat. Common examples of these three components include:

   a. Natural gases, gasoline, kerosene, alcohol, coal, wood, paper, etc.

   b. Air.

   c. Open flame, hot surfaces, friction, etc.

FIRE TRIANGLE:
FUEL SOURCES

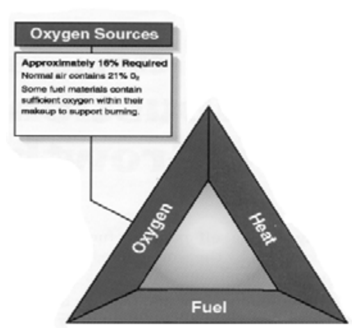


Slide 1-8

2. The three components of the fire triangle are as follows:

   a. Fuel sources include gases, liquids and solids.

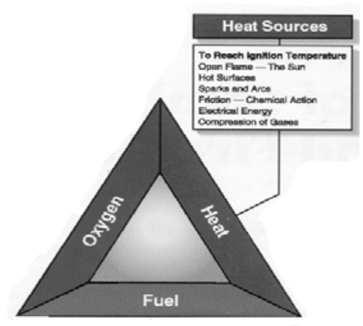
FIRE TRIANGLE:
OXYGEN SOURCES



Slide 1-9

   b. Oxygen sources include air and some fuels which have oxygen in their chemical composition.

FIRE TRIANGLE: HEAT SOURCES



Slide 1-10

c. Heat sources include open flame, hot surface, sparks/arcs, friction, electrical energy, compression of gases, etc.

FIRE TETRAHEDRON

- Fuel, heat, and oxygen plus a **chemical chain reaction.**
- All four elements are required for combustion.

Slide 1-11

C. The fire tetrahedron.

1. The difference between the fire triangle and the fire tetrahedron is that the tetrahedron includes the component of a chemical chain reaction.

2. The fire tetrahedron is more commonly used today.

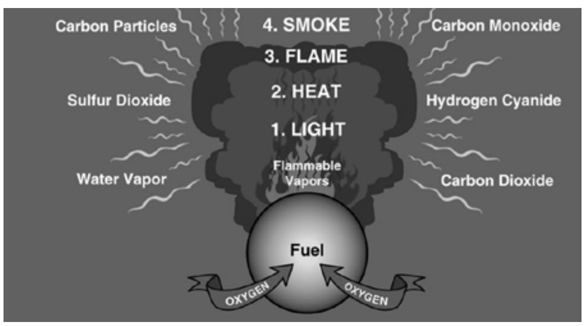
FIRE CHEMISTRY

Stoichiometric (Ideal) Combustion:

$$\text{Fuel} + \text{Oxygen} \xrightarrow{\text{HEAT}} CO_2 + H_2O$$

Slide 1-12

PRODUCTS OF COMBUSTION

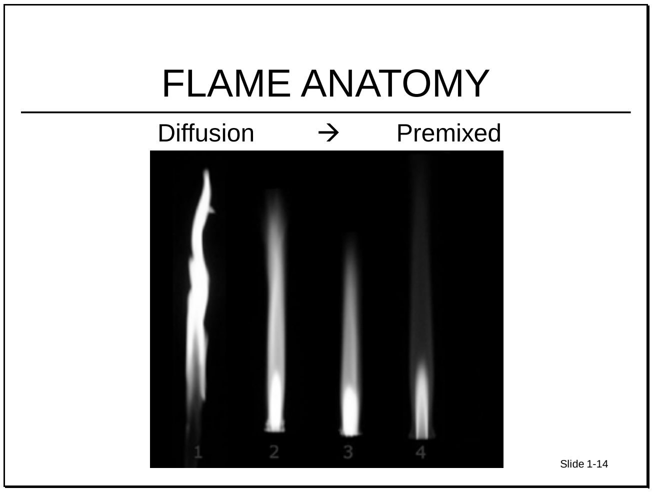


Slide 1-13

D. Products of combustion.

1. The products of combustion produced in an actual fire that investigators would encounter in the field include carbon monoxide, hydrogen cyanide, sulfur dioxide, carbon particles and irritants.

2. The fuel composition and burning stage will dictate the types and amounts of products produced.



E. Diffusion flame versus premixed flame.

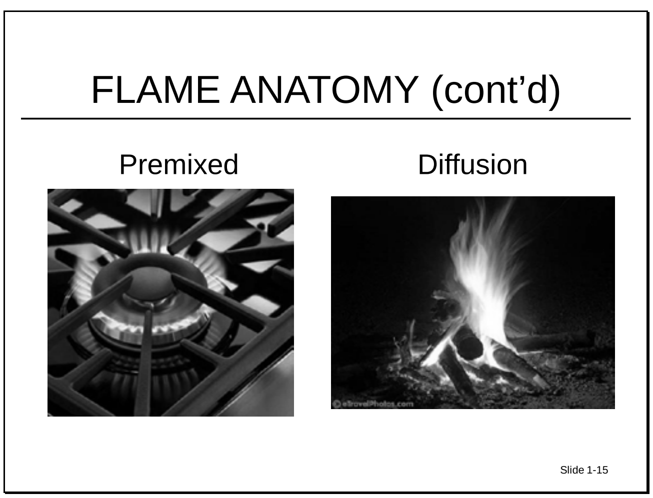
1. A premixed flame occurs when fuel and oxidizer are mixed prior to combustion.

2. A diffusion flame occurs when oxygen mixes with fuel at the combustion zone.

   a. Examples of each type of flame.

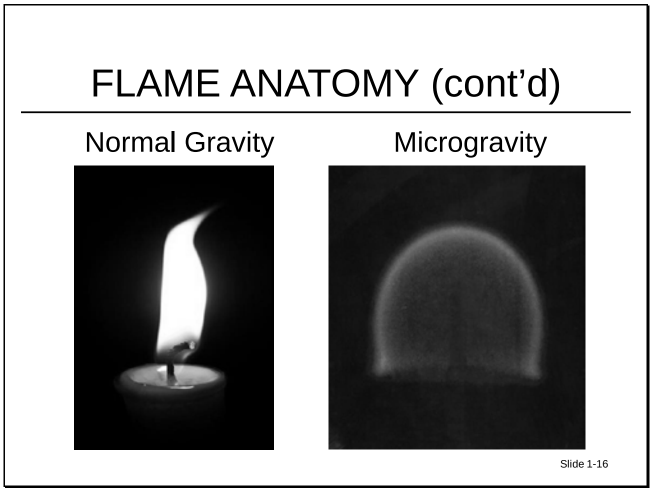
      - Furnace, water heater and stove would exhibit premixed flames.

      - Candle, gasoline pool fire or a house fire would exhibit diffusion flames.

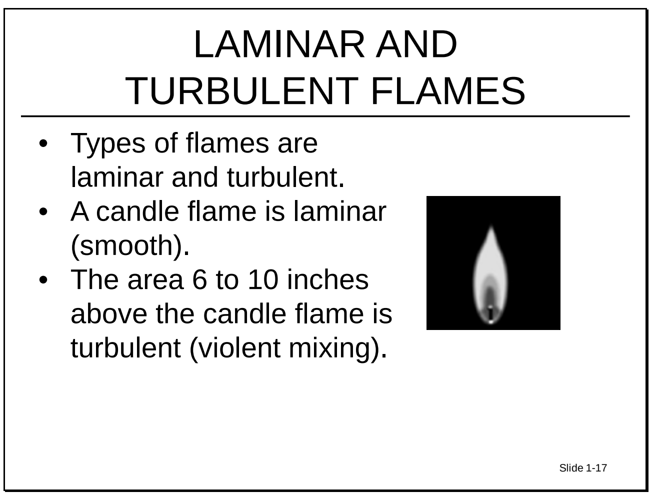


   b. A premixed fuel-air condition could lead to an explosion under ignition, such as gas leaking from an appliance.

c. Premixed flames can achieve higher temperatures than diffusion flames due to higher combustion efficiency.



d. Gravity dictates the shape of a flame due to buoyant forces which cause the pyrolyzates to flow up and the flame front to follow.



F. The two types of flames are laminar and turbulent.

1. A candle flame is laminar (smooth).

2. The area 6 to 10 inches above the candle flame is turbulent (violent mixing).

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ACTIVITY 1.1

Candle Experiment

Purpose

To demonstrate the anatomy of a flame and to show the differences between a diffusion and premixed flame.

Safety Precautions

1. Tuck in all loose clothing, and tie back all hair.
2. Remain a safe distance from the candle and lighter flame.

Directions

1. Clear off your table.
2. Each table will be given one candle. Ensure that your candle is secure in the pie plate.
3. Light the candle.
4. The instructor will demonstrate each exercise at the front of the classroom, one step at a time. Your table group should complete the exercise as demonstrated.

Exercises

1. Place a spoon into the blue luminous zone just above the wick. Observe how this produces little soot.
2. Hold the spoon at the tip of the candle’s flame. Observe how there are large amounts of soot and carbon deposits present.
3. Hold the spoon in a vertical position against the side of the candle flame, limiting the fresh air intake into the candle fire plume. Observe the shadow heat patterns left on the spoon. Note that little soot is present.
4. Hold the mesh screen above the tip of the candle flame, and slowly move it downward towards the base of the flame. While moving the mesh screen through the flame, observe the differences in the flame structure, especially towards the mid-section of the candle.

5. Extinguish the candle. Ignite the white vapors trailing off the wick, causing the flame to jump back to the candle wick.

Discussion Questions

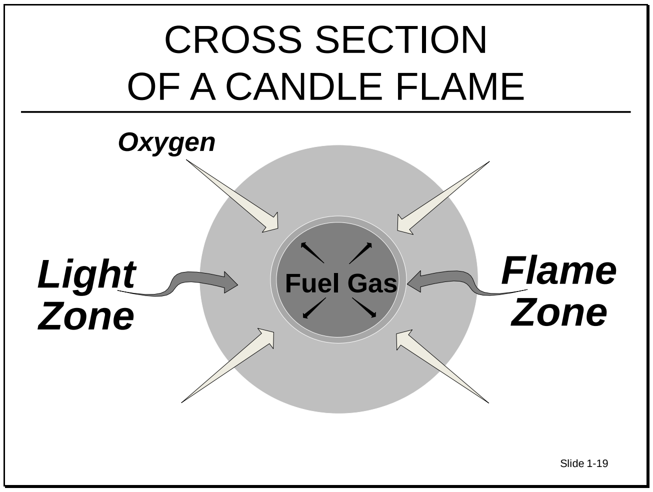
1. Does the candle have a diffusion or premixed flame?

2. How do you explain the different soot patterns formed by holding the spoon in different positions?

3. How did the flame structure change as you moved the screen from tip to base?

4. Why were you able to re-ignite the wick by lighting the vapors coming off the candle?

II. FIRE CHEMISTRY AND FLAME ANATOMY (cont'd)



G. A graphical representation of a candle flame.

1. The flame is not solid; the core is made up of fuel.

2. Flame only occurs at the boundary where the mixing of fuel and oxygen occurs.

PYROLYSIS

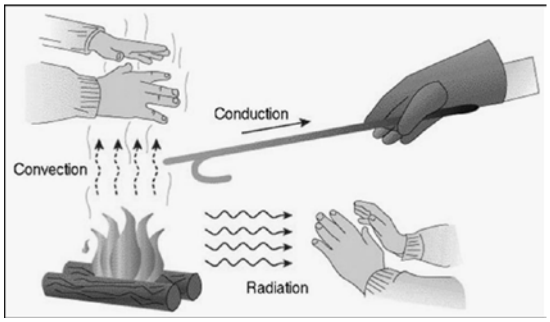
Pyrolysis: Chemical decomposition of a compound into one or more other substances by heat alone.

Slide 1-20

H. Pyrolyis is the process in which solid fuels are transformed into gaseous fuels in order to mix with the oxygen and burn.

III. HEAT TRANSFER

HEAT TRANSFER

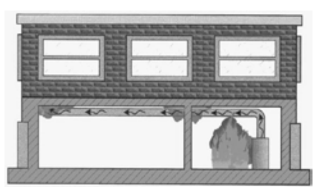


Slide 1-21

The three modes of heat transfer include conduction, convection and radiation.

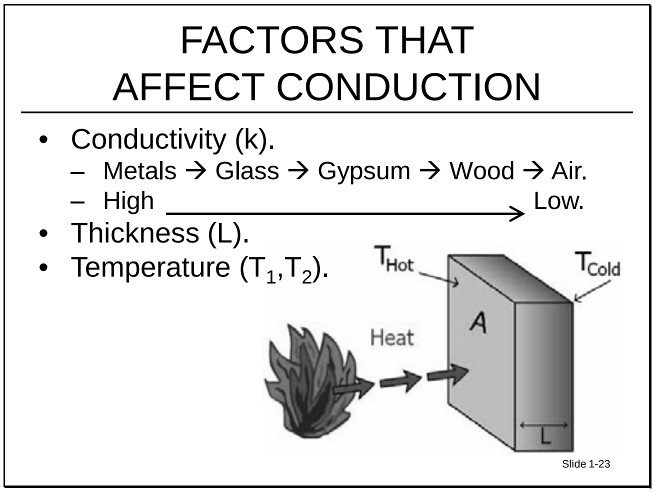
CONDUCTION

Transfer of heat through a solid medium, such as building materials (e.g., brick, metal, etc.).



Slide 1-22

A. Conduction is the transfer of heat through a solid medium, such as building materials (e.g., brick, metal, etc.).



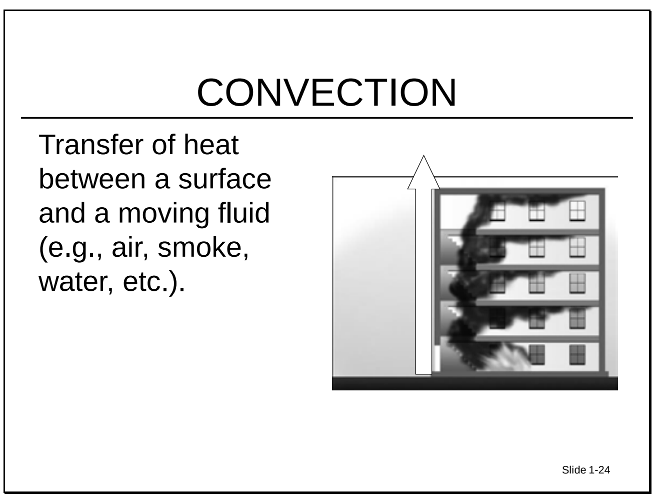
1. The variables that affect conduction of heat through a material include:

    a. Conductivity (K).

    b. Thickness (L).

    c. Temperature (T_1, T_2).

2. Changing these variables will affect the rate of heat transfer (e.g., thicker versus thinner materials or metal versus wood).

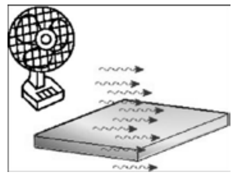


B. Convection is the transfer of heat between a surface and a moving fluid (e.g., air, smoke, water, etc.).

1. A large portion of the flame's energy is transmitted through convection (approximately 70 percent).

FACTORS THAT AFFECT CONVECTION

- Convective Heat Transfer Coefficient (h).
  - Dependent on the fluid conductivity and fluid velocity.
    - -- Forced convection (high velocity = large h).
    - -- Free convection (low velocity = small h).



Slide 1-25

2. The variables that affect convection of heat through a material include:

   a. Heat Transfer Coefficient (h).

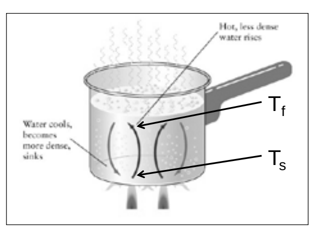
   b. Surface temperature.

   c. Fluid temperature.

3. Changing these variables will affect the rate of heat transfer (e.g., forced versus free).

FACTORS THAT AFFECT CONVECTION (cont'd)

- Fluid Temperature, T_f.
- Surface Temperature, T_s.



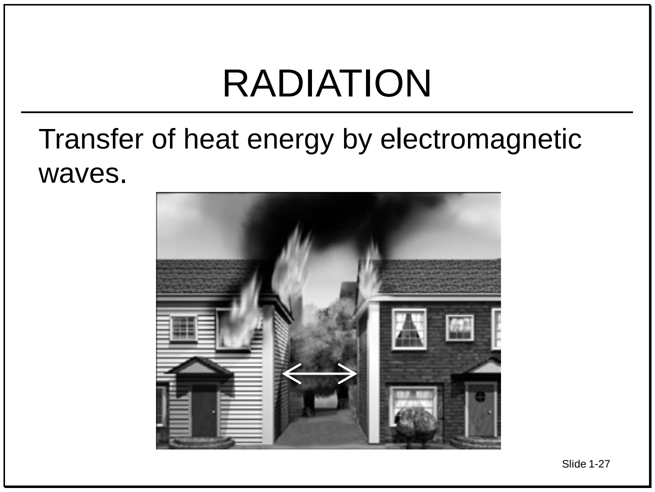
Slide 1-26

4. Delta T affects the heat transfer between the fluid and the solid.

   a. If the difference between the fluid temperature and surface temperature is great, then a large amount of energy will be needed to equilibrate the two surfaces.

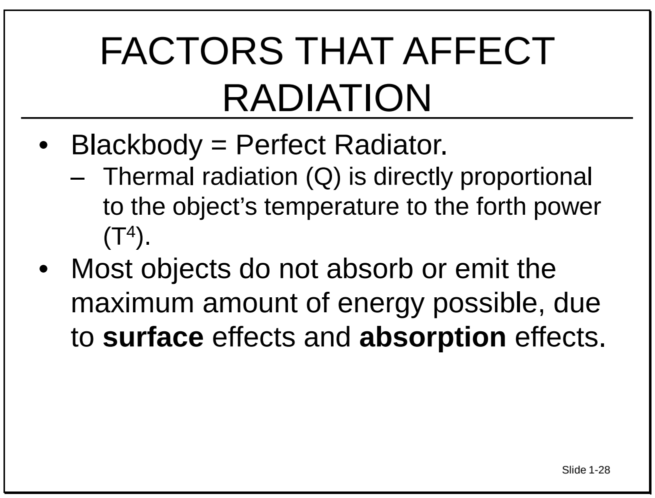
b. If the difference between the temperatures is small, there is a small gradient and little energy is needed to equilibrate the fluid and surface temperatures.

c. A small flame would require more time to transfer heat to the water, whereas, a large flame with a higher British thermal unit (Btu) output would heat the fluid more quickly.



C. Radiation is transfer of heat energy by electromagnetic waves.

1. Approximately 30 percent of a flame's energy is transmitted through radiation.



2. The variables that affect radiation of heat include emissivity, surface temperature, view factor, and the object's properties, including surface and absorbing effects that control the efficiency of radiant heat transfer from the object to surrounding surfaces.

FACTORS THAT AFFECT RADIATION (cont'd)

- Emissivity (ε) accounts for the absorbing abilities of the material.

Black smoke → Gray smoke → White Smoke

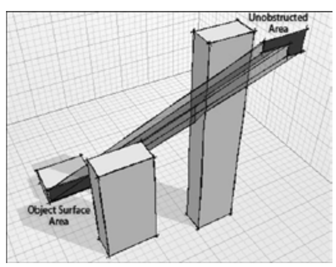
High ε ⟶ Low ε

Slide 1-29

a. Emissivity accounts for the absorbing abilities of the object; changing these variables will affect the rate of heat transfer (e.g., black body versus polished steel, material parallel with source versus a material that is perpendicular to the source).

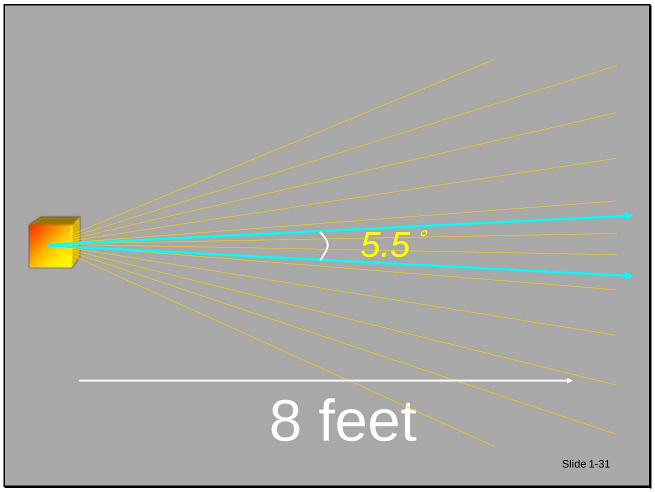
FACTORS THAT AFFECT RADIATION (cont'd)

- Object's surface temperature (TS).
- View Factor (F_{12}).

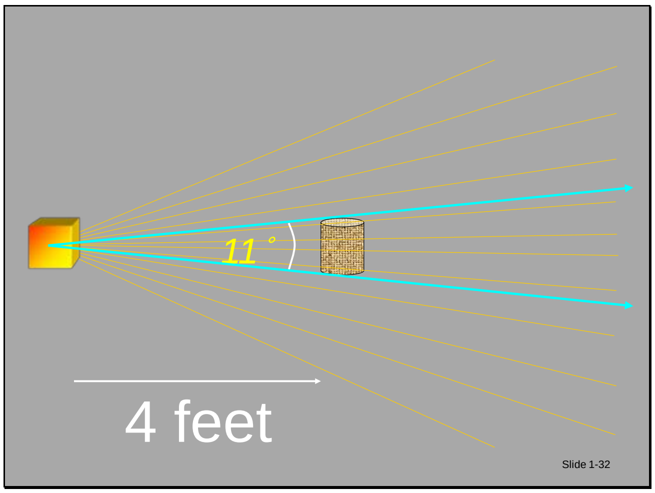


Slide 1-30

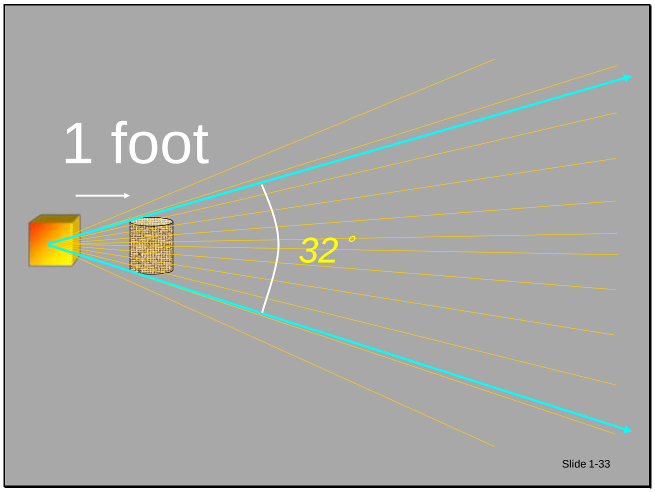
b. The view factor controls the amount of radiation that is actually "seen" by the target that is receiving the heat.



c. At a distance, the amount of the emitted radiation "seen" by the target is only a small portion, here about 5.5 degrees of arc.



d. For the same target at a closer distance from the radiator, the emitted radiation "seen" by the target covers a larger portion of the radiation emitted.



e. At very close distances, the arc of emitted radiation encountered by the target is even larger.

IV. UNITS OF MEASURE

UNITS OF MEASURE

Measurement	Units
Temperature	Celsius (C), Fahrenheit (F), Kelvin (K)
Energy	Joules (J), Calories (cal)
HRR	Watt (W), Kilowatts (kW), Megawatts (MW), British thermal unit per pound (Btu)
Heat Flux	Watts per square centimeter (W/cm^2), Kilowatts per square meter (kW/m^2)

Slide 1-34

A. The four common units of measurement in fire, used for comparative or quantitative discussion, include temperature, energy, heat release rate (HRR) and heat flux.

B. Although the general population uses English units, the scientific population uses metric units. Fire dynamics equations use metric units as well.

1. A Joule (J) is a measure of energy.

2. The term “calories” is another way of representing energy. These calories are the same as the calories associated with food, which represent the amount of energy that a food will provide to the body.

TEMPERATURE

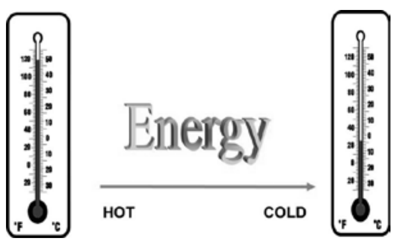
- A measure of the degree of molecular activity of a material compared to a **reference point.**
  - Melting point of ice = 32 F or 0 C.
  - Boiling point of water = 212 F or 100 C.
  - Flashover > 1,100 F or 600 C.

Slide 1-35

3. Temperature is a measure of the degree of molecular activity of a material compared to a reference point. It is used to provide a reference point for comparison.

HEAT ENERGY

The energy needed to change the temperature of an object, given in Joules (J).



Slide 1-36

4. Heat energy is the energy needed to change the temperature of an object, given in J.

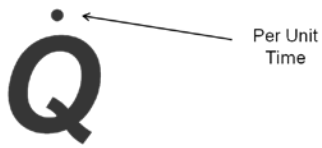
   a. Heat energy is a measure of change.

   b. The laws of thermodynamics support the movement of energy from high to low, so heat will flow from hot areas to cold areas until a steady-state condition is achieved.

V. HEAT RELEASE RATE

HEAT RELEASE RATE

- The energy released per unit time during combustion. Typically given in terms of kilowatts (kW or kJ/s).



Slide 1-37

A. The energy released per unit time during combustion. This is typically given in terms of kilowatts (kW).

B. Heat is a measure of energy.

HEAT RELEASE RATE (cont'd)

- ***H_c*** is the **heat of combustion,** or the amount of energy released per unit of mass consumed (kJ/kg).
- ***$\dot{m}$*** is the **mass loss rate** (MLR), or the mass consumed per unit time (kg/s).

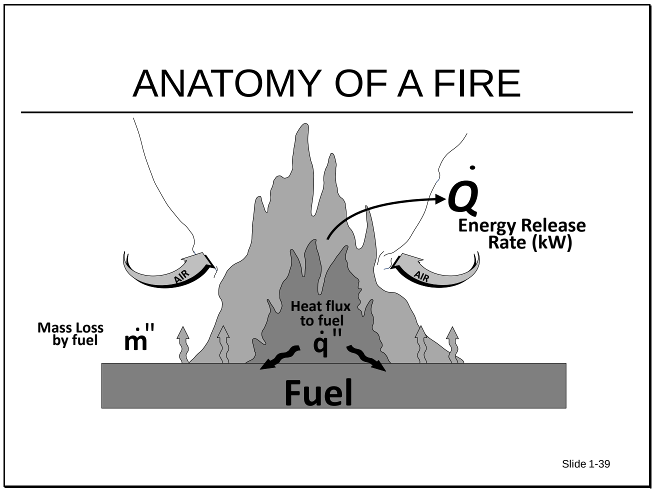
$$\dot{Q} = H_c \times \dot{m}$$

Slide 1-38

C. HRR is a way of representing energy released over some period of time. The two variables that affect HRR are heat of combustion and mass loss rate (MLR).

1. Heat of combustion is the amount of energy that a fuel will produce when it burns.

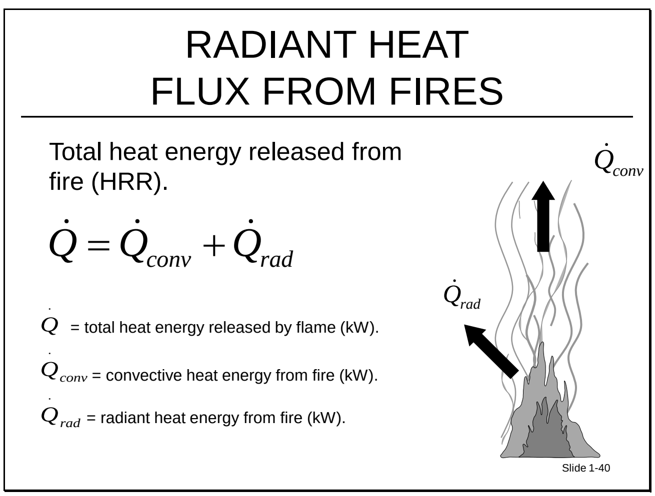
2. MLR is the mass consumed per unit time.



D. A fire is a complex system of interrelated phenomena.

1. Heat from a flame is transferred from the flame to a fuel by radiation and convection.

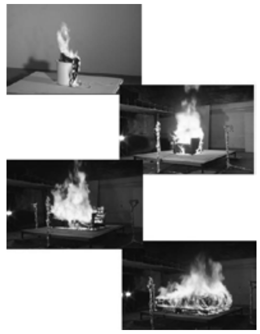
2. The solid or liquid fuel gives off gaseous fuel molecules, either through pyrolysis of solids or vaporization of liquids.



3. The emitted fuel gases then combine with entrained air (air drawn into and mixed with the rising gases to allow for combustion) which releases heat designated by Q-dot.

HEAT RELEASE RATES

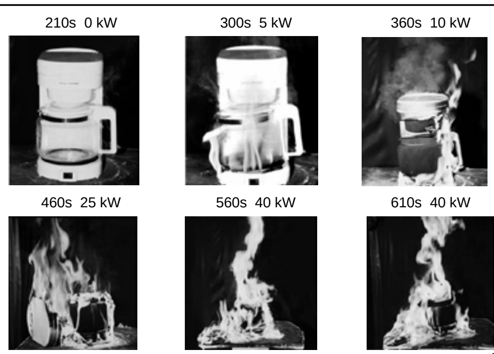
Item	Avg. Peak HRR
Trash container	32 kW
Chair	1.8 MW
Sofa	2.5 MW
Bed	4.3 MW



Slide 1-41

a. The examples of the trash can, chair, sofa and bed provide perspective on what a kW size fire might look like in comparison to a megawatt (MW) size fire. One MW is equal to 1,000 kW.

HRR: COFFEE POT



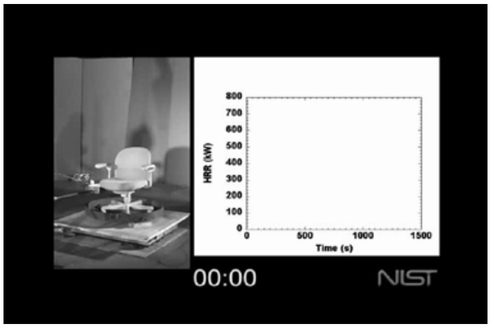
Slide 1-42

b. A coffee pot burning over time:

- The HRR is not constant over time.

- Peak HRR.

HRR: CHAIR



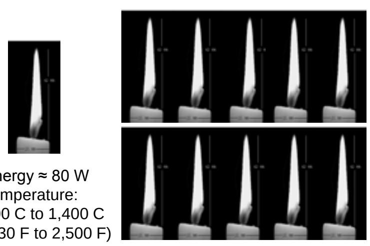
Slide 1-43

c. The fire growth curve:

- The incipient phase, growth phase, peak HRR, and decay phase are shown on the graph.
- What type of fire growth rate would most closely match the chair?

TEMPERATURE VERSUS ENERGY

One candle versus ten candles — same flame temperature but ten times the HRR.



Energy ≈ 80 W
Temperature:
500 C to 1,400 C
(930 F to 2,500 F)

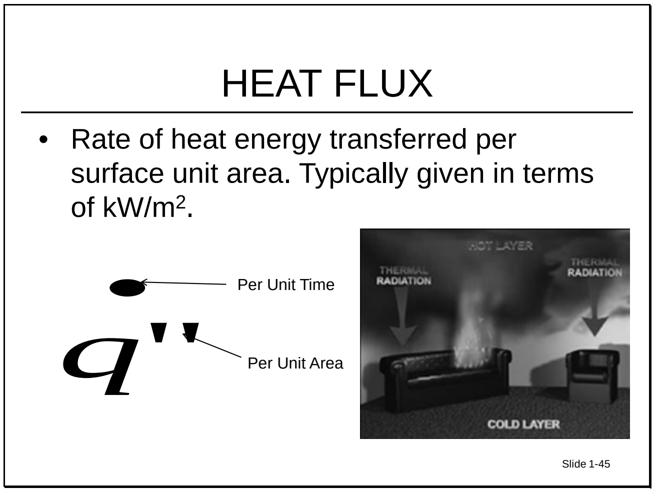
Energy ≈ 800 W

Slide 1-44

E. Temperature versus energy.

1. The temperature of one candle flame is no different from the combination of 10 candle flames; however, the energy output is different.

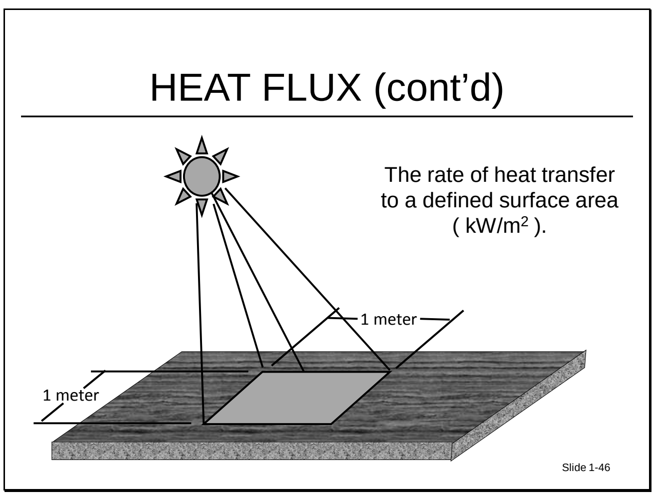
2. This concept relates to the misconception that gasoline "burns hotter" than other ordinary combustibles.



F. Heat flux is the rate of heat energy transferred per unit area and is typically represented by kilowatts per meter squared (kW/m^2).

1. The dot above the "q" shows that it is a rate per unit time.

2. The double prime (") shows that it is measured per unit area.



a. Flux is the measure of HRR over a particular surface area.

HEAT FLUX (cont'd)

- Approximate heat flux ranges:

1.0 kW/m^2	Sunny day.
3-5 kW/m^2	Pain to skin within seconds.
20 kW/m^2	Floor at onset of flashover.
84 kW/m^2	TPP test.
200 kW/m^2	Post-flashover.

Slide 1-47

b. Common flux ranges.

- 1.0 kW/m^2 represents the heat flux on a hot, sunny day.
- 3-5 kW/m^2 represents the heat flux that will cause pain to exposed human skin within seconds.
- 20 kW/m^2 represents the heat flux present at floor level in a compartment at the onset of flashover.
- 84 kW/m^2 represents the exposure heat flux used to evaluate the thermal performance of structural firefighting gear.
- 200 kW/m^2 represents the heat flux present during post-flashover conditions inside a compartment fire.

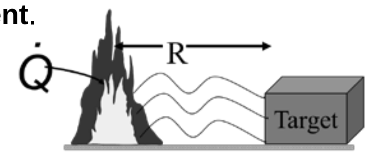
NEWSPAPER MAGNIFY

Slide 1-48

- The newspaper example shows the effect of surface area on flux. The concentration of a particular amount of energy (kW) over a very small surface area can produce sufficient flux to support ignition.

HEAT FLUX (cont'd)

- **X_r** is the radiative fraction or the percentage of radiation given off by the flame and is typically assumed to be **30 percent**.



$$\dot{q}'' = X_r \dot{Q} / 4 \pi R^2$$

Slide 1-49

3. The variables that are important in calculating the amount of flux seen by a target include:

   a. The distance between the source and target.

   b. The fire size.

   c. The percentage of heat being radiated.

4. The flux seen by the target changes inversely with the square of the distance.

   a. "Inversely" — x = 1/y

   b. "Directly" — x = y

VI. IGNITION

IGNITION

- Requires a **competent** heat source in the presence of fuel gases that are within a flammable/combustible range.
  - Requires that heat source can **pyrolyze** the fuel.
  - Pyrolysis is the chemical decomposition of a compound into one or more substances by heat alone.

Slide 1-50

A. The components needed for ignition of a fuel are a **competent** heat source in the presence of fuel gases that are within a flammable/combustible range.

B. Pyrolysis is the chemical decomposition of a compound into one or more substances by heat alone.

IGNITION (cont'd)

- Time and energy required to ignite a material is a function of:
  - Ignition source.
  - Fuel properties, such as thermal inertia, ignition temperature, and geometry.

Slide 1-51

1. It is necessary to have a competent ignition source and the right fuel properties.

2. Is a match a competent ignition source for a two-by-four?

IGNITION: THREE MODES

- **Piloted ignition:** occurs in the presence of a spark, flame, electrical arc, etc. (endothermic process).
- **Auto-ignition:** occurs in the presence of heat but no flame (endothermic process).
- **Spontaneous ignition:** occurs due to biological or chemical oxidation within a material (exothermic process).

Slide 1-52

C. The three modes of ignition.

1. Piloted ignition occurs in the presence of a spark, flame, electrical arc, etc. (endothermic process).

2. Auto-ignition occurs in the presence of heat but no flame (endothermic process).

3. Spontaneous ignition occurs due to biological or chemical oxidation within a material (exothermic process).

IGNITION: FLAMMABILITY (EXPLOSIVE) LIMITS

- Lower flammable limits (LFL) and upper flammable limits (UFL):
  - LFL (also known as lower explosive limit (LEL)) is the concentration of gas or vapor in air below which a flame will not propagate when exposed to an ignition source.
  - UFL (also known as upper explosive limit (UEL)) is the concentration of gas or vapor in air above which a flame will not propagate upon exposure to an ignition source.

Slide 1-53

D. Lower flammable limits (LFL) and upper flammability limits (UFL).

1. LFL is the concentration of gas or vapor in air below which a flame will not propagate when exposed to an ignition source.

2. UFL is the concentration of gas or vapor in air above which a flame will not propagate when exposed to an ignition source.

a. These terms are the same as lower explosive limit (LEL) and upper explosive limit (UEL).

IGNITION: FLAMMABILITY (EXPLOSIVE) LIMITS (cont'd)

Common Fuels	LFL	UFL
Propane	2.1	9.6
Methane	4.7	15
Gasoline	1.4	7.6

Slide 1-54

b. The table shows flammability ranges for some common fuels.

IGNITION: THERMAL INERTIA

- Thermal Conductivity, **k** (W/m·K).
  - Ability to transfer heat by conduction.
- Density, **ρ** (kg/m³).
  - Mass per volume.
- Specific Heat, **c** (kJ/kg·K).
  - Ability of a material to store energy.

Slide 1-55

E. The material properties that affect ignition:

1. Thermal Conductivity (k).

2. Density (ρ).

3. Specific Heat (c).

IGNITION: THERMAL INERTIA (cont'd)

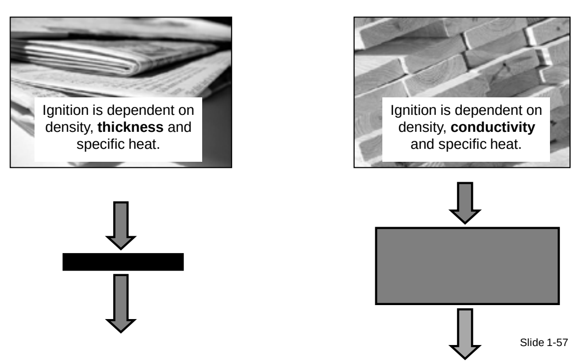
- Thickness, **d** (m).
- Thermal Inertia, **kρc** ($kW^2 \cdot s/m^4 \cdot K^2$).
  - Responsible for the rate of temperature rise in the material.

Slide 1-56

4. Thickness (d).

5. Thermal Inertia (kρc): In the match and the two-by-four example we discussed earlier, the match would not provide sufficient energy because of the density, thickness and low thermal conductivity of the two-by-four.

IGNITION: THERMALLY THIN VERSUS THERMALLY THICK

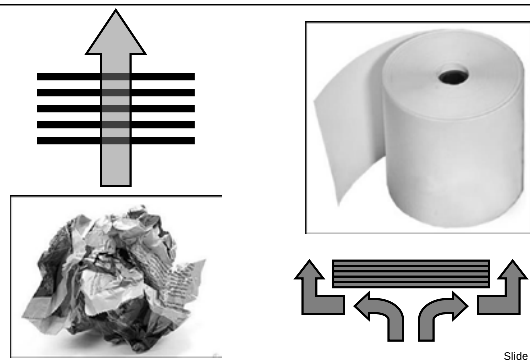


F. Thermally thin versus thermally thick fuel.

1. Calculations need to be performed to evaluate whether a fuel is thermally thin versus thermally thick. It is commonly accepted that fuels less than 1mm in thickness are considered thermally thin.

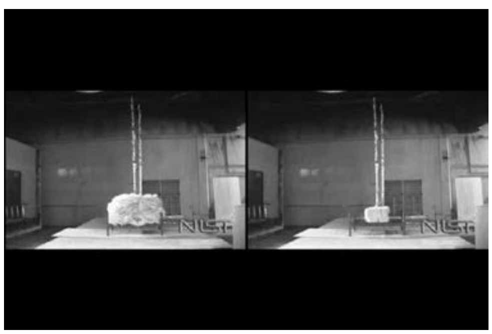
2. Materials with high kρc "pull" heat energy away from the surface (and keep the surface temperature lower), and materials with low kρc allow energy to remain at the surface, thus raising the surface temperature.

IGNITION: LOW DENSITY VERSUS HIGH DENSITY



Slide 1-58

IMPACT OF DENSITY



Slide 1-59

VII. FLAME SPREAD

FLAME SPREAD

- Speed at which a flame front moves across a fuel's surface.
- Natural: Induced solely by buoyancy.
- Forced: Induced by environmental (wind) or man-made (fan) conditions.

Slide 1-60

Flame spread is the speed at which a flame front moves across a fuel's surface.

A. Natural: Induced solely by buoyancy.

B. Forced: Induced by environmental (wind) or man-made (fan) conditions.

FLAME SPREAD (cont'd)

Flame Spread	Rate (cm/s)
Smoldering	0.001 to 0.01
Lateral or downward spread on thick solids	0.1
Wind driven spread through forest debris or brush	1 to 30
Upward spread on thick solids	1 to 100
Horizontal spread on liquids	1 to 100
Premixed fuels	10 to 100 to 10^5 (detonations)

Slide 1-61

1. This chart shows the various types of flame spread and the variations between flame spread rates.

2. Buoyancy-driven flow results in better heat transfer and preheating of the material above the flame front. This causes upward flame spread to be faster than downward flame spread. It is impossible to guarantee that the conditions of testing are exactly the same as those at the time of the incident.

VIII. COMPARTMENT FIRE DYNAMICS

COMPARTMENT FIRE DYNAMICS

- Fire growth is a function of:
  - Fuel properties.
  - Fuel quantity.
  - Ventilation (natural or mechanical).
  - Compartment geometry - volume and ceiling height.
  - Location of fire.
  - Ambient conditions (wind, temperature, and relative humidity).

Slide 1-62

A. Factors which effect fire growth.

1. Fuel properties.

2. Fuel quantity.

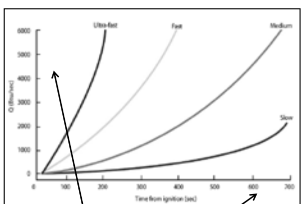
3. Ventilation (natural or mechanical).

4. Compartment geometry (volume and ceiling height).

5. Location of fire.

6. Ambient conditions (wind, temperature, and relative humidity).

FIRE GROWTH RATES



Constant	Alpha Value
Slow Fire	0.00293
Medium Fire	0.02345
Fast Fire	0.0469
Ultra Fast Fire	0.1876

$$\dot{Q} = \alpha t^2$$

Slide 1-63

B. Standard fire growth rates.

1. Slow fire: 0.00293

2. Moderate fire: 0.02345

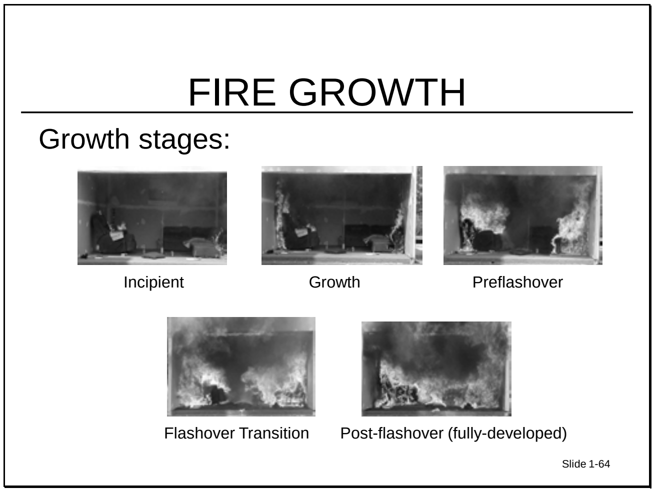
3. Fast fire: 0.0469

4. Ultra fast fire: 0.1876

5. The graph represents the equations for each type of standard fire growth rate, where "$\dot{Q}$" is the HRR of the fire and "t" is the time over which the growth occurs.

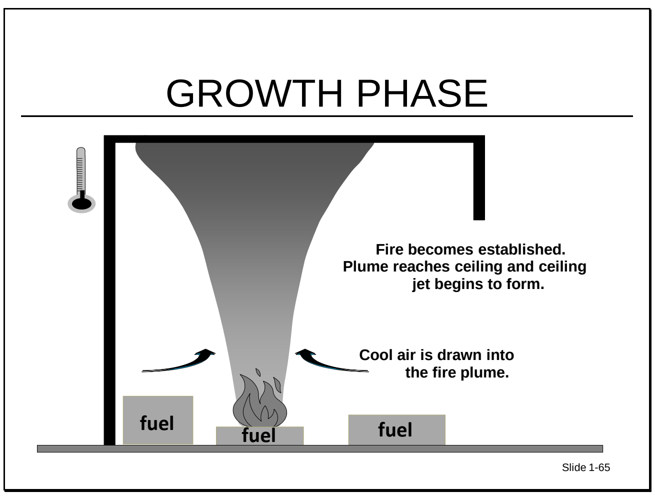
6. Ultra-fast, fast, medium, and slow fires reach approximately 1,000 kW in 75, 150, 300, and 600 seconds.

7. The alpha term (α) is a constant term specific to the fire growth rate.

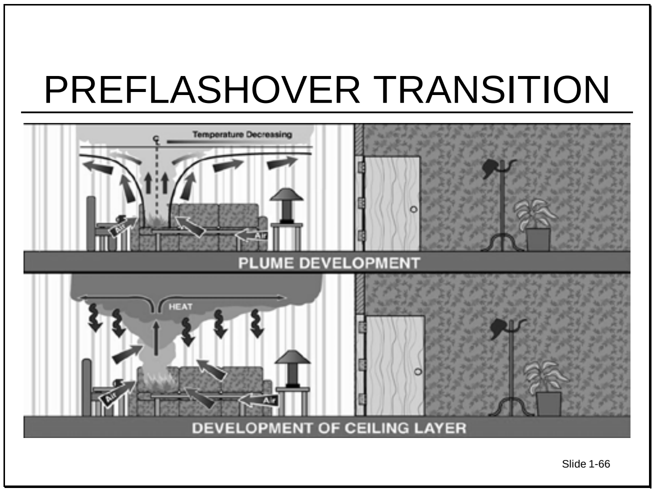


8. This slide shows pictorial representations of fire growth.

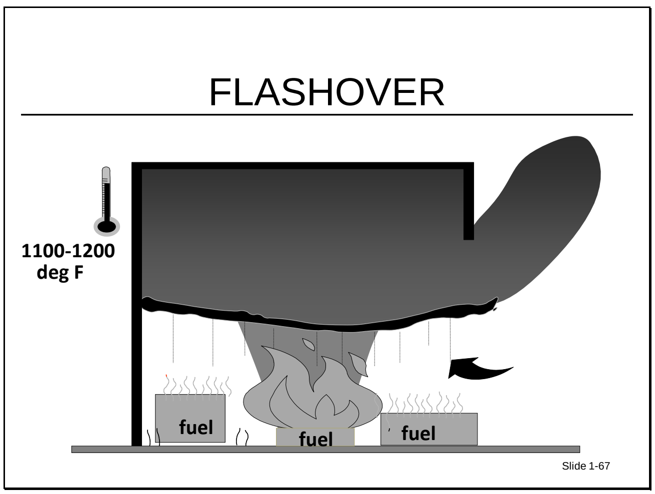
   a. Incipient.



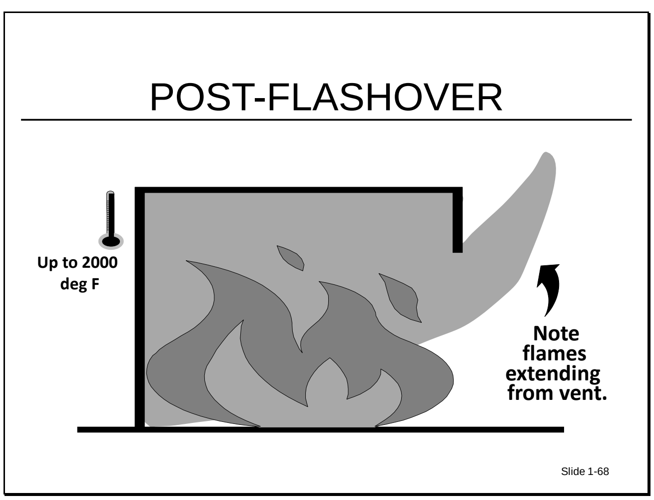
   b. Growth phase.



c. Preflashover transition.



d. Flashover.



e. Post-flashover.

- Fire plume/ceiling jet period.

  -- Buoyant gases rise to the ceiling in a fire plume.

  -- The ceiling jet spreads laterally until confined.

  -- The plume entrains surrounding air.

  -- The temperature decays rapidly with height and radial distance.

- Enclosure smoke-filling period.

  -- The period begins when the ceiling jet reaches the walls.

  -- The period ends when smoke flows through the vents.

  -- The smoke layer fills due to entrainment/expansion.

  -- Initial descent rapid due to entrainment.

  -- The conditions are mostly uniform due to turbulent mixing.

- Preflashover vented period.

  -- The hot gases flowing out are equivalent to the cool gases flowing in (mass balance).

  -- The balance between gases flowing in and gases flowing out is affected by sizes, shapes and locations of vents, and mechanical ventilation.

  -- In the approach to flashover, radiant heat from the smoke layer raises all fuels to near their ignition temperatures.

FULLY DEVELOPED FIRE

Slide 1-69

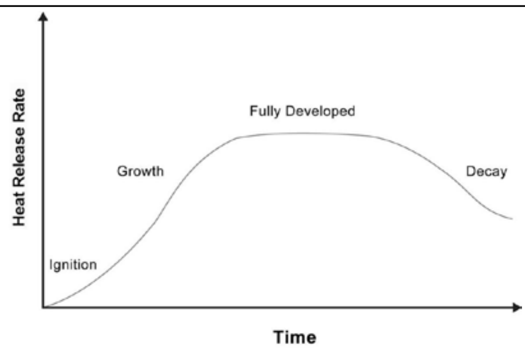
f. Fully developed fire.

- When the fire has approached the post-flashover phase, it is referred to as a fully developed fire.

- During this phase, flames extend outside of the compartment of origin through ventilation openings.

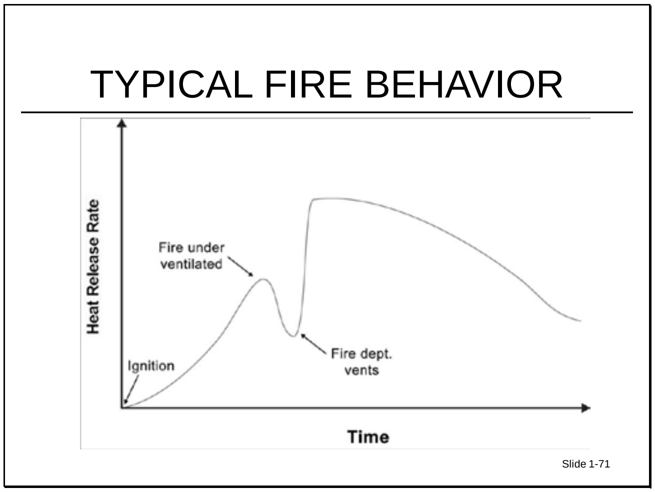
- The extension of flames and hot gases starts the process of ignition of fuels outside of the area of origin and supports spread of the fire to adjacent compartments.

TRADITIONAL FIRE BEHAVIOR



Slide 1-70

- The traditional fire behavior curve represents an ideal fire growth scenario where there is adequate fuel and ventilation to support the growth of the fire through the flashover phase.



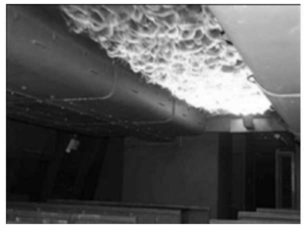
-- The typical fire behavior curve represents the more common scenario where the growth of the fire is limited due to inadequate ventilation within the compartment. Changes in ventilation, such as the breakage of windows due to failure, the opening of doors, or fire department venting, can rapidly increase the growth rate of the fire, resulting in a rapid transition to flashover. This occurrence is responsible for a number of firefighter fatalities and injuries each year.

g. Post-flashover vented period.

- The conditions are relatively uniform throughout the space.
- The airflow is restricted by the opening “ventilation factor.”
- The burning rate inside the room is restricted by airflow.
- The flames from openings indicate the ventilation limit.

FLAMEOVER (ROLLOVER)

- Ignition of unburned fuels that have accumulated within a flammable range in the ceiling layer.
- Occurs at the lower portion of the upper layer where oxygen is entrained.
- Often a precursor to flashover.



Slide 1-72

h. Flameover.

- The ignition of unburned fuels that have accumulated within a flammable range in the ceiling layer.

  -- The upper layer is fuel-rich, so flames typically appear in the lower portion of the layer where the pyrolyzates are mixing with air.

  -- This picture shows an example of rollover as created by a rollover simulator.

FLASHOVER — POST-FLASHOVER

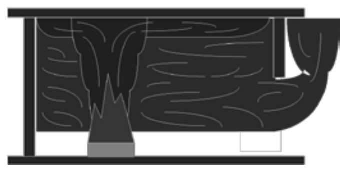
- Fire in a room → room on fire.
- Burn patterns more intense and complex.
- Ventilation dominates in determining fire growth/heat release.
- Flame extension out of vents.
- Fire gases exceed 600 C.

Slide 1-73

i. Flashover is the transition phase in the development of a compartment fire in which surfaces exposed to the thermal radiation, from fire gases in excess of 600 C (1,100 F), reach their ignition temperature more or less simultaneously, and fire spreads rapidly through the space.

FLASHOVER INDICATORS

- Upper layer temperature ~ 600 C.
- Heat flux at floor ~ 20-25 kW/m^2.
- Flames emitting from openings.



Slide 1-74

ISO ROOM LIVING ROOM FLASHOVER

Slide 1-75

BACKDRAFT

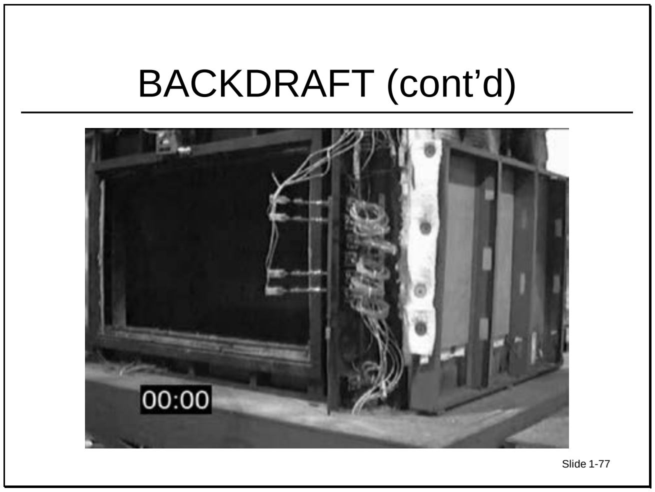
- Oxygen deficient environment filled with incomplete products of combustion.
- Sudden introduction of air.
- Deflagration results.
  - Faster than free-burning but slower than detonation.

Slide 1-76

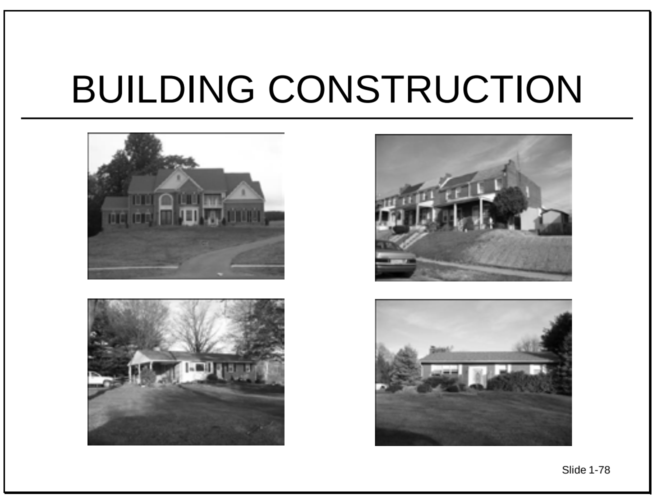
C. Backdraft.

1. Backdraft is a deflagration resulting from the sudden introduction of air into a confined space containing oxygen deficient products of incomplete combustion.

2. Deflagration is faster than open-air burning but slower than a detonation (less than the speed of sound).



IX. BUILDING CONSTRUCTION



A. Building construction affects the spread, growth and overall dynamics of the fire.

B. Changes in construction since 1970s.

1. House size.

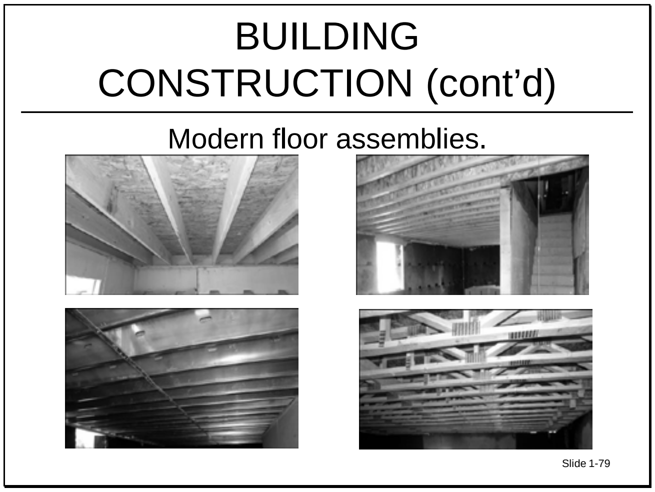
a. Average home in the 1970s: 1,200-1,600 square feet.

b. Average home today: 2,500-4,000 square feet.

2. House lot.

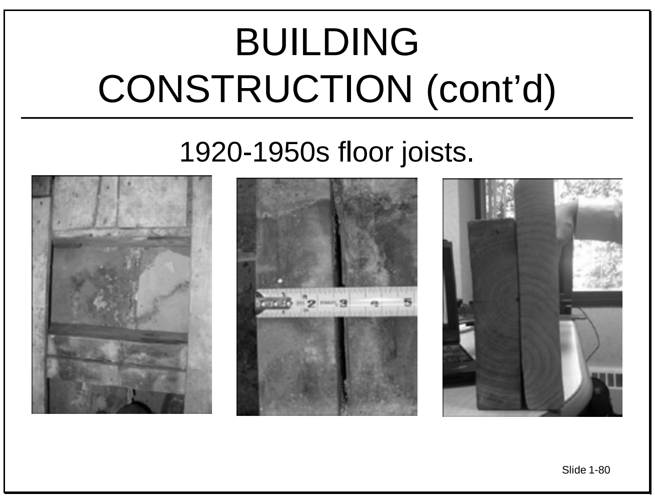
   a. Average home in 1970s: 10,000 square feet.

   b. Average home today: 8,000 square feet.



   c. Fuel loading includes more synthetics and engineered materials.

   d. Compartmentation and open floor plans are more common in modern homes.



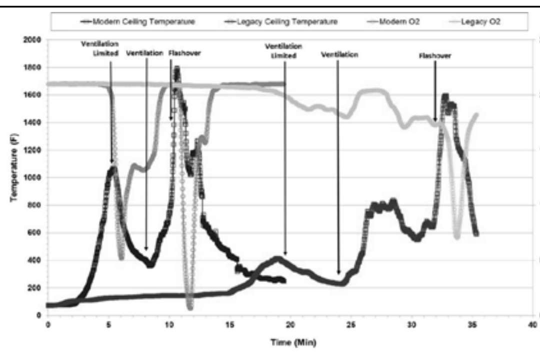
UNDERWRITERS LABORATORIES ROOM

Slide 1-81

MODERN VERSUS LEGACY FUEL

Slide 1-82

MODERN VERSUS LEGACY HOUSE



Slide 1-83

X. MATHEMATICAL MODELING

MATHEMATICAL MODELING

- Single equations (algorithms).
- Typically steady state.
- Single point in time.
- Some are based on a specific data set (empirical).

Slide 1-84

A. Mathematical models.

1. Single equations (algorithms).

2. Typically steady state.

3. Single point in time.

4. Some are based on a specific data set (empirical).

MATHEMATICAL MODELING (cont'd)

- Provide various ways to evaluate dynamics of the fire.
  - HRR.
  - Flame height.
  - Heat flux and radiant ignition.
  - Fire growth rate.

Slide 1-85

B. Ways to evaluate fire dynamics:

1. HRR.

2. Flame height.

3. Heat flux and radiant ignition.

4. Fire growth rate.

MATHEMATICAL MODELING (cont'd)

- Minimum HRR needed for flashover.
- Time to flashover.
- Time to ignition.
- Detector/Sprinkler activation.
- Gas temperature.

Slide 1-86

5. Minimum HRR needed for flashover.

6. Time to flashover.

7. Time to ignition.

8. Detector/Sprinkler activation.

9. Gas temperature.

HEAT RELEASE RATE

$$\dot{Q} = H_c \times \dot{m}$$

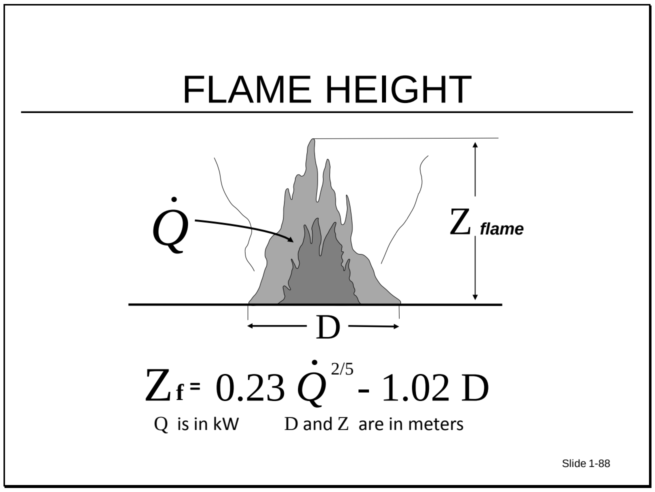
- H_c is the **heat of combustion,** or the amount of energy released per unit of mass consumed (kJ/kg).
- $\dot{m}$ is the **MLR,** or the mass consumed per unit time (kg/s).

Slide 1-87

C. The two variables that affect HRR.

1. Heat of combustion: The amount of energy released per unit of mass consumed is kilojoules per kilogram (kJ/kg). Heat of combustion is the amount of energy that a fuel will produce when it burns.

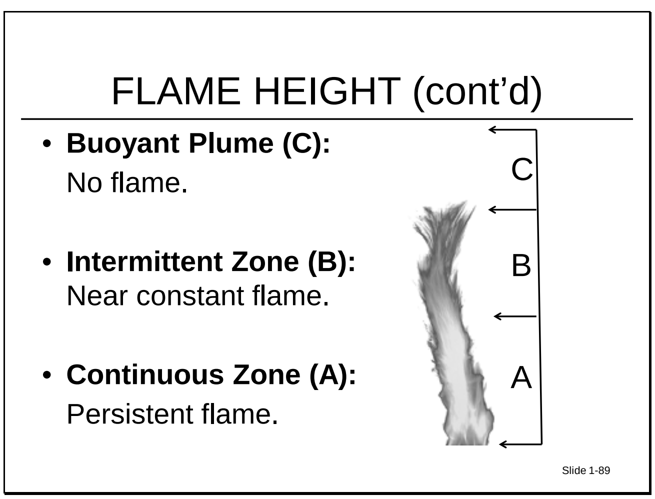
2. MLR: The mass consumed per unit time is kilogram per second (kg/s).



D. The flame height is dependent on:

1. HRR.

2. Diameter of the fire.

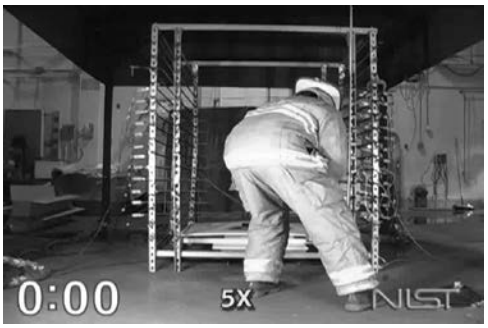


a. The Buoyant Plume is characterized by decreasing velocity and temperature with respect to height. There is no flame in this zone, only smoke.

b. The Intermittent Zone features a near constant flow velocity with a negligible occurrence of chemical reaction and inconsistent occurrence of flames.

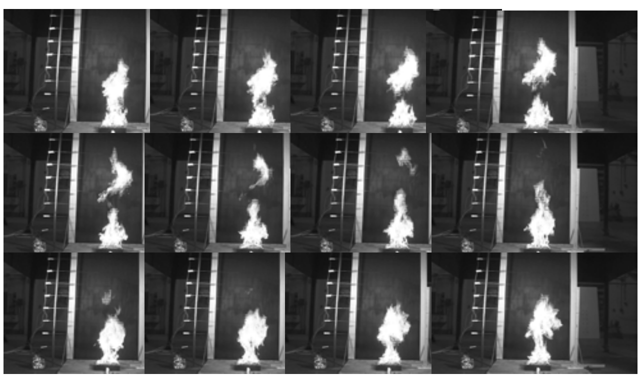
c. The Continuous Zone contains a persistent turbulent diffusion flame yielding an accelerating flow of burning gases that are strongly buoyant.

GASOLINE



Slide 1-90

VIDEO FRAME ANALYSIS



Slide 1-91

E. Burning Money: Tax Evasion.

1. Information obtained through investigation.

   a. Placed cash in a 5-gallon bucket, added gasoline.

   b. Emptied contents of bucket in a metal barrel.

   c. Ignited contents and let it burn for several minutes.

   d. Resulted in 12-15 foot (4 meter (m)) flames.

   e. Suppressed with feed corn.

   f. All the cash was consumed by the fire.

BURNING MONEY (cont'd)

- **Questions:**
  - Would money have been completely consumed?
  - What HRR and flame height would result from money alone?
  - What HRR and flame height would result from money/gasoline combination?

Slide 1-94

2. Based on the findings of the investigator, the following questions were formulated to assess the validity of the witness statements.

   a. Would money have been completely consumed?

   b. What HRR and flame height would result from money alone?

   c. What HRR and flame height would result from money/gasoline combination?

BURNING MONEY (cont'd)

- **Data collection:**
  - Barrel diameter = 23 inches (0.58 meter (m)).
  - Barrel height = 34 inches (0.88 m).

Slide 1-95

3. Data collection.

   a. The barrel diameter and height were known values collected during the scene investigation.

   b. These values were necessary to evaluate the suspect's statement regarding the flame height that resulted from the burning money.

BURNING MONEY (cont'd)

- **Analysis:**
  - Calculation of HRR to determine fire size needed to produce 12-15 foot flames.
  - Calculation of HRR from gasoline alone.
  - Full scale experiments.

Slide 1-96

4. The following analysis was performed to evaluate the questions developed by the investigator.

   a. Calculation of HRR to determine fire size needed to produce 12-15 foot flames.

   b. Calculation of HRR from gasoline alone.

   c. Full scale experiments.

BURNING MONEY (cont'd)

Flame Height

$$Z_f = 0.23\dot{Q}^{2/5} - 1.02D$$

$$Z_f = 12-15\,ft$$

$$D = 23in$$

Slide 1-97

5. The Heskestad flame height correlation can be utilized to evaluate the validity of the suspect's statement regarding the flame height produced by the burning money.

   a. Since two of the three variables are known, the equation can be solved for the unknown variable ("$\dot{Q}$").

BURNING MONEY (cont'd)

$$\dot{Q} = \dot{m}'' \Delta H_c A$$

MLR per unit area for gasoline = 0.055 kg/m^2 s.
Heat of combustion = 43700 kJ/kg.
Area of barrel opening = 0.26 m^2.

Estimated HRR = **625 kW.**

Is the witness telling the truth?

Slide 1-98

- Using literature values for MLR and heat of combustion for gasoline, and neglecting the minimal contribution of the money to the HRR, the expected HRR can be calculated.

- The HRR that would be expected is only 625 kW, but the calculated flame height based on the suspect's statement is more than twice that (1,300-2,500 kW).

Slide 1-99

b. The pictures show the test set up and results of some of the full scale experiments.

BURNING MONEY (cont'd)

- Using the flame height equation and solving for $\dot{Q}$, a flame 12-15 feet in height would have a HRR of 1,300 kW to 2,500 kW. Is gasoline needed to produce this HRR?

Slide 1-100

c. Based on the suspect's statement, the flame was 12-15 feet in height. The collected data showed that the barrel had a diameter of 23 inches. Using this information, the HRR necessary to produce a 12-15 foot flame height can be calculated.

- The HRR would range from 1,300 to 2,500 kW, based on a flame height of 12-15 feet.

BURNING MONEY (cont'd)

- **Conclusions**:
  - Fire size to achieve 12-15 foot flames is significantly larger than what would be produced.
  - Full scale experiments produced two to three foot flames.
  - Cash was still intact after experiment.

Slide 1-101

6. Conclusions.

a. Full scale experiments do **not** support witness statements.

b. The actual flame height was approximately two to three feet.

c. After several burns, the cash was still in good shape.

CASE STUDY 2
Wife Guilty in Hired Killing

Slide 1-102

F. Wife Guilty in Hired Killing.

WIFE GUILTY IN HIRED KILLING

- **Background/Facts:**
  - Wife hired cousin to burn down house.
  - Fire started in laundry basket in basement directly below water pipe.
  - Pipe burst and extinguished fire.
  - Cousin claimed to have set up the arson scenario but did not go through with it.
  - Husband found out about his wife's arson plot and wife hired someone to murder him.

Slide 1-103

1. Background/Facts:

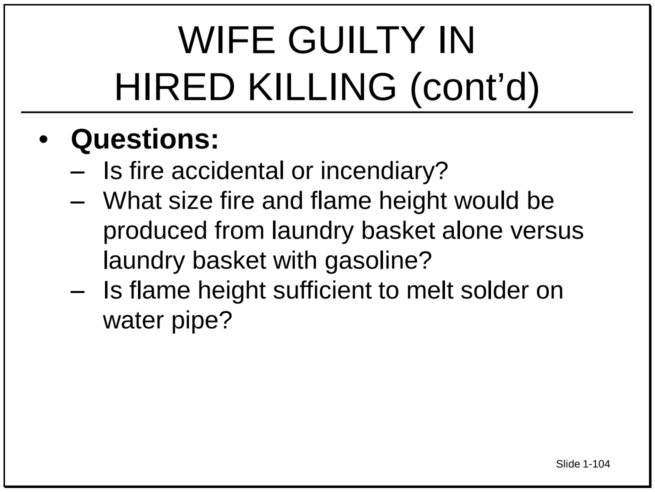
   a. As part of an insurance claim, the wife hired her cousin to burn her house down.

   b. Investigators determined that the fire started in a laundry basket in the basement between a hot water heater and furnace.

   c. The laundry basket fire melted the solder joining the elbow of a copper pipe from the hot water heater, and the fire was extinguished.

   d. The cousin claimed to have set up the arson scenario but also claimed he did not go through with it.

e. The husband found out about the wife's arson plot and intentions to have someone murder him.

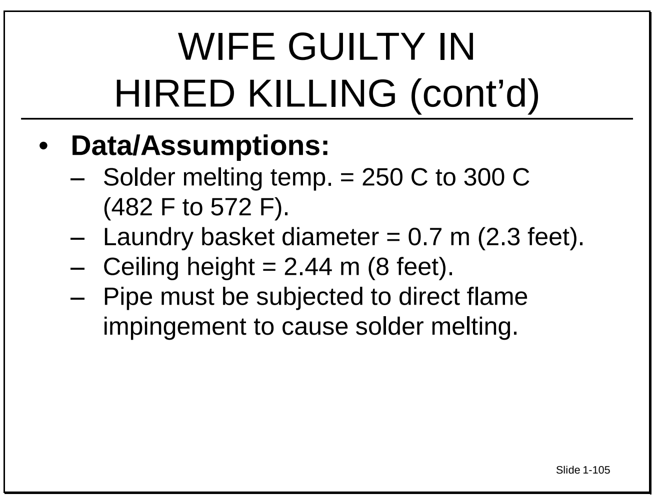


2. Based on the findings of the investigator, the following questions were formulated to assess the validity of the witness statements.

a. Is fire accidental or incendiary?

b. What size fire and flame height would be produced from laundry basket alone versus laundry basket with gasoline?

c. Is flame height sufficient to melt solder on water pipe?



3. Data/Assumptions.

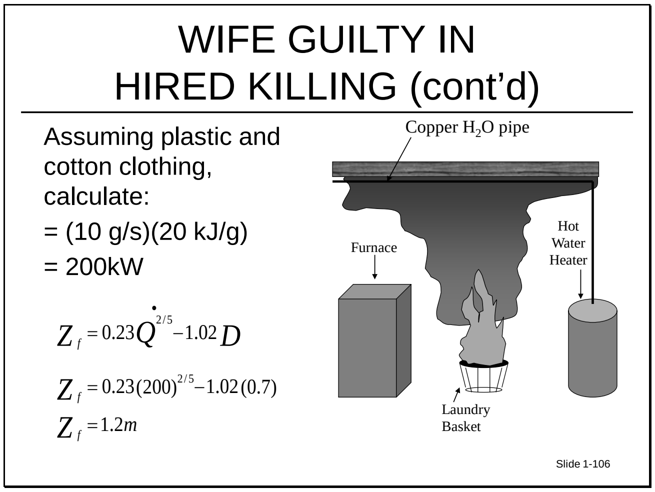
a. Solder melts at 250 C to 300 C (482 F to 572 F).

b. The laundry basket had a diameter of 0.7 m (2.3 feet).

c. Due to good conduction of copper and the significant thermal mass of the water inside pipe, the pipe must be bathed in flame.

d. The ceiling height is 2.44 m (8 feet).

- Make assumptions about burning rate and heat of combustion.



4. The Heskestad flame height correlation can be utilized to determine the height of a flame that would result from the laundry basket only versus the laundry basket with gasoline.

a. Using the average MLR and heat of combustion found in the literature and the information gathered from the scene to establish the approximate diameter of the laundry basket, we find that the flame height with no gasoline would be approximately 1.2 m (4 feet).

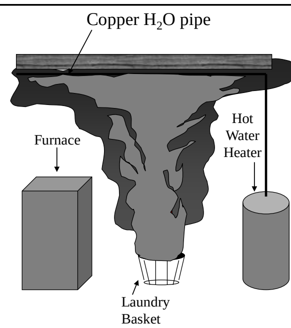
b. Using the same equation, but accounting for the addition of gasoline, the flame height would be more than double the height found without gasoline.

WIFE GUILTY IN HIRED KILLING (cont'd)

If an accelerant, like gasoline, were added to the laundry basket, then:

$= (55\ g/m^2 s)[(\pi/4)(0.7m)^2](43.7kJ/g)$
$= 925\ kW$

Z_f =2.82 meters



Slide 1-107

5. Since direct flame impingement would be necessary to result in the melting of the solder in the pipe joint, it is clear that an accelerant would need to be present to produce sufficient flame heights.

WIFE GUILTY IN HIRED KILLING (cont'd)

- **Conclusions:**
  - Laundry basket alone produces insufficient flame height.
  - Ignitable liquid was necessary to produce sufficient flame height.
  - Fire was incendiary.

Slide 1-108

XI. FIRE MODELING

FIRE MODELING

- Description of different fire phenomena in mathematical or physical terms.

Slide 1-109

A. It is predominantly used to evaluate various aspects of fire phenomenon using the laws of conservation of energy and mass.

FIRE MODELING (cont'd)

- Fire phenomena include:
  - Ignition.
  - Flame spread/fire growth.
  - Smoke filling and movement.
  - Temperature and flashover predictions.
  - Fire detection and suppression.
  - Target damage.

Slide 1-110

1. Models can evaluate phenomena such as ignition, flame spread, smoke filling, temperature, flashover, fire detection and suppression, and ignition of target fuels.

2. Note that some models are better than others at evaluating these phenomena, which will be discussed in more detail in Units 4 and 5.

WHY FIRE MODELING?

- Better understand compartment fire dynamics.
- Better understand scene observations.
- Test hypotheses.
- Timeline development.

Slide 1-111

B. Why fire modeling?

1. To develop a better understanding of enclosure fire processes.
2. How do different variables influence the results?
3. To provide a physical basis for post-fire conditions and observations.
4. As a reality check for fire scenario hypotheses.
5. Support for fire timeline development.

WHY NOT FIRE MODELING?

- Prove your point when it's not supported by the facts.
- Impress the jury even if model has no analytical value.
- Replace expert opinion.

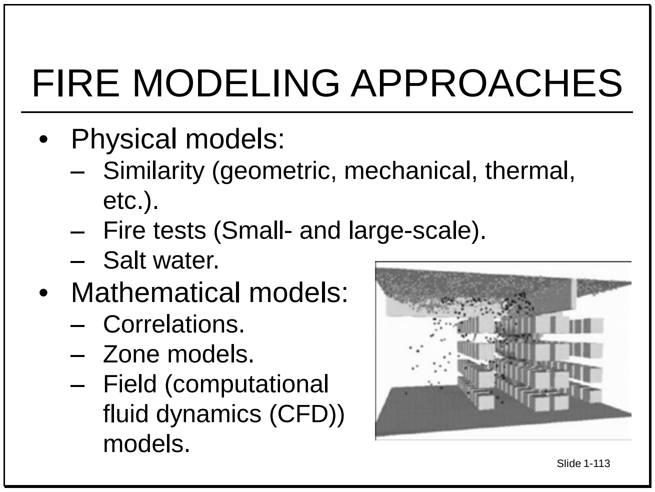
Slide 1-112

C. Why not fire modeling?

1. Black magic — investigator/analyst needs to understand what model is doing and why.

2. "Can get any answer you want." Purpose of modeling is to support expert opinion, not replace it.

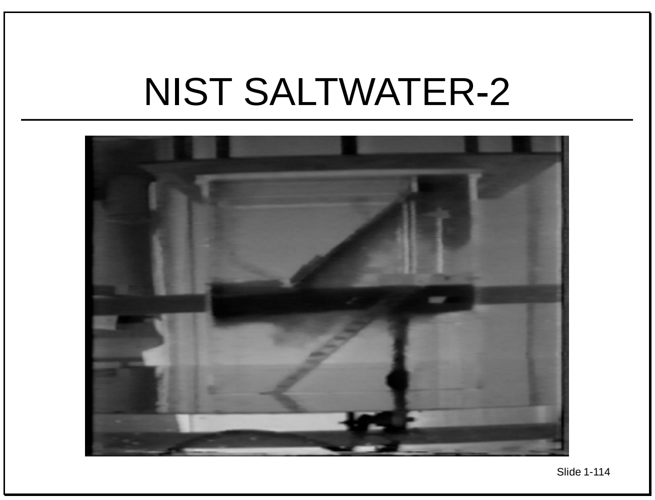
3. Need to be able to justify input parameters, not select parameters to get desired answer.



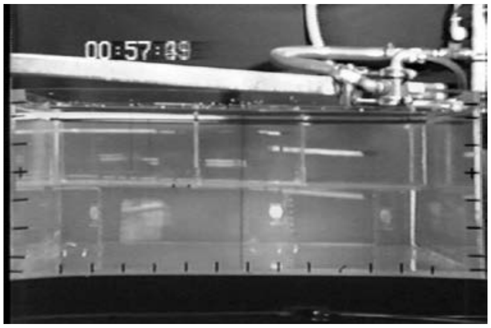
D. There are two types of approaches to modeling. You can evaluate a fire using a physical model or a mathematical model.

1. Fire tests (sometimes referred to as reconstructions), whether they are full-scale or small-scale, are considered physical models.

2. Mathematical models use correlations, equations or computerized programs (which are based on laws of conservation of energy and mass or developed from actual live fire tests).



NIST SALTWATER-1 (ACTUAL ORIENTATION)



Slide 1-115

COMPUTERIZED FIRE MODELS

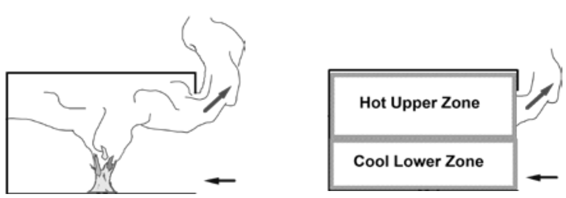
- Zone models (Consolidated Model of Fire Growth and Smoke Transport (CFAST)):
  - Two layer assumption.
  - Mass and energy balance.
  - Point source assumption.
- Field or CFD models (Fire Dynamics Stimulator (FDS)):
  - Increased resolution.
  - Mass, energy and momentum balance.

Slide 1-116

E. The different types of models that will be covered in the course include:

COMPUTERIZED FIRE MODELS (cont'd)

- Zone models divide room into two zones.



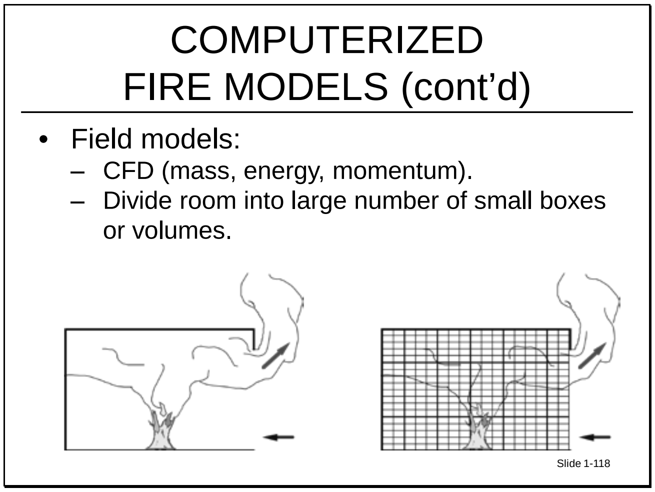
Slide 1-117

1. Zone Models (Consolidated Model of Fire Growth and Smoke Transport (CFAST)).

a. Two-layer assumption.

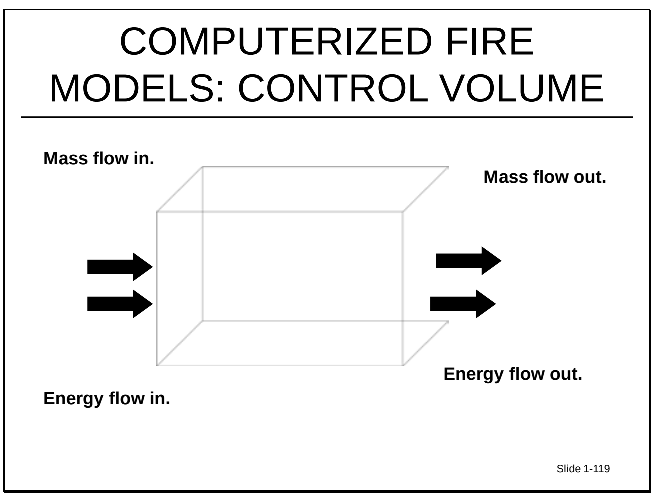
b. Mass and energy balance.

c. Point source assumption.



2. Field or computational fluid dynamics (CFD) Models.

a. Increased resolution.



b. Mass, energy and momentum balance.

c. Fire dynamics simulator (FDS) is an example of a CFD model.

COMPUTERIZED FIRE MODELS: USES

- To evaluate complex phenomena within a fire scenario and test hypotheses.
  - HRR.
  - Ventilation.
  - Heat transfer.

Slide 1-120

F. Computerized fire models are used to evaluate complex phenomena within a fire scenario and test hypotheses regarding:

1. HRR.
2. Ventilation.
3. Heat transfer.

COMPUTERIZED FIRE MODELS: INPUTS

- Blueprints, post fire measurements.
  - Doors, windows, stairwells, vents, etc.
- Photos and videos of building pre- and post-fire.
- Ventilation conditions.
  - Doorway and window positions.

Slide 1-121

G. Information commonly needed for modeling.

1. Blueprints or post-fire comprehensive measurements, including doors, windows, stairwells, vents, etc. and their relative locations in the building and to each other.
2. Photos and video of the entire building and not just the room of origin.

3. Ventilation conditions, including position of doorways and windows (thermal or fire department).

COMPUTERIZED FIRE MODELS: INPUTS (cont'd)

- Fire department observations.
  - Statements and 911 call logs.
- Witness observations.
- Alarm/Security system logs.
- Fuel packages and location.

Slide 1-122

4. Fire department interviews and observations.

5. Witness interviews and observations.

6. Video (news crews, by-standers, surveillance).

7. 911 call logs for timeline development.

8. Fuel packages, their flammability characteristics and HRR.

COMPUTERIZED FIRE MODELS: LIMITATIONS

- The model is a **simulation** of the event.
- The outputs reflect the quality of the inputs.
- Junk in = junk out.

Slide 1-123

9. The model is a simulation of the event.

   a. No model will be able to produce an exact answer that will provide the investigator with 100 percent certainty. Some models are better than others are at predicting certain fire phenomenon.

COMPUTERIZED FIRE MODELS: VALIDATION

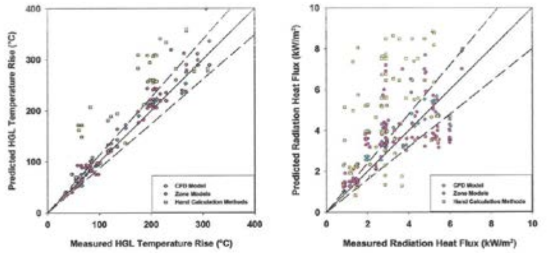


Fig. 1 Measured vs. Predicted Hot Gas Layer Temperature Rise (left) and Measured vs. Predicted Heat Flux (right)

Slide 1-124

b. The graphs show the variations between mathematical models (hand calculations), CFD models such as FDS, and Zone models such as CFAST, in comparison with measured values from a physical model (fire test).

- The graph on the left shows the differences in the measurement of the hot gas layer temperature, and the graph on the right shows the difference in the measurement of the radiant flux.

- The models clearly predict the gas layer temperature more accurately than the heat flux.

QUESTIONS TO CONSIDER

- How does the model work? What is it based on?
- Experimental Data? Physical Principles?
- What assumptions does the model make?
- Are the model assumptions consistent with your fire scenario?

Slide 1-125

H. Questions to consider:

1. How does the model work? What is it based on?

2. Experimental data? Physical principles?

3. What assumptions does the model make?

4. Are the model assumptions consistent with your fire scenario?

QUESTIONS TO CONSIDER (cont'd)

- Is the model sensitive to small changes in a particular input scenario?
- Scenario/Hypothesis testing.
- Comparison with established time lines.
- "What if" analysis.

Slide 1-126

5. Is the model sensitive to small changes in a particular input scenario?

6. Scenario/Hypothesis testing.

7. Comparison with established time lines.

8. "What if" analysis.

XII. SUMMARY/RESOURCES

SUMMARY

- The scientific method.
- Fire chemistry and flame anatomy.
- Heat transfer.
- Units of measure.
- HRR.

Slide 1-127

SUMMARY (cont'd)

- Ignition.
- Flame spread.
- Compartment fire dynamics.
- Building construction.
- Mathematical modeling.
- Fire modeling.

Slide 1-128

RESOURCES

- www.fire.nist.gov.
  - 60,000 articles — web searchable.
  - Data.
  - Fire experiments.
  - Video.
  - Fire model software and verification and validation (V&V) information.
  - Re-creations of fire incidents.

Slide 1-129

RESOURCES (cont'd)

- www.fire.gov.
  - Fire service focus.

Slide 1-130

ACTIVITY 1.2

Howard County, Maryland, Fire

Purpose

To test origin and cause hypotheses and evaluate various fire growth and spread characteristics using the modeling skills learned over the duration of the course.

Directions

1. Review the Howard County, Maryland, Fire packet contents on the evening of Day 1 with specific attention given to the Certified Fire Investigator (CFI) report, photographs and scene diagram.
2. After reviewing the packet contents, develop questions you would like to answer to better understand the growth and spread of the fire and to evaluate origin and cause hypotheses. Questions can be developed individually and within groups.
3. Bring your list of questions to class on Day 2 at which point a discussion will be held.
4. During Unit 4, you will work in groups to evaluate your list of questions using your choice of tools from the CFI Calculator and U.S. Nuclear Regulatory Commission (NRC) spreadsheets.
5. During Unit 5, you will work in groups to evaluate your list of questions by modeling the incident fire utilizing CFAST.
6. Within your group, determine the most probable fire scenario based on the results of your analysis, and present your results to the class.

Discussion Questions

1. What information/data do you believe to be pertinent from the witness statements and origin and cause report?
2. Is there any information/data from the witness statements that does not appear to be consistent with the known science regarding fire growth and spread?
3. What tools could be used to evaluate these inconsistencies?
4. What hypotheses can you make regarding the origin and cause of the fire?
5. What tools did you choose to use to evaluate the fire, and what information have you learned from the use of these tools?

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ACTIVITY 1.2 (cont'd)

Howard County, Maryland, Fire: Origin and Cause Report

Description of Activity

Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) Origin and Cause Determination.

Synopsis

On Dec. 19, 2011, at approximately 11:22 a.m., Special Agent/CFI Eric Hernandez and fire investigators from the Howard County Fire Department (HCFD) responded to a residential structure fire at 4100 College Avenue, Ellicott City, Maryland. The cause of the fire was determined to be incendiary.

Narrative

1. On Dec. 19, 2011, at approximately 11:22 a.m., the HCFD responded to a 911 call in reference to a fire at 4100 College Avenue, Ellicott City, Maryland. The fire was reported to 911 by Becky Laurence who lives at 4102 College Avenue, Ellicott City, Maryland. (See supplemental interview of Becky Laurence.)

2. HCFD Engine 22 and Truck 2 were the first responders to arrive at the scene. The fire attack was initiated with a 1 3/4 inch hose line through the front door (Side A). The front door was closed but not locked. The fire was suppressed at 1:38 p.m. Investigators from the arson task force were subsequently requested at the scene.

3. The HCFD Incident Number for this fire was F011-0543.

4. The Howard County Police Department's Incident Number for this fire was 11-2435-933.

Participating Fire Investigators

S/A Eric Hernandez — ATF/CFI
S/A Thomas Doomerville — ATF/CFI
S/A Donna Jones — ATF/CFI
Lt. Brad Spencer — HCFD — Fire Marshal's Office
Det. Bill Bradley — Howard County Police Department

Witness Statements:

1. Firefighter: Captain John Babcock, Engine Company 22, stated his company was first to arrive at the scene. Captain Babcock immediately conducted a scene size-up and advised that he saw fire emitting out of the (Side A) living room window. He further indicated that the Side C basement door was open. Captain Babcock did not see fire or smoke venting from this door and did not see fire or smoke anywhere in the basement. Captain Babcock indicated that the kitchen slider window (Side C) appeared to be open approximately ten inches with smoke emanating from the window. Captain Babcock stated that no other doors or windows were open at this time.

2. After conducting his scene assessment, Captain Babcock stated that he was approached by a white male, later identified as Jerrod Smith. Captain Babcock said Smith told him that his wife and baby boy were missing and most likely still inside the house.

3. Captain Babcock stated that Engine Company 22 tried to make immediate entry into the house through the front door but was met with a wall of fire. Prior to Company 22's ingress, personnel from Truck 2 made entry via the rear basement door. Truck 2 reported good visibility throughout the basement at this time until they reached the stairs leading to the front door. In this location, they were met by a wall of fire and were not able to gain access to the first floor.

4. Captain Babcock stated that a 1 3/4 inch hose line was used to cool the upper atmosphere from the front steps prior to making entry. Upon making entry, Captain Babcock stated that he grabbed a metal hand railing, and he was nearly burned through his structural firefighting gloves. Using the 1 3/4 inch hose line, Engine Company 22 was able to make it to the first floor living space. Engine 22 reported fire on some of the contents in the living room. Fire in the living room was quickly suppressed. Engine 22 then went to the bedrooms on Side D of the house.

5. Truck 22 and Engine 22 made it into the bedrooms about the same time. Captain Babcock stated that two of the bedrooms were charged with smoke, but there was no fire extension into these rooms. The door to bedroom number one was found open and there was a deceased female lying in the bed. The door to bedroom number 2 was cracked open, and an infant was found in a crib. Both the adult and the infant were immediately taken outside of the house and resuscitation efforts were commenced on the front lawn.

6. 911 Caller: On this date, Mrs. Becky Laurence (W/F, DOB 09/17/75) was interviewed on scene at 4 p.m. Laurence was inside her house starting dinner when she heard faint sounds from what she thought to be a smoke alarm. Laurence then looked out her window and saw smoke coming from the bay window in the living room of 4100 College Avenue. Laurence called 911 to report the fire from her house. She then put on her jacket and went to 4100 College Avenue. While walking towards the structure, Laurence saw one white male run into the woods behind the house and a second male pacing on the side of the house. Laurence indicated that the house was just recently occupied. She had not met her neighbors and did not recognize the two males. A couple of minutes after arriving on scene, Laurence stated that the glass to the bay window "popped" out, and flames were emitting out the window. In addition, Laurence stated that the back basement door was open.

7. Resident: On this date, at approximately 7 p.m., Mr. Jerrod Smith (W/M, DOB 10/09/81) was interviewed at the Howard County Police Department. Below is a summary of the interview.

8. Smith stated that prior to the fire, he was in the living room having a cigarette. He said that he was not allowed to smoke in the house, so he opened the window in the kitchen to air out the house. Smith stated that his wife had a migraine, had taken medicine and was sleeping in the master bedroom. Smith said that his infant son, Daniel, was also taking a nap. Smith advised he had not seen his brother Billy that day but believed he was downstairs in his room. After the cigarette, Smith said that he went to the master bedroom to take a nap. Approximately 15 minutes after laying down, Smith stated that he heard the smoke alarm in the hallway outside of the bedrooms sounding. Smith quickly got out of bed to silence the alarm, as he did not want his wife or son to wake up. Smith said that he took the alarm, out of its base and pulled out the battery. While working on the alarm, he stated that he first smelled smoke and then saw smoke coming from the area of the living room. When he went into the living room, he saw that the couch in the living room was on fire. Smith said that the entire couch was engulfed in flames. According to Smith, the flames were about one foot tall. Smith stated that he then went to the bathroom to get a bucket to fight the fire. When walking back to the bathroom, Smith stated that a cloud of smoke had formed over his head near the ceiling but that visibility was not a problem and that he did not have trouble breathing. Smith filled the bucket from the bath tub and then returned to the living room. He then went to the edge of the coffee table and threw the water on the fire. Smith estimated that he was about five feet away from the center of the couch during his attempt at suppression. Smith stated that he did not receive any burns, and although it was hot, he was tough and had to get the fire out to save his family. Smith said that he was headed back to the bathroom to get more water when he heard his wife calling for him from outside the house. He left the house through the front door. When Smith got outside of the house he could not find his wife and realized that she was calling to him from inside the house. Smith was not able to get back inside the house at this time.

9. Witness: On December 20, 2011, at approximately 1 p.m., Mr. William “Billy” Smith (W/M, DOB 11/19/83) was interviewed at the Howard County Police Department. Billy was picked up by Howard County Police walking the streets at 10 a.m. on 12/20/11. Below is a summary of the interview.

10. Billy stated that on the morning of the fire, he was in his bedroom in the basement listening to music on his iPod. In the middle of AC/DC’s “Hells Bells,” Billy stated that he heard the upstairs smoke alarm sounding. Billy then peeked his head into the hallway outside of his room and saw nothing out of the ordinary. Billy stated that it was around lunchtime and assumed that his brother was burning food on the stove again. Billy turned up the volume on his iPod and went back to listening to music. After several more minutes, the alarm was still sounding, and Billy went upstairs to investigate. When he opened his door, he stated that once again nothing was out of the ordinary. Billy stated as he got near the stairs, he thought that he could smell smoke. When he got to the area of the landing, Billy said that the path in the front door was blocked by smoke. Billy told investigators he did not attempt to go up the stairs. Billy said he left the house through the back door. On the way out of the house, Billy stated that he took a few minutes to get dressed and grab a coat. Billy advised that he then ran into the woods because he was scared. (Note: When Billy was picked up by the authority, he was wearing a jacket and gloves). Billy stated that he spent the night outside and was afraid to talk to law enforcement officials because he has a criminal record and thought that he would be accused of starting the fire.

11. Owner: The structure was owned by Mr. Robert Parker and rented to Mr. and Mrs. Smith for $1,200 per month. The building was insured by The Westgate Insurance, Policy Number: 68739048, telephone number (888) THE-GATE.

Building Construction

1. The structure was a two-story split level, single family house, constructed with wood siding and gypsum wallboard atop a concrete slab. The building faces north.

2. The upstairs consisted of three bedrooms, bathroom, living area and a kitchen. The basement was utilized as an apartment (without a kitchen) by the tenants. The basement had one large room used as a bedroom and several smaller rooms that were vacant.

3. The utilities within the building consisted of natural gas and electricity. The electricity was serviced lateral on Side D. The fire department pulled the electrical meter prior to scene processing. Gas service was turned off at the street at the time of scene processing

4. The building was equipped with a smoke alarm in the upstairs hallway and a smoke alarm in the basement near the bottom of the stairs. Both smoke alarms were manufactured by Kidde model number xxx.

Scene Processing

Note to Reader: The front of the building has been denoted as Side A, moving clockwise from Side A, the left side was Side B, the back of the building was Side C, and the remaining elevation to the right of the front was Side D.

1. The scene was processed on Dec. 19, 2011, under the continuing authority of exigent circumstances.

2. An exterior examination of the fire scene revealed heavy fire damage around the living room's bay window located on Side A nearest the A/B corner. Moderate soot damage was evident above the front doorsill. The front metal door sustained heat damage to its exterior upper half.

3. The fire damage extended from the front bay window into the eaves at the A/B corner on Side B. No other fire damage was evident on Side B.

4. Soot and heat damage was evident around the window sill on Side C (rear) nearest the B/C corner. This window was later identified as the kitchen window. There was no other visible fire damage on Sides C or D.

5. An interior examination revealed extensive fire damage within the foyer area inside the front door on Side A.

6. The fire damage was evident in the foyer area with increasing damage up the stairs and decreasing damage down the stairs.

7. At the top of the stairs, the living room area was located to the immediate left (A/B Corner) as you enter the structure from Side A. The living room sustained heavy fire damage throughout. Fire damage was the most severe in the general area around the bay window.

8. Fire patterns and damage show that the fire extended from the living room area out towards the kitchen, hallway and foyer areas. The fire did not extend to the basement.

9. The kitchen area (B/C corner) was located to the immediate south of the living room. The kitchen sustained heavy heat and soot damage. Investigators checked all appliances within the kitchen, which were all in the "off" position during the scene processing examination.

10. The upstairs hallway sustained heavy fire damage to the wood panel walls. The fire damage decreased as you progressed west from the living room towards the rear bedrooms.

11. The master bedroom (approximate dimensions 13 by 9 by 8 feet) was located on the C/D corner and sustained heavy soot damage. There was no evidence of fire damage in the bedroom. The soot damage extended from the ceiling down to the baseboard.

12. A female, later identified as Mrs. Hillary Smith, was recovered in the bed during suppression. Mrs. Smith was transported to the hospital and pronounced dead on arrival (DOA).

13. The baby's bedroom (approximate dimensions 11 by 8 by 8 feet) was located on the A/D corner and sustained heavy soot damage, however, no visual fire damage. The soot damage also extended from the ceiling down to the baseboard.

14. The baby's crib was located in the corner of the bedroom beneath the window on Side A. An infant child, later identified as Daniel Smith, was recovered from the crib by firefighters and immediately flown via helicopter to the Children's Hospital in Washington, DC.

15. The third bedroom (approximate dimensions 9 by 8 by 8 feet) was located on Side A and sustained light to moderate smoke/soot damage. A twin-sized bed and a small air hockey table were located within this bedroom. An examination of the lower level revealed moderate to light smoke/soot damage, however, no visual fire damage.

16. An examination of the living room (approximate dimensions 14 by 11 by 8 feet) revealed it had transitioned through flashover. Contents of the living room included the remnants of a sofa located along the east wall (Side B) between the remnants of two end tables; two small lamps located within the vicinity of the aforementioned end tables; a television set located on top of the half-wall in front of the bay window (Side A); a second identical sofa located along the stairwell metal railing that separated the foyer and the living room; a stuffed chair between the coffee table and kitchen; an artificial decorative plant in a flower pot located between the loveseat and the north wall (Side A); a coffee table located at the center of the living room between the loveseat and sofa; and a wooden chair located along the east wall between the end table to the right of the sofa and the kitchen.

17. All of the furniture from the living room was documented in place and then removed to the front lawn for further evaluation. In general, most of the upholstery had been consumed from the furniture items. Nearly all wood surfaces were either charred or partially consumed. Furniture items were generally more damaged on the sides and surfaces proximate to the living room bay window than the sides and surfaces not facing or further away from the window. (See the coffee table.) The upholstered couch against the east wall exhibited more damage and material consumption than its counterpart against the railing. Incomparable damage to these couches is not due to ventilation.

18. Two 15-amp electrical receptacles were located within the living room. Specifically, one electrical receptacle was located on the north wall (Side A) below the bay window. The second electrical receptacle was located on the east wall (Side B) between the sofa and the end table nearest the north wall. There were no items plugged into either of the aforementioned electrical receptacles.

19. Investigators removed the receptacles from their outlets and visually inspected the aforementioned two 15-amps electrical receptacles, which showed no signs of fire causation.

20. Evidence of smoking materials was found in the living room. No other ignition sources were found within the area of origin (living room). Per witness interviews, smoking materials have been ruled out as a cause of this fire. Additionally, the initiation of flaming combustion as evidenced by the sounding of the smoke alarm is not consistent with the inherent delay in the transition from smoldering to flaming when initiated by smoking materials.

21. Investigators collected fire debris from the following living room locations: within the sofa area (Exh. 001); within the loveseat area (Exh. 002); and from the carpet area in front of the bay window (Exh. 003).

Evidence

The following four items were taken as evidence on Dec. 19, 2011, by investigators, and all samples tested negative for ignitable liquids:

- Exh. 001 — fire debris taken from within the sofa area located against the east wall (Side B) of the living room.

- Exh. 002 — fire debris taken from within the sofa area located between the stairwell railing and coffee table in the living room.

- Exh. 003 — fire debris (carpet) taken from the living room nearest window (Side A).

- Exh. 004 — comparison sample (carpet) taken from within hallway between master bedroom and baby bedroom.

Photograph and Sketch

The scene was digitally photographed by CFI Hernandez and digitally sketched by CFI's Harper/Jones.

Fire Progression to Other Structures:

There was no extension to other structures.

Number of Fatalities and/or Injuries:

1. Mrs. Hillary Smith, (W/F, DOB 06/09/80) sustained first and second degree burns to her face and upper torso. Mrs. Smith was immediately taken to Howard County General Hospital, 5755 Cedar Lane, Columbia, MD, 21044, where she was pronounced dead of smoke inhalation.

2. Daniel Smith, (W/M, DOB 03/22/11) was Medevaced to the Children's National Medical Center, 111 Michigan Avenue, NW, Washington, DC, 20010. Daniel was subsequently pronounced dead of smoke inhalation.

Estimated Value of Loss:

The total loss was estimated to be approximately $150,000.

Miscellaneous:

Weather was not a factor in the ignition of this fire.

Conclusion:

Based on all available information to date, including witness statements, it is the opinion of the undersigned that the fire originated within the upstairs living room as the result of an open flame to the sofa on the east wall of the living room. The cause of the fire was determined to be incendiary.

Reviewed by:

This report was peer reviewed by CFI Bill Bradley, in accordance with the ATF CFI Peer Review policy.

ACTIVITY 1.2 (cont'd)

Howard County, Maryland, Fire: Day 1/Day 2 Class Exercise Table

Review the Howard County, Maryland, fire origin and cause report, including witness statements, scene diagrams and photographs. Using these documents, develop questions that we might answer using our fire dynamics tools (FDTs), spreadsheets, zone and field models. (Remember that FDTs give us quantifiable answers so we are looking for questions that can be quantified.)

Before we use some of these tools in class, let's pretend that we are designing a test in a laboratory to answer our question. Make a list of all the variables that could have a **substantial** impact on the result of the test. (The process of designing a test will help us think of the variables that are critical to accurately answering our question.)

Fill out the table below so that you are prepared for class instruction tomorrow. An example has been provided for you.

Question	Variables
How big (kW) would a fire on the couch in the living room be to activate the smoke alarm in the upstairs hallway?	• HRR/Fire size. - How much is burning (MLR in g/s)? - What is burning (heat of combustion in kJ/kg — K)? • Smoke production in g $_{soot}$/g $_{fuel\ burned}$. - Species yield. - Vitiated versus nonvitiated. • Smoke alarm. - Type (ionization versus photoelectric). - Settings (default or nonstandard). • Compartment. - Ceiling height. - Radial distance and fluid flow obstructions. • Air movement. - Wind from an open window. - Heating, ventilating and air conditioning (HVAC).

Question	Variables

Question	Variables

Question	Variables

UNIT 2: COMPARTMENT FIRE DYNAMICS

TERMINAL OBJECTIVE

The students will be able to:

2.1 Describe and analyze the behavior of fire in compartment conditions.

ENABLING OBJECTIVES

The students will be able to:

2.1 Apply knowledge of compartment fire behavior.

2.2 Describe fuel-limited versus ventilation-limited fires.

2.3 Describe how fuel package placement affects burning rate in compartment conditions.

2.4 Describe how changes in ventilation influence fire behavior in compartment conditions.

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UNIT 2: COMPARTMENT FIRE DYNAMICS

Slide 2-1

ENABLING OBJECTIVES

- Apply knowledge of compartment fire behavior.
- Describe fuel-limited versus ventilation-limited fires.
- Describe how fuel package placement affects burning rate in compartment conditions.

Slide 2-2

ENABLING OBJECTIVES (cont'd)

- Describe how changes in ventilation influence fire behavior in compartment conditions.

Slide 2-3

I. COMPARTMENT FIRE STAGES

COMPARTMENT FIRE STAGES

- Ignition.
  - Established burning → spread.
- Growth.
  - Fuel-controlled.
- Full-room involvement.
  - Ventilation-controlled.
- Decay.

Slide 2-4

A. The development of a fire inside a compartment is typically described by four stages.

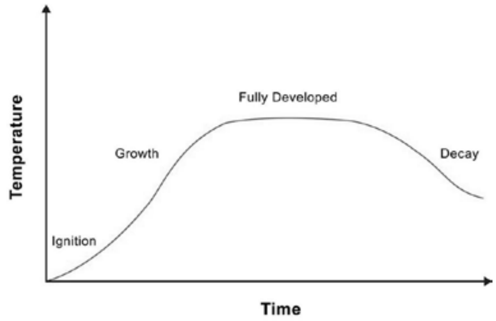
1. Ignition — refers to the time period during which the fire is transferring sufficient heat outside of the initial point of ignition to support flame spread.

2. Growth — occurs when the fire begins to spread beyond the point of ignition and, in some cases, beyond the first fuel ignited.

3. Full-room involvement — also referred to as flashover. In order for the fire to reach this stage, it must have sufficient fuel and ventilation. At this stage in the fire, there is a transition from fuel-controlled to ventilation-controlled. There is ample fuel for combustion, so the growth of fire is limited by the available ventilation openings.

4. Decay — starts once the fuel is consumed or ventilation is insufficient to support further growth.

COMPARTMENT FIRE STAGES (cont'd)



Slide 2-5

B. The diagram provides a graphical representation of four fire stages in a compartment. Note that full development may not occur if sufficient fuel or ventilation is not available to support flashover.

IGNITION STAGE

- Three modes:
  - Piloted, auto, spontaneous.
- Necessary criteria to sustain:
  - Fire tetrahedron components.
  - Sufficient energy released for sufficient period of time (competent).
    - Flammability limits, thermal inertia, material density.

Slide 2-6

C. The ignition stage refers to the time period during which the fire is transferring sufficient heat outside of the initial point of ignition to support flame spread.

1. The three modes of ignition are piloted ignition, auto-ignition, and spontaneous ignition.

IGNITION STAGE (cont'd)

- Once ignition is established, fire is in the incipient phase.
  - Period between ignition and spread outside of the point of ignition.

Slide 2-7

2. Once ignition is established, fire is in the incipient phase. This is the period between ignition and when the fire spreads outside of the point of ignition.

GROWTH STAGE

- Driven by flame spread.
  - Fuel orientation and arrangement.
  - Quantity.
- Fire is **fuel-controlled.**
  - Rate of growth is controlled by characteristics of the fuel.
  - Adequate air for combustion.

Slide 2-8

D. Growth.

1. The growth period occurs when the fire begins to spread beyond the point of ignition.

2. The rate of growth will be dependent upon three factors that affect the flame's ability to spread outside of the point of ignition.

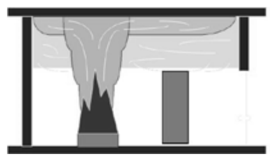
   a. The first is the orientation of the fuel, meaning whether it is vertical or horizontal.

   b. The second is the arrangement of the compartment, as far as where the fuel is located in proximity to other fuels.

c. The third is the amount of fuel and whether there is enough fuel for a flashover.

GROWTH STAGE: ELEMENTS OF COMPARTMENT FIRES

- Fire source.
- Fire plume.
- Ceiling jet.
- Boundaries.
- Upper gas layer.
- Lower gas layer.
- Ventilation.



Slide 2-9

3. There are various elements involved in compartment fires.

   a. Fire source.

   b. Fire plume.

   c. Ceiling jet.

   d. Boundaries.

   e. Upper gas layer.

   f. Lower gas layer.

   g. Ventilation.

WHAT IS A FIRE PLUME?

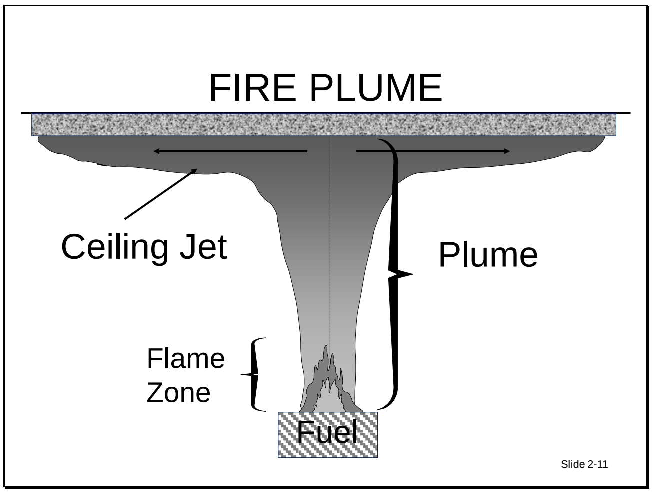
- Column of hot gases, flames and smoke rising above a fire.
- Also known as:
  - Convective column.
  - Thermal updraft.
  - Thermal column.
- Follows path of least resistance.

Slide 2-10

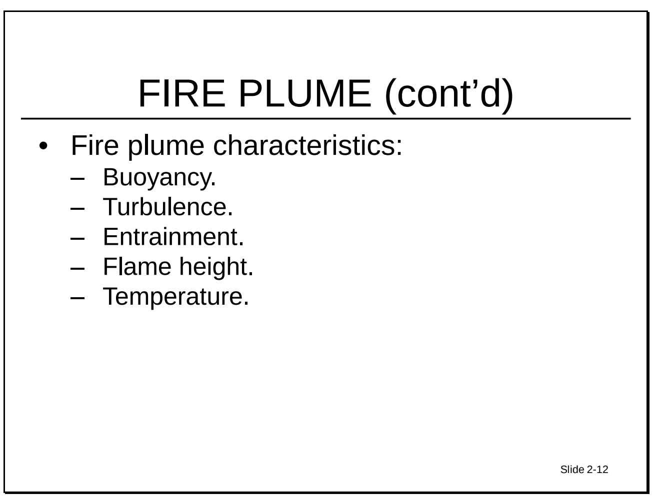
4. What is a fire plume?

   a. According to National Fire Protection Association (NFPA) 921, *Guide for Fire and Explosion Investigations*, a plume is a column of hot gases, flames, and smoke rising above a fire. It is also called a convection column, thermal updraft or thermal column.

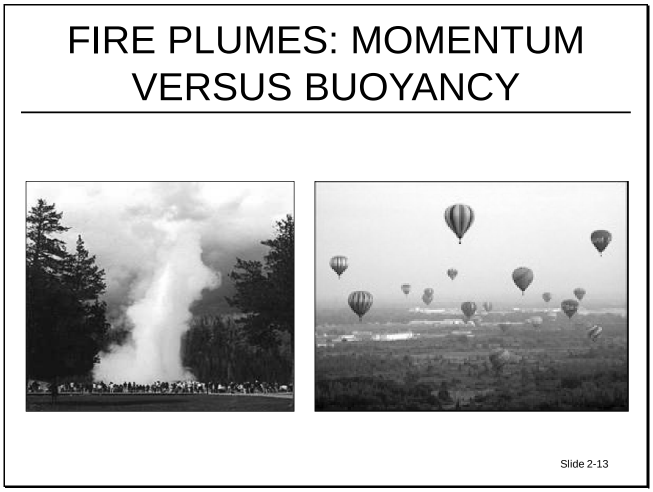
   b. According to Quintiere, in “Principles of Fire Behavior,” a fire plume is the buoyant column of flame and hot combustion products rising above the fuel source.



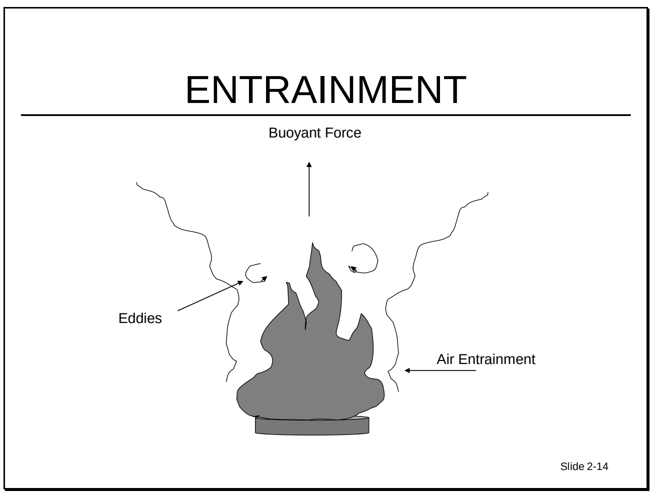
   c. The figure demonstrates some of the components involved in the growth stages, such as the initial fuel ignited, the development of a flame, the development of a gas plume above the burning fuel, and the spreading out of the plume to form a ceiling jet.



   d. Fire plumes are characterized by buoyancy, turbulence, entrainment, flame height and temperature.



e. This slide shows two examples of momentum and buoyancy; fire plumes are a mixture of both.



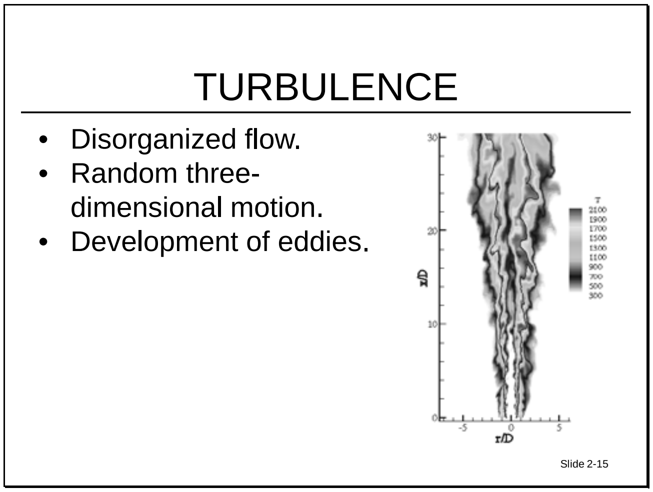
f. Entrainment is the process of air or gases being drawn into the fire plume.

- Air entrainment into the near field of the fire plume provides the oxygen necessary for combustion.

- Fire plumes typically entrain five to 15 times the amount of air necessary for stoichiometric combustion.

- Far field entrainment cools the fire plume, resulting in a decreased buoyancy force as the plume rises.

- Air entrainment and fire are intertwined. That is, they are interdependent. Flow patterns relate to air entrainment by dictating fire growth.

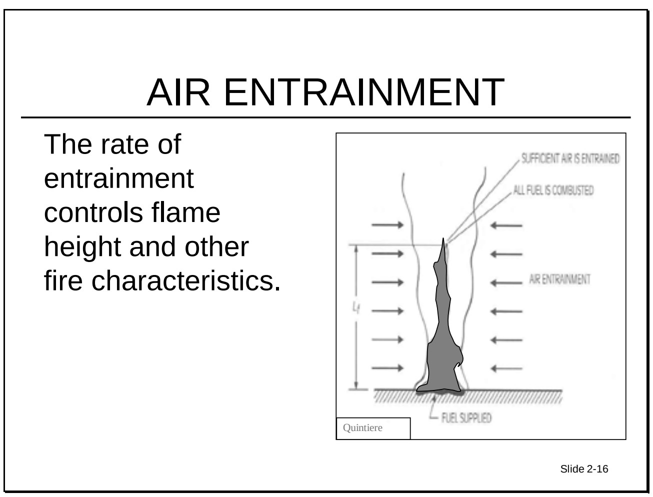


g. Fire plumes are turbulent.

- The term turbulence is used to describe the disorganized, fluctuating behavior of the flames and hot gases.

- The plume moves three-dimensionally.

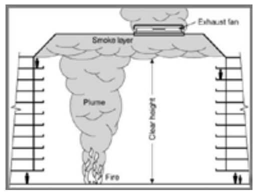
- One of the primary causes for turbulence is the formation of eddies, which act to entrain air into the plume.



h. The height of the flame is largely controlled by air entrainment. As hot gases and unburned products of combustion rise above the fuel source, air is entrained into the mixture and combustion occurs up to some point above which the fuel or temperature is insufficient to support combustion.

STRATIFICATION

- Restriction of vertical movement.
- Equilibration of hot gases with air.
  - Loss of buoyancy.
- Viscous drag between plume and air.
- Problem areas: atriums, stairwells, high ceilings.



Slide 2-17

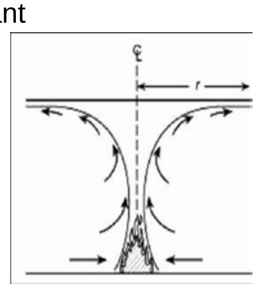
i. Stratification is the horizontal movement of the smoke due to equilibration with surrounding cool air.

- The plume will continue to rise until it meets an obstruction or until its temperature equilibrates with the surrounding cool air.

- Stratification is problematic for fire protection system design in areas with high ceilings such as atriums.

CEILING JETS

- The horizontal redirection of gases once the buoyant plume intersects with the ceiling.
- Important in establishing time to activate sprinkler or smoke detector.



Slide 2-18

j. The horizontal redirection of gases, once the buoyant plume intersects with the ceiling, creates a ceiling jet.

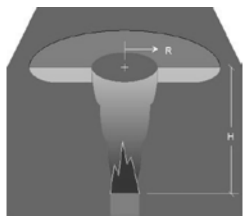
- The ceiling jet will lead to the development of a hot upper layer as more products of combustion are buoyantly driven upward.

- A thermal layer must develop in order to produce significant radiant flux to result in the ignition of remote fuels and the transition to flashover.

- Ceiling jets are commonly described as unconfined or confined.

CEILING JET DETAILS

- Features:
  - Relatively thin layer beneath ceiling (~0.1H).
  - Temperature and velocity decrease as R increases.
- Design issues:
  - Target damage.
  - Fire detector operation.
  - Smoke spread.



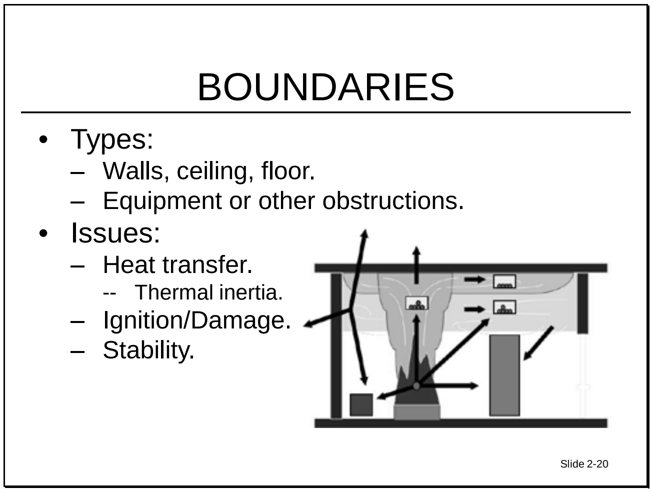
Slide 2-19

- The difference between a ceiling jet and a gas layer is that the ceiling jet is thin, typically about 10 percent of the height between the base of the flame and the top of the ceiling.

- The development of a ceiling jet is important in smoke detector and sprinkler activation.

  -- The temperature and velocity of the ceiling jet decreases as you move away from the center point of the plume, hence, detection systems that are further away from the centerline will take longer to respond.

  -- There may be instances where the temperature and velocity of the jet is insufficient to result in activation of detection systems, or results in delayed activation.

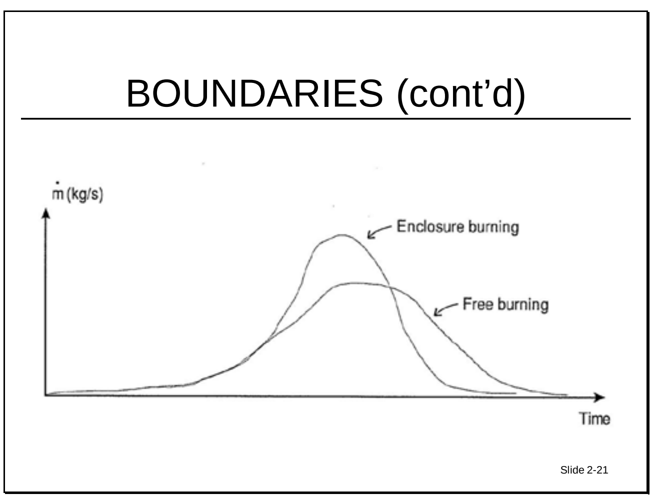


5. Various boundaries exist in a compartment.

   a. The most common boundaries are walls, ceilings and floors.

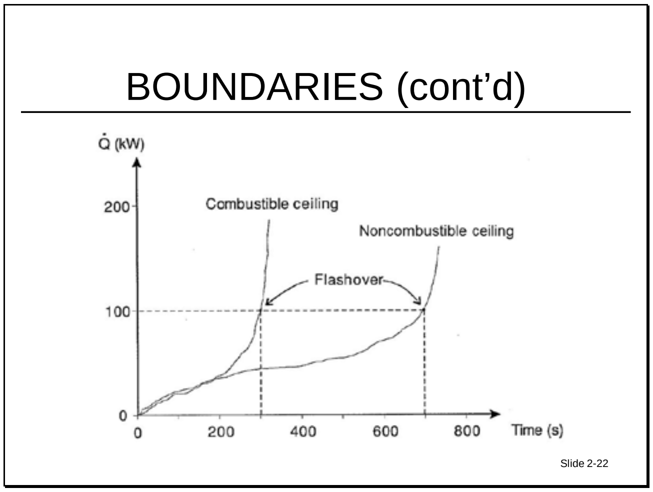
   b. In some cases, there may be other obstructions such as beams, projections, or equipment mounted in the pathway of smoke and heat travel.

   c. The boundary characteristics will affect heat transfer (gypsum board walls versus steel walls), they may ignite and contribute to the fire load, or they may act to reduce spread through compartmentation.



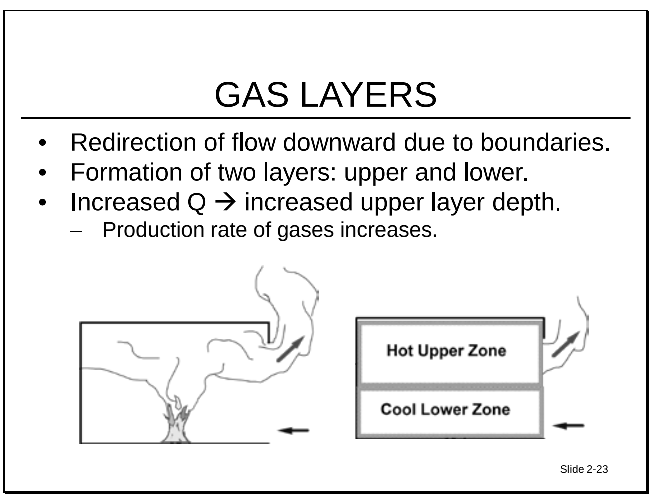
- The graph provides an example of the effect of boundaries and compartmentation.

-- When the fire is free burning (open air, no compartmentation), the peak heat release rate (HRR) is less.



- The figure shows the effects of combustible boundaries.

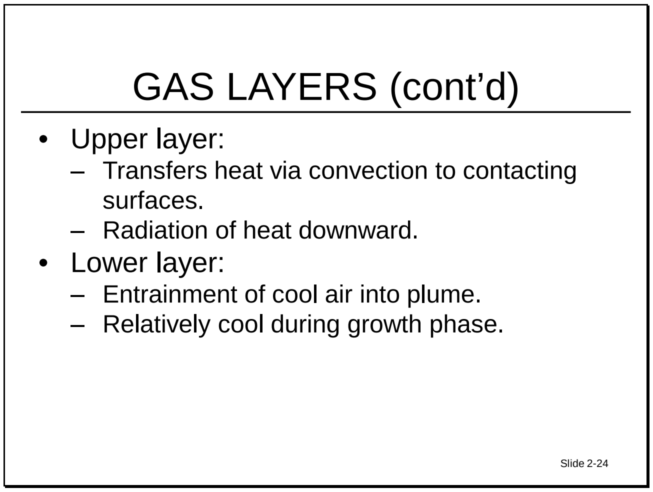
-- As would be expected, the combustible ceiling adds to the overall fire load, and flashover is achieved in a significantly shorter period of time when compared to a noncombustible ceiling.



d. The gas layer begins to build when the ceiling jet is bounded and begins to descend.

- There are two layers that form inside the compartment: an upper and a lower layer.

-- A larger HRR will result in the quicker development of an upper layer, due to a higher production rate of pyrolysis products.

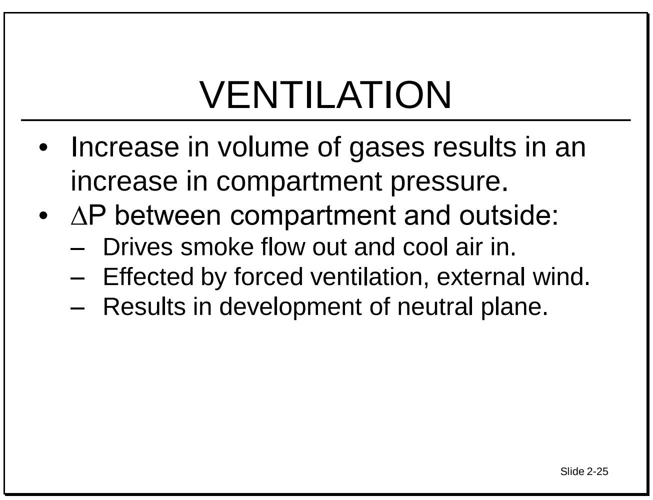


- The upper layer transfers heat to walls and the ceiling, which it is contacting via convection.

- Once the layer has sufficient depth, it will also begin to project radiation downward.

  -- This is a critical factor in the transition to flashover. Entrainment of cool air through ventilation openings occurs in the lower layer.

- The upper layer and lower layer temperatures show a significant difference during the growth phase; however, once the fire approaches full-room involvement, temperatures become more uniform.



e. The direction of flow can be affected by forced ventilation inside or outside of the compartment (e.g., exhaust fan inside compartment or positive-pressure ventilation (PPV) fan outside of compartment), and can also be affected by wind.

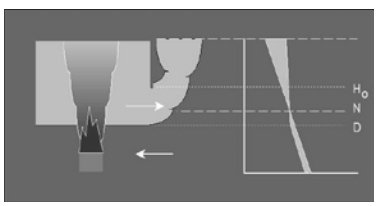
- As the gas layer builds inside the compartment, the increased volume of gases inside the compartment will result in an increase in pressure inside the compartment.

- This increased pressure will cause mass flow in and out of the compartment.

- The movement of gases in and out of the compartment results in the development of a neutral plane.

VENTILATION (cont'd)

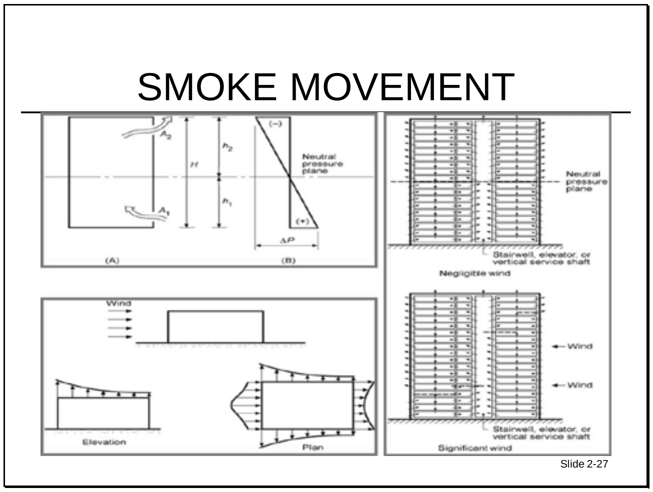
- Neutral plane — no flow occurs.
  - Flow in = flow out.
  - Moves downward as upper layer descends.



Slide 2-26

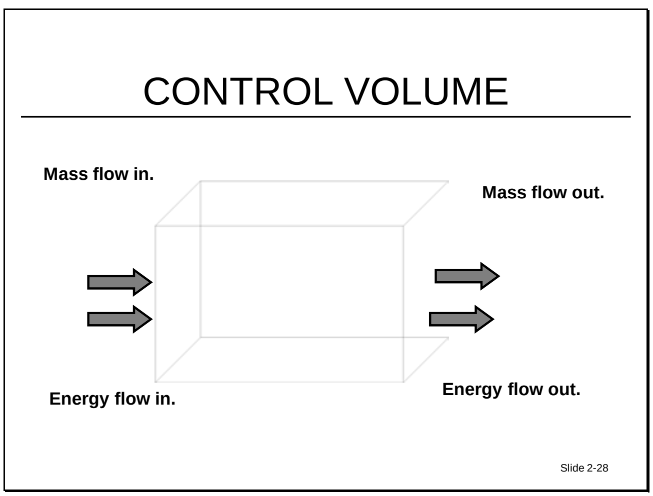
6. The neutral plane occurs at the point where flow in is equal to flow out (forces cancel each other out and no movement occurs at this point).

a. The location of the neutral plane will change throughout the fire's development and is dependent upon layer position.



- The neutral plane is important when designing smoke evacuation systems in stairwells and other vertical openings.

- Pressure differences associated with wind, such as those that may occur in high-rise buildings, can result in a change in the neutral plane location.



b. A compartment is often represented by control volume.

- The control volume will have some flow inward and outward depending on the stage of fire growth.

LAWS OF CONSERVATION

- **Conservation of Mass.**
  (Rate of change of mass in control volume or CV) + ($Flow_{in}$ – $Flow_{out}$) = 0

- **Conservation of Energy.**
  (Rate of change of energy in CV) = (Rate of heat added to CV) - (Rate of work done by fluid in CV)

Slide 2-29

c. The flow inward and outward is controlled by conservation laws.

- Mass and energy must be conserved in the process; therefore, the overall change in mass inside the compartment (control volume) must be zero.

- Similarly, the rate of change of energy inside the compartment is driven by the rate of heat added to the compartment from the fire minus the rate of heat absorption and flow out of the compartment.

ENERGY BALANCE

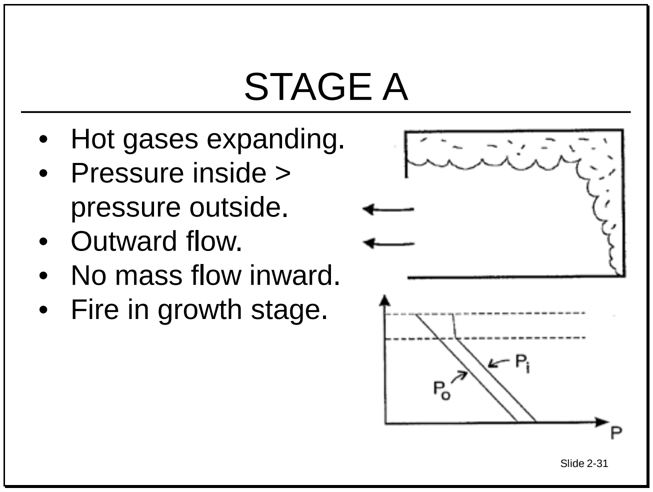
$Energy_{(generated)} = Energy_{(Flow\ in)} + Energy_{(Flow\ out)} + Energy_{(stored)} + Energy_{(lost)}$

$\mathbf{Energy_{(generated)}}$	**Fire (HRR)**
$Energy_{(flow\ in)}$	Flow in door (m_{in})
$Energy_{(flow\ out)}$	Flow out door (m_{out})
$Energy_{(stored)}$	Gas volume
$Energy_{(lost)}$	Compartment linings

Slide 2-30

- The amount of energy generated in the process will be dependent on the HRR of the fire, flow into and out of the compartment, the amount of energy stored in the compartment in the gas volume, and the losses of energy to surfaces through convection and radiation.

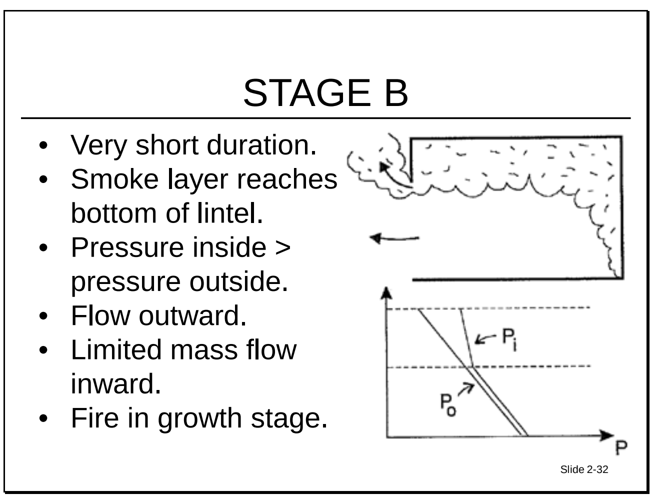
d. According to Karlsson and Quintiere, the development of a fire and its effects on the neutral plane can be broken down into four stages.



- The first stage, Stage A, occurs in the early development stage of the fire.

  -- At this point, the pressure inside the compartment is greater than the pressure outside of the compartment, so flow only occurs "out."

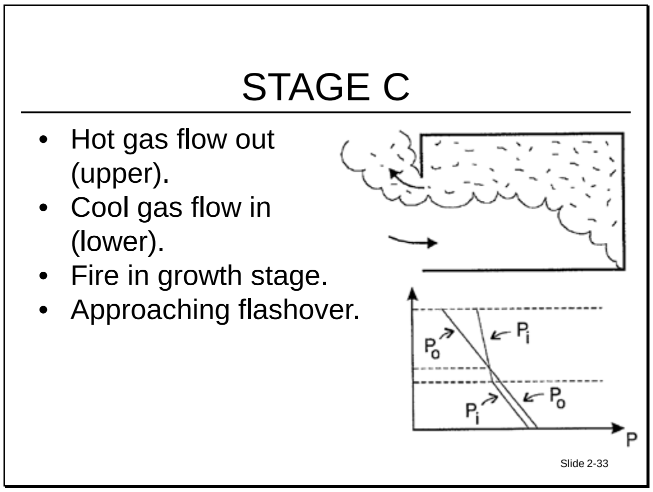
  -- Since flow is only occurring in one direction, no neutral plane is formed.



- The second stage, Stage B, represents a transition point where smoke has reached the top of a doorway (or other ventilation opening) and begins to exit from the opening.

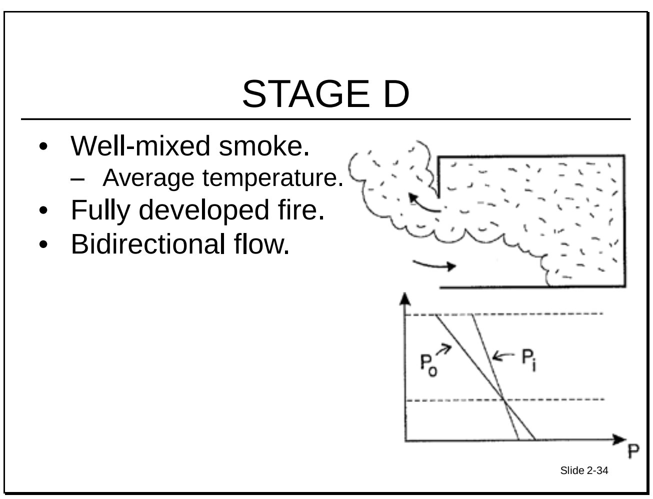
-- At this point, the pressure inside the compartment is still greater than the pressure outside of the compartment, and flow only occurs in the outward direction.

-- No neutral plane is formed.



- Stage C occurs when the fire approaches flashover.

-- The rapid exhaustion of smoke from the compartment results in the entrainment of air into the compartment, creating a bidirectional flow, and resulting in the development of a neutral plane.



- As the fire continues to develop, it approaches Stage D, during which the fire is fully developed and the layers become more uniform.

-- Bidirectional flow is still occurring; however, the neutral plane has moved closer to the floor.

FULL-ROOM INVOLVEMENT

- Fire in a room results in a room on fire.
  - Highly dependent on available fuel and oxygen.
    - -- Is there sufficient fuel to achieve flashover?
    - -- Are there sufficient ventilation openings to achieve flashover?

Slide 2-35

E. Leaving the ignition and growth stages, we enter into the full-room involvement stage.

1. There may be situations where you can have full-room involvement without flashover.

2. The ability of a compartment to achieve flashover is highly dependent on fuel and oxygen.

FULL-ROOM INVOLVEMENT (cont'd)

- Factors:
  - Ambient temperature.
  - Enclosure geometry.
  - Dimensions of ventilation openings.
  - Lining materials.

Slide 2-36

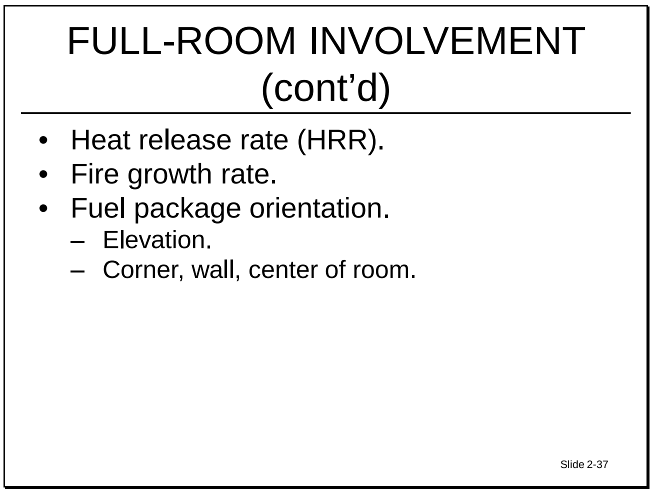
3. Other factors that affect flashover include the compartment's ambient temperature, the enclosure geometry, ventilation openings, and lining materials.

   a. More energy is required when ambient temperatures are very cold.

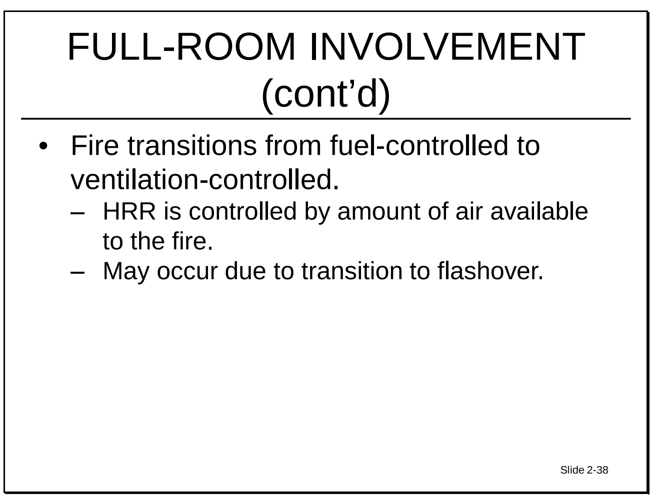
b. More energy is required for very large rooms with high ceilings as part of their enclosure geometry.

c. If insufficient ventilation openings exist, or openings are all high in the compartment, heat losses may affect total energy available.

d. Heat losses to lining materials need to be considered, especially if the lining material has a high rate of conductivity.

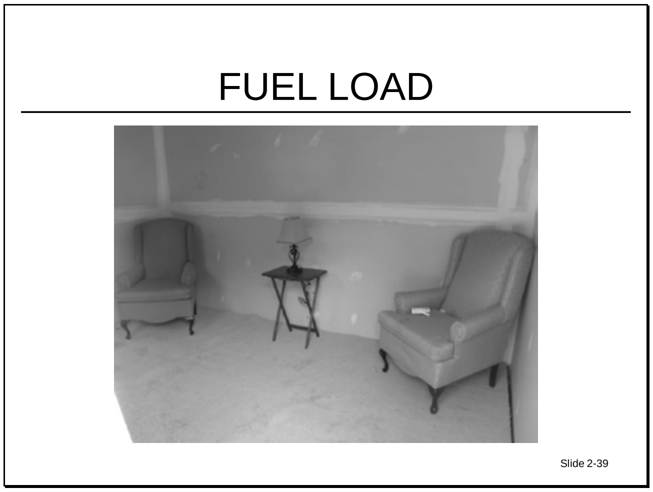


4. Flashover is also dependent on the HRR of the fuel, the fire growth rate of the fuel (slow, medium, fast, ultra), and the location and orientation of the fuel.

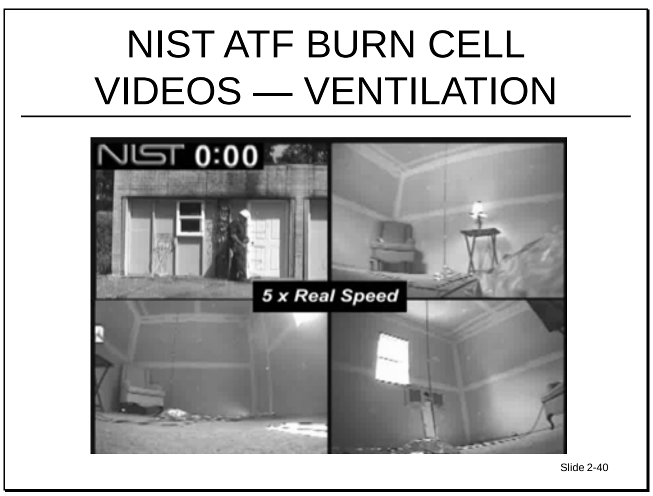


5. During flashover, the fire transitions from fuel-controlled to ventilation-controlled.

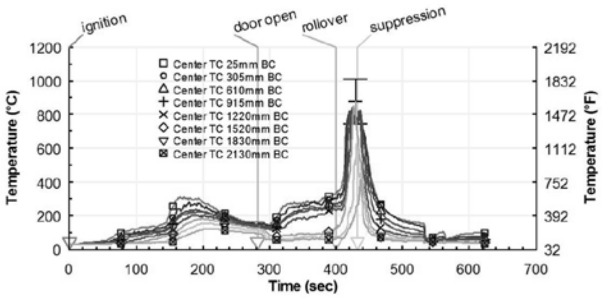
a. Since the heat produced during flashover causes pyrolyzation of all the fuels within the compartment, more than enough fuel is available for combustion.



b. The growth of the fuel is controlled by the air available for entrainment and mixing with the fuel.

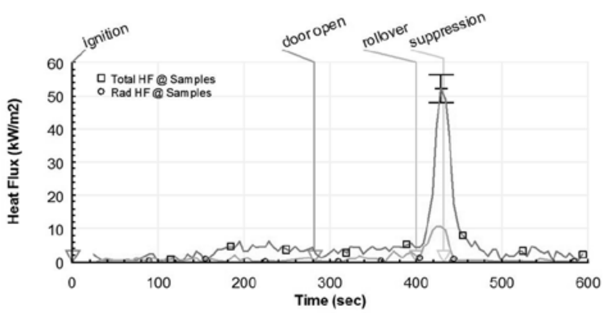


TEMPERATURE — CENTER OF THE ROOM



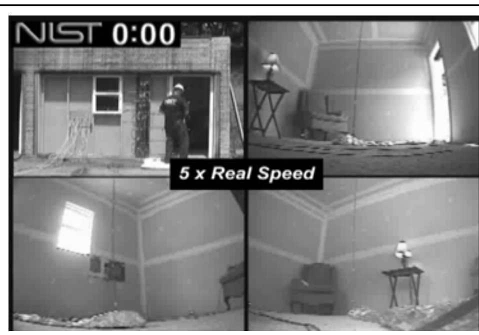
Slide 2-41

TOTAL AND RADIANT HEAT FLUX



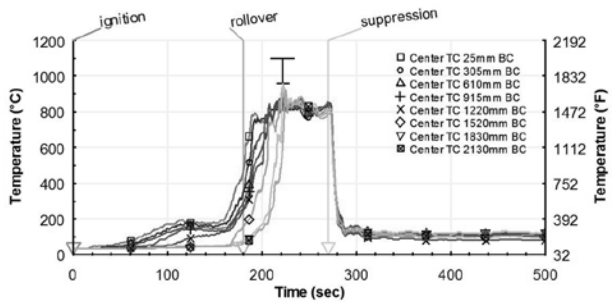
Slide 2-42

NIST ATF BURN CELL VIDEOS — FUEL



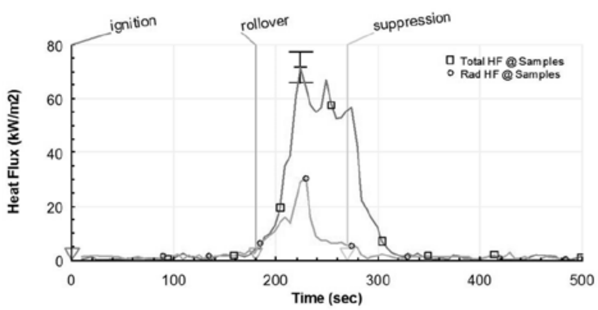
Slide 2-43

TEMPERATURE — CENTER OF THE ROOM (cont'd)



Slide 2-44

TOTAL AND RADIANT HEAT FLUX (cont'd)



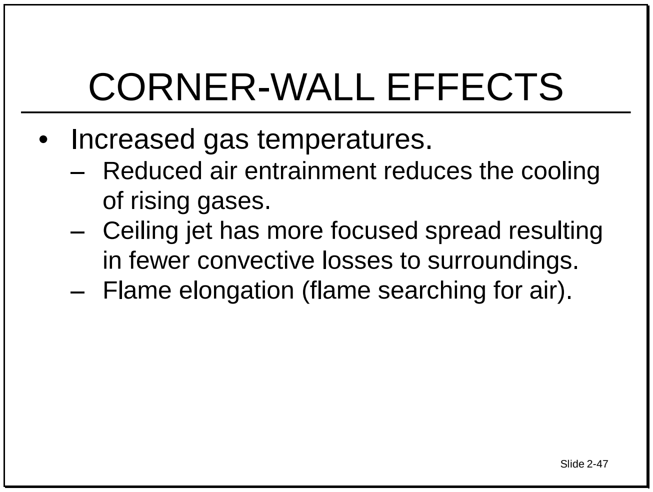
Slide 2-45

FUEL PACKAGE LOCATION

- Affects the following factors:
  - HRR.
  - Heat flux.
  - Smoke layer position.
  - Compartment temperatures.
  - Mass flow in/out.
  - Location of neutral plane.

Slide 2-46

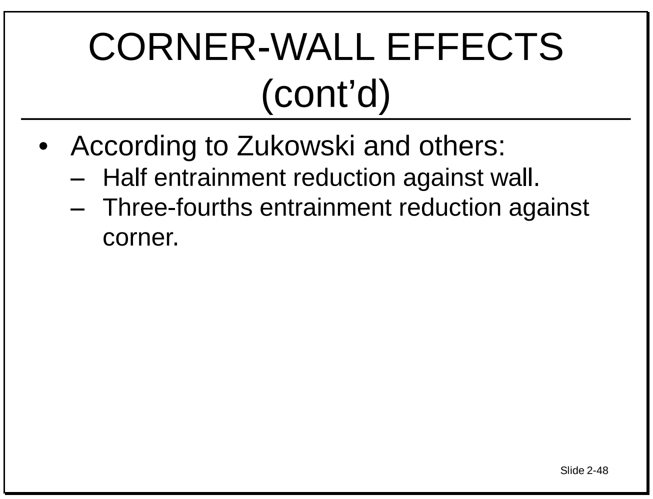
6. The location of the fuel within the compartment can have substantial effects on the growth of the fire, gas layer temperatures, smoke layer heights, and flow into and out of the compartment.



a. Gas temperatures in a compartment will be higher when fuel packages are located in the corner of a room or against a wall, compared to fuel packages located in the center of a room.

- The increased temperature results from reduced cooling of the fire plume gases due to limited entrainment zones.

-- Since the ceiling jet is not able to spread 360 degrees, it is a confined jet; therefore, the distribution of heat is more confined as well, resulting in increased layer temperatures.



-- Research by Zukowski suggests that entrainment is reduced by half when the flame is against the wall and by three-fourths when the flame is in the corner.

CORNER-WALL EFFECTS (cont'd)

- Increased flame height means increased unburned fuel.
- Less air for entrainment increases the flame height.
- Layer ignition.
- Significant increase in toxic gas production.

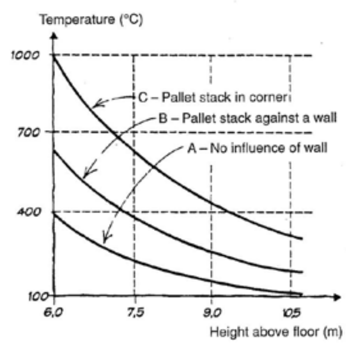
Slide 2-49

- The corner-wall effects result in flame elongation as the flame "searches" for air to support combustion.

  -- However, the reduction of air flow into the plume also increases the inefficiency of burning, therefore increasing the phi.

  -- A higher concentration of unburned hydrocarbons is being pumped into the upper layer, so layer ignition is common.

CORNER-WALL EFFECTS (cont'd)



Slide 2-50

- This graph shows corner-wall effects on three pallets that were each 1.22 meters (m) (4 feet) high.

  -- Curve A shows temperatures at varying heights above the pallet when they are placed in the center of the room.

-- Curve B shows temperatures at varying heights above the pallet when they are placed against a wall.

-- Curve C shows temperatures at varying heights above the pallet when they are placed in a corner.

-- The figure demonstrates that the gas temperatures increase as the flame becomes more obstructed from air entrainment.

ELEVATION EFFECTS

- Quicker peak temperatures.
- Higher peak temperatures.
- Decreased burning rate due to vitiation of flame.
- Overall lower temperatures.
- Doorway flame extension sooner.
- Increased toxic gas production.

Slide 2-51

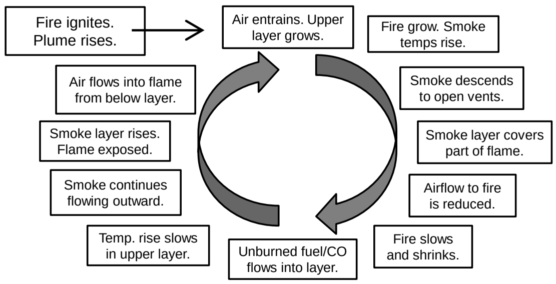
b. Since the plume gases have less time to cool before they hit the ceiling, the elevation of fuels in a compartment results in quicker and higher peak temperatures.

- The emersion of the plume in the upper layer often results in decreased burning rates because the fire becomes vitiated.

- The vitiation of the fire will result in an increase in toxic gas production.

- It is common to see flames extending out of the doorway sooner because more significant horizontal extension of the flame occurs.

ELEVATION EFFECTS (cont'd)

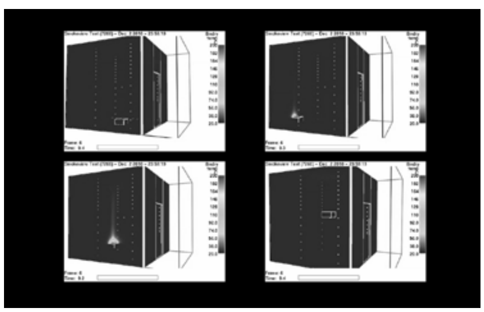


(Fig. 9) Proposed mechanism for the cyclic behavior during elevated fire tests

Slide 2-52

- The figure shows the factors that are to be considered when the fuel package is elevated in a compartment. (Image from "Investigation of an Elevated Fire — Perspective on the 'Z-factor'" by S. Carman.)

"ATF RESEARCH COMPARTMENT VIDEOS"



Slide 2-53

EQUIVALENCE RATIO

- Commonly represented as Φ.
  - Φ = (fuel/air) actual/(fuel/air) stoichiometric.
  - Fuel-lean $\Phi < 1$ (fuel-limited).
  - Fuel-rich $\Phi > 1$ (ventilation-limited).

Slide 2-54

7. The equivalence ratio (known as phi, Φ) is often used to describe the deviation of the fire outside of stoichiometric conditions.

    a. Recall from Unit 1 that stoichiometry refers to a state where fuel and oxygen are present in sufficient quantities to allow for complete combustions with the production of only carbon dioxide and water.

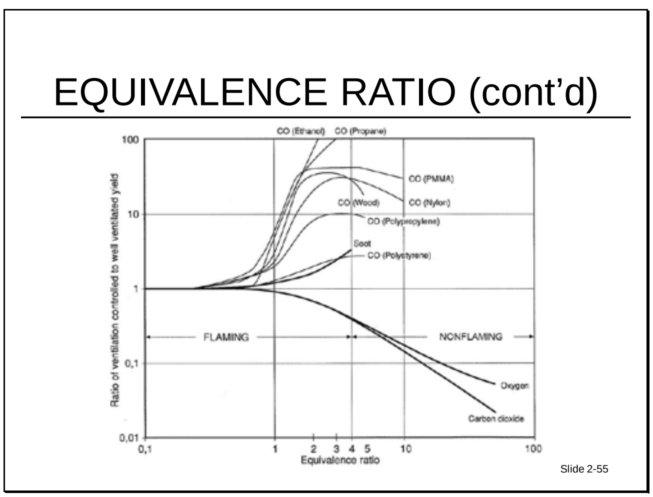
        - The presence of a stoichiometric mixture is represented by a phi of one.

            -- This is an ideal condition that does not exist in real fires.

        - When the fire is fuel-limited, such as during the growth stage, it is said to be fuel-lean, and the phi is less than one.

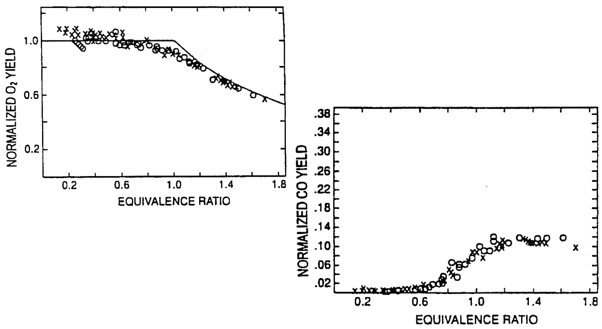
        - When the fire is ventilation-limited, such as during flashover, it is said to be fuel-rich, with a phi greater than one.

    b. As the fire becomes more ventilation-controlled, there will be more incomplete products of combustion (an insufficient amount of air is available for combustion).



        - This graph shows a significant increase in carbon monoxide and soot productions for various types of materials once the equivalence ratio exceeds one. (Images from Enclosure Fire Dynamics — Karlsson and Quintiere.)

EQUIVALENCE RATIO (cont'd)



Slide 2-56

- The figures provide another graphical representation, showing that the significant decrease in oxygen concentrations results in a significant increase in carbon monoxide yields once an equivalence ratio of one is exceeded.

FLASHOVER CORRELATIONS

- **Methods:** Thomas, Babrauskas, McCaffrey/ Quintiere/Harkleroad (MQH).

Babrauskas Method

$$\dot{Q}_{fo} = 750 A_v \sqrt{h_v}$$

A_v = area of ventilation opening (m^2)
h_v = height of ventilation opening (m)

Slide 2-57

8. As previously mentioned, one important factor that affects flashover is ventilation.

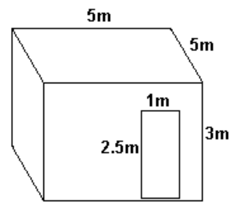
   a. There are three methods to establish the HRR needed to support flashover within a compartment.

   b. The most simplistic is the Babrauskas method.

      - The method only considers the effects of the ventilation opening or, more specifically, the area and height of the vent.

FLASHOVER CALCULATION

- Determine the minimum HRR to result in flashover. The bedroom is 5m (length) by 5m (width) by 3m (height). The doorway opening is 2.5m (height) by 1m (width).



Slide 2-58

FLASHOVER CALCULATION (cont'd)

- Using resources discussed in the course, determine if a bunk bed would produce a sufficient peak HRR to result in flashover of the bedroom?
  - All calculations must be performed by hand.
  - One representative from the group will present the answers.

Slide 2-59

DECAY

- Fuel and/or oxygen is depleted.
- HRR and temperature decrease.
- Transition from ventilation-controlled to fuel-controlled.
- Threats are still present.
  - Products of combustion from smoldering.

Slide 2-60

F. The final stage of a compartment fire is decay.

1. During this stage, the HRR and temperature in the compartment are decreasing.

2. The decay stage may result from a lack of sufficient oxygen to support combustion, or it may occur because insufficient fuel remains.

3. During this stage, the fire transitions back to being fuel-controlled.

4. While visible flame is significantly decreased, incomplete combustion results in high levels of products of combustion.

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ACTIVITY 2.1

Live Burn Experiment

Purpose

To demonstrate the effects of ventilation and fuel configuration and placement on compartment fire dynamics.

Directions

1. You will be placed in groups and assigned a burn cell to set up with the supplied materials.
2. The goal is to achieve one of the following: a) lowest position (height) in door opening to reach a temperature of 600 C (1,100 F), or b) first team to reach a temperature of 600 C (1,100 F) at the mid-height of the window (17.5 inches below window soffit).
3. You may only use the provided materials. Additional fuel, gasoline, etc., is **not** allowed.
4. You cannot cut additional ventilation holes.
5. You may close off existing ventilation openings (doorway and window) with provided materials.
6. You may modify or arrange the provided materials within the burn cell as the team desires.
7. You may not place the materials denoted by an "*" (upholstered chair, coffee table, wastebasket and newspaper) within 3 feet of the door or window "exclusion zone." The gypsum board and plywood are allowed in the "exclusion zone."
8. You will have 30 minutes to set up your burn cell.

Discussion Questions

1. How does fuel configuration affect growth and spread?
2. How does ventilation affect growth and spread?
3. How does fuel placement affect growth and spread?

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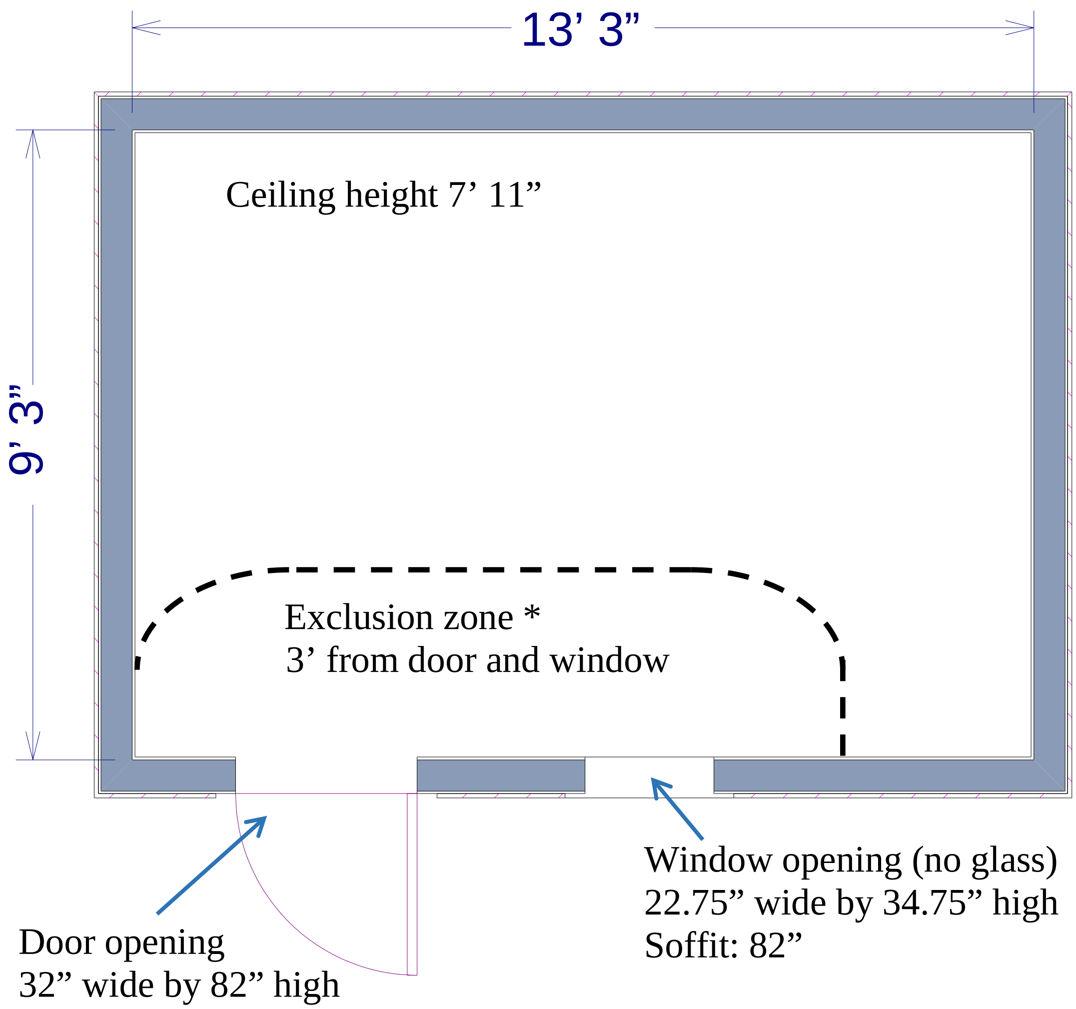
ACTIVITY 2.1 (cont'd)

Live Burn Experiment: Burn Cell Practical Exercise Handout



Burn Cell Scenario

Each team will be assigned a burn cell to set up with the supplied materials. The goal of the exercise is to demonstrate knowledge of fire dynamics to achieve one of the following goals:

- Lowest position (height) in door opening to reach a temperature of 600 C (1,100 F).
- First team to reach a temperature of 600 C (1,100 F) at the mid-height of the window (17.5 inches below window soffit) or ignite a sheet of newsprint in door threshold.

Materials

Each team will have the following materials available for positioning within the compartment:

- Upholstered chair.*
- Coffee table.*
- Wastebasket.*
- Twin/Full egg crate polyurethane foam pad.
- Ten sheets of newspaper.*
- A 1/2 sheet of gypsum board (4 by 4 feet).
- A 1/2 sheet of plywood (4 by 4 feet).

Rules

1. The ignition source will be a lighter.

2. The burn duration will be five minutes.

3. Only the provided materials may be used. Additional fuel, gasoline, etc., is **not** allowed.

4. You cannot cut additional ventilation holes (these structures need to be used again).

5. Existing ventilation (doorway and window opening) may be closed off with provided materials.

6. The provided materials may be modified and arranged within the burn cell as the team desires.

7. **Exception:** The materials denoted by an "*" (upholstered chair, coffee table, wastebasket and newspaper) may not be placed within 3 feet of the door or window "exclusion zone." The gypsum board and plywood are allowed in the "exclusion zone."

8. The teams will have 30 minutes to set up their burn cell.

Instrumentation

A single thermocouple (TC) will be used to measure gas temperature during the exercise. The method for fixing the TC in its location is TBD.

Goal

Use what you have learned throughout the course to make a fire that will interact with the building elements "better" than the other teams' burn cells.

ACTIVITY 2.2

Baltimore County LODD, Live Fire Experiment

Purpose

To demonstrate how ventilation openings and compartmentation affect fire and smoke flow throughout a structure.

Directions

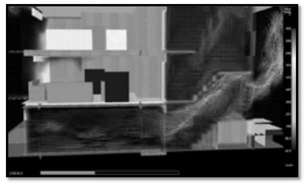
You will assemble at the burn range.

Discussion Questions

1. How did the lack of door closures affect the spread of fire and smoke to adjacent compartments?

2. What actions could have been taken to minimize fire growth and spread?

BALTIMORE COUNTY, MARYLAND, LINE-OF-DUTY DEATH



Engineering Analysis of 30 Dowling Circle Using Fire Dynamics Simulator (FDS)

Slide 2-63

OUTLINE

- The role of the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) Fire Research Laboratory in the investigation.
- Overview of engineering analysis methodology.
- Review modeling video that encompasses the entire fire.
- Answer questions.

Slide 2-64

ATF FIRE RESEARCH LABORATORY INVOLVEMENT

- ATF Certified Fire Investigators, Fire Protection Engineers and Electrical Engineers responded to the scene.
- ATF documented entire building (dimensions/photos) in anticipation of generating a computer fire model.

Slide 2-65

ATF FIRE RESEARCH LABORATORY INVOLVEMENT (cont'd)

- Worked with Baltimore County Postincident Analysis (PIA) Team to collect information, conducted independent analysis of data.

Slide 2-66

FIRE RESEARCH LABORATORY ENGINEERING ANALYSIS

- PIA Team requested engineering expertise to help understand:
  - The complex route of fire spread through the building.
  - Rapid flashover of the third floor soon after the second floor.
  - High temperatures in the stairwell initially experienced by the first due engine.

Slide 2-67

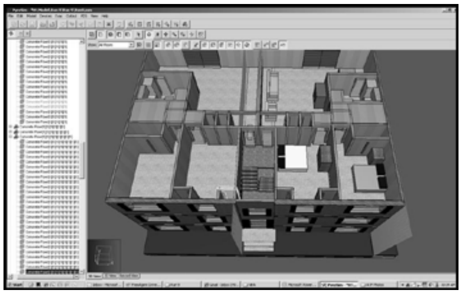
FIRE RESEARCH LABORATORY ENGINEERING ANALYSIS (cont'd)

- Possible methods of preventing future tragedies similar to this fire.

Slide 2-68

MODELING PROGRAMS

Used PyroSim, FDS and SmokeView.



Slide 2-69

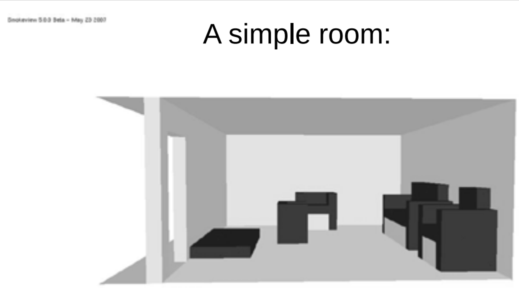
COMPUTER FIRE MODELING

- FDS uses computational fluid dynamics (CFD) to predict the movement of mass, energy, momentum and species throughout a three-dimensional space.

Slide 2-70

COMPUTER FIRE MODELING (cont'd)

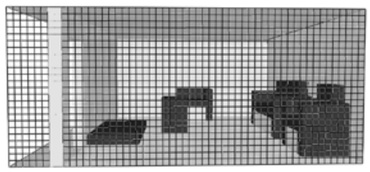
A simple room:



Slide 2-71

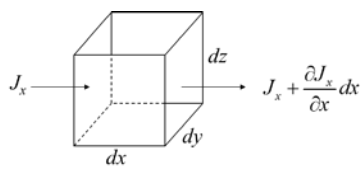
COMPUTER FIRE MODELING (cont'd)

- The same room as seen by a CFD model. Conservation equations are repeatedly calculated over each 3-D "grid cell."
- Tracks movement of mass, energy, momentum and species through each cell.



Slide 2-72

COMPUTER FIRE MODELING (cont'd)



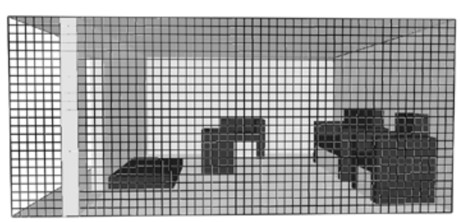
J = any quantity to be tracked by program
mass, momentum, energy, gas specie, soot density, etc.

Energy is conserved: Output = Input + Change.

Slide 2-73

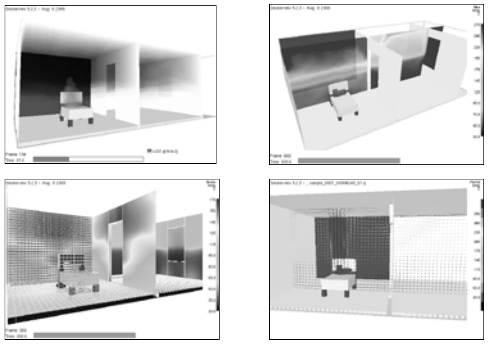
COMPUTER FIRE MODELING (cont'd)

- CFD breaks a larger model into smaller discrete pieces over which conservation equations are calculated at each time step.



Slide 2-74

TYPES OF FDS/SMOKEVIEW OUTPUT FILES



Slide 2-75

FDS USES AND LIMITATIONS

What FDS does well …

- Show you the movement of heat and smoke from a specified fire size.
- Calculate the effects of conduction, convection and radiation from a specified fire.
- Help reduce the number of full-scale tests that are needed by testing effects of leaving out part of the building, turning HVAC on/off, etc.
- Answer a specific question given thorough documentation of a scene.

What FDS does not do well …

- Calculate flame spread and fire size (without mid- to full-scale testing).
- Predict the suppression of a fire by sprinklers or the fire department.
- Answer wide-sweeping questions like, “What would this fire have looked like?”

Slide 2-76

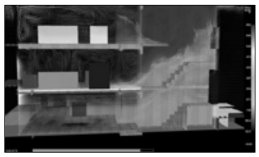
MODELING THE INCIDENT

- Input data:
  - Witness statements (firefighters on second and third floors).
  - Photos detailing fire progression.
  - Minimal early suppression of second floor fire.
  - “Hard” times associating witness statements and audio.
  - Very few “unknowns.”

Slide 2-77

MODELING THE INCIDENT (cont'd)

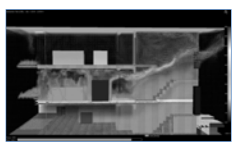
- Output Data:
  - Show travel of heat and smoke throughout stairwell (explain rapid flashover of third story).
  - Use model as a visualization tool of complex route of fire spread (exterior Side C, to second floor interior, through stairwell to third floor).



Slide 2-78

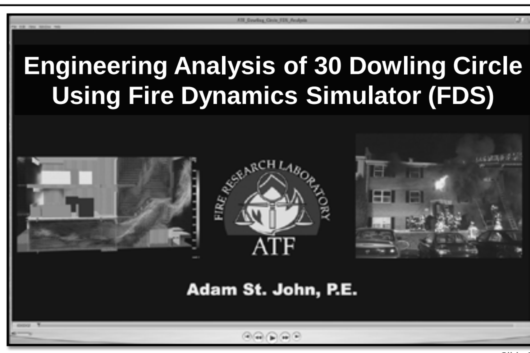
MODELING THE INCIDENT (cont'd)

- Illustrate impact of compartmentation on fire spread using doors (both occupants and firefighters).
- Video incorporates 911 audio, dispatch audio, operations audio and photographs to illustrate the fire in its totality.



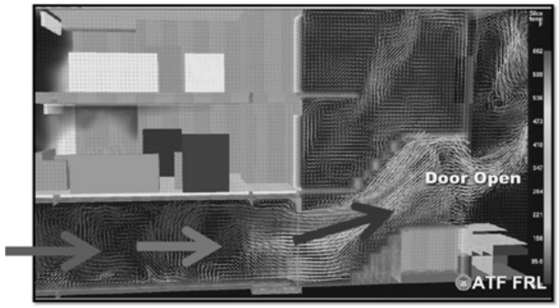
Slide 2-79

ENGINEERING ANALYSIS OF 30 DOWLING CIRCLE USING FDS



Slide 2-80

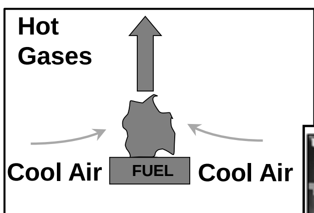
VENTILATION FLOW PATHS

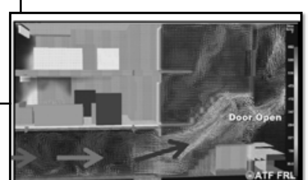


Terrace Level

Slide 2-81

VENTILATION FLOW PATHS (cont'd)

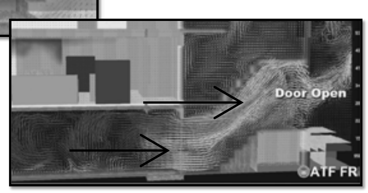




Slide 2-82

VENTILATION FLOW PATHS (cont'd)

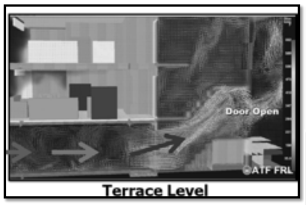
Bidirectional Flow

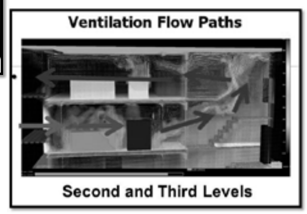


Unidirectional Flow

Slide 2-83

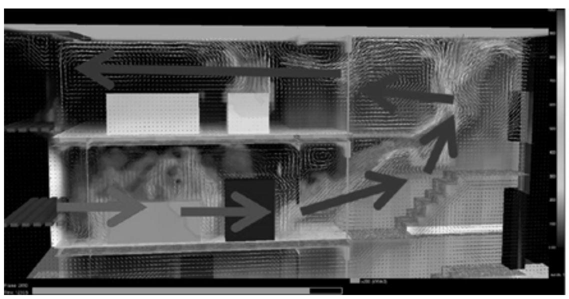
VENTILATION FLOW PATHS (cont'd)





Slide 2-84

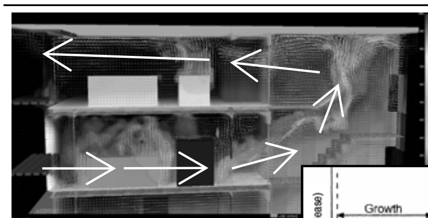
VENTILATION FLOW PATHS (cont'd)

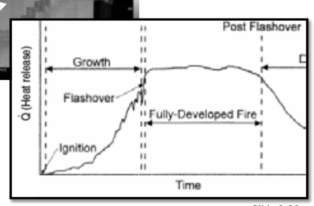


Second and Third Levels

Slide 2-85

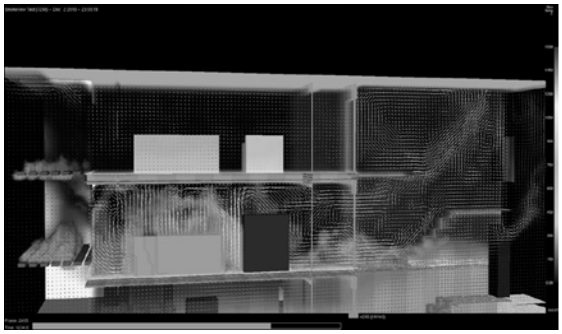
RAPID FIRE PROGRESSION





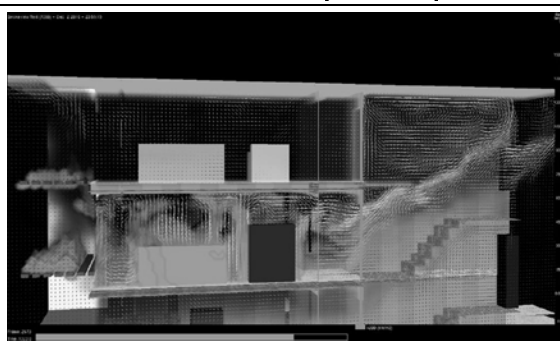
Slide 2-86

VENTILATION LIMITED BURNING



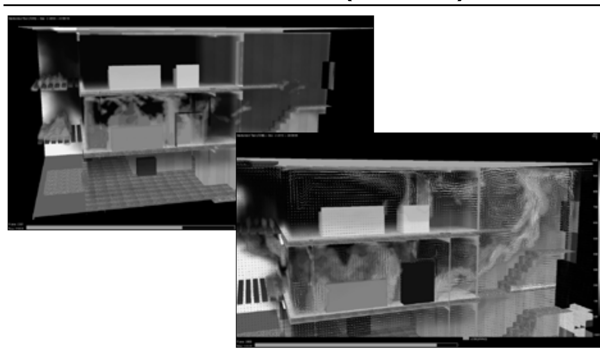
Slide 2-87

VENTILATION LIMITED BURNING (cont'd)



Slide 2-88

VENTILATION LIMITED BURNING (cont'd)



Slide 2-89

ALTERNATIVE RUN, VENTED ROOF

Newest run exploring the effects of vertical ventilation in the roof (5-by-5 foot hole) cut just before flashover.

Slide 2-90

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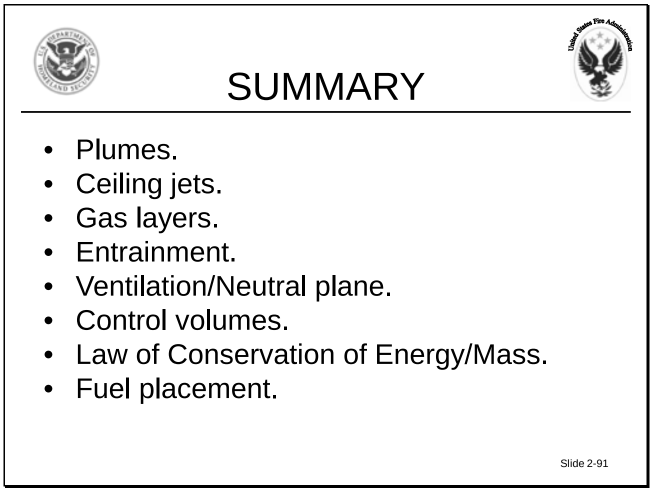
II. SUMMARY


SUMMARY
• Plumes.
• Ceiling jets.
• Gas layers.
• Entrainment.
• Ventilation/Neutral plane.
• Control volumes.
• Law of Conservation of Energy/Mass.
• Fuel placement.
Slide 2-91

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UNIT 3: TEST METHODS

TERMINAL OBJECTIVE

The students will be able to:

3.1 Locate and select appropriate data sources for use in modeling.

ENABLING OBJECTIVES

The students will be able to:

3.1 Identify the various types of test methods used to characterize the thermal properties of fuels.

3.2 Differentiate between standardized testing and physical modeling as methods for identifying thermal properties used in fire analysis.

3.3 Describe the various types of equipment used to gather test data.

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UNIT 3:
TEST METHODS

Slide 3-1

ENABLING OBJECTIVES

- Identify the various types of test methods used to characterize the thermal properties of fuels.
- Differentiate between standardized testing and physical modeling as methods for identifying thermal properties used in fire analysis.
- Describe the various types of equipment used to gather test data.

Slide 3-2

I. STANDARD TESTING

STANDARD TESTING

- Standardized test methods:
  - American Society for Testing and Materials (ASTM) E1354 (National Fire Protection Association (NFPA) 271, *Standard Method of Test for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter*).

Slide 3-3

STANDARD TESTING (cont'd)

- ASTM E1537 (NFPA 266, *Standard Method of Test for Fire Characteristics of Upholstered Furniture Exposed to Flaming Ignition Source*).
- ASTM E84 (NFPA 255, *Standard Method of Test of Surface Burning Characteristics of Building Materials*).

Slide 3-4

STANDARD TESTING (cont'd)

- ASTM E119 (NFPA 251, *Standard Methods of Tests of Fire Resistance of Building Construction and Materials*).
- ASTM E648 (NFPA 253, *Standard Method of Test for Critical Radiant Flux of Floor Covering Systems Using a Radiant Heat Energy Source*).
- ASTM 1321.

Slide 3-5

A. Two different topics will be covered: standardized tests and physical models.

1. These topics will be covered under standardized test methods.

2. Each American Society for Testing and Materials (ASTM) standard that will be discussed has an accompanying National Fire Protection Association (NFPA) standard, with the exception of ASTM 1321.

STANDARDS DEVELOPMENT

- Underwriters Laboratories (UL).
- NFPA.
- International Standards Organization (ISO).
  - American National Standards Institute (ANSI).
- ASTM.
- Code of Federal Regulations (CFR).

Slide 3-6

B. These are examples, at the federal, national and international levels, of different standard development agencies/organizations.

STANDARDIZED TESTING LABORATORIES

- Fire test laboratories (not inclusive):
  - UL.
  - Factory Mutual Research Corporation (FMRC).
  - Southwest Research Institute (SwRI).
  - Exponent.
  - Western Fire Center.

Slide 3-7

C. These are some of the various organizations that perform standardized testing (the list is not inclusive).

1. ASTM has a list of vendors that can perform a specified standardized test which is searchable on their website.

2. Products with the Underwriters Laboratories (UL) label have something called an E-number.

   a. The E-number does not indicate that the product is UL-approved; the product must still have the UL label.

   b. The E-number is searchable on the UL database and provides information about the product, the manufacturer, and the UL standard related to the product.

STANDARDIZED FIRE TESTS

- Positives:
  - Compare the behavior or response of different materials to a given set of test conditions.
  - Performed in a controlled environment.
  - Extensive documentation in support of test method.
  - Repeatable results.
  - Known precision and bias.

Slide 3-8

D. The positive aspects of standardized fire tests:

1. Because standardized tests are performed in a controlled environment, variability is reduced and tests have high repeatability.

2. The controlled environment, well-defined variables and repeatability also allow for the determination of the precision and accuracy associated with the test method.

3. Standardization also eliminates bias since the same criteria is used across the board.

4. Some standards undergo a “round robin” during the development process.

    a. The round robin process includes the involvement of multiple laboratories that construct their own apparatus based on the requirements of the standard and test the same fuel.

    b. Test results are compared to ensure that the data is repeatable and has little variability between laboratories.

    c. This ensures that the standard is of sufficient detail to allow multiple laboratories to derive the same data when testing the same type of specimen.

STANDARDIZED FIRE TESTS (cont'd)

- Possible limitations:
  - Test conditions may not mimic actual incident conditions.
  - Sample size and mounting.
  - Substrate that the sample is mounted on.
  - Geometry consideration (usually flat samples).
  - Test environment — temperature, humidity and ventilation.

Slide 3-9

E. The limitations of standardized fire tests:

1. The highly specific nature of the test may not accurately mimic the true use of the material being tested.

2. Samples may be tested in sizes or mounting orientations that do not allow for the analysis of the material in its true use condition (e.g., testing a material in the horizontal position when it will be used in the vertical position).

STANDARDIZED FIRE TESTS (cont'd)

- No spread to other fuels.
- No hot layer effects.

Slide 3-10

3. The exposure criteria may also fall short of actual conditions that may be present in a fire environment, for example, fast t-squared fire growth rate versus a standard time-temperature curve (to be discussed in more detail in the following slides).

ASTM E1354

- Cone calorimeter test.
- Sample size: 4 inches by 4 inches and up to 2 inches thick.
- Exposure fluxes up to 100 kilowatts per meter squared (kW/m^2) from a conical radiant heater.
- Ignition: piloted (spark igniter) or nonpiloted (cone heater only).

Slide 3-11

F. The ASTM E1354 Standard describes the testing of specimens using a cone calorimeter.

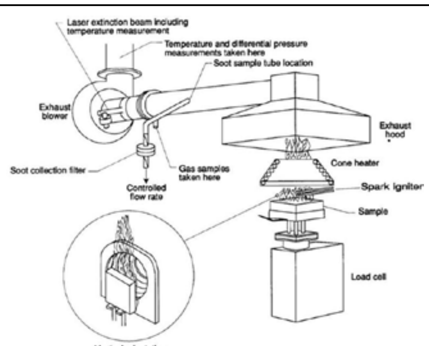
1. The specifics:

   a. Specimens are small in size, only approximately 4 inches by 4 inches, and are limited to a 2-inch thickness.

   b. The specimen is heated underneath a conical heater, and time to ignition is monitored.

   c. The specimen can be tested at various fixed fluxes, and ignition can be supported with or without the present of a flame igniter.

ASTM E1354 (cont'd)



Slide 3-12

d. The components of the cone calorimeter are the heater element (which is conical in shape), a spark igniter to ignite the vapors produced when the material is heated, a sample holder to expose the same area of material for each test, and a load cell to monitor the mass loss rate (MLR). There is also an exhaust hood that sits above the sample and collects the smoke and gases evolved from the material during combustion.

e. The photograph shows a burning sample within the cone calorimeter. The photograph shows the heater element, the sample and holder resting on the load cell, and the exhaust hood above.

ASTM E1354 (cont'd)

- Test data collected:
  - Heat release rate (HRR).
    - -- A single gram of O_2 reacted produces 13.1 kilojoules (kJ) of energy regardless of the fuel burning.
  - Mass loss rate (MLR).
  - Smoke obscuration.
  - Ignition time.
  - Critical ignition flux.

Slide 3-14

2. Data that can be collected from the cone calorimeter test.

a. A single gram of O_2 consumed produces 13.1 kilojoules (kJ) of energy, and this is the method by which the heat release rate (HRR) is determined.

b. The fuel's MLR and heat of combustion could also be used to establish the HRR curve, but that is not always the best method to use due to issues with identifying an appropriate H_c. For example, what H_c do you use when the material is multicomposite?

ASTM E1354 (cont'd)

Item	Exposure Heat Flux	
	35 kW/m^2	70 kW/m^2
	Average Peak HRR (kW/m^2)	Average Peak HRR (kW/m^2)
Carpeting	260	380
Ceiling Tile	10	40
Monitor Case	410	490
Letter Tray	1,020	1,170
Chair	210	350
Paper w/cb	320	460
Wastebasket	1,560	2,970
Wk Stn WS	340	590

Slide 3-15

c. Examples of HRR measurements taken using the cone calorimeter.

- The higher heat flux exposure produces higher peak HRR.

-- This is due to the faster rate of pyrolysis of materials from the fuel surface, allowing for more mass consumption per unit of time.

-- The peak HRR and overall HRR curve may be different, but the total energy released from the product when the same mass of product is consumed is the same.

ASTM E1537

- Furniture calorimeter.
- Sample size: full-sized upholstered furniture.
- Test room or open calorimeter.
- Ignition: gas burner.

Slide 3-16

G. The ASTM E1537 Standard describes the testing of specimens underneath a hood referred to as a furniture calorimeter.

1. Different from the cone calorimeter, the furniture calorimeter can accommodate full-sized upholstered furniture. This allows for consideration of specimen orientation and configuration on HRR and MLR.

2. The effluents are collected under a hood. The test may be performed with the piece of furniture directly under the hood or within some type of test room or compartment from which effluents are collected.

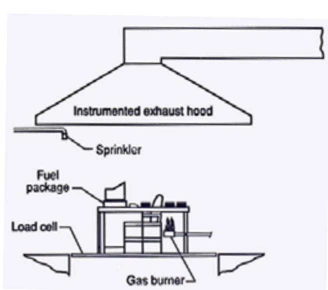
ASTM E1537 (cont'd)

- Test data collected:
  - HRR.
  - MLR.
  - Smoke obscuration.
  - Gas concentrations.
  - Time to ignition.
  - Room temperatures.

Slide 3-17

3. HRR, MLR, smoke obscuration, gas concentrations (as defined by the user but typically CO, CO_2 and O_2), time to ignition, and room temperatures (when a compartment is utilized) are all specified measurements in the standard.

ASTM E1537 (cont'd)



Slide 3-18

4. The picture provides an example of a furniture calorimeter and the types of materials that can be tested under it.

ASTM E84

- Steiner Tunnel test for burning characteristics of walls and ceilings.
- Sample size: width = 20-24 inches, length = 24 feet, thickness = 4 inch maximum.
- Test sample mounted in ceiling position.
- Test environment: furnace.
- Ignition: flame impingement via two gas burners.

Slide 3-19

H. ASTM E84 is also referred to as the Steiner Tunnel test.

1. The test is conducted inside a tunnel-like structure approximately 24 feet long.

2. The specimen is mounted to the ceiling, and the material is exposed to flame via two gas burners.

ASTM E84 (cont'd)

- Test data collected:
  - Flame spread index (FSI).
  - Smoke development index.

Slide 3-20

3. The temperature production inside the tunnel from the burning of the specimen is recorded over time.

4. Additionally, the flame spread on the material and smoke development from the material is classified.

ASTM E84 (cont'd)

- FSI.
  - A or 1 = 0-25.
  - B or 2 = 26-75.
  - C or 3 = 76-200.
- Maximum smoke development index of 450.

Slide 3-21

a. The flame spread index (FSI) is calculated using the area under the distance versus time curve.

b. Materials can receive one of three different types of classification based on the rate at which flame spreads on the material.

- Classification A represents a slower flame spread, and Classification C represents a faster flame spread.

- The codes will dictate the type of material that is allowed in a structure, depending on the occupancy.

  -- The material will also receive a smoke development index, which can not exceed 450.

- Some points for consideration are the orientation of the material in the tunnel versus in its use condition, as well as the ventilation conditions and how they effect smoke production.

ASTM E84 (cont'd)

Slide 3-22

5. The picture shows the components of the tunnel.

ASTM E119

- Fire endurance and hose stream test.
- Performance of walls, partitions, columns, floors, roofs, girders, slabs, beams and protective membranes.
- Test environment: vertical or horizontal furnace.

Slide 3-23

I. ASTM E119 is intended for the evaluation of the fire endurance of various structural components, such as walls, columns, floors, roofs, etc. Structural components can be tested in the vertical or horizontal orientation depending on the typical use position.

ASTM E119: FIRE ENDURANCE

- Specimens are exposed to standard time-temperature curve.
- Developed in the 1920s prior to understanding of HRR.
- Lacks consideration for synthetic fuels.
- Actual failures occur prior to rated failure time.

Slide 3-24

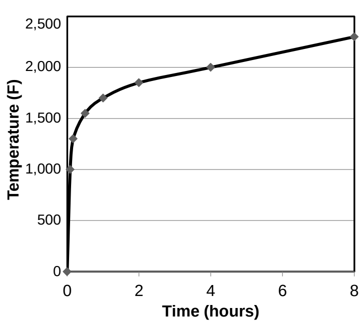
The E119 furnace exposes the specimen to the standard time-temperature curve, which was developed in the 1920s.

1. The curve does not adequately represent the temperature profiles associated with modern day synthetic materials.

   Therefore, it is expected that failure of materials and assemblies will occur quicker under real fire conditions.

ASTM E119 (cont'd)

Time	Temp (F)
5 minutes	1,000
10 minutes	1,300
30 minutes	1,550
1 hour	1,700
2 hours	1,850
4 hours	2,000
8 hours or more	2,300



Slide 3-25

2. The curve represents the standard time-temperature curve.

ASTM E119 (cont'd)

- Gas temperature in fully developed room fires.
  - Natural ventilation.
  - Wood cribs.

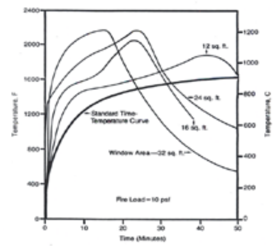


Figure 8. Effect of window area on fire temperatures during burnout tests with natural

Slide 3-26

This slide provides a comparison between the standard curve and data from the burning of a wood crib under various ventilation conditions. The comparison clearly shows that the standard curve underpredicts a typical exposure.

ASTM E119 — SAMPLE SIZE

- Walls and partitions:
  - Not less than 100 square feet with neither dimension less than 9 feet.
- Columns (with and without protection):
  - Length not less than 8-9 feet.

Slide 3-27

3. The requirements for sample size vary depending on the type of specimen being tested.

ASTM E119 — SAMPLE SIZE (cont'd)

- Floors and roofs:
  - Not less than 180 square feet with neither dimension less than 12 feet.
- Beams:
  - Length not less than 12 feet.

Slide 3-28

ASTM E119 (cont'd)

- Test data collected:
  - Heat transfer through specimen.
  - Changes in load-carrying capacity.
  - Smoke and toxic gas production.
  - Passage of smoke through specimen.
  - Flame spread.

Slide 3-29

4. Test data collected:

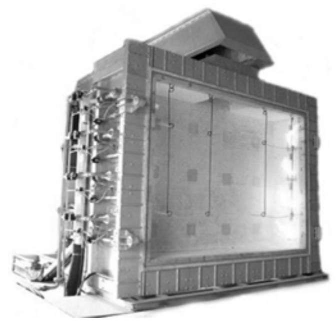
   a. Heat transfer through the specimen is monitored with thermocouples to establish temperature conditions on the exposed surface and unexposed surface.

   b. Changes in load-carrying capacity are monitored based on the amount of deflection due to weighting of the specimen during exposure.

   c. Smoke and toxic gases and flame spread are monitored.

   d. The passage of smoke through a specimen is also monitored to determine the duration that it remains as a smoke barrier.

ASTM E119 — VERTICAL FURNACE



Slide 3-30

- The picture shows an example of a vertical furnace.

ASTM E119 — HORIZONTAL FURNACE

Slide 3-31

- The picture shows an example of a horizontal furnace.

ASTM E648

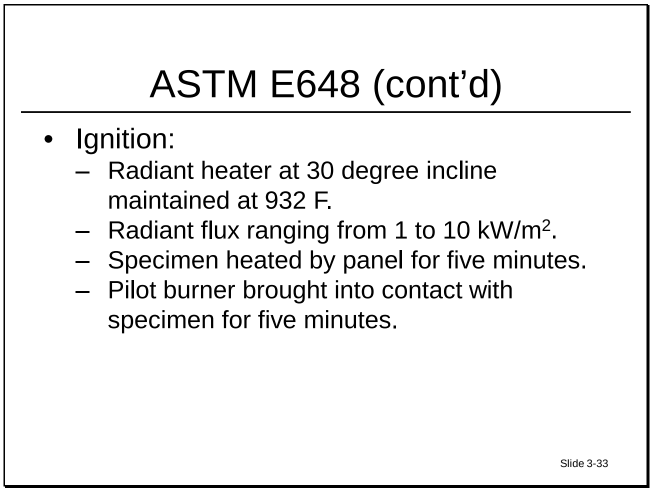
- Critical ignition flux of floor covering.
- Sample size: 8 inches (W) by 39 inches (L) by 2 inches (T); horizontally mounted.

Slide 3-32

J. The ASTM E648 standard evaluates the critical flux required to ignite floor coverings, such as carpet and hardwood.

1. The test is designed specifically for flooring systems that may be used in building exit corridors.

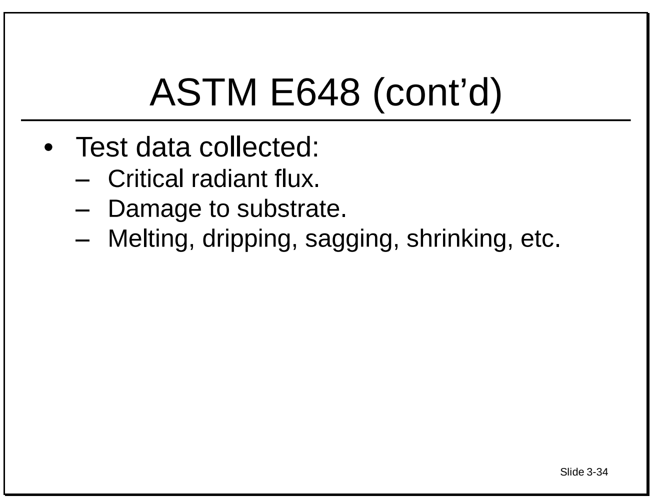
2. Samples are subjected to a radiant panel in the horizontally mounted position.



3. The specimens are preheated by the panel and then exposed to a small pilot flame for five minutes.

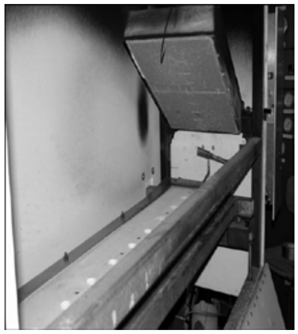
a. If the specimen does not ignite within the preheat or pilot exposure period, the test is terminated.

b. If it does ignite, the flame spread is monitored until the flame reaches the end of the specimen.



4. The critical flux and flame spread data are collected as well as any other pertinent information related to the behavior of the specimen.

ASTM E648 (cont'd)

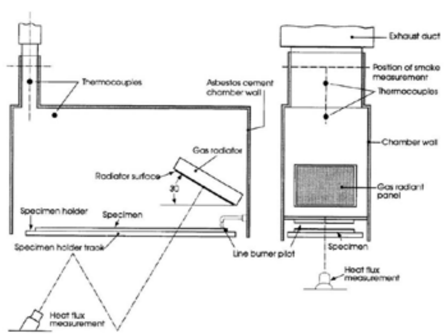


Slide 3-35

5. The apparatus:

   a. This is the apparatus, showing the horizontal mounting position of the panel and specimen.

ASTM E648 (cont'd)



Slide 3-36

   b. This is a side view of the apparatus, showing all of its components.

ASTM E1321

- Lateral ignition and flame spread.
- Radiant heater at 15 degree incline.
- Ignition test:
  - 6 inches by 6 inches, thermally thick.
  - Uniform flux of 30 kW/m^2 with pilot (adjust down until no ignition occurs).

Slide 3-37

K. ASTM 1321 evaluates lateral ignition and flame spread using a device known as the lateral ignition and flame spread test (LIFT) apparatus. It is similar in concept to the ASTM E648 apparatus, with the exception of its vertical orientation.

1. The sample can be of two different sizes depending on whether the ignition or the spread test is being performed.

2. The sample is required to be thermally thick (typically greater than 1 millimeter as a rule of thumb).

3. For ignition testing, the sample is exposed to a starting flux of 30 kilowatts per meter squared (kW/m^2).

   a. The flux is then adjusted down until no ignition of the material occurs.

   b. The critical ignition flux is then determined.

ASTM E1321 (cont'd)

- Spread test:
  - 6 inches by 31.5 inches, thermally thick.
  - 5 kW/m^2 higher than minimum for ignition.

Slide 3-38

4. For the spread test, the sample is exposed to a flux that is 5 kW/m^2 higher than the minimum flux needed for ignition as determined in the ignition test.

ASTM E1321 (cont'd)

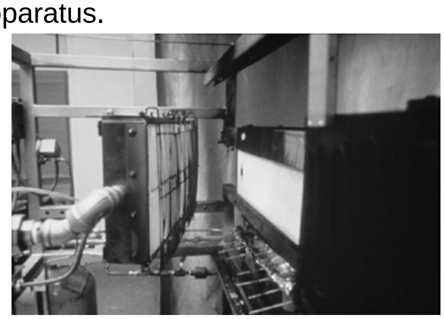
- Test data collected:
  - Minimum surface flux and temperature for ignition.
  - Minimum surface flux and temperature for lateral spread.
  - Thermal inertia (kiloparsec (kρc)).
  - Flame heating parameter.

Slide 3-39

5. Various parameters are calculated based on the collected data to represent the flammability associated with the material.

ASTM E1321 (cont'd)

- Lateral ignition and flame spread test apparatus.



Slide 3-40

6. This is a picture of the LIFT apparatus.

II. PHYSICAL MODELING

A. The previous unit discussed a few of many standardized tests that are used to evaluate the fire hazards and flammability characteristics of interior finishes and building materials and assemblies. Now, we will move onto a discussion of physical fire modeling to evaluate the performance of materials under user-defined conditions.

NFPA 921 – ROLE OF FIRE TESTING

- Provides data that complements data collected at the scene.
- Provides insights into the characteristics of fuels or items consumed in the fire.
- Used to test hypotheses.
  - Is hypothesis consistent with the case facts and the laws of fire science?
- Ranges from bench-scale to full-scale.

Slide 3-41

1. According to NFPA 921, fire testing can serve to complement data collected at the fire scene, provide additional insight, and test hypotheses.

2. Depending on the specific requirements or desired outcomes, testing may be performed in a small-scale or full-scale environment.

NFPA 921 – ROLE OF FIRE TESTING (cont'd)

- Should follow or be modeled after standard tests or test methods reported in the literature.
  - Contributes to the scientific credibility of the results.
- Testing not performed to a recognized standard should be consistent with the **relevant facts** of the case.

Slide 3-42

B. It is always helpful to model the test after one that has an established track record.

1. When testing modeled after a standardized or recognized testing method is not feasible, it is important to ensure that the developed test methodology is based on the relevant facts of the case.

   a. Developing a test to prove a theory that is not supported by the facts of the case is misleading and biased.

   b. Where no facts exist to support a hypothesis, the hypothesis should be discarded.

NFPA 921 – ROLE OF FIRE TESTING (cont'd)

- Test design should eliminate:
  - Expectation bias.
    - Premature conclusion without having examined or considered all the relevant data.
    - Using data that only supports the previously drawn conclusion.
    - Discarding data when it doesn't support conclusion.

Slide 3-43

2. The test should be designed such that expectation bias is eliminated.

NFPA 921 – ROLE OF FIRE TESTING (cont'd)

- Confirmation bias.
  - Attempting to prove a hypothesis rather than disprove a hypothesis.
  - Failure to consider alternative hypotheses.
- Presumption.
  - Developing opinions prior to data collection and hypotheses testing.

Slide 3-44

3. The test should be designed to eliminate confirmation bias and presumption.

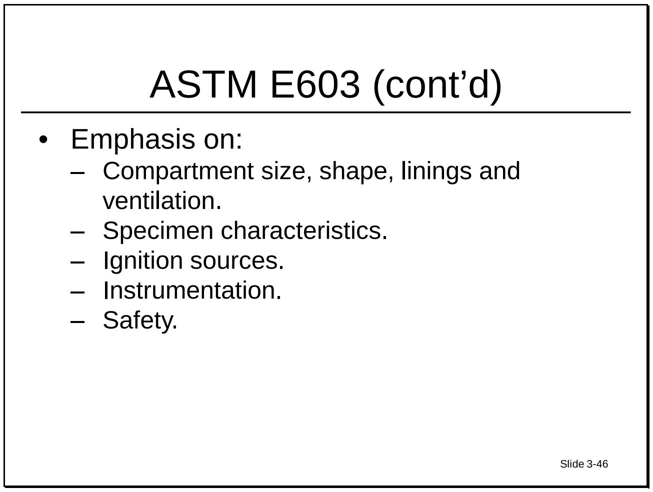
ASTM E603

- Guide for Room Fire Experiments.
  - Assists with planning of full-scale compartment fire experiments.

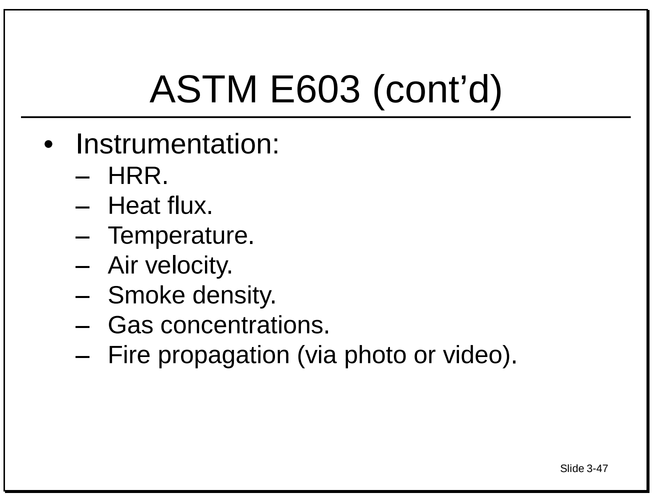
Slide 3-45

C. ASTM E603.

1. The ASTM E603 document is a guide, not a standard. It assists researchers in developing full-scale fire tests by providing a “methodology” to follow.



2. It stresses the importance of determining the appropriate compartment size, ventilation, lining, ignition sources, instrumentation, safety and specimen characteristics to address the research question.



3. The guide recommends that the following items be measured when conducting a full-scale test:

a. HRR.

b. Heat flux.

c. Temperature.

d. Air velocity.

e. Smoke density.

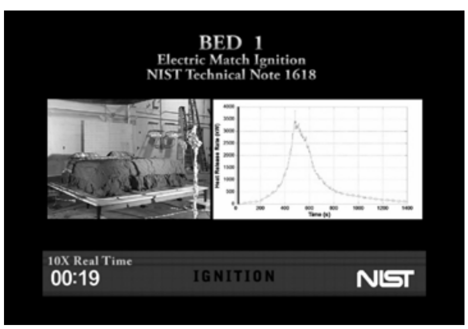
f. Gas concentrations.

g. Fire propagation (via photo or video).

ISO LIVING ROOM FLASHOVER

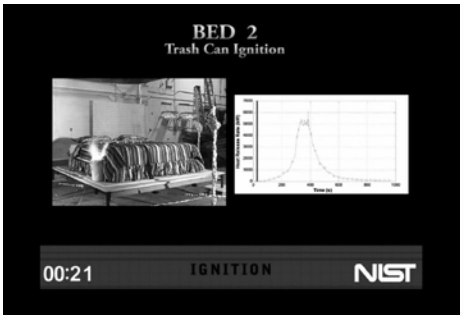
Slide 3-48

BED 1 — ELECTRIC MATCH IGNITION



Slide 3-49

BED 2 — TRASH CAN IGNITION



Slide 3-50

III. METHODOLOGY FOR CONDUCTING A FIRE TEST

METHODOLOGY FOR CONDUCTING A FIRE TEST

Read more: How to Conduct a Scientific Experiment at eHow.com: http://www.ehow.com/how_5101362_conduct-scientific-experiment.html#ixzz1am2p2wXh.

Slide 3-51

A. A sound methodology should be utilized to support the development of any test method and ensure the elimination of bias and presumption.

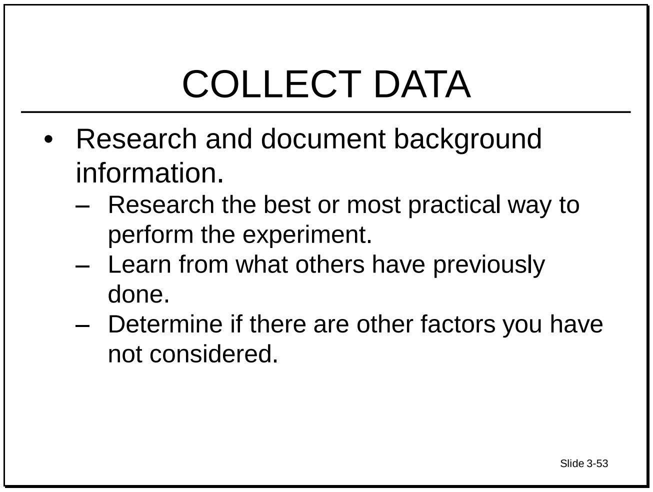
DEFINE THE PROBLEM

- State the purpose: “To get a better understanding of ... ”
  - Can a tossed cigarette ignite a pool of gasoline?
  - How long will the couch smolder?
  - Is the candle a competent ignition source for an artificial Christmas wreath?
  - Is the loveseat the only fuel needed to flash over the compartment?

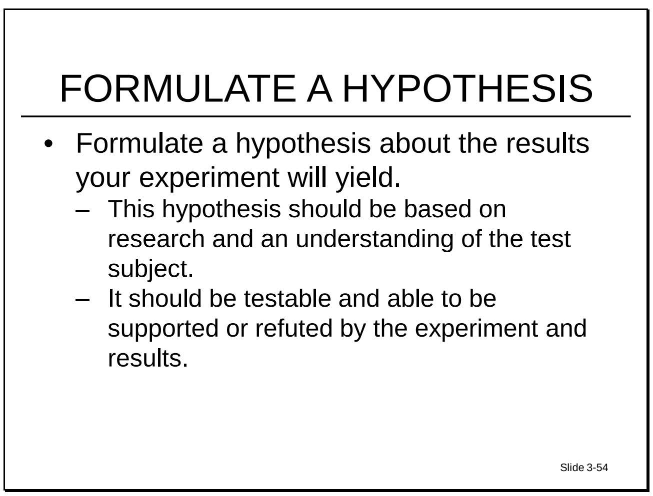
Slide 3-52

B. There are various steps to this methodology.

1. The first step in test development is to define the problem.



2. Second, background information on the topic must be researched and documented.



3. Next, a hypothesis must be formulated based on the background information.

PROPOSE AN EXPERIMENT

- Review experiment proposal with peers.
  - Identify and eliminate bias and presumption.
- Develop a well-defined, reproducible experiment that can be performed by others.
- Establish which variables to test — limit the number of variables.
- Establish what data to collect.

Slide 3-55

4. The fourth step in the test development is to design and propose an experiment to evaluate the problem.

   a. Experiments should include a control group to serve as a comparison.

   b. Only one element should be varied among test groups. Too many variables will lead to inconclusive results.

PROPOSE AN EXPERIMENT (cont'd)

- Determine number of experiments needed for scientific validity.

Slide 3-56

   c. Any test performed should be reproducible.

   d. Enough information about the test setup and design must be provided and documented to allow for reproduction by another party.

GATHER MATERIALS

- Assess the impact of materials on test outcomes based on the stated purpose of the tests.
- Materials selection.
  - Test structure.
  - Contents.
  - Ignition source.

Slide 3-57

5. Gather and set up materials needed to conduct the experiment.

GATHER MATERIALS (cont'd)

- Gather directly from the scene.
- Purchase exemplars.

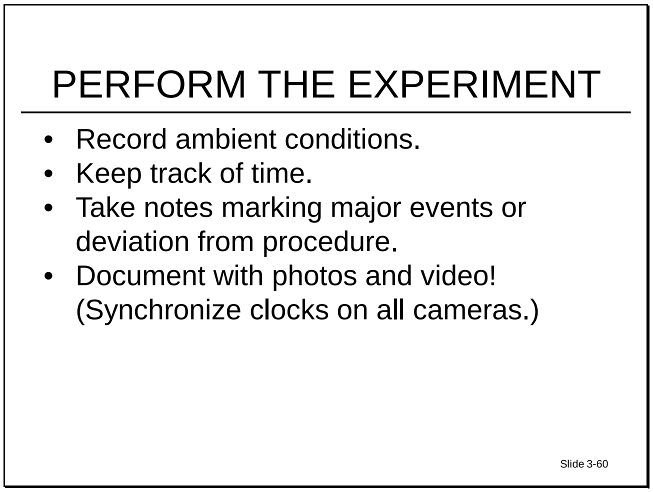
Slide 3-58

DOCUMENT SETUP

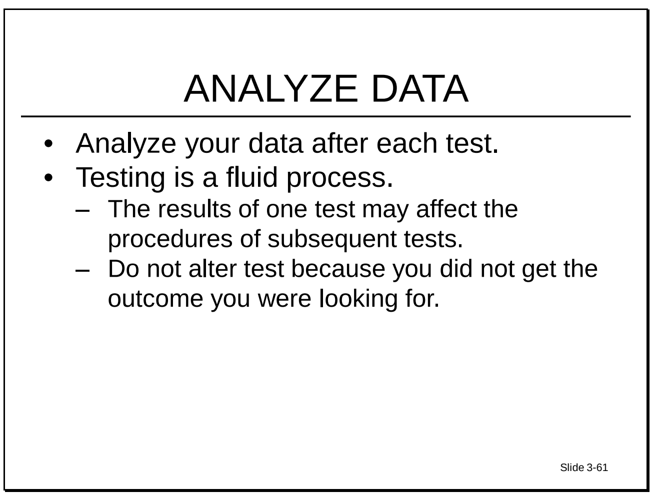
- Make a drawing or test schematic.
- Note the specific items, configuration and quantities for each test. (They may differ between tests.)
- Outline all procedures and variables.
- Have a safety briefing, including multiple methods to extinguish the fire.

Slide 3-59

6. An important part of any test is documentation. Any test performed should be reproducible. Hence, enough information about the test setup and design must be provided and documented to allow for reproduction by another party.



7. Perform the experiment, documenting all relevant data and observations.



8. Then, organize the data so that any patterns or trends in the results become evident and can be easily compared.

RESULTS AND CONCLUSIONS

- Determine what the data means in the context of your investigation.
- Does the data support or refute a potential hypothesis?
- Is the data consistent with the other facts or evidence from the case?
  - Resolve inconsistencies.

Slide 3-62

9. Finally, analyze the results to derive any conclusions.

   a. Was the hypothesis supported or refuted by the data? Why or why not?

   b. Were there any problems with the experiment or with collecting the data that should be addressed by performing a newly designed experiment?

      - If so, what were the problems?

      - What format would a new experiment take that would eliminate such problems?

IV. THE LIMITS OF PHYSICAL MODELING

THE LIMITS OF PHYSCIAL MODELING

- Conditions will not be exactly as they were at the time of the incident.
- Establish that potential differences do not significantly affect outcomes.
- The test is not a …
  - Recreation.
  - Reconstruction.
  - Re-enactment.

Slide 3-63

A. There are some important limitations that must be considered when conducting fire tests.

1. An investigator will never be able to reproduce, recreate, reconstruct or re-enact what happened at the fire scene.

2. It is impossible to guarantee that the conditions of testing are exactly the same as those at the time of the incident.

a. It is important to determine if sufficient information is available to develop a sound test method.

b. In some cases, insufficient information is available to perform physical modeling.

c. If the unknowns are numerous, then the value of the test is not discernible.

FULL-SCALE VERSUS SMALL-SCALE

Pros:
- Better experimental control.
- Replicate testing.
- Less expensive.
- Vary more parameters.

Cons:
- Physical fire properties do not scale the same.
- Less like the "real thing."
- Test facility may cause differences.
- Test uncertainties due to materials, weather, source of ignition.

Slide 3-64

B. There are pros and cons to performing full-scale versus small-scale testing.

1. In some cases, full-scale testing may be unnecessary to evaluate a specific issue.

2. In other cases, financial limitations may make full-scale testing unfeasible.

FIRE TESTING — MODELING

- Provides input data for models.
- Provides benchmark data to assess model accuracy and applicability.
- Provides insight into differences between standardized, experimental and theoretical outputs.

Slide 3-65

C. Fire tests are useful in cases where modeling is to be conducted. In some cases, available data may be such that important inputs are not available for the model.

D. The graph provides a comparison of standard test data (yellow) against measured (experimental) test data (green) versus derived (theoretical) test data (blue).

V. SOURCES OF DATA

SOURCES OF DATA

- ASTM.
- National Institute of Standards and Technology (NIST).
- UL.
- FMRC.

Slide 3-66

There are various sources of data related to standardized and nonstandardized tests.

SOURCES OF DATA (cont'd)

- SwRI.
- NFPA.
- ISO.
- Society of Fire Protection Engineers (SFPE).

Slide 3-67

A. These sources can be helpful in collecting input data for modeling or for evaluating the performance of a material when full-scale or standardized testing cannot be performed.

SOURCES OF DATA (cont'd)

- NIST — fire on the Web.
  - Test data.
  - Moving Picture Experts Group (MPEG)/QuickTime movies of fire tests.
  - Publications.
  - Software/Models.
  - http://nist.gov/fire.

Slide 3-68

B. Additional sources of data can be found on the National Institute of Standards and Technology (NIST) website.

VI. IGNITION TESTING FOR FIRE INVESTIGATION

IGNITION TESTING
FOR FIRE INVESTIGATION

Slide 3-69

A. The following slides present information about five fire tests that were developed to evaluate potential fire causes and the competency of fuels and ignition sources related to those causes.

HOW DO YOU PROVE A NEGATIVE?

"No amount of experimentation can ever prove me right; a single experiment can prove me wrong." — Albert Einstein

Slide 3-70

B. The purpose of experimental testing is not to prove that a hypothesis is correct but rather to determine if the hypothesis can stand the test of scientific challenge.

CHARCOAL BRIQUETTES IN A TRASH CAN

Slide 3-71

C. Charcoal briquettes in a trash can.

1. A fire started at a church. Investigators identified charcoal incense briquettes as a potential ignition source.

2. According to a church official, the briquettes were used for the first time during mass. The official stated that he took the briquettes out of the holder, placed them in a wet paper towel, and squeezed them. Once they felt cool to the touch, he then placed them in a plastic trash container.

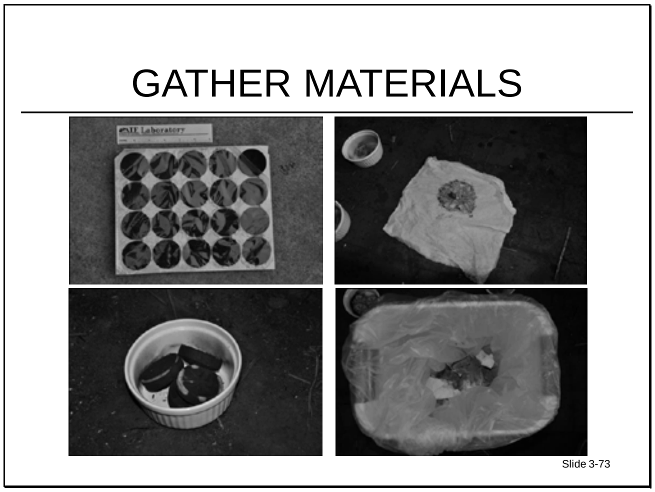
3. Approximately 90 minutes after the briquettes were placed in the trash, flames were visible outside the church at the roofline. No one was present in the church at the time of the fire.

CHARCOAL BRIQUETTES IN A TRASH CAN

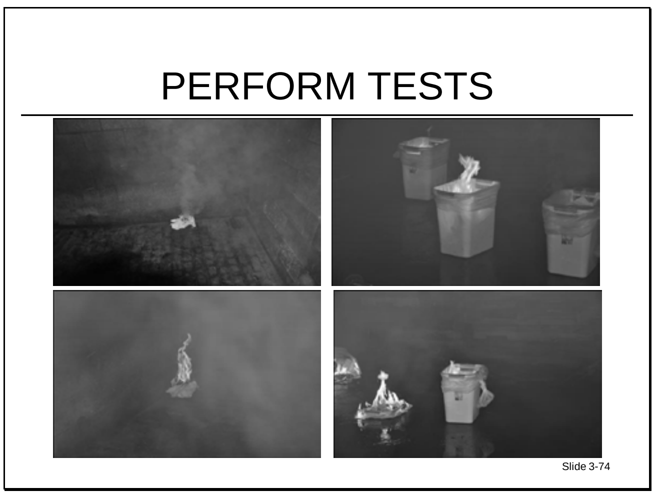
Purpose: Determine if partially burned coals (two to three hours of preburn) are a competent ignition source for paper towels (wet and dry) in a trash can.

Slide 3-72

4. Physical testing was conducted to evaluate if smoldering briquettes that were crushed in a damp paper towel could ignite the plastic trash can or its contents.



5. The exact same briquettes, trash can liners and trash containers were purchased for testing to minimize variables. The ignition sequence was evaluated both outside and inside the trash containers.



6. Multiple tests were conducted to evaluate several different scenarios. The preburn time of the briquette was varied as well as the relative moisture of the paper towel.

7. Dry paper towels began to smoke almost instantly, followed by flaming combustion several minutes later. This smoke would likely have been noticed prior to the church official leaving the office.

8. Wet paper towels took about 20 minutes to begin to smolder prior to visible smoke production. Hence, the church official would not have observed any smoke when he discarded the briquettes in the trash can and before he left the church. In more than three tests, the smoldering towel ignited and flames spread to the trash can within 90 minutes.

ANALYZE DATA

- The most significant variable affecting the likelihood of ignition was the extent of time the charcoal briquettes were allowed to preburn.
  - When the preburn duration was increased, the likelihood of ignition decreased.

Slide 3-75

9. Testing showed that the accidental ignition scenario involving the briquettes was highly probable, with ignition occurring in eight out of 10 tests. Simple field tests confirmed that the ignition sequence was competent.

ANALYZE DATA (cont'd)

- Flaming ignition of the trash can occurred:
  - When the coals were wrapped in a dry or wet paper towel.
  - When they were put directly atop paper towels in the trash can.

Slide 3-76

LIGHT FIXTURE IGNITION OF STYROFOAM

Slide 3-77

D. Light fixture ignition of Styrofoam.

1. A closet inside a laboratory on the campus of Colorado State University was determined to be the area of origin in a fire. The closet contained two recessed lights. Based on the position of the light switch, it was determined that the lights were on at the time of the fire.

2. A Styrofoam cooler that sat on the top shelf of the closet was pressed tightly against one of the recessed lights such that it was obscured from view, and most employees at the lab thought that there was only one light in the closet. Investigators hypothesized that the light may have ignited the cooler.

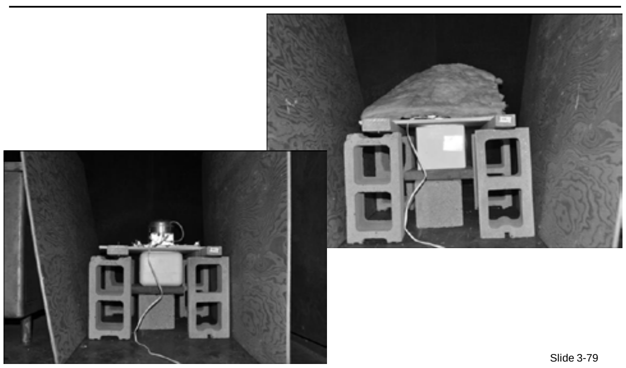
LIGHT FIXTURE IGNITION OF STYROFOAM

Purpose: To get a better understanding of whether or not a recessed light fixture with a 100 W bulb covered in roll-in batt insulation will ignite a Styrofoam cooler stored below.

Slide 3-78

3. The purpose of the testing was to determine if the recessed light was capable of igniting the Styrofoam cooler.

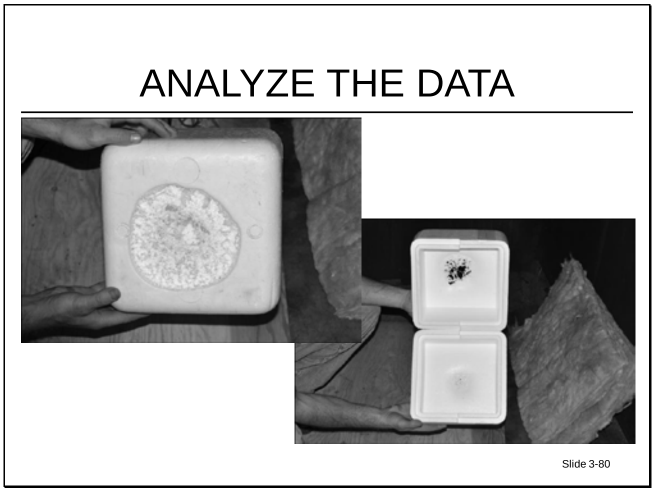
PERFORM THE TESTS



Slide 3-79

4. Materials were purchased from a local hardware store and configured as they were at the time of the fire. The thermal cutoff was removed from the test light since no apparent safety device was present in the incident light.

5. The light was hung from a piece of drop ceiling. Insulation was placed on top of the light, and an exemplar Styrofoam cooler, supplied by the laboratory, was placed in contact with the light.



6. As the Styrofoam was heated, it began to melt away from the heat source. The picture shows the damage to the Styrofoam after approximately one hour of exposure to the light.

7. It is unlikely that the Styrofoam was the first item ignited since the fuel melted away from the ignition source over time.

8. Testing was not conducted to determine if a recessed light that is insulated on the top and the bottom (Styrofoam cooler) is a competent ignition source of wood studs in the attic space.

BABY CARRIER ON A STOVE

Slide 3-81

E. Baby carrier on a stove.

1. Federal investigators have worked on several cases where baby carriers containing an infant were placed on top of electric ranges. In all of these cases, the stove turned on, the baby carrier caught on fire, and the infant died.

BAY CARRIER ON A STOVE

Purpose: To get a better understanding of whether or not a baby carrier placed on a stove top can accidentally turn on a range element.

Slide 3-82

2. The purpose of the testing was to determine if the stove could accidentally be turned on when the carrier was placed on top of it.

GATHER MATERIALS

Slide 3-83

3. An infant was left in the care of the infant's mother's ex-husband. An exemplar stove and infant car seat were purchased for testing.

PERFORM THE TESTS

Slide 3-84

4. It was determined that the burner knob could be accidentally knocked to the “on” position when the carrier was placed on top of the stove.

SPONGEBOB SQUAREPANTS LAUNDRY BAG

Slide 3-85

F. SpongeBob SquarePants laundry bag.

1. A fire occurred in a single-family house in a rural area of Pennsylvania. Two children under the age of 5 were found dead in their bedroom.

2. The area just inside of the bedroom doorway was determined to be the area of origin based on witness observations and burn damage. A SpongeBob SquarePants laundry bag was hanging on the inside of the bedroom door and was believed to be the first item ignited.

3. Investigators performed testing to determine if a cigarette lighter was a competent ignition source. Specifically, they were focused on the duration of time that the lighter would have to be placed on the laundry basket to initiate fire spread.

4. The mother of the children claimed that she was lighting a cigarette as she was leaving the children's room and must have accidentally made contact with the bag as she walked by it.

SPONGEBOB SQUAREPANTS LAUNDRY BAG

- Purpose: To get a better understanding of whether or not a butane lighter that is accidentally brushed across the surface of a hanging SpongeBob SquarePants laundry bag will cause it to ignite.

Slide 3-86

5. The purpose of the testing was to determine if the laundry bag could have been accidently ignited from momentary exposure of the bag to a lighter flame.

DVD PRESENTATION

"SPONGEBOB VIDEO"

Slide 3-87

SPONGEBOB SQUAREPANTS LAUNDRY BAG (cont'd)

- Results: Testing showed that the fire was not caused by momentary accidental contact of the lighter with the laundry basket.
- The fire was determined to be incendiary.

Slide 3-88

6. The testing showed that the lighter would have to be placed on the laundry bag for multiple seconds prior to sustained flame spread. Momentarily brushing the laundry basket with the flame from the lighter was not sufficient to ignite and spread flames on the basket.

DVD PRESENTATION

"CIGARETTE IGNITION OF GASOLINE"

Slide 3-89

CIGARETTE IGNITION OF GASOLINE

Purpose: To get a better understanding of whether or not a lit cigarette is a competent ignition source for gasoline vapors at normal atmospheric conditions.

Slide 3-90

G. Cigarette ignition of gasoline.

1. The purpose of testing was to determine if a lit cigarette was capable of igniting gasoline vapors under various test configurations.

CIGARETTE IGNITION OF GASOLINE VAPORS

- History/Literature.
  - No scientist has ignited gasoline with a burning cigarette in a controlled laboratory environment.
  - Literature prior to 2004 suggested that more tests were needed to put the negative results on a more sound basis.
  - It is impossible to prove with absolute certainty that something will not happen.

Slide 3-91

2. Previous laboratory experimentation has shown that a lit cigarette is not a competent ignition source for gasoline vapors, even though this is a common belief in the general population.

3. Experimentation can never prove something with 100 percent certainty, but it can increase the level of confidence in the hypothesis.

CIGARETTE IGNITION OF GASOLINE VAPORS (cont'd)

- Experimental variables.
  - Targets.
    - -- Gasoline pools, soaked fabrics, vapors above/ beside pools, and gasoline spray.
    - -- Freshly poured gasoline and "weathered" pools.
    - -- Different brands and octane levels.

Slide 3-92

4. Experiments focused on various configurations, including pools/pans of gasoline, gasoline on textile substrates (clothing), and sprays of gasoline.

5. Researchers evaluated fresh and "weathered" gasoline as well as different octanes of gasoline.

CIGARETTE IGNITION OF GASOLINE VAPORS (cont'd)

- Ignition sources.
  - Popular commercial cigarettes (various brands, filtered, nonfiltered).
  - Idling cigarettes and cigarettes under draw.
  - With and without ash attached.
  - Glowing tobacco fragments.

Slide 3-93

6. Five major brands of commercially manufactured tobacco cigarettes were tested.

CIGARETTE IGNITION OF GASOLINE VAPORS (cont'd)

- Ambient conditions.
  - Temperature.
  - Humidity.
  - Wind speed.

Slide 3-94

IGNITION FACTORS

- Auto-ignition temperature (500 C).
- Flammability limits (1 to 6 percent).
- Flash point (87 C).
- Fuel + Heat + O_2 = Flame.

Slide 3-95

7. Gasoline has an auto-ignition temperature of 500 C, a flammability range of 1 percent to 6 percent, and a flash point of 87 C.

CIGARETTE COAL TEMPERATURES

	Solid Phase Temperature	Gas Phase Temperature
Induced Smoldering (Puffing)	900 C to 950 C (Max reported 1,200 C)	About 850 C
Natural Smoldering	700 C to 850 C	700 C to 850 C

Slide 3-96

8. The cigarette coals had higher temperature ranges during induced smoldering when compared to natural smoldering.

IGNITION FACTORS (cont'd)

- Ignition delay (time for ignition).
- Contact time — energy and fuel.
- Minimum ignition energy.
- Gas movement.
- Surface effects.

Slide 3-97

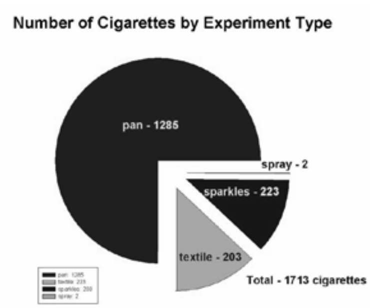
9. Various ignition factors need to be considered when determining if the cigarette is a competent ignition source for the gasoline vapors.

DVD PRESENTATION

“CIGARETTES IN PAN OVER GASOLINE”

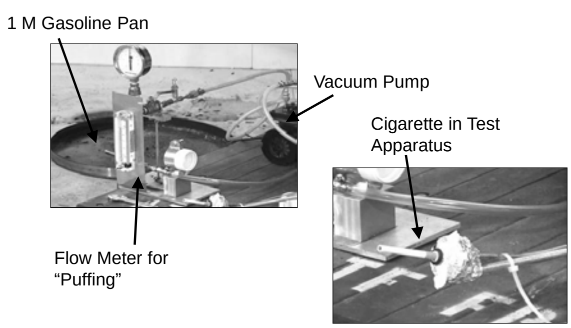
Slide 3-98

CIGARETTE IGNITION OF GASOLINE VAPORS (cont’d)



Slide 3-99

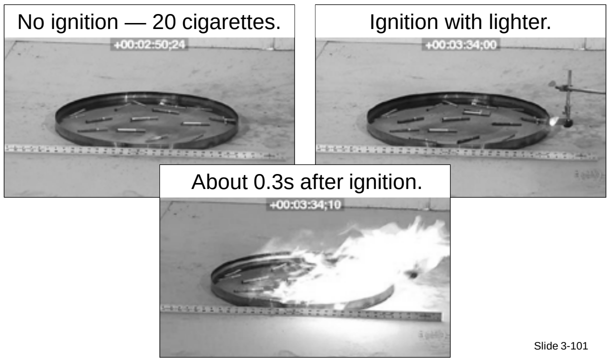
TESTING APPARATUS



Slide 3-100

10. The slide depicts the testing apparatus that was used to create the simulated drag on the cigarettes.

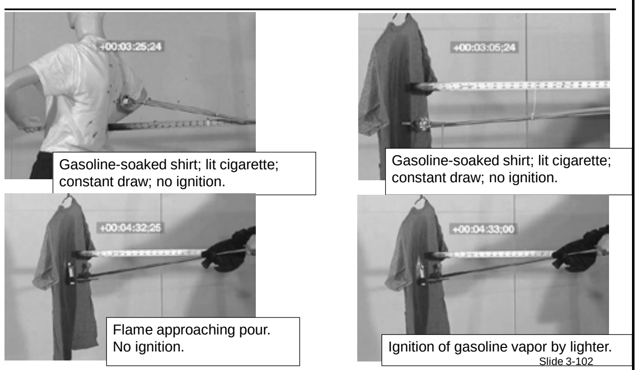
POOL IGNITION TESTS



Slide 3-101

11. Pools of gasoline were not ignited after exposure to 20 lit cigarettes.

FABRIC IGNITION TESTS



Slide 3-102

12. Gasoline-soaked fabric did not ignite after exposure to lit cigarettes.

RESULTS

Thus, 1,700 or more cigarettes, amounting to more than 2,000 “probes” of vapor by cigarettes, over a wide range of conditions, yielded zero ignitions.

Slide 3-103

13. After thousands of tests, the lit cigarettes did not ignite the gasoline vapors under any test conditions.

CONCLUSIONS

- The ignition of gasoline vapors by a burning cigarette is a most highly unlikely event.
- Scientists have never been able to ignite gasoline vapors with a burning cigarette.

Slide 3-104

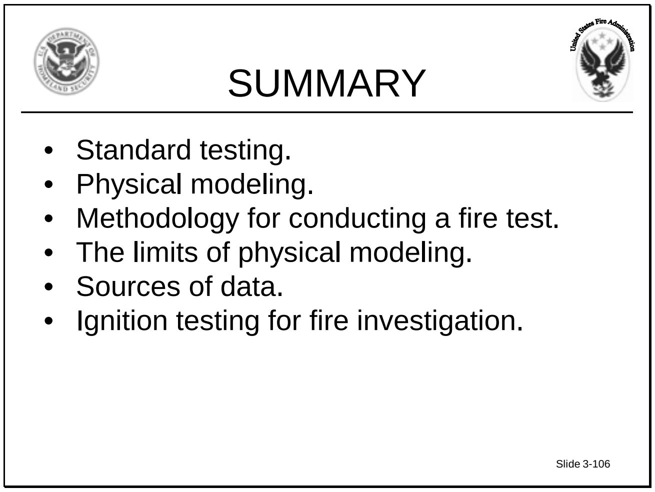
14. The ignition of gasoline vapors by a lit cigarette is highly improbable. The lit cigarette is not a competent ignition for gasoline vapors.

CONCLUSIONS (cont'd)

- It is not my opinion that a glowing cigarette is an impossible source of ignition for gasoline vapor.
- Produced compelling visual tool for investigators and the courts.

Slide 3-105

VII. SUMMARY


SUMMARY
• Standard testing.
• Physical modeling.
• Methodology for conducting a fire test.
• The limits of physical modeling.
• Sources of data.
• Ignition testing for fire investigation.
Slide 3-106

UNIT 4: MATHEMATICAL MODELING

TERMINAL OBJECTIVE

The students will be able to:

4.1 Identify and use basic mathematical models for estimating a variety of fire behaviors.

ENABLING OBJECTIVES

The students will be able to:

4.1 Differentiate between the Certified Fire Investigator (CFI) Calculator Tool and the U.S. Nuclear Regulatory Commission's (NRC's) fire dynamics tools (FDTs).

4.2 Use the appropriate fire dynamics calculations to analyze specific problems.

4.3 Obtain the expected output parameters using the various input parameters.

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UNIT 4:
MATHEMATICAL MODELING

Slide 4-1

ENABLING OBJECTIVES

- Differentiate between the Certified Fire Investigator (CFI) Calculator Tool and the U.S. Nuclear Regulatory Commission's (NRC's) fire dynamics tools (FDTs).
- Use the appropriate fire dynamics calculations to analyze specific problems.
- Obtain the expected output parameters using the various input parameters.

Slide 4-2

I. OVERVIEW OF MODELS

OVERVIEW OF MODELS

- Typically based upon steady-state conditions.
- Calculated for a single point in time.
- In some cases based on a specific data set (empirical).
- Many limitations and assumptions.

Slide 4-3

SOURCES OF EQUATIONS

- Some equations have been derived using scientific/engineering analysis methods.
- Based upon fundamental scientific laws:
  - Conservation of Energy.
  - Conservation of Mass.
  - Conservation of Momentum.

Slide 4-4

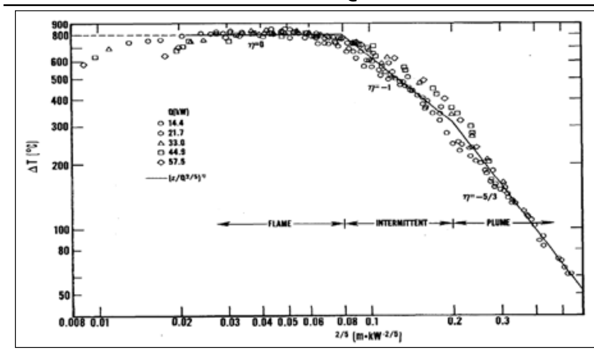
A. Some equations and tools have been derived using common scientific/engineering analysis methods, based upon fundamental scientific laws:

1. Conservation of Energy.

2. Conservation of Mass.

3. Conservation of Momentum.

EMPIRICAL EQUATIONS

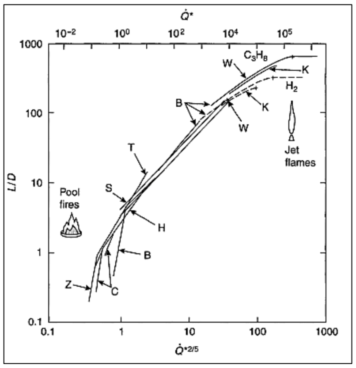


Slide 4-5

B. Empirical equations are derived after experiments are conducted and data is collected.

1. This slide depicts the change in temperature between the consistent flame, intermittent flame and plume zones.

EMPIRICAL EQUATIONS (cont'd)



Slide 4-6

2. The specific constants used in the equations come from formulas of curves that are determined to be a "best fit" for the data. Note that not all data points fall directly on the line, so an inherent error can result when using the formulas.

FIRE DYNAMICS CALCULATIONS

- Remember that these calculations are estimates (at best) and do not prove anything.
- We are trying to "bound" the problem.
  - What is the likely maximum/minimum?
- If our calculated answers don't seem to fit what we observe at the scene, we have to ask, "What is different, missing or wrong?"

Slide 4-7

C. Remember that these calculations are estimates (at best) and do not prove anything.

1. We are trying to "bound" the problem.

2. What is the likely maximum/minimum?

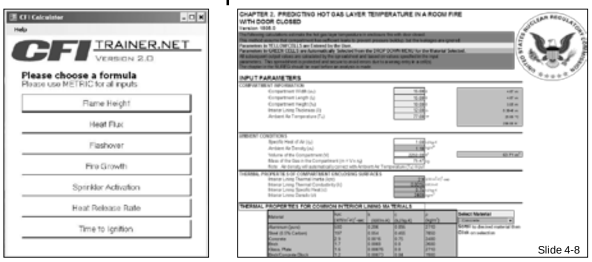
3. If our calculated answers do not fit what we observe at the scene, we have to ask, "What is different, missing or wrong?"

4. Is it our estimations? Inputs? Understanding of the fire scene?

5. Such calculations help us to test our hypotheses.

COMMON TOOLS

- International Association of Arson Investigators (IAAI) — CFI Calculator.
- NRC — FDT spreadsheets.



Slide 4-8

D. There are some fire-specific tools:

1. The Certified Fire Investigator (CFI) Calculator is a tool that can be used to assist with fire dynamics hand calculations.

2. Another set of tools is the U.S. Nuclear Regulatory Commission's (NRC's) set of spreadsheets called "fire dynamics tools" (FDTs).

USES

- Testing hypotheses.
- Proving estimates.
- Bounding the problem.
- Evaluating data.
  - Witness' statements.
  - Damage patterns.
  - Timeline of events.

Slide 4-9

E. Why use the CFI Calculator and/or FDTs?

1. They allow investigators to test their hypotheses and opinions related to ignition, growth, development and spread.

2. Investigators can also use the tools to evaluate witness' statements.

3. Bounding the problem.

4. The tools can be used for hypothesis testing to include:

a. Heat release rate (HRR).

b. HRR/Flame height.

c. Radiant heat flux.

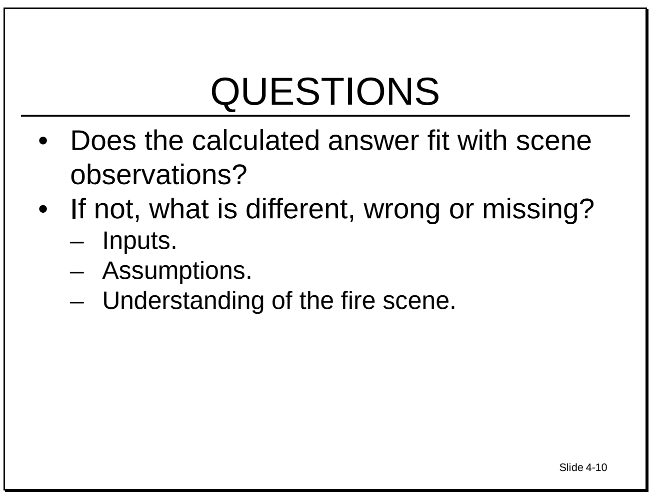
d. Flashover energy.

e. Fire growth/Time to flashover.

f. Time to ignition.

g. Upper layer gas temperature.

h. Sprinkler/Detector activation.

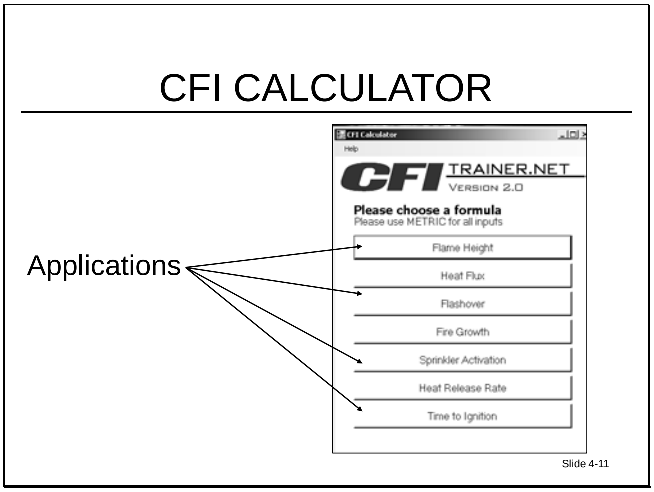


F. Does the calculated answer fit with scene observations? If not, what is different, wrong or missing?

1. Inputs.

2. Assumptions.

3. Understanding of the fire scene.



G. CFI Calculator.

1. Primary user interface or "home page" contains the fundamental fire dynamics applications.

2. Additionally, the help/additional information menu can be accessed.

CFI CALCULATOR (cont'd)

- Developed by IAAI (www.cfitrainer.net).
- Calculations that can be run on a Windows computer.
- Simplified algebraic calculations for use in seven types of problems.
- Can be run at a fire scene or in the office using computers or smartphones.

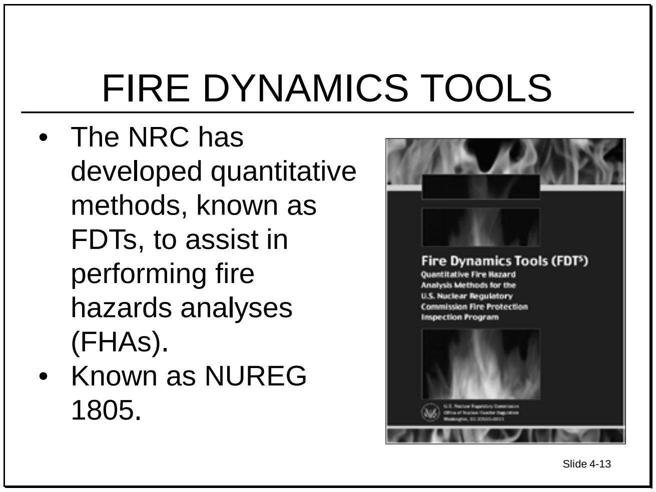
Slide 4-12

3. Developed by International Association of Arson Investigators (IAAI) (www.cfitrainer.net).

4. Calculations that can be run on a Windows computer.

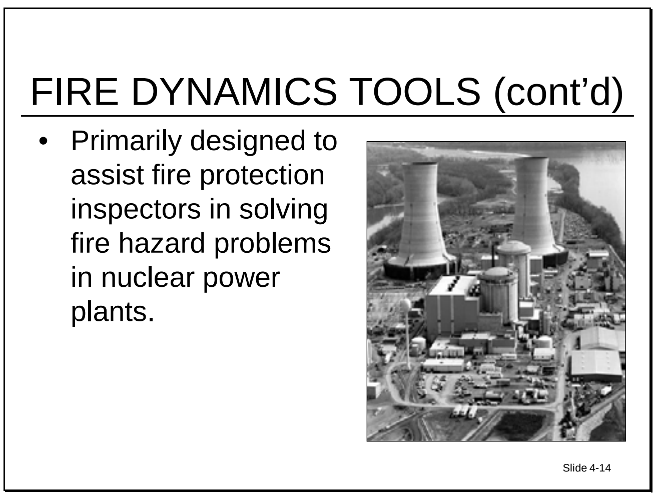
5. Simplified algebraic calculations for use in seven types of problems.

6. Can be run at a fire scene or in the office using computers or smartphones.



H. The NRC has developed quantitative methods, known as FDTs, to assist in performing fire hazards analyses (FHAs).

1. Known as NUREG 1805.



2. Primarily designed to assist fire protection inspectors in solving fire hazard problems in nuclear power plants.

FIRE DYNAMICS TOOLS (cont'd)

- Can also be used by fire protection engineers and investigators to solve problems.

Slide 4-15

3. Can also be used by fire protection engineers and investigators to solve problems.

FIRE DYNAMICS TOOLS (cont'd)

- Based on quantitative methods developed to describe fire and related processes (i.e., ignition, flame spread, fire growth and smoke movement) and their effects in an enclosure.
- The methodology uses simplified FHA techniques for credible fire scenarios integrated into a series of Microsoft Excel spreadsheets.

Slide 4-16

4. Based on quantitative methods developed to describe fire and related processes (i.e., ignition, flame spread, fire growth and smoke movement) and their effects in an enclosure.

5. The methodology uses simplified FHA techniques for credible fire scenarios integrated into a series of Microsoft Excel spreadsheets.

FIRE DYNAMICS TOOLS (cont'd)

- The spreadsheets are designed to incorporate empirical correlations and mathematical calculations based upon fire dynamics principles.
- Users enter in the required data, and the spreadsheets automatically calculate the results.

Slide 4-17

6. The spreadsheets are designed to incorporate empirical correlations and mathematical calculations based upon fire dynamics principles.

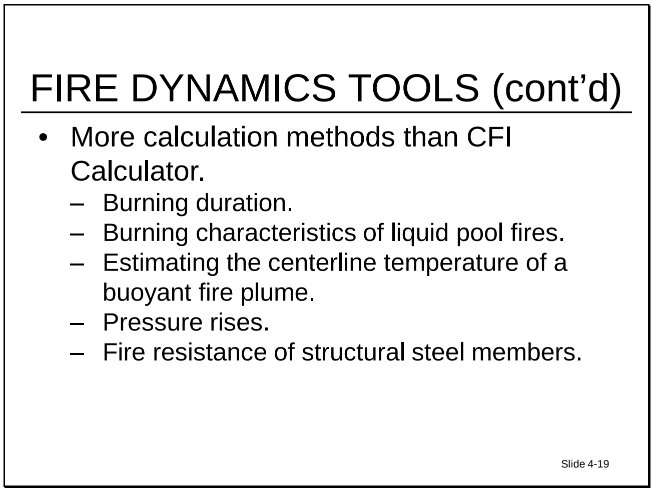
7. Users enter in the required data, and the spreadsheets automatically calculate the results.

FIRE DYNAMICS TOOLS (cont'd)

- NUREG 1805 and spreadsheets can be downloaded at http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1805/s1/sr1805-sup1-vols-1-2.html.

Slide 4-18

8. NUREG 1805 and spreadsheets can be downloaded at http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1805/s1/sr1805-sup1-vols-1-2.html.



I. NUREG 1805 features more calculation methods than CFI Calculator.

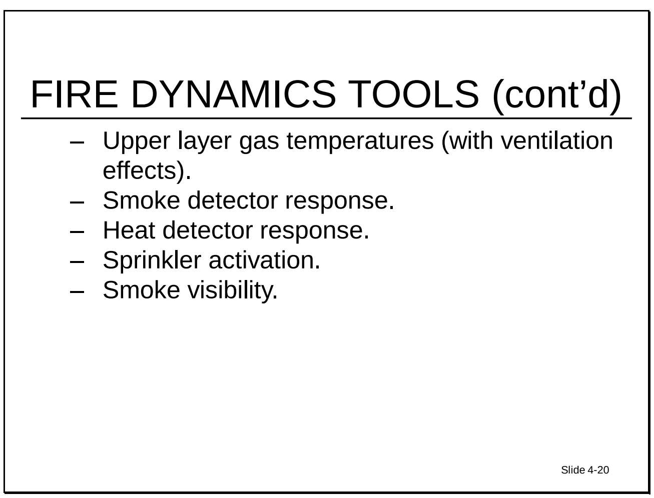
1. Burning duration.

2. Burning characteristics of liquid pool fires.

3. Estimating the centerline temperature of a buoyant fire plume.

4. Pressure rises.

5. Fire resistance of structural steel members.



6. Upper layer gas temperatures (with ventilation effects).

7. Smoke detector response.

8. Heat detector response.

9. Sprinkler activation.

10. Smoke visibility.

FIRE DYNAMICS TOOLS (cont'd)

- Estimating wall fire flame height, line fire against a wall, and corner flame height.
- Estimating the pressure increase and explosive energy release associated with explosions.
- Calculating the rate of hydrogen gas generation in battery rooms.

Slide 4-21

11. Estimating wall fire flame height, line fire against a wall, and corner flame height.

12. Estimating the pressure increase and explosive energy release associated with explosions.

13. Calculating the rate of hydrogen gas generation in battery rooms.

SAMPLE REFERENCES

- National Fire Protection Association (NFPA) Fire Protection Handbook.
  - Simplified fire growth calculations.
  - Simple fire hazard calculations.
- Society of Fire Protection Engineers (SFPE) Handbook.
- "Principles of Fire Behavior" by Quintiere.
- "Fire Dynamics" by Gorbett/Pharr.

Slide 4-22

J. National Fire Protection Association (NFPA) Fire Protection Handbook.

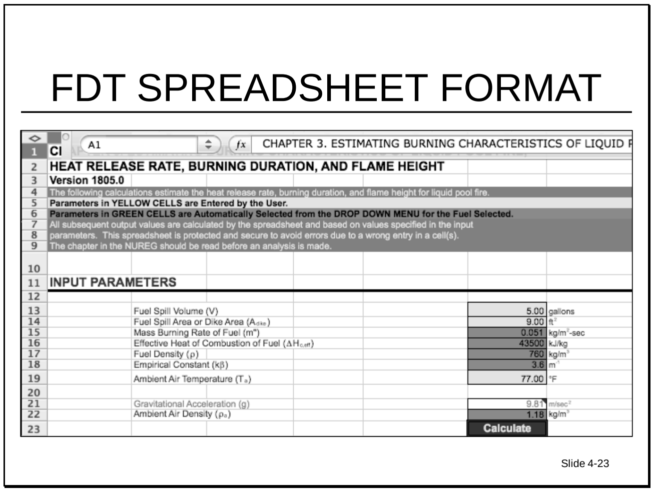
1. Simplified fire growth calculations.

2. Simple fire hazard calculations.

K. Society of Fire Protection Engineers (SFPE) Handbook.

1. "Principles of Fire Behavior" by Quintiere.

2. "Fire Dynamics" by Gorbett/Pharr.



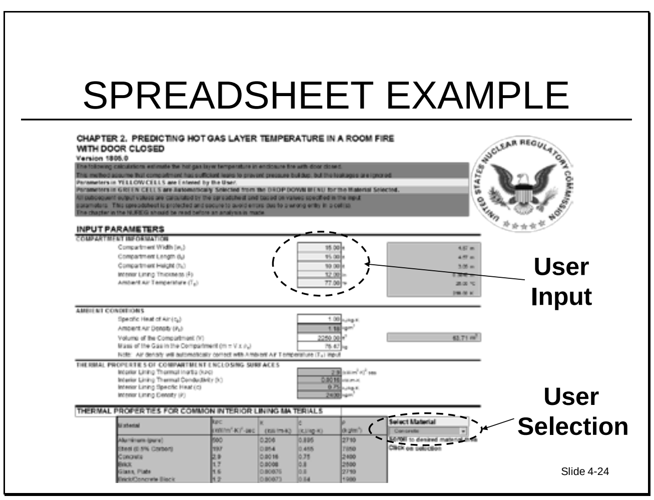
L. Input parameters.

1. Parameters in yellow cells are entered by the user.

2. Parameters in green cells are automatically populated from the drop-down menu for the material selected.

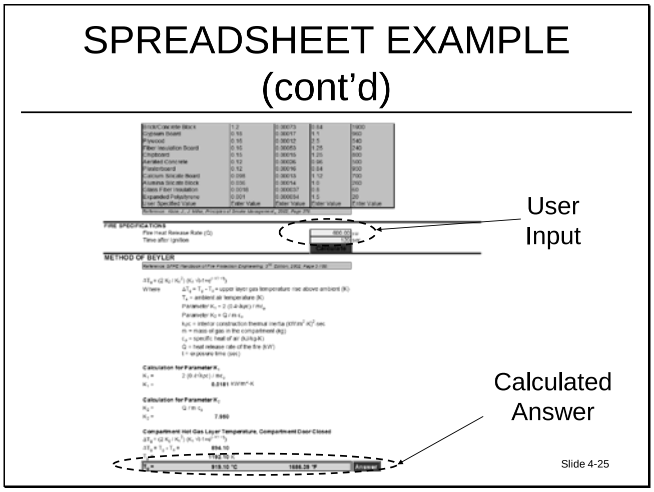
3. If the desired material properties are not in the drop-down menu, the user must enter the values manually.

4. Results of the calculations are designated by the word "**answer**" in the spreadsheets.

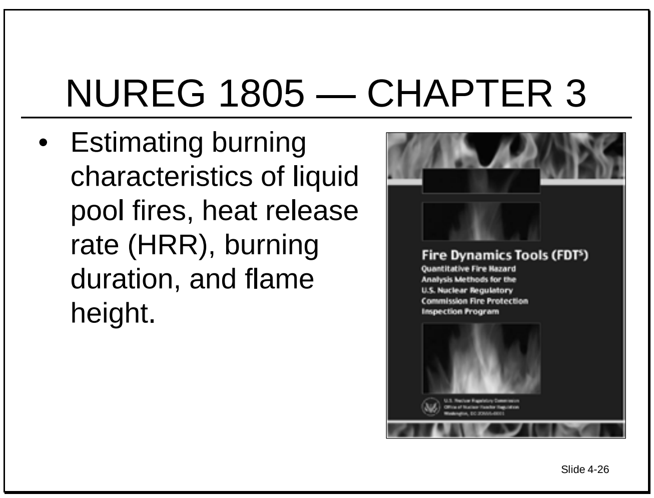


5. The yellow boxes are completed by the user.

6. The green boxes are filled in automatically by values chosen by the user from drop-down menus.



7. This is a screen shot of the portion of the spreadsheet where the user would input the required parameters for the calculation and the area of the spreadsheet where the calculated result appears.



M. NUREG 1805 — Chapter 3.

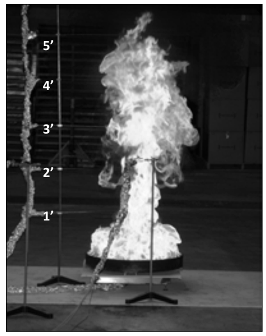
1. Describes in detail the science behind the calculations used for calculating the burning characteristics of liquid pool fires, HRR, burning duration, and flame height.

2. Each of the spreadsheets is titled based upon the chapter of NUREG 1805 that addresses the particular type(s) of calculations.

II. HEAT RELEASE RATE

HEAT RELEASE RATE

- HRR is a primary input for all fire calculations.
- Flame height is useful for evaluating witness statements and is a driving factor of secondary ignitions, flame spread and fire spread.



Slide 4-27

A. HRR is a primary input for all fire calculations.

B. Flame height is useful for evaluating witness statements and is a driving factor of secondary ignitions, flame spread and fire spread.

FLAME HEIGHT CALCULATIONS

- These calculations are used to estimate the continuous and intermittent height of a turbulent diffusion flame.
  - Useful in post-fire examination to compare the fuels present with damage observed (consistency).
  - Can also be used to estimate the HRR of a burning object based on its flame height.

Slide 4-28

C. These calculations are used to estimate the continuous and intermittent height of a turbulent diffusion flame.

1. Useful in post-fire examination to compare the fuels present with damage observed (consistency).

2. Can also be used to estimate the HRR of a burning object based on its flame height.

FLAME HEIGHT CALCULATIONS (cont'd)

- Range of solutions can be used to bound the problem.
- Narrows parameters believed to be involved in the fire event.
- Establishes reasonable upper and lower boundaries.

Slide 4-29

3. Range of solutions can be used to bound the problem.

4. Narrow parameters believed to be involved in the fire event.

5. Establishes reasonable upper and lower boundaries.

ASSUMPTIONS/LIMITATIONS

- Not all calculations will give an exact value.
- Remember that most of these equations are based upon empirical data that is derived from experiments.

Slide 4-30

D. There are some assumptions and limitations for these calculations.

1. Remember that most of these equations are based upon empirical data that is derived from experiments.

ASSUMPTIONS/LIMITATIONS (cont'd)

- Many of the experiments were run with slightly different conditions that may not perfectly fit your scenario.
- Even when the original experiments match your scenario, there are still errors that may result from curve fitting.

Slide 4-31

2. Many of the experiments were run with slightly different conditions that may not perfectly fit your scenario.

3. Even when the original experiments match your scenario, there are still errors that may result from curve fitting.

ASSUMPTIONS/LIMITATIONS (cont'd)

- The pool fire is burning in the open.
- There is no fire growth period.
  - Real liquid pool fires grow very quickly.
- The pool fire is circular or nearly circular, or an equivalent diameter is calculated.
  - Correlations should only be applied to axi-symmetrical sources.

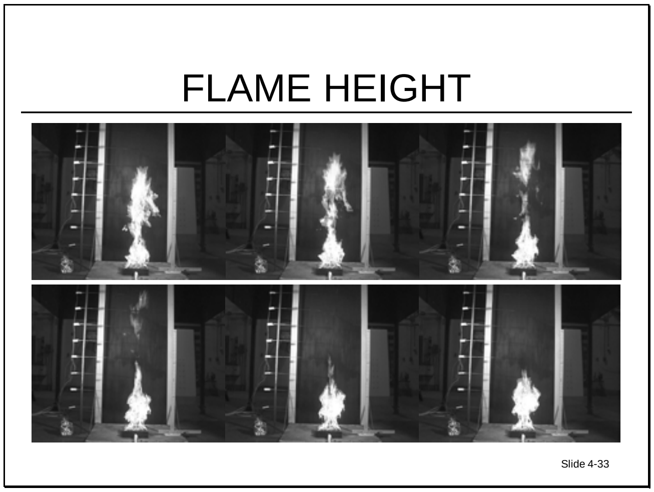
Slide 4-32

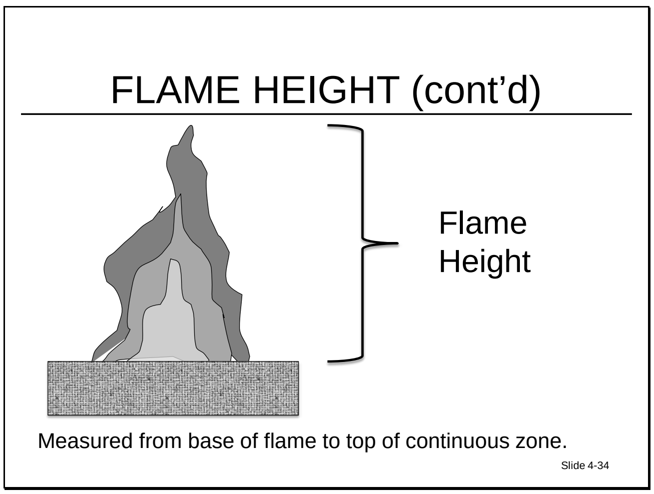
4. The pool fire is burning in the open.

5. There is no fire growth period. Real liquid pool fires grow very quickly.

6. The pool fire is circular or nearly circular, or an equivalent diameter is calculated. Correlations should only be applied to axi-symmetrical sources.

III. FLAME HEIGHT



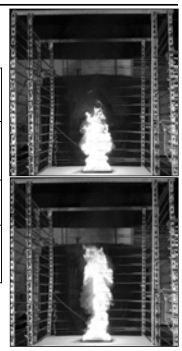


A. The flame height is generally measured at the "consistent flame" height.

B. The height is from the base of the fire to the top of the continuous flame.

FLAME HEIGHT REPEATABILITY

Fuel	Mean H_f(m)	Range H_f(m)
Natural Gas	0.70	0.40 to 0.98
Gasoline	0.84	0.52 to 1.1
Polyurethane Foam	0.46	0.30 to 0.78



Slide 4-35

C. Depending upon the fuel type as well as the size of the flame, there is some variance.

D. Other factors affecting flame height:

1. Air flow.

2. Diameter of flame.

3. Condition of fuel (humidity, packing density, etc.).

HEAT RELEASE RATE, FLAME HEIGHT

- HRR.
  - Primary input for all fire calculations.
- Flame height.
  - Useful for evaluating witness statements.
  - Driving factor of secondary ignitions, flame spread and fire spread.

Slide 4-36

E. Again, HRR is a primary input for all fire calculations.

F. Flame height is useful for evaluating witness statements and is a driving factor of secondary ignitions, flame spread and fire spread.

FLAME HEIGHT CALCULATIONS

- The FDTs use both the Heskestad equation as well as a new equation, the Thomas equation.

$$H_f = 42D\left(\frac{\dot{m}''}{\rho_a\sqrt{gD}}\right)^{0.61}$$

Where:
H_f = Flame height
D = Diameter of the fire
$\dot{m}''$ = Mass loss rate (MLR) per unit area kg/m^2/s
ρ_a = Ambient air density
g = Gravitational constant (9.8 m/s^2)

Slide 4-37

G. This is an example of one of the calculations used in determining flame heights.

1. This is different from the Heskestad equation because it also considers ambient air density and mass loss rate (MLR).

2. Heskestad uses HRR, which in turn is proportional to MLR.

EFFECTIVE DIAMETER

$$D = \sqrt{\frac{4A_f}{\pi}}$$

A_f = Surface area of the noncircular pool (m^2)
D = Diameter of the fire (m)

Slide 4-38

H. This is a method to arrive at the value of "D" when the fire is not circular.

HEAT RELEASE RATE, FLAME HEIGHT PRACTICAL PROBLEM

NUREG 1805 Example Problem 3.10-2

- A standby diesel generator room in a power plant has a 3-gallon spill of diesel fuel over a 1 square foot diked area. This event allows the diesel fuel to form a pool. The diesel is ignited, and fire spreads rapidly over the surface, reaching steady burning almost instantly. Compute the HRR, burning duration and flame height of the pool fire.

Slide 4-39

I. This is an example problem that is described and solved in the NUREG 1805 manual (and can be later referenced as a reminder of how to use the tools).

HEAT RELEASE RATE, FLAME HEIGHT PRACTICAL PROBLEM (cont'd)

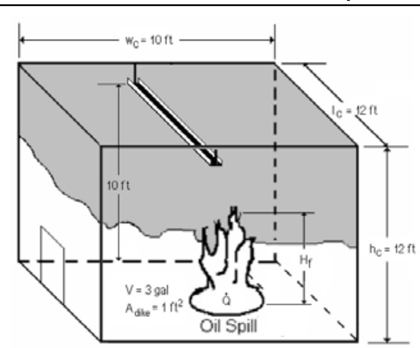
NUREG 1805 Example Problem 3.10-2 continued

- The dimensions of the compartment are 10 feet wide by 12 feet deep by 12 feet high. The cable tray is located 10 feet above the pool fire. Ambient temperature is 77 F. Determine whether flame will impinge upon the cable tray.
- Also, determine the minimum surface area required for the pool fire to have flame impinge upon the cable tray.

Slide 4-40

J. Follow-up information for the example problem.

HEAT RELEASE RATE, FLAME HEIGHT PRACTICAL PROBLEM (cont'd)



Slide 4-41

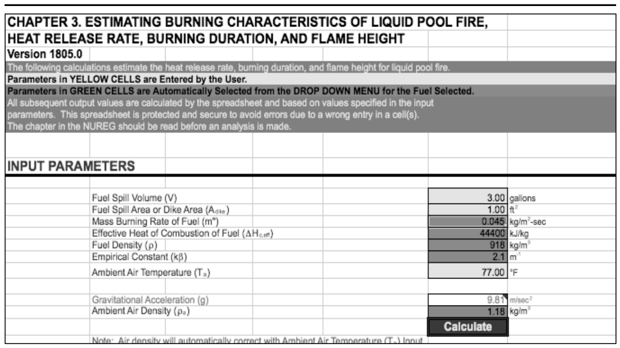
HEAT RELEASE RATE, FLAME HEIGHT PRACTICAL PROBLEM (cont'd)

- Steps:
  - Determine the HRR of the fire source.
  - Determine the burning duration of the pool fire.
  - Determine the flame height of the pool fire.
  - Determine whether the flame will impinge upon the cable tray.
  - Determine the minimum dike area required for the flame to impinge upon the cable tray.

Slide 4-42

K. These are steps that one would need to follow to solve the problem using the NUREG 1805 manual, Chapter 3 FDT spreadsheet.

FDT INPUT SCREEN



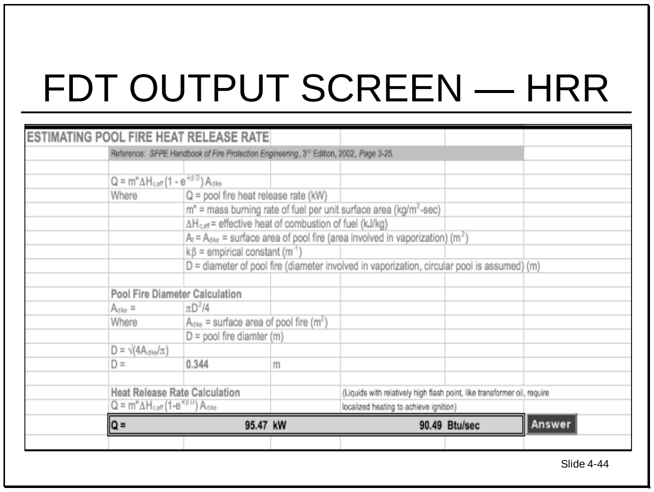
Slide 4-43

L. A screen shot of the upper part of the spreadsheet.

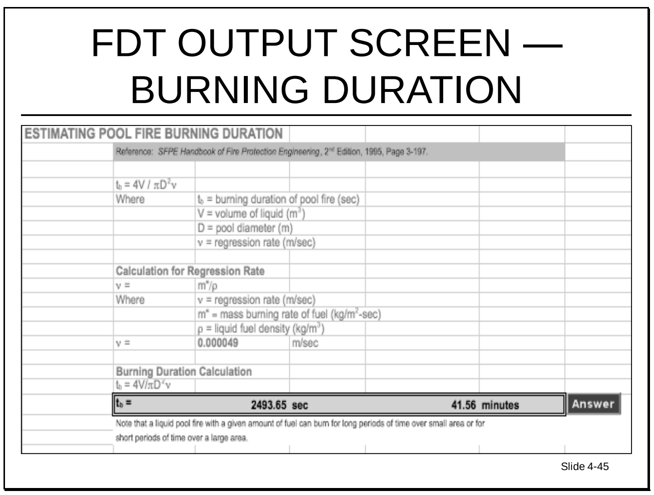
1. Go over the actual spreadsheet and how to navigate through it.

2. Demonstrate how selection of various fuels provided in the tables below populates the **green** boxes.

3. Show how clicking on the **red** cell calculates the problem's answers.

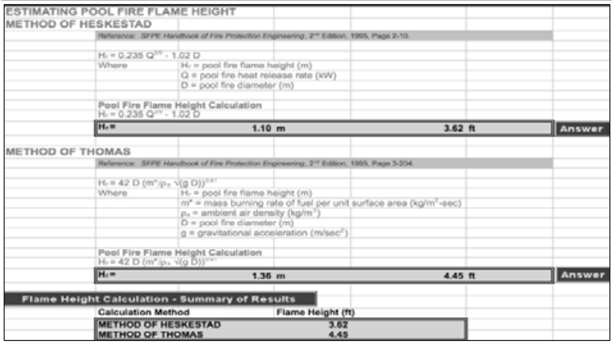


M. Example of the FDT Output Screen for estimating pool fire HRR based upon the given equation.



N. Example of the FDT Output Screen of the pool fire's burning duration based upon the given equations and inputs.

FDT OUTPUT SCREEN — FLAME HEIGHT



ESTIMATING POOL FIRE FLAME HEIGHT
METHOD OF HESKESTAD

Reference: SFPE Handbook of Fire Protection Engineering, 2nd Edition, 1995, Page 2-10.

$H_f = 0.235\, Q^{2/5} - 1.02\, D$

Where H_f = pool fire flame height (m)
Q = pool fire heat release rate (kW)
D = pool fire diameter (m)

Pool Fire Flame Height Calculation
$H_f = 0.235\, Q^{2/5} - 1.02\, D$

H_f = 1.10 m 3.62 ft **Answer**

METHOD OF THOMAS

Reference: SFPE Handbook of Fire Protection Engineering, 2nd Edition, 1995, Page 3-204.

$H_f = 42\, D\, (m''/\rho_a \sqrt{g D})^{0.61}$

Where H_f = pool fire flame height (m)
m'' = mass burning rate of fuel per unit surface area (kg/m^2-sec)
ρ_a = ambient air density (kg/m^3)
D = pool fire diameter (m)
g = gravitational acceleration (m/sec^2)

Pool Fire Flame Height Calculation
$H_f = 42\, D\, (m''/\rho_a \sqrt{g D})^{0.61}$

H_f = 1.36 m 4.45 ft **Answer**

Flame Height Calculation - Summary of Results

Calculation Method	Flame Height (ft)
METHOD OF HESKESTAD	3.62
METHOD OF THOMAS	4.45

Slide 4-46

O. Example of the FDT Output Screen for pool fire flame height based upon the two given equations and inputs.

1. Show how each method has a copy of the equation right on the screen.

2. Note how the two values are different but both are of the same **"order of magnitude."**

3. Final answers for each method are compared with each other at the bottom of the screen.

HEAT RELEASE RATE, FLAME HEIGHT PRACTICAL PROBLEM (cont'd)

Results*

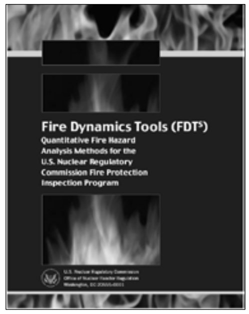
Heat Release Rate (HRR) $\dot{Q}$ kW (Btu/sec)	Burning Duration (t_b) (min.)	Pool Fire Flame Height (H_f) m (ft)	
		Method of Heskestad	Method of Thomas
95 (90)	42	1.1 (3.6)	1.4 (4.5)

Slide 4-47

P. Comparisons of the different solutions provided on the previous screen.

NUREG 1805 — CHAPTER 5

- Estimating radiant heat flux from a fire to a target fuel.



Slide 4-48

Q. Chapter 5 of the NUREG 1805 manual describes in detail the science behind the calculations used for estimating radiant heat flux from a fire to a target fuel. Each of the spreadsheets is titled based upon the chapter of NUREG 1805 that addresses the particular type(s) of calculations.

IV. HEAT FLUX

HEAT FLUX

- Important in determining if items remote from the initial fuel package will ignite, allowing the fire to grow.
- Important in determining the tenability conditions for an occupant within a room.

Slide 4-49

A. Radiant heat flux from fires: Why do we care?

1. Important in determining if items remote from the initial fuel package will ignite, allowing the fire to grow.

2. Important in determining the tenability conditions for an occupant within a room.

RADIANT HEAT FLUX FROM FIRES: HOW DOES IT WORK?

- Radiant heat transfer from a fire.
  - Primarily from soot particles.
  - Also from water vapor and carbon dioxide.
- Two radiation models.
  - Point source (fire is represented by a point source).
  - Solid flame (fire is represented by a solid body of a simple geometrical shape, such as cylindrical).

Slide 4-50

B. These are a few examples of when one might be interested in determining a heat flux value.

1. Used to determine how much energy is being radiated from a burning object and being received by a target object.

2. Used to analyze flame spread from separated fuels through radiant heat transfer.

RADIANT HEAT FLUX FROM FIRES: HOW DOES IT WORK? (cont'd)

Typical Radiative Energy Fraction Values

Fuel Fire diameter > 0.5 m (1.6 ft)	Total Radiative Energy Fraction χ_r
Methanol, methane	15-20%
Butane, benzene, wood cribs	20-40%
Hexane, gasoline, polystyrene	40-60%

Quintiere, Principles of Fire Behavior, 1998: pg. 59

Slide 4-51

C. Examples of typical values.

1. Emissivity, also considered the efficiency of the radiator, is different depending upon how dark the smoke and flames are.

2. The darker the smoke/flames, the higher the emissivity.

HEAT FLUX (cont'd)

- Common uses:
  - Energy radiated from a burning object to a target object.
  - Flame spread from separated fuels through radiant heat transfer.
  - **Radiant heat flux from fire, practical example: point source.**

Slide 4-52

D. Common uses:

1. Energy radiated from a burning object to a target object.

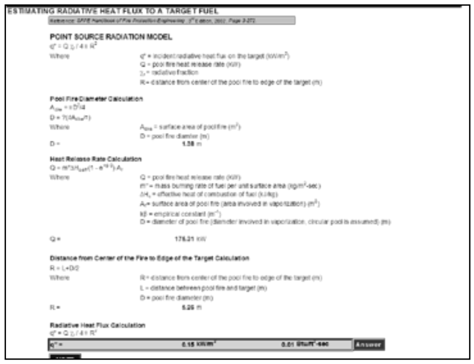
2. Flame spread from separated fuels through radiant heat transfer.

RADIANT HEAT FLUX FROM FIRE, PRACTICAL EXAMPLE

Slide 4-53

E. This is a screen shot of the NUREG 1805 manual, Chapter 5 FDT spreadsheet example used to calculate radiant heat flux from fire.

RADIANT HEAT FLUX FROM FIRE, PRACTICAL EXAMPLE (cont'd)



Slide 4-54

F. This is a screen shot of the NUREG 1805 manual, Chapter 5 FDT spreadsheet used to calculate radiant heat flux using the point source method.

POINT SOURCE METHOD

$$\dot{q}'' = \chi_r \dot{Q} / 4\pi r^2$$

Where:
$\dot{q}''$ = Heat flux
X_r = Radiative fraction (often 0.30-0.35)
$\dot{Q}$ = HRR of source fire
r = Distance from the center of the fire to the target

- Point source model is appropriate for situations in which the distance from the edge of the flame to the target is greater than two and a half times the diameter of the fire.
  L > 2.5D

Slide 4-55

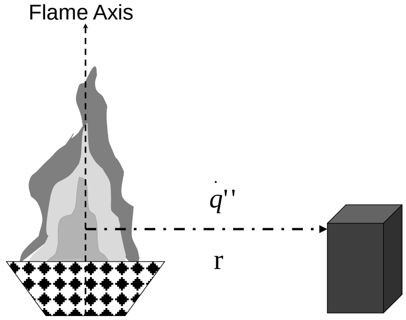
G. Point source method assumes same flux along sphere of radius "r" from the flame.

1. The distance "r" is measured from the surface of the target to the **center** of the burning flame, not the edge.

2. Discuss the concept of radiative fraction. The darker the smoke, the higher the value.

3. Commonly used values are 0.30 to 0.35. This is also the default in many other computer programs.

POINT SOURCE METHOD (cont'd)



Slide 4-56

POINT SOURCE METHOD (cont'd)

$$\dot{q}'' \propto \frac{1}{R^2}$$

Slide 4-57

H. The radiant heat flux at any distance from the source fire varies with the inverse square of the horizontal distance, R.

POINT SOURCE METHOD (cont'd)

- Assumption:
  - All the radiant energy is released at a point located at the center of the fire.

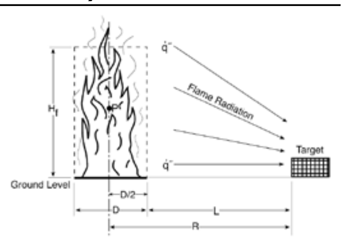
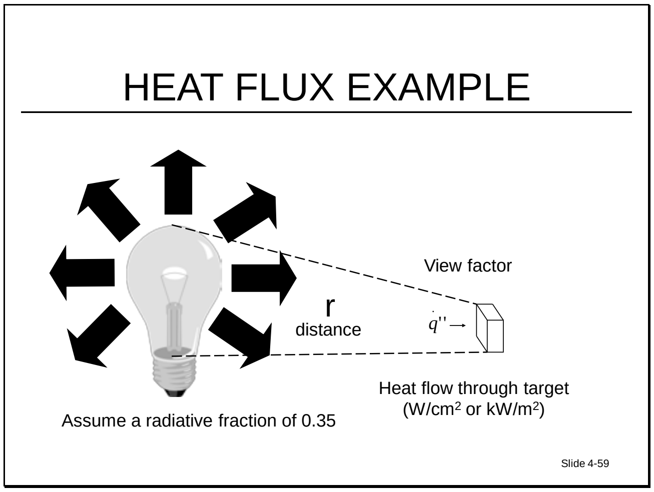


Figure 5-1 Radiant Heat Flux from a Pool Fire to a Floor-Based Target Fuel (Point Source Model)

Slide 4-58

I. The graphic contained in NUREG 1805 describes the point source theory of radiant flux calculations.



J. How much of the radiation given off by the radiator is absorbed by the target?

NUREG 1805 — CHAPTER 5
HEAT FLUX: POINT SOURCE

- Fire is represented by a point source.
- Radiation calculations are based on a fire in a large open space.
  - No hot layer development.
- Radiation is to a point on the target.
- Edge of the fire to the target is more than 2.5 times the diameter of the flame.
- Pool is circular or nearly circular.

Slide 4-60

K. The NRC's FDTs can also be used to estimate heat flux.

1. Performing this type of calculation is important to determine whether items remote from the initial fuel package will ignite, allowing the fire to grow.

2. Such information can be important in determining the tenability conditions for an occupant within a room.

HEAT FLUX — POINT SOURCE

Mass Burning Rate of Fuel (m'')	0.01082	kg/m^2-sec
Effective Heat of Combustion of Fuel ($\Delta H_{c,eff}$) FALSE	10900	kJ/kg
Empirical Constant ($k\beta$)	100	m^{-1}
Heat Release Rate (Q)	175.31	kW
Fuel Area or Dike Area (A_{dike})	16.00	m^2 (1.49 m^2)
Distance between Fire and Target (L)	15.00	ft (4.572 m)
Radiative Fraction (χ_r)	0.30	

OPTIONAL CALCULATION FOR GIVEN HEAT RELEASE RATE

Select "User Specified Value" from Fuel Type Menu and Enter Your HRR here ? ____ kW

Calculate

THERMAL PROPERTIES DATA

BURNING RATE DATA FOR FUELS

Fuel	Mass Burning Rate m'' (kg/m^2-sec)	Heat of Combustion $\Delta H_{c,eff}$ (kJ/kg)	Empirical Constant $k\beta$ (m^{-1})
Methanol	0.017	20,000	100
Ethanol	0.015	26,800	100
Butane	0.078	45,700	2.7
Benzene	0.085	40,100	2.7
Hexane	0.074	44,700	1.9
Heptane	0.101	44,600	1.1
Xylene	0.09	40,800	1.4
Acetone	0.041	25,800	1.9
Dioxane	0.018	26,200	5.4

Select Fuel Type

Douglas Fir Plywood

Scroll to desired fuel type the
Click on selection

Slide 4-61

L. This example is a **point source** calculation. This is only one of two models used by the FDTs. The other is **solid flame,** shown later.

HEAT FLUX — POINT SOURCE (cont'd)

Q = **175.31** kW

Distance From Center of the Fire to Edge of the Target Calculation

R = L+D/2

Where: R = Distance from center of the pool fire to edge of the target (m)
L = Distance between pool fire and target (m)
D = Pool fire diameter (m)

R = **5.26** m

Radiative Heat Flux Calculation

$q'' = Q\,\chi_r / 4\,\pi\,R^2$

q" = 0.15 kW/m²

Slide 4-62

NUREG 1805 — CHAPTER 5 HEAT FLUX: SOLID FLAME

- Fire is represented by a solid body of a simple geometrical shape (e.g., cylindrical).
- Emissive power correlation is based on tests with luminous flames (e.g., kerosene, gasoline, liquefied natural gas (LNG)).
  - Correlation should be valid for most fuels.
- Pool is circular or nearly circular.

Slide 4-63

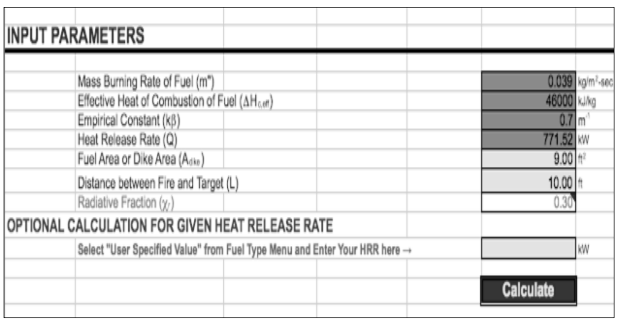
M. Solid flame.

1. Fire is represented by a solid body of a simple geometrical shape (e.g., cylindrical).

2. Emissive power correlation is based on tests with luminous flames (e.g., kerosene, gasoline, liquefied natural gas (LNG)). Correlation should be valid for most fuels.

3. Pool is circular or nearly circular.

FDT INPUT SCREEN — HEAT FLUX



Slide 4-64

N. Discuss the input parameters for heat flux.

1. Fuel area or diked area.

2. Distance between fuel and target.

3. Fuel type/Mass burning rate or MLR.

4. Radiative fraction.

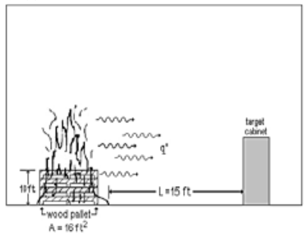
   a. Typically 0.30 to 0.35.

   b. Higher for darker fuels (e.g., aromatic hydrocarbons, tar paper, etc.).

   c. Lower for white smoke, alcohol fires, etc.

HEAT FLUX EXERCISE

A transient combustible fire scenario may arise from burning wood pallets (4 feet by 4 feet = 16 feet squared), stacked 10 feet high on the floor of a compartment with a very high ceiling. Calculate the flame radiant heat flux to a target (safety-related cabinet) at ground level with no wind, using the point source radiation model and the solid flame radiation model. The distance between the fire source and the target edge (L) is assumed to be 15 feet.



Example Problem 5-2: Radiant Heat Flux from a Burning Pallet to a Target Fuel

Slide 4-65

O. Practical example provided in NUREG 1805 to show users how to apply the fire dynamics and become familiar with the spreadsheet.

HEAT FLUX EXERCISE (cont'd)

- Input parameters.
  - Fuel type is Douglas fir.
  - Fuel curbed area equals 16 feet squared.
  - Horizontal distance between fire and target equals 15 feet.
  - Vertical distance of target from ground level equals 0 feet.
  - No wind.

Slide 4-66

HEAT FLUX — SOLID FLAME

Mass Burning Rate of Fuel (m")		0.01082	kg/m²-sec
Effective Heat of Combustion of Fuel ($\Delta H_{c,eff}$)	FALSE	10900	kJ/kg
Empirical Constant (kβ)		100	m⁻¹
Heat Release Rate (Q)		175.31	kW
Fuel Area or Dike Area (A_{dike})		16.00	ft² (1.49 m²)
Distance between Fire and Target (L)		15.00	ft (4.572 m)

OPTIONAL CALCULATION FOR GIVEN HEAT RELEASE RATE

Select "User Specified Value" from Fuel Type Menu and Enter Your HRR here ? ____ kW

Calculate

THERMAL PROPERTIES DATA

BURNING RATE DATA FOR FUELS

Fuel	Mass Burning Rate m" (kg/m²-sec)	Heat of Combustion $\Delta H_{c,eff}$ (kJ/kg)	Empirical Constant kβ (m⁻¹)
Methanol	0.017	20,000	100
Ethanol	0.015	26,800	100
Butane	0.078	45,700	2.7
Benzene	0.085	40,100	2.7

Select Fuel Type: Douglas Fir Plywood

Scroll to desired fuel type then Click on selection

Slide 4-67

P. This example is calculated based upon a solid flame model calculation. Compare the differences in radiant heat flux between this and a point source calculation.

HEAT FLUX — SOLID FLAME (cont'd)

$S = 2R/D =$	**7.647**			
$h = 2H_f/D =$	**0.658**			
$A = (h^2+S^2+1)/2S =$	**3.917**			
$B = (1+S^2)/2S =$	**3.889**			
		F_{H1}	F_{H2}	F_{H3}
$F_{1\text{->}2,H} =$	**0.000**		0.318	0.851
$F_{1\text{->}2,V} =$	**0.008**	F_{V1}	F_{V2}	F_{V3}
$F_{1\text{->}2,\,max} = ?(F^2_{1\text{->}2,H} + F^2_{1\text{->}2,V}) =$	**0.008**		0.004	0.020

Radiative Heat Flux Calculation

$q'' = EF_{1\text{->}2}$

q" =	**0.45 kW/m²**	**0.04Btu/ft²-sec**

Slide 4-68

V. FLASHOVER CALCULATIONS

FLASHOVER CALCULATIONS

- NUREG 1805, Chapter 13: predicting compartment flashover.

Slide 4-69

A. Chapter 13 of the NUREG 1805 manual describes in detail the science behind the calculations used for predicting compartment flashover.

B. Each of the spreadsheets is titled based upon the chapter of NUREG 1805 that addresses the particular type(s) of calculations.

WHAT IS FLASHOVER?

- A stage in the development of a contained fire in which all exposed surfaces reach ignition temperatures more or less simultaneously and fire spreads rapidly throughout the space (NFPA 555, *Guide on Methods for Evaluating Potential for Room Flashover*, Sec. 3.3.2).
- Transition from a growing fire to a fully developed fire in which all combustible items in the compartment are involved in the fire (SFPE Handbook of Fire Protection Engineering, third edition, p. 3-171).

Slide 4-70

C. Flashover is a stage in the development of a contained fire in which all exposed surfaces reach ignition temperatures more or less simultaneously and fire spreads rapidly throughout the space (NFPA 555, *Guide on Methods for Evaluating Potential for Room Flashover*, Sec. 3.3.2).

1. Transition from a growing fire to a fully developed fire in which all combustible items in the compartment are involved in the fire (SFPE Handbook of Fire Protection Engineering, third edition, p. 3-171).

2. Simply stated, flashover is a transition from a fire in a room to a room on fire.

WHAT IS FLASHOVER? (cont'd)

- Flashover is the phenomenon that defines the point at which all combustibles in the compartment are involved in the fire and flames appear to fill the entire compartment.
- The temperature rise in the hot gas layer reaches 500 C to 600 C (932 F to 1,112 F).
- The radiant heat flux density at the floor of the compartment reaches a minimum value of 20 kW/m^2.

Slide 4-71

3. Flashover is the phenomenon that defines the point at which all combustibles in the compartment are involved in the fire and flames appear to fill the entire compartment.

4. The temperature rise in the hot gas layer reaches 500 C to 600 C (932 F to 1,112 F).

5. The radiant heat flux density at the floor of the compartment reaches a minimum value of 20 kilowatts per meter squared (kW/m^2).

FLASHOVER: WHY DO WE CARE?

- The compartment of fire origin is no longer tenable after flashover has occurred.
- Onset of flashover provides a substantially increased hazard to occupants in other areas of a building.

Slide 4-72

D. Flashover: Why do we care?

1. The compartment of fire origin is no longer tenable after flashover has occurred.

2. Onset of flashover provides a substantially increased hazard to occupants in other areas of a building.

FLASHOVER: WHY DO WE CARE? (cont'd)

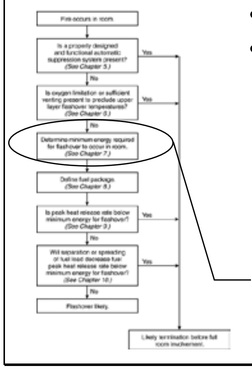
- Post-flashover conditions pose a threat to the structure itself.
- Post-flashover fires are the most difficult to investigate.

Slide 4-73

3. Post-flashover conditions pose a threat to the structure itself.

4. Post-flashover fires are the most difficult to investigate.

PREDICTING COMPARTMENT FLASHOVER: METHODOLOGY



- NFPA 555, 2009 edition.
- Developed in recognition that life safety and property protection can be enhanced by preventing the occurrence of flashover or at least decreasing its probability.

NRC spreadsheets used here

FIGURE 4.2 Flowchart for Use of NFPA 555

Slide 4-74

E. NFPA 555, 2009 edition was developed in recognition that life safety and property protection can be enhanced by preventing the occurrence of flashover or at least decreasing its probability.

PREDICTING COMPARTMENT FLASHOVER: METHODOLOGY (cont'd)

- Three different methods for predicting flashover in a compartment will be analyzed:
  - Method of McCaffrey, Quintiere and Harkleroad (MQH).
  - Method of Thomas.
  - Method of Babrauskas.
- NFPA 555, Sec. 7.2.1 states, "room flashover potential is best estimated by using Thomas' flashover correlation."

Slide 4-75

F. Three different methods for predicting flashover in a compartment will be analyzed.

1. Method of McCaffrey, Quintiere and Harkleroad (MQH).

2. Method of Thomas.

3. Method of Babrauskas.

G. NFPA 555, Sec. 7.2.1 states, "room flashover potential is best estimated by using Thomas' flashover correlation."

ASSUMPTIONS/LIMITATIONS

- The correlations were developed from a simplified mass and energy balance on a single compartment with ventilation openings.
- The experimental data used to develop the correlation included compartments with thermally thick walls and fires of wood cribs. Typically, heat transfer through compartment surfaces is accounted for with a semi-infinite solid approximation.

Slide 4-76

H. Assumptions/Limitations.

1. The correlations were developed from a simplified mass and energy balance on a single compartment with ventilation openings.

2. The experimental data used to develop the correlation included compartments with thermally thick walls and fires of wood cribs. Typically, heat transfer through compartment surfaces is accounted for with a semi-infinite solid approximation.

ASSUMPTIONS/LIMITATIONS (cont'd)

- The fire severity correlation is not appropriate for compartments that do not have openings for ventilation. While no precise minimum can be stated, it is suggested that this method not be used unless the size of the opening is at least 0.4 meters squared (m^2) (4 feet squared).

Slide 4-77

3. The fire severity correlation is not appropriate for compartments that do not have openings for ventilation. While no precise minimum can be stated, it is suggested that this method not be used unless the size of the opening is at least 0.4 meters squared (m^2) (4 feet squared).

I. Flashover calculations.

1. Another frequently used calculation by investigators.

2. Used to determine the amount of heat energy necessary to cause a compartment to become fully involved (flashover).

3. By determining the amount of energy necessary for flashover, you can consider if the fuel load present was enough to drive a compartment to flashover.

4. If the fuel load is not consistent with reaching flashover, further investigation is in order — an accelerant might have been used.

FLASHOVER CALCULATIONS (cont'd)

- Where:
  - $\dot{Q}$ = Energy/HRR
  - A_t = Total area of the inner boundary surfaces, such as walls, ceiling, floor (m^2)
  - A_o = Area of the opening (m)
  - H_o = Height of the opening (m)
  - h_k = Heat transfer coefficient (kW/m^2)

Slide 4-80

PREDICTING COMPARTMENT FLASHOVER

- Comparison of methods.

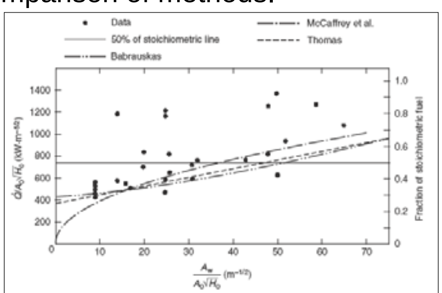


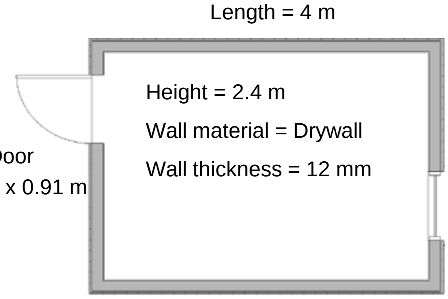
Figure 3-6.12. ***The effect of room wall area (gypsum walls) on the heat required for flashover.***

Slide 4-81

J. An example of how the various equations relate to the empirical data.

FLASHOVER EXERCISE 1

Length = 4 m



Slide 4-82

FLASHOVER EXERCISE 1 (cont'd)

INPUT PARAMETERS

COMPARTMENT INFORMATION

Compartment Width (w_c)	3.00	m
Compartment Length (l_c)	4.00	m
Compartment Height (h_c)	2.40	m
Vent Width (w_v)	0.91	m
Vent Height (h_v)	1.08	m
Interior Lining Thickness (δ)	12.00	cm
Interior Lining Thermal Conductivity (k)	0.00017	kW/m-K

Calculate

THERMAL PROPERTIES DATA

MATERIAL	THERMAL CONDUCTIVITY k (kW/m-K)	Select Material
		Gypsum Board
Aerated Concrete	0.00026	Scroll to desired material
Alumina Silicate Block	0.00014	Click on selection
Aluminum (pure)	0.206	

Slide 4-83

K. This is a screen shot of the NUREG 1805 manual, Chapter 13 FDT Input Screen detailing the parameters required to perform the flashover calculation.

FLASHOVER EXERCISE 1 (cont'd)

Summary of Results

CALCULATION METHOD	FLASHOVER HRR (kW)
METHOD OF McCAFFREY, QUINTIERE, AND HARKLEROAD (MQH)	274
METHOD OF BABRAUSKAS	1910
METHOD OF THOMAS	1398

Slide 4-84

L. This is a screen shot of the FDT Output Screen showing the results of the flashover calculation for each calculation method.

FLASHOVER EXERCISE 2

- Using the same room dimensions, determine the effect of doubling the width of the doorway opening.

Slide 4-85

M. To demonstrate the variability of the various answers by simply adding another vent of the same size, recompute the calculations using the following information.

FLASHOVER EXERCISE 2 (cont'd)

INPUT PARAMETERS

COMPARTMENT INFORMATION

Compartment Width (w_c)	3.00	m	3.00 m
Compartment Length (l_c)	4.00	m	4.00 m
Compartment Height (h_c)	2.40	m	2.40 m
Vent Width (w_v)	1.82	m	1.820 m
Vent Height (h_v)	1.98	m	1.98 m
Interior Lining Thickness (δ)	12.00	cm	0.12 m
Interior Lining Thermal Conductivity (k)	0.00017	kW/m-K	

Calculate

THERMAL PROPERTIES DATA

MATERIAL	THERMAL CONDUCTIVITY k (kW/m-K)	Select Material
		Gypsum Board
Aerated Concrete	0.00026	Scroll to desired material

Slide 4-86

N. This is a screen shot of the NUREG 1805 manual, Chapter 13 FDT Input Screen showing the input parameters for compartment information to change the size of the ventilation opening.

FLASHOVER EXERCISE 2 (cont'd)

Summary of Results

CALCULATION METHOD	FLASHOVER HRR (kW)
METHOD OF McCAFFREY, QUINTIERE, AND HARKLEROAD (MQH)	380
METHOD OF BABRAUSKAS	3803
METHOD OF THOMAS	2338

Slide 4-87

O. This is a screen shot of the FDT Output Screen showing the results of the flashover calculation for each calculation method based on the change of the size of the ventilation opening.

FLASHOVER EXERCISE 3

- Calculate the HRR needed to cause flashover in a room 10 feet by 10 feet (3 m by 3 m) in floor area and 8 feet (2.4 m) high with a door opening 6 feet (1.8 m) high and 2 feet (0.6 m) wide. The room is naturally ventilated. Ambient air temperature is 81 F (27 C). The wall lining material is 0.016 m (5/8 inch) gypsum plaster on metal lath.

  ρ = Wall material density (1,440 kg/m^3)
  k = 0.48 × 10^{-3} kW/m·c
  c = 0.84 kJ/kg°C
  δ = 0.016 m

Slide 4-88

FLASHOVER EXERCISE 3 (cont'd)

INPUT PARAMETERS

COMPARTMENT INFORMATION

Parameter	Value	Unit	Converted
Compartment Width (w_c)	10.00	ft	3.048 m
Compartment Length (l_c)	10.00	ft	3.05 m
Compartment Height (h_c)	8.00	ft	2.4384 m
Vent Width (w_v)	2.00	ft	0.610 m
Vent Height (h_v)	6.00	ft	1.83 m
Interior Lining Thickness (δ)	0.63	in	0.015875 m
Interior Lining Thermal Conductivity (k)	0.00048	kW/m-K	

Calculate

THERMAL PROPERTIES DATA

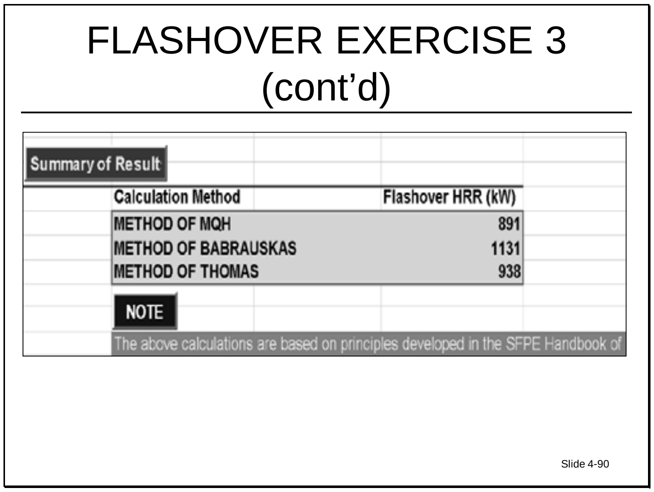
Material	Thermal Conductivity k (kW/m-K)
Aluminum (pure)	0.206
Steel (0.5% Carbon)	0.054

Select Material: User Specified Value

Scroll to desired material then Click on selection

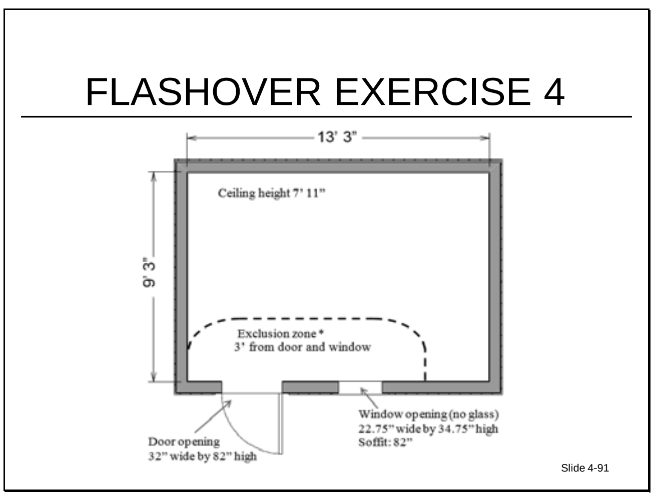
Slide 4-89

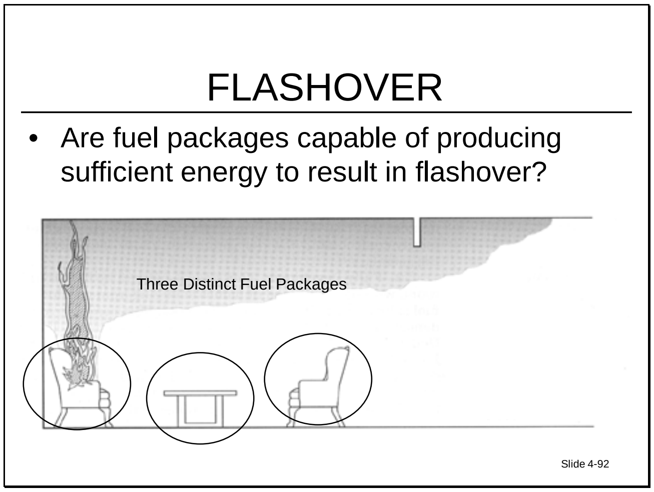
P. This is a screen shot of the NUREG 1805 manual, Chapter 13 FDT Input Screen detailing the compartment size parameters required to perform the flashover calculation.



Calculation Method	Flashover HRR (kW)
METHOD OF MQH	891
METHOD OF BABRAUSKAS	1131
METHOD OF THOMAS	938

Q. This is a screen shot of the NUREG 1805 manual, Chapter 13 FDT Output Screen based on the input parameters.





R. Will the fuel packages be able to burn simultaneously or closely enough in time so that they can provide an additive HRR to reach flashover?

1. Proximity — objects that are close enough in physical proximity so that continuous flame spread from item to item is possible generally are considered to be a fuel package. In such a situation, the ignition delays associated with object-to-object spread do not dominate the HRR history.

2. Items that are near enough to other items or fuel packages that ignition of an item is possible due to heat transfer from other items or fuel packages are not included as part of a fuel package if any of the following apply:

    a. The ignition delay is sufficiently long that the peak HRR will have passed before the item reaches its peak burning rate.

    b. Three 1,000 kilowatt (kW) chairs may not be able to cause flashover in a room needing 1,800 kWs to get to flashover if only one chair burns aggressively at a time.

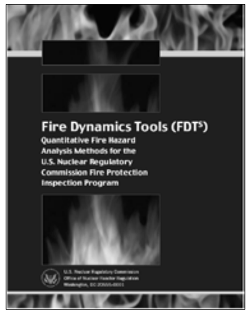
    c. If these packages can all burn at about the same time, their added energy release might drive the room to experience flashover.

    d. If they are too far separated, their HRRs may not add together to reach a high-enough heat input.

VI. TIME TO IGNITION

TIME TO IGNITION

- NUREG 1805, Chapter 6: estimating the ignition time of a target fuel exposed to a constant radiative heat flux.



Slide 4-93

A. Chapter 6 of the NUREG 1805 manual describes in detail the science behind the calculations used for estimating the ignition time of a target fuel exposed to a constant radiative heat flux.

WHAT IS IGNITION?

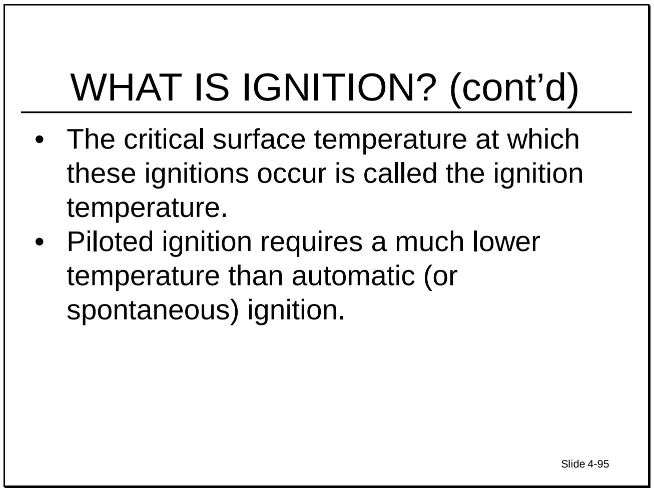
- For ignition, the solid fuel must be heated sufficiently to vaporize and form a flammable, premixed system. An ignition source (spark or small flame) must also be present for piloted ignition.
- A gas mixture must be heated sufficiently to cause auto-ignition.

Slide 4-94

B. For ignition, the solid fuel must be heated sufficiently to vaporize and form a flammable, premixed system.

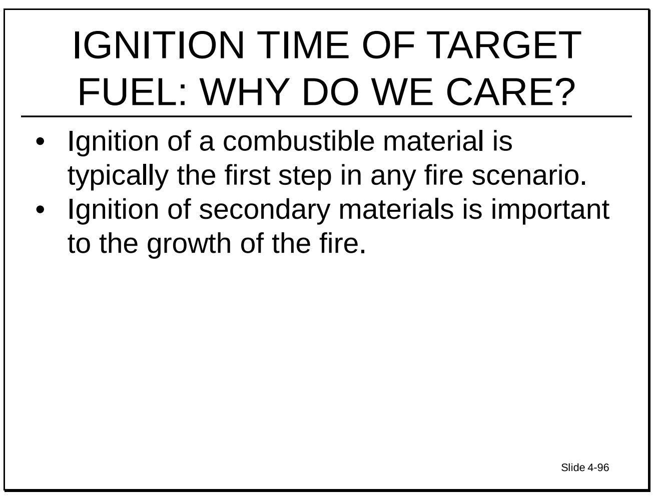
1. An ignition source (spark or small flame) must also be present for piloted ignition.

2. A gas mixture must be heated sufficiently to cause auto-ignition.



3. The critical surface temperature at which these ignitions occur is called the ignition temperature.

4. Piloted ignition requires a much lower temperature than automatic (or spontaneous) ignition.



C. Ignition time of target fuel: Why do we care?

1. Ignition of a combustible material is typically the first step in any fire scenario.

2. Ignition of secondary materials is important to the growth of the fire.

IGNITION TIME OF TARGET FUEL: HOW DOES IT WORK?

- Thermally thin materials:
  - Uniform temperature throughout solids when heated.
  - Physical thickness of 1 to 2 millimeters (mm) or less than 1/16 inch.
- Thermally thick materials:
  - Temperature varies throughout solids when heated.
- Spreadsheet calculations are for thermally thick materials only.

Slide 4-97

D. Ignition time of target fuel: How does it work?

1. Thermally thin materials:

    a. Uniform temperature throughout solids when heated.

    b. Physical thickness of 1 to 2 millimeters (mm) or less than 1/16 inch.

2. Thermally thick materials:

    a. Temperature varies throughout solids when heated.

    b. Spreadsheet calculations are for thermally thick materials only.

IGNITION TIME OF TARGET FUEL: HOW DOES IT WORK? (cont'd)

- **Ignition temperature** (T_{ig}) is the minimum temperature required to cause ignition.
- **Ignition time** is the time required to achieve sufficient vaporization to result in a flammable mixture plus the time for the mixture to ignite.

Slide 4-98

3. **Ignition temperature** (T_{ig}) is the minimum temperature required to cause ignition.

4. **Ignition time** is the time required to achieve sufficient vaporization to result in a flammable mixture plus the time for the mixture to ignite.

TIME TO IGNITION (cont'd)

$$t_{ig} = \frac{\pi}{4}\kappa\rho c\left[\frac{T_{ig} - T_s}{\dot{q}''}\right]$$

Slide 4-99

E. This routine is used to estimate the amount of time it will take for a certain fuel to ignite based on the level of radiant heat it is absorbing as well as its ignition properties.

1. Such an analysis can be useful in examining fire progression and flame spread to subsequent fuel packages items.

2. Time to ignition (t_{ig}) is measured in seconds.

3. Thermal inertia (kρc) is the product of thermal conductivity (k), density (ρ), and specific heat capacity (c). Higher kρc means it is more difficult to ignite, and lower kρc means it is easier to ignite.

4. Auto-ignition temperature of fuel (T_{ig}) is measured in degrees Celsius.

5. Ambient or starting temperature (T_s) is measured in degrees Celsius.

6. Heat flux ($\dot{q}$) being applied is measured in kW/m^2.

TIME TO IGNITION (cont'd)

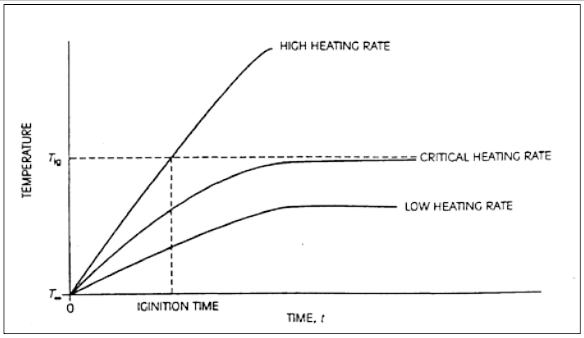


Figure 4-4: Quintiere, Principles of Fire Behavior, 1998: pg. 70)

Slide 4-100

TIME TO IGNITION (cont'd)

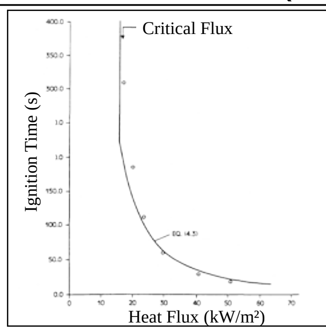


Figure 4-8: Quintiere, Principles of Fire Behavior, 1998: pg. 70)

Slide 4-101

TIME TO IGNITION (cont'd)

- Five methods available:
  - Mikkola and Wichman.
  - Quintiere and Harkleroad.
  - Janssens.
  - Toal, Silcock and Shields.
  - Tewarson.

Slide 4-102

F. Five methods available:

1. Mikkola and Wichman.

2. Quintiere and Harkleroad.

3. Janssens.

4. Toal, Silcock and Shields.

5. Tewarson.

ASSUMPTIONS/LIMITATIONS (cont'd)

- Thermally thick material.
  - Thickness approximately greater than 1/16 inch.
  - Parameters used in some calculations (e.g., critical heat flux (CHF), TRP) are obtained using specific test equipment.
  - The use of different test equipment will result in different values.
  - Methods all assume a piloted ignition source.

Slide 4-103

ASSUMPTIONS/LIMITATIONS (cont'd)

- The methods are all derived through the solid with radiant heating on the surface.

Slide 4-104

G. The methods are all derived through the solid with radiant heating on the surface.

TIME TO IGNITION EXERCISE

- Input parameters.
  - Using Spreadsheet 1.
  - Fuel type is Douglas fir particle board.
  - Radiant heat flux to target = 25 kW/m^2.
  - Ambient temperature 77 F.

Slide 4-105

TIME TO IGNITION EXERCISE (cont'd)

INPUT PARAMETERS		
MATERIAL FLAME SPREAD PROPERTIES		
Material Ignition Temperature (T_{ig})	382.00	°C
Material Thermal Inertia ($k\rho c$)	0.94	$(kW/m^2\text{-}K)^2$-sec
Material Critical Heat Flux for Ignition ($q''_{critical}$)	16.00	kW/m^2
Flame Spread Parameter b	0.05	$(s)^{1/2}$
Exposure or External Radiative Heat Flux (q''_e)	25.00	kW/m^2
Ambient Air Temperature (T_a)	77.00	°F
Heat Transfer Coefficient at Ignition (h_{ig})	0.0275	kW/m^2-K
	Calculate	

FLAME SPREAD PROPERTIES OF COMMON MATERIALS

Materials	Ignition Temp. T_{ig} (°C)	Thermal Inertia $k\rho c$ $(kW/m^2\text{-}K)^2$-sec	Critical Heat Flux for Ignition $q''_{critical}$ (kW/m^2)	Flame Spread Parameter b $(s)^{1/2}$	Select Material
					Douglas Fire Particle Board (1.27 cm
PMMA Polycast (1.59 mm)	278	0.73	9	0.04	Scroll to desired material then
Hardboard (6.35 mm)	298	1.87	10	0.03	Click on selection
Carpet (Acrylic)	300	0.42	10	0.06	

Slide 4-106

H. Here is an example problem that is offered in the reference guide for NUREG 1805 showing users how to perform the calculations. Determine the time for 2-inch thick Douglas fir plywood to ignite when it is subjected to a flame heat flux of 25 kW/m^2, assuming the surface of the plywood is initially at 77 F (20 C).

TIME TO IGNITION EXERCISE (cont'd)

Calculation Method	Time to Ignition (minute)
MIKKOLA AND WICHMAN	19.36
QUINTIERE AND HARKLEROAD	2.73
JANSSENS	33.43

Slide 4-107

I. This is a screen shot of the FDT Output Screen showing the results of three calculation methods for time to ignition based on the input parameters.

VII. GAS LAYER TEMPERATURE

GAS LAYER TEMPERATURE

- NUREG 1805, Chapter 2: predicting hot gas layer temperature and smoke layer height in a room fire with natural ventilation.

Slide 4-108

A. Chapter 2 of the NUREG 1805 manual describes in detail the science behind predicting the hot gas layer temperature and smoke layer height in a room fire with natural ventilation. Each of the spreadsheets is titled based upon NUREG 1805, Chapter 2, which addresses the particular type(s) of calculations.

GAS LAYER TEMPERATURE: WHY DO WE CARE?

- Onset of hazardous conditions.
- Onset of flashover.
- Changes in burning rate.
- Ignition of objects.

Slide 4-109

B. Gas layer temperature: Why do we care?

1. Onset of hazardous conditions.

2. Onset of flashover.

3. Changes in burning rate.

4. Ignition of objects.

ASSUMPTIONS/LIMITATIONS (cont'd)

- Upper layer gas does not exceed 600 C.
  - Fire is not post-flashover.
- Heat loss is primarily through wall conduction.
  - Fire is not rapidly developing in large enclosures. Significant fire growth has not occurred before smoke exits compartment.
- Release rate is known and constant.
- Fuel is on ground in center of room.

Slide 4-110

C. Assumptions/Limitations.

1. Upper layer does not exceed 600 C. Fire is not post-flashover.

2. Heat loss is primarily through wall conduction.

3. Fire is not rapidly developing in large enclosures. Significant fire growth has not occurred before smoke exits compartment.

4. Release rate is known and constant.

5. Fuel is on ground in center of room.

6. The correlation is based on data from a limited number of experiments and does not contain extensive data on ventilation-controlled fires nor data on combustible walls or ceilings.

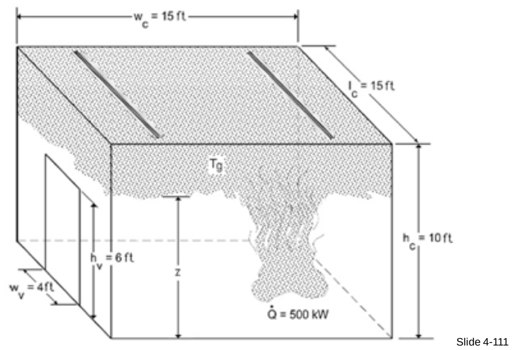
   a. Most of the fuel in the test fires was located on the floor near the center of the room.

   b. These calculations work well **up to the time of flashover.**

7. They do not apply well during underventilated compartment fires.

8. They do not apply well when the burning fuel is either elevated or against a wall or in a corner.

GAS LAYER TEMPERATURE EXERCISE 1



Slide 4-111

D. Consider a compartment that is 15 feet wide by 15 feet long by 10 feet high (wc by lc by hc), with a simple vent that is 4 feet wide by 6 feet tall (wv by hv).

1. The fire is constant with an HRR of 500 kWs.

2. The only ventilation is natural ventilation.

3. Compute the hot gas layer temperature in the compartment and smoke layer height at two minutes assuming that the compartment interior boundary material is 1-foot thick concrete and 1-inch thick gypsum board. Assume that the top of the vent is 6 feet.

GAS LAYER TEMPERATURE EXERCISE 1 (cont'd)

- Use the NV spreadsheet.
- Compute the hot gas layer temperature and smoke layer height at two minutes.
  - Assume interior lining material is 1-foot thick concrete and 1-inch thick gypsum board.
  - Assume that the top of the vent is 6 feet.
  - Assume ambient air temperature is 77 F.

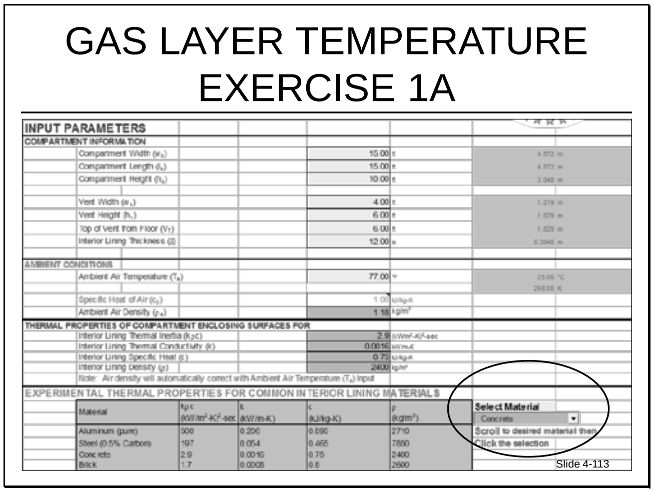
Slide 4-112

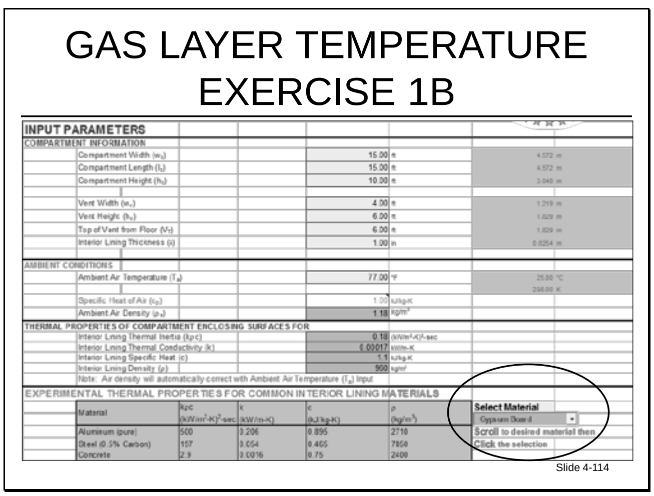
E. Use the NV spreadsheet to compute the hot gas layer temperature and smoke layer height at two minutes.

1. Assume interior lining material is 1-foot thick concrete and 1-inch thick gypsum board.

2. Assume that the top of the vent is 6 feet.

3. Assume ambient air temperature is 77 F.





F. These are examples of the FDT Input Parameter Screen showing where the material is selected to perform the desired calculation for estimating gas layer temperature.

GAS LAYER TEMPERATURE EXERCISE 1 (cont'd)

Interior Boundary Material	Hot Gas Layer Temperature (T_{ig}) °C (°F) Method of MQH	Smoke Layer Height (z) m (ft) Method of Yamana and Tanaka
Concrete	147 (296)	1.83 (6) Smoke Exiting Vent, $z < V_T$
Gypsum Board	218 (425)	1.83 (6) Compartment Filled With Smoke

Slide 4-115

G. Answers can vary substantially depending on the wall lining materials. In this case, the smoke layer height is similar for both materials, but the difference in thermal inertia between concrete and gypsum results in a much different upper layer temperature.

GAS LAYER TEMPERATURE EXERCISE 2

- Using interior boundary materials of 1-inch thick plywood for one run and 0.625-inch gypsum for another, determine the following for a 1,000 kilowatt (kW) fire:
  - The hot gas layer temperature in the compartment (T_g) at t = 2 minutes after ignition.
  - The smoke layer height (z) at t = 2 minutes after ignition.

Slide 4-116

GAS LAYER TEMPERATURE EXERCISE 2A

INPUT PARAMETERS

COMPARTMENT INFORMATION			
Compartment Width (w_c)	15.00	ft	4.572 m
Compartment Length (l_c)	15.00	ft	4.572 m
Compartment Height (h_c)	10.00	ft	3.048 m
Vent Width (w_v)	4.00	ft	1.219 m
Vent Height (h_v)	6.00	ft	1.829 m
Top of Vent from Floor (V_T)	6.00	ft	1.829 m
Interior Lining Thickness (δ)	1.00	in	0.0254 m
AMBIENT CONDITIONS			
Ambient Air Temperature (T_a)	77.00	°F	25.00 °C / 298.00 K
Specific Heat of Air (c_p)	1.00	kJ/kg-K	
Ambient Air Density (ρ_a)	1.18	kg/m³	
THERMAL PROPERTIES OF COMPARTMENT ENCLOSING SURFACES FOR			
Interior Lining Thermal Inertia ($k\rho c$)	0.16	(kW/m²-K)²-sec	
Interior Lining Thermal Conductivity (k)	0.00012	kW/m-K	
Interior Lining Specific Heat (c)	2.5	kJ/kg-K	
Interior Lining Density (ρ)	540	kg/m³	
Note: Air density will automatically correct with Ambient Air Temperature (T_a) Input			

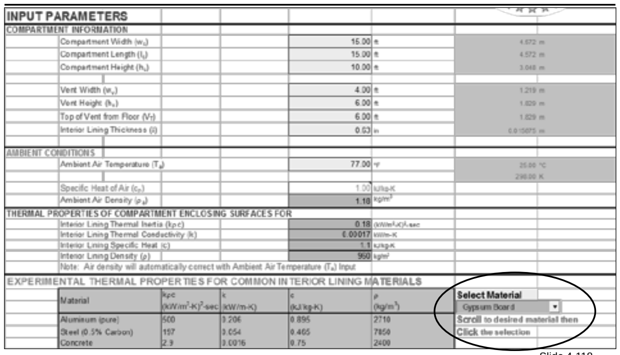
EXPERIMENTAL THERMAL PROPERTIES FOR COMMON INTERIOR LINING MATERIALS

Material	$k\rho c$ (kW/m²-K)²-sec	k (kW/m-K)	c (kJ/kg-K)	ρ (kg/m³)
Aluminum (pure)	500	0.206	0.895	2710
Steel (0.5% Carbon)	197	0.054	0.465	7850
Concrete	2.9	0.0016	0.75	2400
Brick	1.7	0.0008	0.8	2600
Glass, Plate	1.6	0.00076	0.8	2710

Select Material: Plywood
Scroll to desired material then Click the selection

Slide 4-117

GAS LAYER TEMPERATURE EXERCISE 2B



INPUT PARAMETERS			
COMPARTMENT INFORMATION			
	Compartment Width (w_c)	15.00	ft
	Compartment Length (l_c)	15.00	ft
	Compartment Height (h_c)	10.00	ft
	Vent Width (w_v)	4.00	ft
	Vent Height (h_v)	6.00	ft
	Top of Vent from Floor (V_T)	6.00	ft
	Interior Lining Thickness (δ)	0.63	in
AMBIENT CONDITIONS			
	Ambient Air Temperature (T_a)	77.00	°F
	Specific Heat of Air (c_p)	1.00	kJ/kg-K
	Ambient Air Density (ρ_a)	1.18	kg/m³
THERMAL PROPERTIES OF COMPARTMENT ENCLOSING SURFACES FOR			
	Interior Lining Thermal Inertia ($k\rho c$)	0.18	(kW/m²-K)²-sec
	Interior Lining Thermal Conductivity (k)	0.00017	kW/m-K
	Interior Lining Specific Heat (c)	1.1	kJ/kg-K
	Interior Lining Density (ρ)	960	kg/m³
	Note: Air density will automatically correct with Ambient Air Temperature (T_a) Input		

EXPERIMENTAL THERMAL PROPERTIES FOR COMMON INTERIOR LINING MATERIALS

Material	$k\rho c$ (kW/m²-K)²-sec	k (kW/m-K)	c (kJ/kg-K)	ρ (kg/m³)
Aluminum (pure)	500	0.206	0.895	2710
Steel (0.5% Carbon)	157	0.054	0.465	7850
Concrete	2.9	0.0016	0.75	2400

Slide 4-118

H. These are examples of the FDT Input Parameter Screen showing where the material is selected to perform the desired calculation for gas layer temperature.

GAS LAYER TEMPERATURE EXERCISE 2 (cont'd)

Interior Boundary Material	Hot Gas Layer Temperature (T_{lg}) °C (°F) Method of MQH	Smoke Layer Height (z) m (ft) Method of Yamana and Tanaka
Plywood	338 (640)	1.83 (6)
Gypsum	332 (629)	1.83 (6)

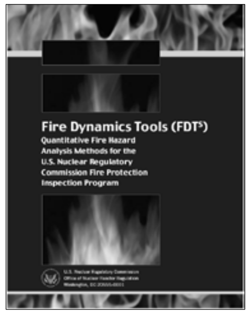
Slide 4-119

I. This is an example of the FDT Output Screen showing the smoke layer height results for plywood and gypsum board.

VIII. DETECTOR ACTIVATION TIME

DETECTOR ACTIVATION TIME

- NUREG 1805, Chapter 10: estimating smoke detector response time.



Slide 4-120

A. Chapter 10 of the NUREG 1805 manual describes in detail the science estimating smoke detector response time. Each of the spreadsheets is titled based upon NUREG 1805, Chapter 11, which addresses the particular type(s) of calculations.

SMOKE DETECTION

- Two essential factors influencing the performance of smoke detectors are the particle size of the smoke and the fire-induced air velocities.
- Typically, a smoke detector will detect most fires more rapidly than a heat detector.

Slide 4-121

B. Two essential factors influencing the performance of smoke detectors are the particle size of the smoke and the fire-induced air velocities. Typically, a smoke detector will detect most fires more rapidly than a heat detector.

SMOKE DETECTION: WHY DO WE CARE?

- Document notification/warning of occupants.
- Help establish area of origin.
- Establish timeline.
- Support/Refute witness statements.
- Examine to determine if it was intentionally disabled.

Slide 4-122

C. Information concerning smoke detection activation can be used to:

1. Document notification/warning of occupants.

2. Help establish area of origin.

3. Establish timeline.

4. Support/Refute witness statements.

5. Examine to determine if it was intentionally disabled.

DETECTOR ACTIVATION TIME (cont'd)

- Three methods:
  - Alpert.
  - Mowrer.
  - Milke.

Slide 4-123

D. Three different methods for predicting the activation times of smoke detectors under unobstructed ceilings for steady-state fires are presented.

ASSUMPTIONS/LIMITATIONS (cont'd)

- The fire is steady-state.
- The forced ventilation system is off. As ventilation is increased, detector response times increases.
- Both flaming and nonflaming fire sources can be used.

Slide 4-124

E. Assumptions/Limitations.

1. The fire is steady-state.

2. The forced ventilation system is off. As ventilation is increased, detector response times increase.

3. Both flaming and nonflaming fire sources can be used.

ASSUMPTIONS/LIMITATIONS (cont'd)

- Caution should be exercised with this method when the overhead area is highly obstructed.
- The detectors are located at ceiling or "very near to ceiling."

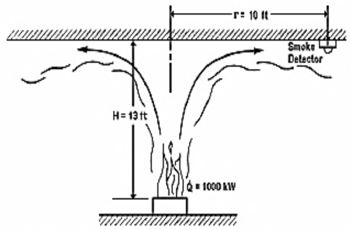
Slide 4-125

4. Caution should be exercised with this method when the overhead area is highly obstructed.

5. The detectors are located at ceiling or "very near to ceiling."

DETECTOR ACTIVATION TIME EXERCISE

Problem Statement
Estimate the response time of a smoke detector that is located 10 feet radially from the centerline of a 1,000 kW pool fire in a 13-foot tall compartment.



Example Problem 11-1: Fire Scenario with Smoke Detector

Slide 4-126

F. This is a basic problem covered in NUREG 1805 along with explanations using graphics.

DETECTOR ACTIVATION TIME EXERCISE (cont'd)

INPUT PARAMETERS

Heat Release Rate of the Fire (Q) (Steady State)	1000.00	kW
Radial Distance to the Detector (r) **never more than 0.707 or 1/2√2 of the listed spacing**	10.00	ft
Height of Ceiling above Top of Fuel (H)	13.00	ft
Activation Temperature of the Smoke Detector ($T_{activation}$)	86.00	°F
Smoke Detector Response Time Index (RTI)	5.00	$(m\text{-}sec)^{1/2}$
Ambient Air Temperature (T_a)	77.00	°F
Convective Heat Release Rate Fraction (χ_c)	0.70	
Plume Leg Time Constant (C_{pl}) (Experimentally Determined)	0.67	
Ceiling Jet Lag Time Constant (C_{cj}) (Experimentally Determined)	1.2	
Temperature Rise of Gases Under the Ceiling (ΔT_c) for Smoke Detector to Activate	18.00	°F

r/H = 0.77

Calculate

Slide 4-127

G. This is an example of the FDT Input Screen showing the input parameters required for calculating smoke detector activation.

DETECTOR ACTIVATION TIME EXERCISE (cont'd)

- Results.

	Calculation Method	Smoke Detector Response Time (sec)
Summary of Results	METHOD OF ALPERT	0.33
	METHOD OF MOWRER	0.74
	METHOD OF MILKE	0.26

Slide 4-128

IX. SPRINKLER ACTIVATION

SPRINKLER ACTIVATION

- NUREG 1805, Chapter 10: estimating sprinkler response time.

Slide 4-129

A. Chapter 10 of the NUREG 1805 manual describes in detail the science behind estimating sprinkler response time. Each of the spreadsheets is titled based upon NUREG 1805, Chapter 10, which addresses the particular type(s) of calculations.

SPRINKLER RESPONSE

- Sprinklers are designed to control a fire by producing a cooling effect when the water from a sprinkler vaporizes to cool the burning materials below their ignition temperature.
- Many times, the sprinkler system extinguishes the fire because the surrounding materials can no longer heat to their ignition temperature.

Slide 4-130

B. Sprinklers are designed to control a fire by producing a cooling effect when the water from a sprinkler vaporizes to cool the burning materials below their ignition temperature.

C. Many times, the sprinkler system extinguishes the fire because the surrounding materials can no longer heat to their ignition temperature.

SPRINKLER RESPONSE: WHY DO WE CARE?

- Help establish area of origin.
- Establish timeline.
- Support/Refute witness statements.
- Examine to determine if it operated as designed or system was intentionally disabled.

Slide 4-131

D. Sprinkler response can be used to:

1. Help establish area of origin.

2. Establish timeline.

3. Support/Refute witness statements.

4. Examine to determine if it operated as designed or whether system was intentionally disabled.

ASSUMPTIONS/LIMITATIONS

- The method assumes that the ceiling is unconfined, unobstructed, smooth, flat and horizontal.
- The plume ceiling jet correlations of temperature and velocity assume that the fire source is located away from walls and corners.

Slide 4-132

E. Assumptions/Limitations.

1. The method assumes that the ceiling is unconfined, unobstructed, smooth, flat and horizontal.

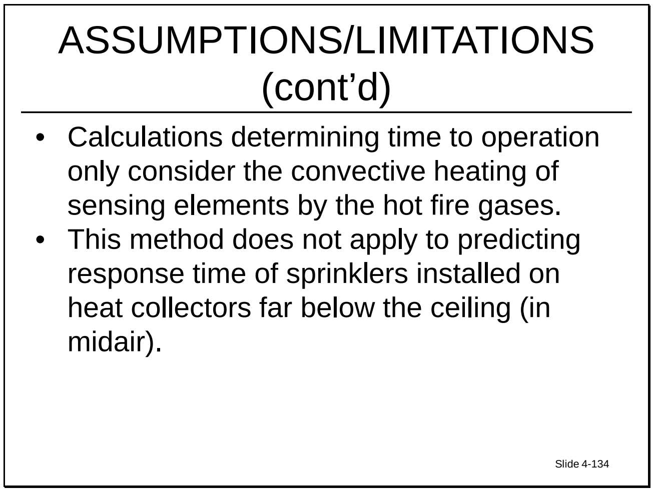
2. The plume ceiling jet correlations of temperature and velocity assume that the fire source is located away from walls and corners.

ASSUMPTIONS/LIMITATIONS (cont'd)

- The correlations for estimating the maximum ceiling jet temperature and velocity were developed for steady-state fires and plumes under unconfined ceilings.
- Plume ceiling jet correlations are valid for unconfined ceilings.

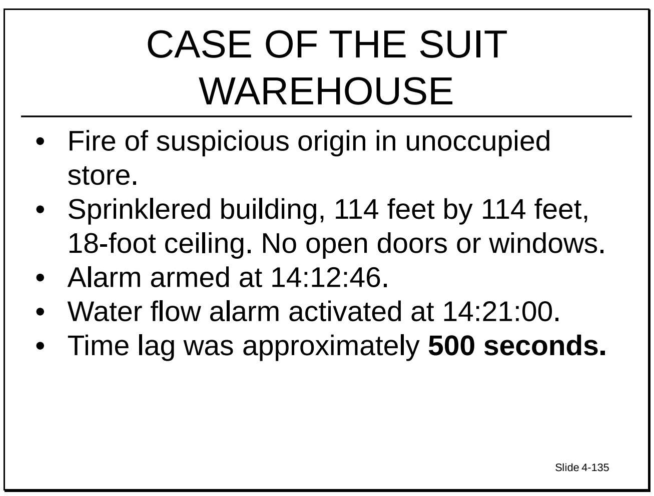
Slide 4-133

3. The plume ceiling jet correlations of temperature and velocity assume that the fire source is located away from walls and corners.



4. Calculations determining time to operation only consider the convective heating of sensing elements by the hot fire gases.

5. This method does not apply to predicting response time of sprinklers installed on heat collectors far below the ceiling (in midair).



F. Case of the suit warehouse.

CASE OF THE SUIT WAREHOUSE (cont'd)

Slide 4-136

1. A fire occurred in a suit warehouse. This photograph shows the extent of the damage; basically one rack of suits burned prior to the sprinkler activating and suppressing the fire. With the investigator's clear photographs of the space and measurement of the floor tile, the scene could be recreated in terms of spacing in between the suit racks and the number of suits hanging per rack by counting the number of hangers. This would assist with tests that could be conducted to examine the hypothesis.

2. During the investigation, it was learned what time the purveyors locked the business and when the sprinklers activated based on data from the central alarm company. The employees left the building shortly before the owner. The owner left and locked the building for lunch. Per the employee statements and his statements, no smoke was visible at the time of their departure. The owner was a smoker, but only smoked outside in the rear of the building.

3. Investigators found a significant number of cigarette butts at the rear of the building that supported his claim. When the owner returned from lunch, he found that the fire department was mopping up from the fire. Based on the alarm company records, the time between locking the door and arming the alarm and the water flow alarm for the sprinklers activating was approximately 500 seconds.

CASE OF THE SUIT WAREHOUSE (cont'd)

Slide 4-137

4. Investigators wanted to determine whether or not the fire would have been able to be ignited and burn and still activate the sprinklers without the knowledge of the departing employees/owner. No electrical outlets or any electrical power sources were near the area of origin.

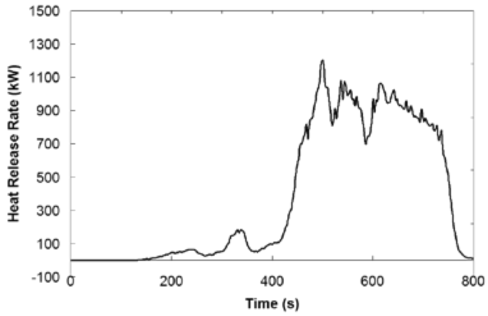
CASE OF THE SUIT WAREHOUSE (cont'd)

- Full-scale HRR experiment.

Slide 4-138

5. A series of experiments were conducted to measure the HRR of a comparable rack of men's suits. A detailed summary of the tests and conclusions can be found in National Institute of Standards and Technology (NIST) Fire Tests of Men's Suits on Racks — Report of Tests (FR4013), December 2011. A copy of the report can be downloaded at http://fire.nist.gov/bfrlpubs/fire01/art071.html.

HRR FROM FULL-SCALE EXPERIMENT



Slide 4-139

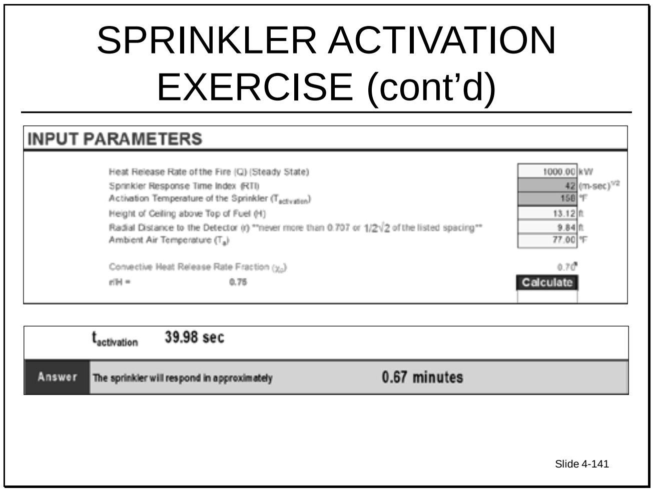
6. An HRR curve was obtained from a full scale test run in a manner consistent with an open flame ignition.

SPRINKLER ACTIVATION EXERCISE

- Quick bulb sprinkler (response time index (RTI) 42).
- Activation temperature of 70 C.
- 1,000 kW fire.
- Closest sprinkler was 4 meters (m) above the top of the suit rack at a radial distance of 3 m.

Slide 4-140

7. After reviewing the full-scale HRR experiment for the suit warehouse, estimate how long it would take for a quick bulb sprinkler (response time index (RTI) 42) with an activation temperature of 70 C to activate from a 1,000 kW fire if the closest sprinkler was 4 meters (m) above the top of the suit rack at a radial distance of 3 m.



8. Piloted ignition for this thermally thick fuel is estimated to occur under these conditions at 110 seconds, assuming the given radiant exposure is greater than the critical heat flux (CHF).

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ACTIVITY 4.1

Howard County, Maryland, Fire: Mathematical Modeling

Purpose

To apply the modeling principles learned in this class to the Howard County Fire case.

Directions

1. You will need to review the following items:

    a. Origin and cause report.

    b. Witness statements.

    c. Drawings.

    d. Photos.

    e. Prosecutor's request memorandum.

2. Analyze the witness' statements, and develop questions that can be answered using fire dynamics.

3. You should quantify each of these questions using a variety of tools, including:

    a. Hand calculations.

    b. CFI Calculator.

    c. FDT spreadsheets.

WITNESS' STATEMENT

- Jerrod Smith (resident):
  - Approximately 15 minutes after laying down, he heard the bedroom hallway smoke alarm sounding.
  - Quickly got out of bed to silence the alarm to prevent waking up wife and son.
  - Disconnected alarm from its base and removed the batteries.

Slide 4-143

WITNESS' STATEMENT (cont'd)

  - Around the same time, he smelled smoke and saw smoke coming from the living room area.
  - Entered living room and stated that the entire couch was engulfed in flames.
  - Flames were about 1 foot tall.

Slide 4-144

QUESTION 1

How tall are flames on the couch when it is fully involved?

Slide 4-145

1. How tall are flames on the couch when it is fully involved?

SUGGESTED APPROACH

- Flame height inputs: HRR, effective diameter, wall factor.
- HRR of the couch can be estimated using the FDT spreadsheets:
  - Assume the couch is approximately 84 inches (2.1336 m) long by 32 inches (0.8128 m) wide.
  - Assume the couch is made of polyurethane (PU) foam.
  - Assume the couch is against the wall.

Slide 4-146

a. Before the flame height can be calculated, the HRR and effective diameter need to calculated.

SUGGESTED APPROACH (cont'd)

- Use FDT HRR spreadsheet.
  - -- Set to "Standard" and click on "Materials Drop Down."
  - -- Select "PU Foam" from Materials Drop-Down menu.
  - -- Enter dimensions of couch.

Slide 4-147

b. The CFI Calculator HRR tool can be used to determine the fire size when the entire couch is on fire.

SUGGESTED APPROACH (cont'd)

- Use the FDT flame height spreadsheet.
  - Use the calculated HRR and set the wall factor as "Against the Wall."
  - Calculate the effective diameter of the couch using the following equation.

$$D = \sqrt{\frac{4A_f}{\pi}}$$

Slide 4-148

c. After the HRR is calculated, the CFI Calculator flame height tool can be used.

QUESTION 2

Determine the time required for the fire to become fully involved.

Slide 4-150

2. How long does it take for the fire to reach full involvement?

SUGGESTED APPROACH

- Fire growth inputs: HRR, growth rate.
- Fire growth can be estimated by:
  - Assume a fast growth rate for the fire.
  - Use the HRR calculated in Question 1.

Slide 4-151

The fire growth formula requires inputs of HRR and growth rate. A polyurethane (PU) couch will likely have a fast growth rate.

QUESTION 3

- Determine the time to smoke detector activation using an HRR that is 1/10 of the calculated HRR from Question 1.

Slide 4-153

3. Determine the time to smoke detector activation when the fire is only 1/10 of its calculated HRR from Question 1.

SUGGESTED APPROACH

- Smoke detector activation inputs:
  - HRR.
  - Radial distance from fire to detector.
  - Vertical distance from base of fire to detector.
  - Ambient air temperature.
- Smoke detector activation can be estimated using the NRC spreadsheet “Estimating Sprinkler Response Time.”

Slide 4-154

a. In order to calculate the smoke detector activation time, define the HRR, radial distance between the fire and detector, vertical distance between the base of the fire and the detector, and the ambient air temperature.

SUGGESTED APPROACH (cont'd)

- Click on the "Smoke Detector" tab at the bottom of the spreadsheet.
  - Assume the couch is 20 feet from the smoke detector.
  - Assume the base of the fire is 1.5 feet from the floor and the ceilings are 8 feet in height.
    - -- Vertical distance between base of fire and smoke detector would be 8 feet - 1.5 feet = 6.5 feet.
  - Assume ambient air temperature = 77 F.

Slide 4-155

b. Assume a radial distance of 20 feet, a vertical distance of 6.5 feet, and an ambient air temperature of 77 F.

WITNESS' STATEMENT (cont'd)

- Threw water on the fire from about 5 feet away.
- He did not receive any burns.

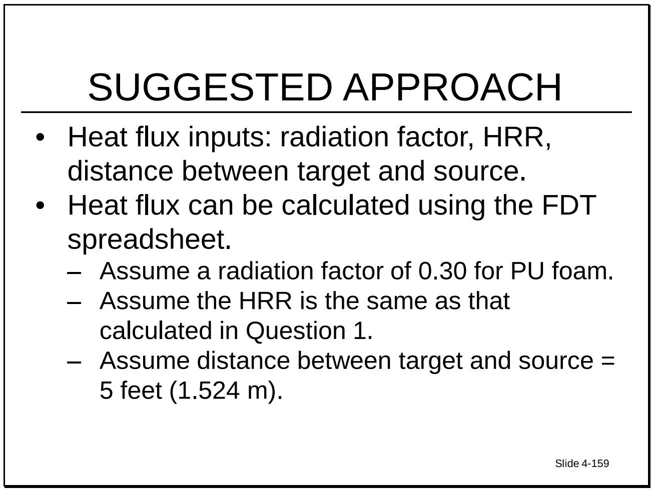
Slide 4-157

QUESTION 4

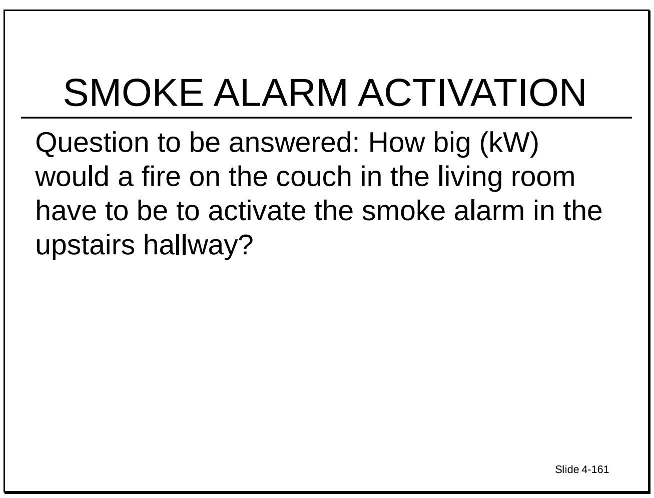
What is the heat flux 5 feet away from the center of the couch when it is fully involved?

Slide 4-158

4. Determine the heat flux that Mr. Smith would have been subjected to given his distance from the fire when he attempted to extinguish it.



In order to calculate the heat flux, the HRR radiation factor and distance between the target and source need to be defined.



SMOKE ALARM ACTIVATION PRIMARY VARIABLES

- HRR/Fire size.
  - How much is burning (mass loss rate (MLR) in g/s).
  - What is burning (heat of combustion in kJ/kg — K, HRR/fire size).
- Smoke production in gsoot/g fuel burned.
  - Species yield.
  - Vitiated versus nonvitiated.
- Smoke alarm.

Slide 4-162

SMOKE ALARM ACTIVATION PRIMARY VARIABLES (cont'd)

  - Type (ionization versus photoelectric).
  - Settings (default or nonstandard).
- Compartment.
  - Ceiling height.
  - Radial distance and fluid flow obstructions.
- Air movement.
  - Wind from an open window.
  - Heating, ventilating and air conditioning (HVAC).

Slide 4-163

SMOKE ALARM ACTIVATION NONCRITICAL VARIABLES

- Other rooms.
  - Bedroom, basement (size of rooms, door position, fuel load).
- Other fuels in living room.

Slide 4-164

FLAME HEIGHT

- Question to be answered: How tall are the flames at the time of smoke detector operation in the upstairs hallway? How tall are the flames when the couch is fully involved?

Slide 4-165

FLAME HEIGHT PRIMARY VARIABLES

- HRR/Fire size.
  - How much is burning (MLR in g/s).
  - What is burning (heat of combustion in kJ/kg — K).
- Fuel bed area.
- Vertical obstruction (free entrainment).
  - Walls, corners, etc.

Slide 4-166

FLAME HEIGHT NONCRITICAL VARIABLES

- Compartmentalization.

Slide 4-167

WITNESS' STATEMENT (cont'd)

- He then went to the bathroom to get a bucket of water.
- When walking back to the bathroom, he stated that a cloud of smoke had formed over his head near the ceiling.
- Visibility was not a problem, no trouble breathing, he said.
- He filled up the bucket and returned to the living room.

Slide 4-168

SMOKE LAYER POSITION

- Question to be answered: What is the smoke layer position and average temperature on the first floor given a couch fire in the living room? (This position should be predicted for different fire sizes and times in the fire timeline.)

Slide 4-169

SMOKE LAYER POSITION PRIMARY VARIABLES

- HRR/Fire size.
  - How much is burning (MLR in g/s).
  - What is burning (heat of combustion in kJ/kg — K).
- Fuel bed area.
- Vertical obstruction (free entrainment).
  - Walls, corners, etc.
- Compartment.

Slide 4-170

SMOKE LAYER POSITION PRIMARY VARIABLES (cont'd)

- Ceiling height.
- Volume (additional rooms for smoke to fill).
- Boundary material properties.

- Ventilation.
  - Window and door openings.
  - Open area and location in compartment.

Slide 4-171

SMOKE LAYER POSITION NONCRITICAL VARIABLES

- Other fuels in living room.

Slide 4-172

VISIBILITY

- Jerrod Smith had stated that visibility was not a problem.
- Question to be answered: What is the visibility (m) in the main living area of the first floor when the couch is fully involved?

Slide 4-173

VISIBILITY PRIMARY VARIABLES

- Fire size and smoke production.
  - First item ignited — type of fuel, ignition location, ventilation (fuel-limited or ventilation-limited combustion).
- Compartment.
  - Ceiling height.
  - Volume (additional rooms for smoke to fill).
- Ventilation (mass loss).
  - Window and door openings.

Slide 4-174

VISIBILITY NONCRITICAL VARIABLES

- Other fuels in living room.
- Compartment boundary material properties.

Slide 4-175

WITNESS' STATEMENT (cont'd)

- He then went to the edge of the coffee table and threw the water on the fire.
- Mr. Smith estimates that he was 5 feet away from the center of the couch during his attempt at suppression.
- He stated that he did not receive any burns, and although it was hot, he was tough and had to put the fire out to save his family.

Slide 4-176

HEAT FLUX TO TARGET

- Question to be answered: What is the heat flux 5 feet away from the center of the couch when it is fully involved?

Slide 4-177

HEAT FLUX PRIMARY VARIABLES

- HRR/Fire size.
  - How much is burning (MLR in g/s).
  - What is burning (heat of combustion in kJ/kg — K).
- Fuel bed area.
- Distance between target and fuel.
- Vertical obstructions (free entrainment).
  - Walls, corners, etc.

Slide 4-178

HEAT FLUX PRIMARY VARIABLES

- Other fuels in living room.
- Compartment.
  - Ceiling height.
  - Volume (additional rooms for smoke to fill).
  - Boundary material properties.

Slide 4-179

SPRINKLER ACTIVATION

- The house was not provided with residential sprinklers, but under county law, it was required to be protected.
- The county is contemplating the pursuit of negligent homicide charges against the landlord.

Slide 4-180

SPRINKLER ACTIVATION (cont'd)

- When considering charging the landlord with negligent homicide, the state would not just have to prove that the landlord was negligent in failing to provide an automatic sprinkler system, but also it would have to **clearly establish** that if it weren't for the **negligent act,** the **mother and father would have survived.**

Slide 4-181

SPRINKLER ACTIVATION (cont'd)

- Question to be answered: How big of a couch fire is required to fuse a sprinkler head in a properly installed residential system?

Slide 4-182

SPRINKLER ACTIVATION PRIMARY VARIABLES

- HRR/Fire size.
  - How much is burning (MLR in g/s).
  - What is burning (heat of combustion in kJ/kg — K).
- Fuel bed area.
- Sprinkler.
  - RTI.
  - Activation temperature of the sprinkler ($T_{activation}$).

Slide 4-183

SPRINKLER ACTIVATION PRIMARY VARIABLES (cont'd)

- Compartment.
  - Height of ceiling above top of fuel (H).
  - Radial distance to the detector (r).
  - Fluid flow obstructions.
- Ambient air temperature (T_a).

Slide 4-184

SPRINKLER ACTIVATION NONCRITICAL VARIABLES

- Primary fuel — soot protection, species yields.
- Other fuels in living room.
- Compartment boundary material properties.

Slide 4-185

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ACTIVITY 4.2

Case Study: Commonwealth of PA v. Paul Camiolo

Purpose

To demonstrate the different models that can be used to evaluate origin and cause hypotheses by showing a representative case.

Directions

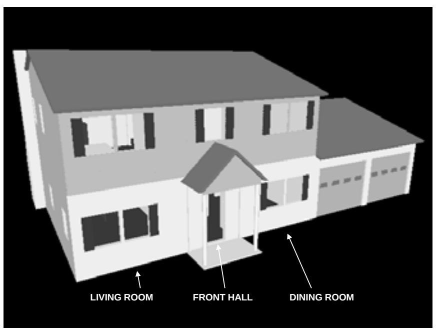
1. The instructor will present the background of the Paul Camiolo case.
2. Work with your table to formulate a hypothesis about the cause of the fire.
3. The instructor will list the hypotheses you develop on an easel pad.
4. The instructor will present the hypotheses that were developed by the case investigators.
5. The instructor will present some tools that you could use to evaluate your hypothesis.
6. The instructor will discuss how fire modeling was used in the case.
7. The instructor will show a video that reveals the actual outcome of the case.

CASE BACKGROUND

- Home located in upper Moreland, Pennsylvania.
- Two-story house, wood-frame construction (circa 1970).
- Three residents.
  - Mother, age 57 (smoker, infirm).
  - Father, age 81 (infirm).
  - Son, age 31.
- Fire occurred on Sept. 30, 1996.

Slide 4-187

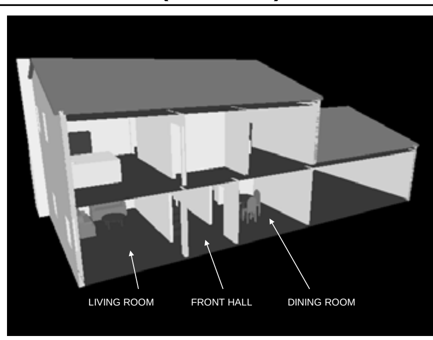
GEOMETRY OF RESIDENCE



View From the Front of the House, North Face

Slide 4-188

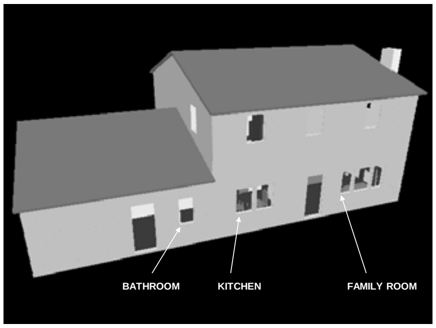
GEOMETRY OF RESIDENCE (cont'd)



View From the Front of the House, North Face

Slide 4-189

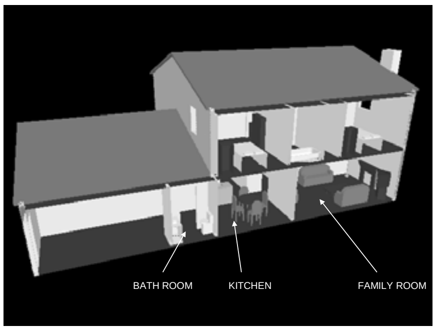
GEOMETRY OF RESIDENCE (cont'd)



View From the Rear of the House, South Face

Slide 4-190

GEOMETRY OF RESIDENCE (cont'd)



View From the Rear of the House, South Face

Slide 4-191

INCIDENT HISTORY

- Fire reported 4:30 a.m.
- Police arrive at 4:35 a.m.
  - Son outside front of house.
  - Mother found on back porch.
- Fire department on-scene at 4:40 a.m.
  - Father found dead in rear bathroom.
- Fire under control at 5:03 a.m.

Slide 4-192

INCIDENT HISTORY (cont'd)

- Mother and son transported to hospital.
  - Mother died three months later from complications.
  - Son released shortly after treatment.
- Father dead at the scene.
  - Nonlethal burns to the head and upper torso.
  - Cause of death: smoke inhalation.

Slide 4-193

SCENE INVESTIGATION

- Room of origin: family room.
- Fuel load: couch, loveseat, lift-chair.
- Extensive burn damage throughout with minor extension.
- Irregular pattern noted on hardwood flooring.
- Samples of the carpet, carpet padding, newspaper and wood flooring sent for analysis.

Slide 4-194

THE SON'S STORY

- Father called for help at 4:30 a.m.
- Went downstairs to find his father in the lift-chair and his mother on the couch.
- His mother was patting out a small fire on the couch.
- Attempted to put out fire with a pitcher of water.
- Fire "flared up."

Slide 4-195

THE SON'S STORY (cont'd)

- Told parents to get out of the house.
- Called 911 from the dining room.
- Observed his parents heading toward the back porch.
- Exited out the front door.
- Retrieved sweatpants from his parked car.
- Went to the rear of the house to locate parents.

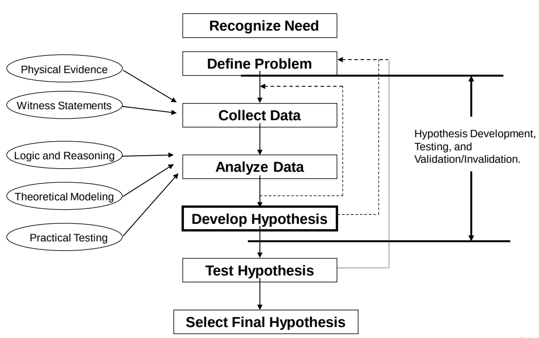
Slide 4-196

THE SON'S STORY (cont'd)

- Pulled mother from the floor of the house just inside back porch exit.
- He could not enter further to find his father due to heat and smoke.
- Ran to the front of the house for help and met with the arriving officer.

Slide 4-197

HYPOTHESIS DEVELOPMENT: WHAT CAUSED THE FIRE?



Slide 4-198

ONE INVESTIGATOR'S THEORY

- Irregular burn patterns and positive sample → incendiary cause.
- Motive.
  - Collection of assets.
  - Elimination of burden.
- Parents asleep upstairs.

Slide 4-199

ONE INVESTIGATOR'S THEORY (cont'd)

- Son spreads 1 gallon of gasoline on the carpet in the family room.
- Ignites gasoline, grabs cordless phone, goes outside through the front door, calls 911, holds front door shut.
- Parents forced to use the rear exit.

Slide 4-200

SCENE INVESTIGATION (cont'd)

- Two hypotheses:
  - **Accidental fire** as the result of carelessly discarded smoking materials.
  - **Incendiary fire** based on possible:
    - -- Positive for gasoline on wood.
    - -- Negative for gasoline on newspaper, carpet and padding.

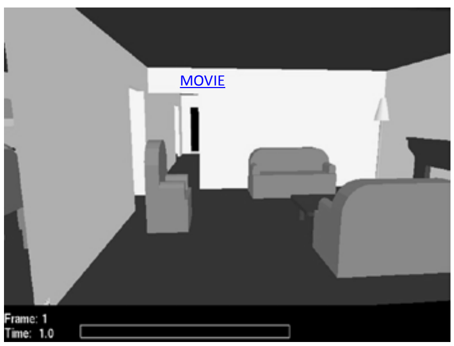
Slide 4-201

ANALYSIS

- What types of tools could be used to evaluate the hypotheses?
  - Fire size.
  - Fire growth rate.
  - Layer temperature.
  - Radiant heat to a target.

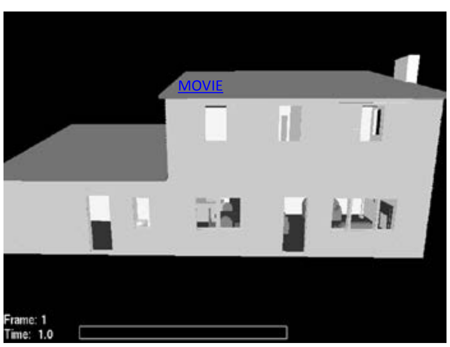
Slide 4-202

"ACCIDENTAL CASE MOVIE (REAR VIEW)"



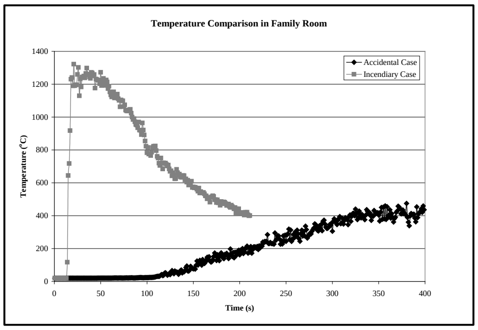
Slide 4-203

"INCENDIARY CASE MOVIE (REAR VIEW)"



Slide 4-204

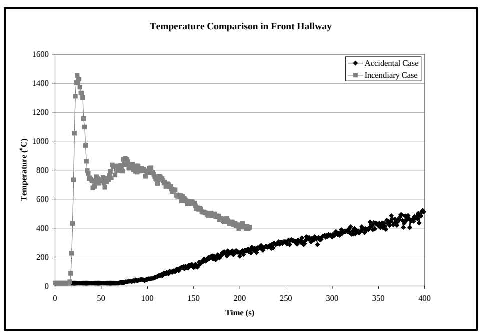
TEMPERATURE VERSUS TIME



(Family Room — Single Point, Near Lift-Chair)

Slide 4-205

TEMPERATURE VERSUS TIME (cont'd)



(Front Hallway — Single Point, Near Front Door)

Slide 4-206

ANALYSIS (cont'd)

- For the first 200 seconds of the accidental case, the temperature within the family room does not exceed 200 C.
- This is consistent with the story dictated by the son.
- For the incendiary scenario, the son would have had 15 seconds to exit the house without getting scorched by the set fire.

Slide 4-207

ANALYSIS (cont'd)

- For the incendiary scenario, the parents would not have been able to traverse the stairs by the time they were alerted to the fire (therefore they would have been found dead upstairs).

Slide 4-208

DVD PRESENTATION

"FORENSIC FILES - SEASON 10, EP 4: UP IN SMOKE "

Slide 4-209

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X. SUMMARY

SUMMARY

- Overview of models.
- HRR.
- Flame height.
- Heat flux.
- Flashover calculations.
- Time to ignition.
- Gas layer temperature.

Slide 4-210

SUMMARY (cont'd)

- Detector activation time.
- Sprinkler activation.

Slide 4-211

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UNIT 5: COMPUTER MODELING

TERMINAL OBJECTIVE

The students will be able to:

5.1 Critically evaluate the uses and limitations of computer modeling in fire prevention and investigation.

ENABLING OBJECTIVES

The students will be able to:

5.1 Differentiate between a zone and field model.

5.2 List the capabilities and limitations of different models.

5.3 Use a zone model to evaluate a fire scenario.

5.4 Identify appropriate input data for use in a fire model.

5.5 Use graphical user interfaces (GUIs), as they relate to the fire dynamics simulator (FDS).

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UNIT 5:
COMPUTER MODELING

Slide 5-1

ENABLING OBJECTIVES

- Differentiate between a zone and field model.
- List the capabilities and limitations of different models.
- Use a zone model to evaluate a fire scenario.
- Identify appropriate input data for use in a fire model.

Slide 5-2

ENABLING OBJECTIVES (cont'd)

- Use graphical user interfaces (GUIs) as they relate to the fire dynamics simulator (FDS).

Slide 5-3

I. INTRODUCTION TO MODELING

TYPES OF FIRE MODELS

- Physical models.
- Hand calculations/Mathematical correlations.
- Computer models.
  - Zone models.
  - Field models.

Slide 5-4

A. Types of fire models:

1. Physical models.

2. Hand calculations/Mathematical correlations.

3. Computer models.

   a. Zone models — Consolidated Model of Fire Growth and Smoke Transport (CFAST).

   b. Field models — fire dynamics simulator (FDS)/computational fluid dynamics (CFD).

INTRODUCTION TO COMPUTER FIRE MODELS

- Use of a computer to re-create or “model” the fire environment.
- Attempted using mathematical equations.
- Concept has been around since the 1960s.

Slide 5-5

B. Use of a computer to re-create or “model” the fire environment is another tool for the investigator to use in fire scene analysis.

1. The modeling of the fire environment is attempted using mathematical equations.

2. The concept of computer fire modeling has been around since the 1960s.

INTRODUCTION TO COMPUTER FIRE MODELS (cont'd)

- Scientific principles of fire growth, spread and flashover.
- Focus of researchers at National Institute of Standards and Technology (NIST) since the 1970s.
- Initial work included identifying gas temperatures and fuel consumed in fire.

Slide 5-6

3. The need to understand and explain scientific principles is relevant to fire growth, spread and flashover.

4. Focus of researchers at the National Institute of Standards and Technology (NIST) since the 1970s.

5. Initial work included identifying gas temperatures and the fuel being consumed in a fire.

ORIGINAL SIX ISSUES OF FIRE MODELING (1970s)

- Avoid cost and repetition of full-scale testing.
- Building design and fire safety.
- Establish database on flammability of materials.
- Increase flexibility and reliability of fire codes.
- Identify and support further research.
- Use of models for investigation and litigation.

Slide 5-7

C. In the 1970s, NIST began to develop computer fire models to address six issues.

1. Avoiding cost and repetition of full-scale testing.

2. Building design and fire safety.

3. Establish database related to flammability of materials.

4. Increase the flexibility and reliability of fire codes.

5. Identify and support further fire research.

6. Use of models for investigation and litigation.

USES OF FIRE MODELS

- Predicting the impact of fire on a structure.
- Flammability of contents, finishes and structural members.
- Examining conditions such as fuel loading and ventilation arrangements.
- Demonstrating the impact of fire phenomena and research on fire service operations (e.g., flow path).

Slide 5-8

D. Use of fire models.

1. Fire models are regularly used to predict the impact of fire on a structure.

2. Often measured in terms of the flammability of contents, finishes and structural members.

3. Provides an inexpensive way to examine various conditions such as different fuel loading and ventilation arrangements.

4. Demonstrating the impact of fire phenomena and research on fire service operations (e.g., flow path).

IMPACT OF COMPUTER MODELING ON FIRE RESEARCH

- Creation of flexible, performance-based designs.
- Optimization of occupant evacuation rates.
- Reduction of cost and time associated with traditional testing.
- Used to support investigations by testing hypotheses.

Slide 5-9

E. Impact of computer modeling on fire research.

1. Creation of flexible building designs based on modeling.

2. Designs can be developed to optimize occupant evacuation rates.

3. Cost and time associated with traditional testing has been greatly reduced.

4. Modeling can be used to support investigations by testing hypotheses.

USE OF COMPUTER MODELS IN FIRE INVESTIGATION

- To supplement other areas of an investigation.
- To simulate fire environment/physical fire.
- To test hypotheses, rationalize timelines and validate witness statements.

Slide 5-10

F. Use of computer models in fire investigation.

1. Can be used to supplement other areas of an investigation, such as witness statements and fire scene evidence.

2. Can be used to simulate the fire environment as well as the physical fire.

3. Can be used to test hypotheses, rationalize timelines, and validate witness statements.

VARIABILITY AND UNCERTAINTY

- Repeat tests will not provide identical results due to:
  - Measurement errors.
  - Construction materials.
  - Geometry.
  - Ventilation.
  - Physical conditions.

Slide 5-11

G. Variability and uncertainty.

1. Even under idealized test conditions, repeat tests will not provide identical results.

2. Uncertainty is in part due to measurement errors and other factors such as construction materials, geometry, ventilation, physical conditions, etc.

ACCURACY OF COMPUTER MODELING

- Not more accurate than the physical world.
- Cannot re-create a fire scenario to 100 percent accuracy.

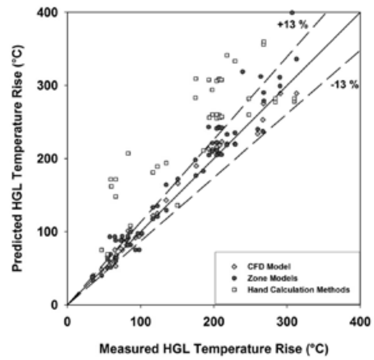
Slide 5-12

H. Accuracy of computer modeling.

1. No model should be expected to be more accurate than the physical world it attempts to represent.

2. No fire model can conclusively re-create a fire scenario to 100 percent accuracy.

ACCURACY OF COMPUTER MODELING (cont'd)



Slide 5-13

I. This slide gives an example of upper layer gas temperatures predicted by three types of models.

1. Hand calculations — Certified Fire Investigator (CFI) Calculator, fire dynamics tools (FDTs).

2. Zone models — CFAST.

3. CFD/Field models — FDS.

4. In general, hand calculations can be seen to over-predict upper layer, hot gas temperatures.

5. Zone models are typically around plus or minus 20 percent.

6. Field models, in this diagram, are plus or minus 13 percent.

7. In some cases, this error is not far off from the measurement errors involved.

SENSITIVITY ANALYSIS

- Demonstrates the relative change in output that can be expected by changing an input.
  - Some changes in input result in comparable changes in output.
  - Other similar changes result in much larger or much smaller changes.

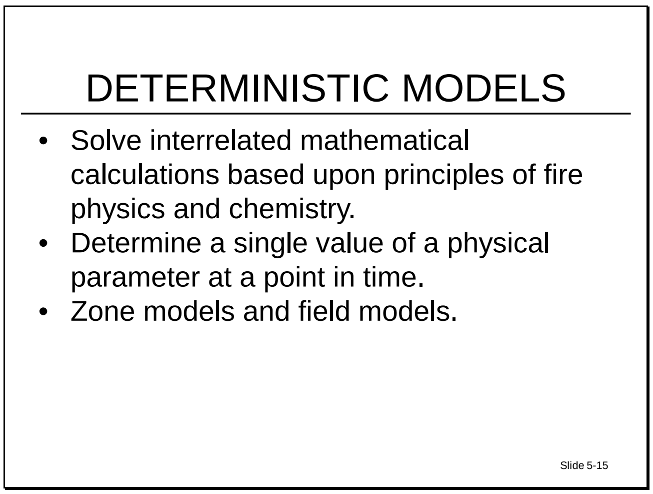
Slide 5-14

J. Sensitivity analysis demonstrates the relative change in output that can be expected by changing an input by a certain amount.

1. Some changes in input parameters result in comparable changes in output predictions.

2. Other similar changes in input parameters result in much larger or much smaller changes in predicted values.

3. Important to understand whether critical results are significant or occurred by chance.



K. Deterministic models.

1. Address fire processes by solving interrelated mathematical calculations based upon underlying principles of fire physics and chemistry.

2. Iterations generally result in the determination of a single value of a physical parameter at a point in time.

a. Upper layer gas temperature.

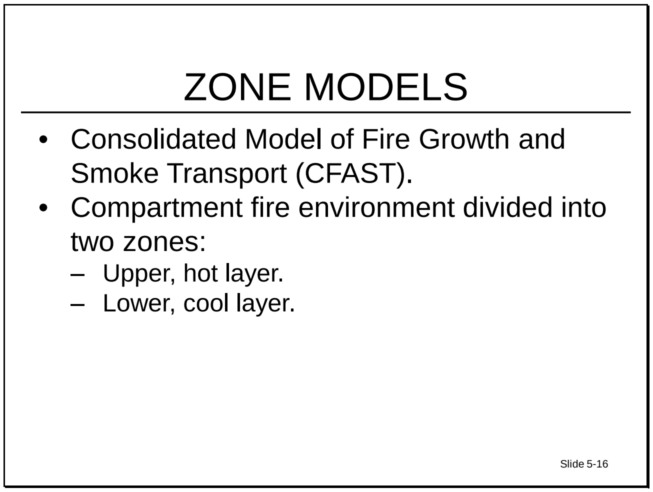
b. Heat flux.

c. Oxygen concentration.

3. Two types:

a. Zone models.

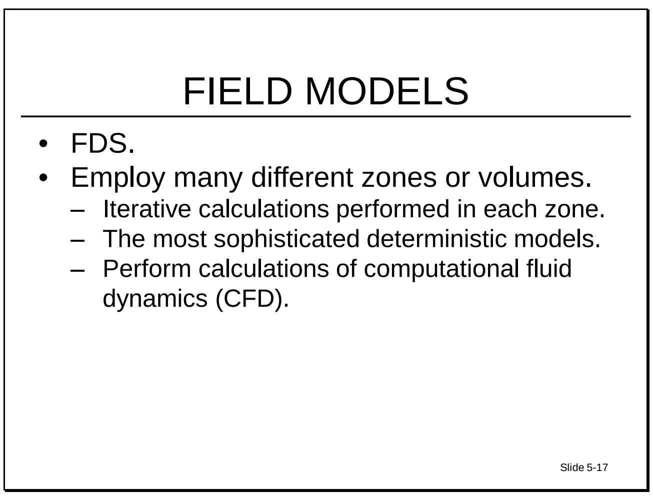
b. Field models.



L. Zone models, including CFAST, are based upon the concept of the compartment fire environment being divided into two distinct zones:

1. Upper, hot layer.

2. Lower, cool layer.



M. Field models, including FDS, employ many different zones or volumes, sometimes in the hundreds of thousands or more.

1. Iterative calculations are performed in each zone.

2. These are the most sophisticated deterministic models.

3. They perform calculations of the mathematical formulas associated with CFD.

APPLICATIONS OF FIRE MODELING

- To assess:
  - Sprinkler activations and impact.
  - The effects of various heat release rates (HRRs) at different locations.
  - Impacts of the changes of fire codes.
  - Transport of gases.
  - Temperatures reached in different locations.

Slide 5-18

N. Use of fire modeling in forensic investigations.

1. Sprinkler activations and impact.
2. The effects of various heat release rates (HRRs) at different locations.
3. Impacts of the changes of fire codes
4. Transport of gases (e.g., toxic).
5. Temperatures reached in different locations.

II. VERIFICATION AND VALIDATION

Society of Fire Protection Engineers' (SFPE's) Guidelines for Substantiating a Fire Model for a Given Application

Slide 5-19

A. Society of Fire Protection Engineers' (SFPE's) Guidelines for Substantiating a Fire Model for a Given Application.

PURPOSE

- To provide a framework for determining and documenting the suitability of a particular fire model for use in a specific fire protection application.

Slide 5-20

1. The purpose of the SFPE Guide is to provide a framework for determining and documenting the suitability of a particular fire model for use in a specific fire protection application.

PURPOSE (cont'd)

– Currently, there is no formal process by which fire models are approved. The user of the fire model has responsibility for determining its suitability. In some cases, the authority that has jurisdiction evaluates the acceptability of that determination.
– The SFPE Guide serves both the fire model user and the consumer of the results.

Slide 5-21

a. Currently, there is no formal process by which fire models are approved. The user of the fire model has responsibility for determining its suitability. In some cases, the authority that has jurisdiction evaluates the acceptability of that determination.

b. The SFPE Guide serves both the fire model user and the consumer of the results.

SCOPE

This guide applies once a decision has been made to use a fire model for a fire protection application.

Slide 5-22

2. This guide applies once a decision has been made to use a fire model for a fire protection application.

STEPS TO SUBSTANTIATING A FIRE MODEL

- The first step toward substantiating a fire model as being appropriate for a given application is to define the problem of interest using the following steps:
  - Provide background and introduction.
  - Identify relevant phenomena and key physics.
  - Collect available information.
  - Determine analysis objectives.

Slide 5-23

B. Steps to substantiating a fire model.

1. The first step toward substantiating a fire model as being appropriate for a given application is to define the problem of interest.

PROVIDE BACKGROUND AND INTRODUCTION

- The background for the problem of interest should be provided to explain the significance of the problem, why the problem deserves a numerical study, and what has been done in the past on similar topics.

Slide 5-24

2. The background for the problem of interest should be provided to explain the significance of the problem, why the problem deserves a numerical study, and what has been done in the past on similar topics. To avoid repeating previous work, a literature review of published information on the relevant subject should be conducted in this step.

PROVIDE BACKGROUND AND INTRODUCTION (cont'd)

  – To avoid repeating previous work, a literature review of published information on the relevant subject should be conducted in this step.

Slide 5-25

VERIFICATION AND VALIDATION

- As with many other fire models, FDS has undergone and continues to undergo many iterations of testing for verification and validation (V&V).
- Modelers must be aware of the limitations of the program as well as the applications.

Slide 5-26

C. As with many other fire models, FDS has undergone and continues to undergo many iterations of testing for verification and validation (V&V). Modelers must be aware of the limitations of the program as well as the applications.

VERIFICATION AND VALIDATION (cont'd)

- Model and scenario definition.
- Theoretical basis for model.
- Mathematical and numerical robustness.
- Model sensitivity.
- Model evaluation.

ASTM E1355 — Guide for Model Assessment

Slide 5-27

1. CFAST has gone through a V&V process by both practitioners and NIST personnel.

2. Nuclear Regulatory Guides (NUREGs) published on the applicability of CFAST to various U.S. Nuclear Regulatory Commission (NRC) problems.

3. These topics are all part of the V&V process established and practiced by the NRC.

VERIFICATION

- Are differences between model and experiment due to the numerical solution, the physical sub-models, or both?
- Have correct principles of mathematics been used?

Slide 5-28

a. Verification is the process of determining if differences between models and experiments are due to limitations, errors in the numerical solution, the physical sub-models, or a combination of factors. There must be verification that the correct principles of mathematics have been used.

VALIDATION

- Is a calculation method an accurate representation of the real world?
- Have the correct physics been used?
  - Compare model predictions to experimental measurements.
  - Quantify uncertainties in measurements and model inputs.
  - Decide if model is appropriate.

Slide 5-29

b. Validation is the process of determining the degree to which a calculation method is an accurate representation of the real world from the perspective of its intended uses.

- Check that correct physics have been used.

- Compare model predictions to experimental measurements.

- Quantifying differences in terms of uncertainties in measurements and model inputs.

- Deciding if model is appropriate for given application.

USER RESPONSIBILITIES

- Determining appropriateness of model use in any particular application.
- Justifying relevancy and reliability of model.

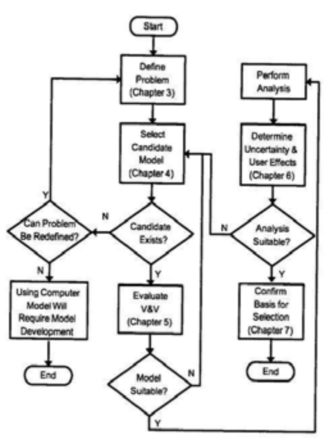
Slide 5-30

c. User responsibilities.

- Users assume full responsibility and liability for determining appropriateness of use in any particular applications.

- Users should be prepared to justify relevancy and reliability of models when presenting results of investigations or designs.

FIGURE 1. FIRE MODEL SELECTION FLOW CHART



Slide 5-31

IDENTIFY RELEVANT PHENOMENA AND KEY PHYSICS

- The relevant phenomena for the problem of interest should be described in detail to allow for the identification of key physics for the analysis.
  - For example, flame spread on a solid fuel surface is a relevant phenomenon to evaluate combustible building materials.

Slide 5-32

4. The relevant phenomena for the problem of interest should be described in detail to allow for the identification of key physics for the analysis. For example, flame spread on a solid fuel surface is a relevant phenomenon to evaluate combustible building materials.

IDENTIFY RELEVANT PHENOMENA AND KEY PHYSICS (cont'd)

- The key physics are heat transfer between the flame and the fuel, as well as pyrolysis within the solid fuel.
- Inclusion of key physics for the phenomena relevant to the problem of interest is necessary, but not sufficient, to justify the selection and use of a fire model.

Slide 5-33

a. The key physics are heat transfer between the flame and the fuel, as well as pyrolysis within the solid fuel.

b. Inclusion of key physics for the phenomena relevant to the problem of interest is necessary, but not sufficient, to justify the selection and use of a fire model.

IDENTIFY RELEVANT PHENOMENA AND KEY PHYSICS (cont'd)

- Commonly encountered key physics in numerical modeling of fire phenomena are thermodynamics, fluid dynamics, heat transfer, combustion, and materials response.
- The appendix lists fire-related phenomena and quantities, with general descriptions, applications, key physics, and discussions of various models.

Slide 5-34

c. Commonly encountered key physics in numerical modeling of fire phenomena are largely covered by thermodynamics, fluid dynamics, heat transfer, combustion, and materials response.

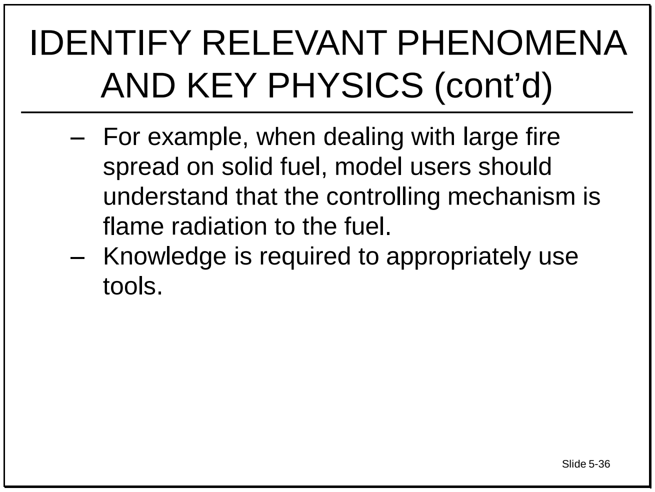
d. The appendix lists fire-related phenomena and quantities, with general descriptions, applications, key physics, and discussions of various models.

IDENTIFY RELEVANT PHENOMENA AND KEY PHYSICS (cont'd)

- Identification of relevant phenomena and key physics requires knowledge of the details of the problem of interest and of the underlying chemical and physical processes.

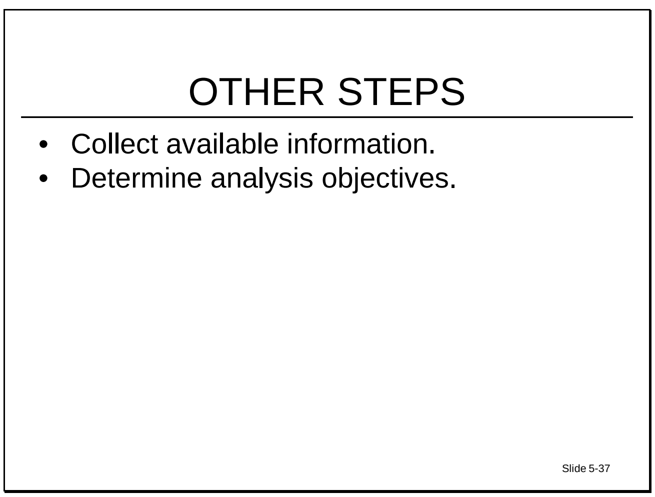
Slide 5-35

e. Identification of relevant phenomena and key physics requires knowledge of the details of the problem of interest and of the underlying chemical and physical processes.



- For example, when dealing with large fire spread on solid fuel, model users should understand that the controlling mechanism is flame radiation to the fuel.

- An appropriate level of knowledge is required to prevent users from treating a fire model as a black-box tool, which can result in using the model beyond the scope of its capability.



5. Collect available information.

6. Determine analysis objectives.

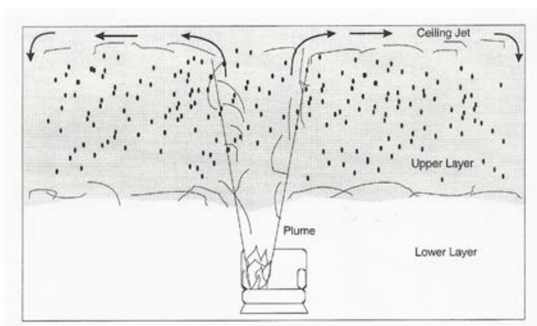
WHERE TO GET A COPY

- SFPE Bookstore.
- https://netforum.avectra.com/eWeb/Shopping/Shopping.aspx?Site=SFPE&WebCode=Shopping.

Slide 5-38

III. ZONE MODELS (CFAST)

ZONE MODELS (CFAST)



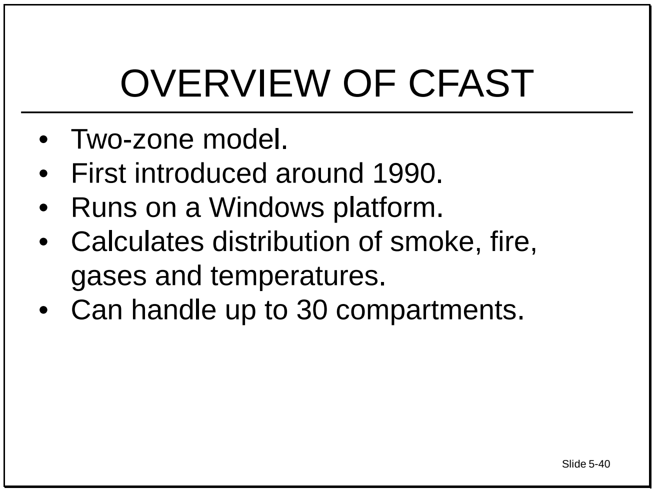
Slide 5-39

A. Basic view of compartment fire development. This shows how a compartment can be divided into two main sections and one subsection.

1. Hot upper layer with smoke.

2. Cool lower layer of fresher air.

3. The plume which includes combustion products is treated as a third, smaller zone.



B. Overview of CFAST.

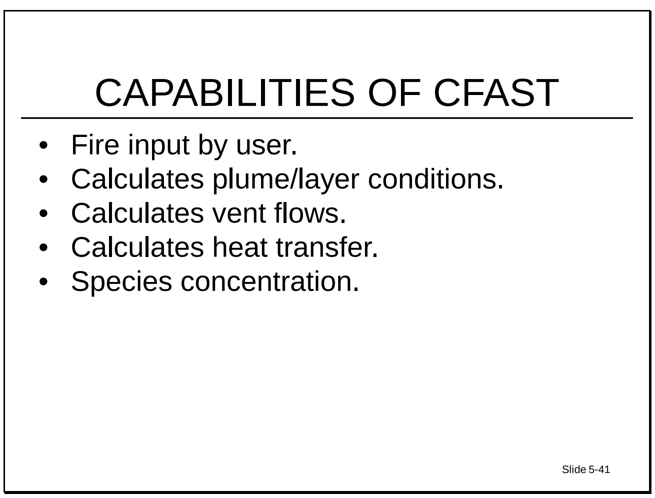
1. Two-zone model.

2. First introduced around 1990.

3. Runs on a Windows platform.

4. Calculates distribution of smoke, fire, gases and temperatures.

5. Can handle up to 30 compartments.



C. Basic capabilities of the CFAST Zone Model.

1. The fire is defined by the user. The model does not predict a fire growth without user input.

2. CFAST calculates the temperatures in the plume and upper layers.

3. Depth of the smoke layer.

4. Vent flow calculates the flow out of a compartment.

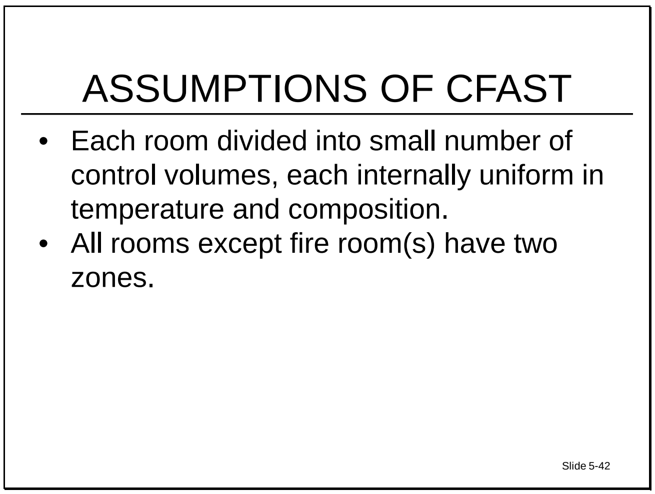
5. Heat transfer can be used to estimate radiant heat flux at a defined target.

6. CFAST can be used to estimate species concentrations with user input.

    a. Carbon dioxide.

    b. Oxygen.

    c. Carbon monoxide.



D. Assumptions of CFAST.

1. Each room divided into small number of control volumes, each internally uniform in temperature and composition.

2. All rooms except fire room(s) have two zones.

ASSUMPTIONS OF CFAST (cont'd)

- Fire room(s) have additional zone for plume.
- Buoyancy stratified layers form in spaces close to fire.
- Variations in temperature within a layer are small compared to variation between layers.

Slide 5-43

3. Fire room(s) have additional zone for plume.

4. Buoyancy stratified layers form in spaces close to fire.

5. Variations in temperature within a layer are small compared to variation between layers.

LIMITATIONS OF CFAST

- Compartment volumes should be strongly stratified.
- Heat release should not exceed 1 MW/m^3.

Slide 5-44

E. Limitations of CFAST.

1. Compartment volumes should be strongly stratified.

2. Heat release should not exceed 1 megawatt per meter cubed (MW/m^3).

LIMITATIONS OF CFAST (cont'd)

- Ratio of area of vents connecting one compartment to another to the volume of the compartment should not exceed 2 m^{-1}.
- Accuracy of predictions limited by accuracy of the thermophysical properties data used.

Slide 5-45

3. Ratio of area of vents connecting one compartment to another to the volume of the compartment should not exceed 2 m^{-1}.

4. Accuracy of predictions limited by accuracy of the thermophysical properties data used.

TYPICAL CFAST INPUTS

From CFAST Technical Manual

Parameter	Inputs (Items in **bold** are inputs that may vary due to error in measurements)
Ambient Conditions	Inside **temperature** and **pressure** Outside **temperature** and **pressure** Wind **speed** **Relative humidity** (0 % to 100 %)
Building Geometry	**Compartment width**, **depth**, **height**, and surface material properties (**conductivity**, **heat capacity**, **density**, **thickness**) Horizontal Flow Vents: **Height of soffit above floor, height of sill above floor, width of vent, angle of wind to vent, time history of vent openings and closings** Vertical Flow Vents: **Area of vent**, shape of vent Mechanical Ventilation, Orientation of vent, **Center height of vent, area of vent, length of ducts, diameter of ducts, duct roughness, duct flow coefficients, fan flow characteristics**
Fire Specification	Fire room, **X, Y, Z position in room, fire area** Fire Chemistry: Molar Weight, **Lower oxygen limit**, **heat of combustion**, **initial fuel temperature**, **gaseous ignition temperature**, **radiative fraction** Fire History: Mass loss rate, heat release rate, species yields for **HCN**, **HC1**, **H/C**, O_2/C, C/CO_2, CO/CO_2

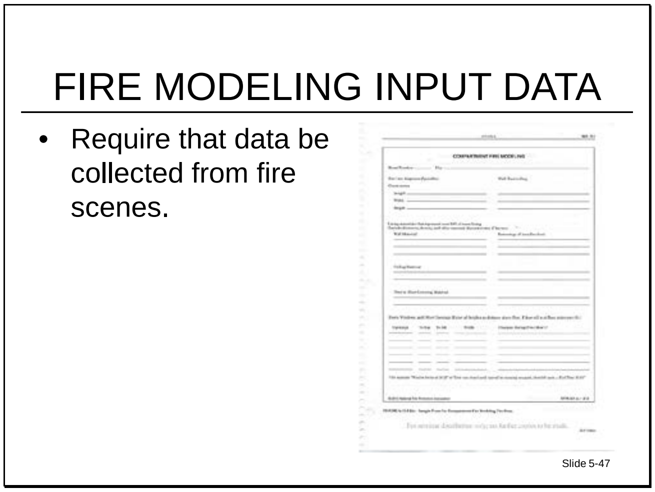
Slide 5-46

F. Typical CFAST inputs.

1. Ambient conditions: temperature and pressure; inside and outside, relative humidity, wind speed and direction, etc.

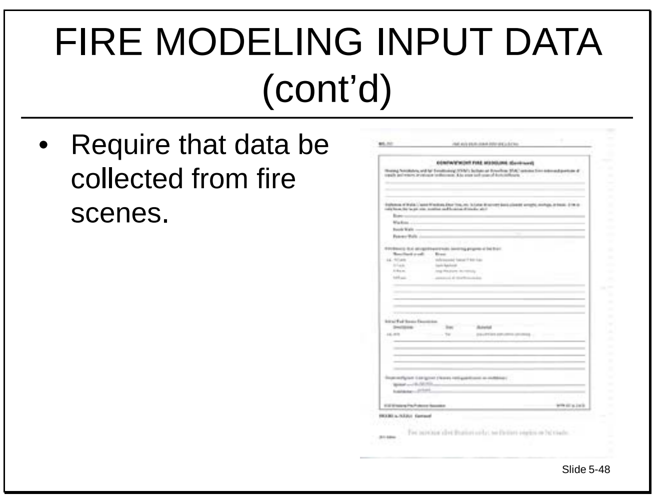
2. Building geometry: compartment width, depth, height, number of compartments, natural and mechanical vents (type, area, shape, and location), soffit height, sill height, etc.

3. Fire specification: fire room, xyz position in room, fire area, lower oxygen limit, heat of combustion, growth rate, mass loss rate (MLR), HRR, species yields for hydrogen cyanide, hydrochloric acid hydrocarbons, carbon dioxide, carbon monoxide, oxygen, water, etc.



G. Fire modeling inputs require that data be collected from fire scenes.

1. This is page one of the computer fire modeling data collection sheet given in National Fire Protection Association (NFPA) 921, *Guide for Fire and Explosion Investigations*.



2. This is page two of the computer fire modeling data collection sheet given in NFPA 921.

TYPICAL CFAST OUTPUTS

From CFAST Technical Manual

Parameter		Output (typically time histories)
Compartment Environment	for each compartment	Compartment pressure and layer interface height
	for each layer and compartment	Temperature Layer mass density, layer volume, heat release rate, gas concentrations (N_2, O_2, CO_2, CO, H_2O, HC1, HCN, soot optical density), radiative heat into layer, convective heat into layer, heat release rate in layer
	for each vent and layer	Mass flow, entrainment, vent jet fire
	for each fire	Heat release rate of fire, mass flow from plume to upper layer, plume entrainment, pyrolysis rate of fire
	for each compartment surface	Surface temperatures
Tenability		Temperature Fractional Exposure Dose (FED)

Slide 5-49

H. Typical CFAST outputs.

1. Compartment environment includes pressure, layer interface height, temperature, layer mass density, gas concentrations, radiative and convective heat into the layer, HRR in layer, mass flow into upper layer, entrainment, mass flow out vents, overall HRR, surface temperatures, etc.

TYPICAL CFAST OUTPUTS (cont'd)

- Tenability — the time period before which conditions in a compartment become life-threatening, due to temperature, obscuration, smoke and toxic gases, or heat flux.

Slide 5-50

2. Tenability — the time period before which conditions in a compartment become life-threatening, due to temperature, obscuration, smoke and toxic gases, or heat flux.

TYPICAL CFAST OUTPUTS (cont'd)

- Investigative applications.
  - Fire death caused by carbon monoxide poisoning.
  - Fire victim displaying second-degree burns.
- Performance (prefire) use or application.
  - Pass/Fail criteria for performance-based design.

Slide 5-51

3. Investigative applications.

   a. Fire death caused by carbon monoxide poisoning.

   b. Fire victim displaying second-degree burns.

   c. The performance (prefire) use or application is as pass/fail criteria for performance-based design.

OUTPUT FILE

- CFAST creates an output text file at time intervals set by the user.
- The file can either be printed out or scrolled through at the workstation after each run for quick examination.

Slide 5-52

I. Output file.

1. CFAST creates an output text file at time intervals set by the user.

2. The file can either be printed out or scrolled through at the workstation after each run for quick examination.

EXCERPT FROM OUTPUT FILE

Compartment	Upper Temp. (C)	Lower Temp. (C)	Inter. Height (m)	Upper Vol. (m^3)	Upper Absorb (m^-1)	Lower Absorb (m^-1)	Pressure (Pa)	Ambient Target (W/m^2)	Floor Target (W/m^2)
1	20.00	20.00	2.400	2.73E-03(0%)	1.000E-02	1.000E-02	6.345E-02	28.1	28.1

Fires

Compartment	Fire	Plume Flow (kg/s)	Pyrol Rate (kg/s)	Fire Size (W)	Flame Height (m)	Fire in Upper (W)	Fire in Lower (W)	Vent Fire (W)	Convec. (W)	Radiat. (W)
	wardrobe	2.34	8.446E-03	2.500E+05	1.33				1.750E+05	7.499E+04
1		2.34	8.446E-03	2.500E+05		0.00	2.500E+05	0.00		

Surfaces and Targets

Compartment	Ceiling Temp. (C)	Up wall Temp. (C)	Low wall Temp. (C)	Floor Temp. (C)	Target	Target Temp. (C)	Flux To Target (W/m^2)	Fire Rad. (%)	Surface Rad. (%)	Gas Rad. (%)	Convect. (%)
1	20.00	20.00	20.00	20.00	Floor	20.0	446.9	1.7	96.7	1.6	0.0
					1	20.0	435.0	0.0	97.0	2.2	0.0

Slide 5-53

3. This is an excerpt from an output file.

SPREADSHEET OUTPUTS

- CFAST also creates spreadsheet files capturing various data from HRR, upper and lower layer temperatures, vent flows, smoke layer height, oxygen and other species concentrations, etc.
- The data can be used to generate various charts to visually represent the output.

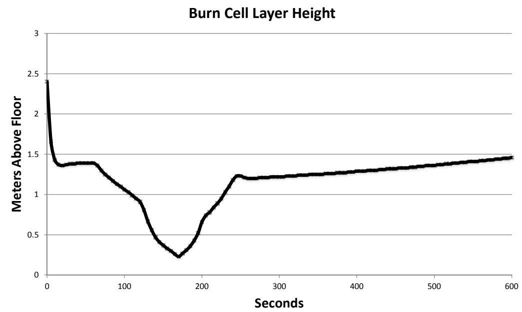
Slide 5-54

J. Spreadsheet outputs.

1. CFAST also creates spreadsheet files capturing various data from HRR, upper and lower layer temperatures, vent flows, smoke layer height, oxygen and other species concentrations, etc.

2. The data can be used to generate various charts to visually represent the output.

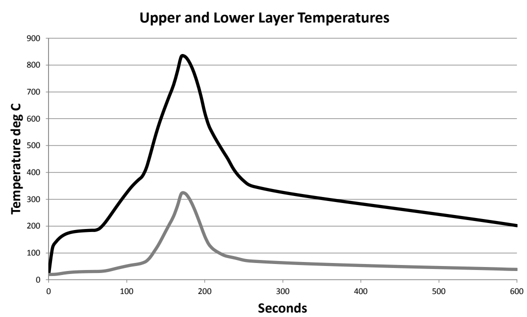
EXAMPLE DATA CHARTS



Slide 5-55

a. This is an example data chart, showing burn cell layer height.

EXAMPLE DATA CHARTS (cont'd)



Slide 5-56

b. This is an example data chart, showing upper and lower layer temperatures.

CFAST DATA ENTRY

- Data entry is based on pull down menus.
- In several instances, "canned" values are available for selection.
- Geometry is based on the "x, y, z" Cartesian coordinate system.

Slide 5-57

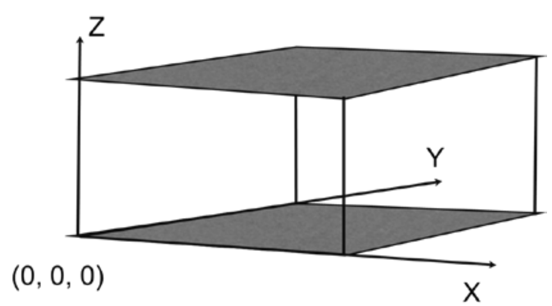
K. CFAST data entry.

1. Data entry is based on pull down menus.

2. In several instances, “canned” values are available for selection.

3. Geometry is based on the “x, y, z” Cartesian coordinate system.

CFAST COMPARTMENT GEOMETRY



Slide 5-58

OTHER CFAST FEATURES

- Can have multiple vents, both vertical and horizontal.
- Mechanical ventilation can be included.
- Detector (heat and smoke) activations.
- Sprinkler activation and operation.
- Output visible in SmokeView.

Slide 5-59

L. Other CFAST features.

1. Can have multiple vents, both vertical and horizontal.

2. Mechanical ventilation can be included.

3. Detector (heat and smoke) activations.

4. Sprinkler activation and operation.

5. Output visible in SmokeView.

PRESCRIBING A FIRE

- An unconstrained fire — fuel limited.
- A constrained fire — ventilation limited.
- CFAST has a limited database of sample fires and properties of materials.
- User-defined fires are also acceptable.

Slide 5-60

M. Prescribing a fire.

1. An unconstrained fire — fuel limited.

2. A constrained fire — ventilation limited.

3. CFAST has a limited database of sample fires and properties of materials.

4. User-defined fires are also acceptable.

SMOKEVIEW

- SmokeView is used to view CFAST results.
- Provides animations of the simulation.
- Supplies visual output of the layer development and temperature conditions.

Slide 5-61

N. SmokeView.

1. SmokeView is used to view CFAST results.

2. Provides animations of the simulation.

3. Supplies visual output of the layer development and temperature conditions.

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ACTIVITY 5.1

Build Ventilation Model for Burn Cell in CFAST

Purpose

To use input parameters (e.g., geometry, ventilation openings and fire size) for CFAST to build and execute a zone model and interpret and analyze results using SmokeView and output data.

To compare the results derived from the model to the observations obtained from the live compartment fire exercise.

Directions

1. Read the background information and observations from the live burn that was previously conducted (Burn Cell Data Handout).

2. Observe the instructor's demonstration on populating fields in CFAST.

3. Input the data from the Burn Cell Data Handout into CFAST on your computer, based on the demonstration you just observed.

4. Observe the instructor's demonstration of running the CFAST model to produce output in SmokeView that shows fire growth, layer height and temperature.

5. Run the CFAST model on your own to produce output in SmokeView that shows fire growth, layer height and temperature.

6. Observe the instructor's demonstration of how to use and manipulate SmokeView to analyze output.

7. Analyze SmokeView output and record peak temperature, time to flashover and HRR curve.

8. Compare and contrast the data on the Burn Cell Data Handout with the data from the SmokeView output, using peak temperature, time of flashover, HRR curve and areas of uncertainty. Display this on a Venn diagram.

9. Discuss comparisons as a class.

ACTIVITY 5.1 NOTES

IV. GENERAL HINTS FOR USING CFAST AND SMOKEVIEW

SMOKEVIEW NAVIGATION

- SmokeView is controlled by the mouse.
- Hold down left button and drag to rotate.
- Left button + CTRL + dragging zooms in and out.

Slide 5-63

A. SmokeView Navigation.

1. SmokeView is controlled by the mouse.

 a. Hold down left button and drag to rotate.

 b. Left button + CTRL + dragging zooms in and out.

SMOKEVIEW NAVIGATION (cont'd)

- Right click the mouse, and several options are available.
- Load/Unload.
  – Output files:
    -- 3-D Smoke, Slice Files, Vector Files.
    -- Boundary Files, Isosurface Files.

Slide 5-64

2. Right click the mouse, and several options are available.

 a. Load/Unload:

  - Output files:

   -- 3-D Smoke, Slice Files, Vector Files.

-- Boundary Files, Isosurface Files.

SMOKEVIEW NAVIGATION (cont'd)

- Show/Hide.
- Various display options, turn textures on or off, turn labels on or off.
  - Geometry.
  - Labels.
  - 3-D smoke.

Slide 5-65

b. Show/Hide:

- Various display options.
- Turn textures on or off.
- Turn labels on or off.
  - -- Geometry.
  - -- Labels.
  - -- 3-D Smoke.

SMOKEVIEW NAVIGATION (cont'd)

- Actual versus requested blockages.
  - "Actual" shows how FDS calculates using the inputs moved to fit the grid.
  - "Requested" is that input by the user.
- Clip blockages like walls or ceilings for better viewing.

Slide 5-66

3. Actual versus requested blockages.

a. "Actual" shows how FDS calculates using the inputs moved to fit the grid.

b. "Requested" is that input by the user.

c. Clip blockages like walls or ceilings for better viewing.

SMOKEVIEW NAVIGATION (cont'd)

- Options.
  - Color shading.
  - Units — metric versus English.
  - Rotation allows for different types of viewing.
    - -- Eye-centered — as if moving your head.
    - -- World-centered — rotating around the scene.

Slide 5-67

4. Options.

a. Color shading.

b. Units — metric versus English.

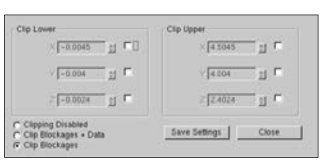
c. Rotation allows for different types of viewing.

- Eye-centered — as if moving your head.

- World-centered — rotating around the scene.

SMOKEVIEW NAVIGATION (cont'd)

- Dialogs:
  - Clip geometry lets you remove walls to see inside the building.

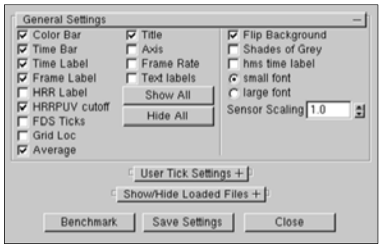


Slide 5-68

-- This slide shows the dialog box for clip geometry.

SMOKEVIEW NAVIGATION (cont'd)

– "Display" shows visualization options.



Slide 5-69

-- This slide shows the dialog box for display options.

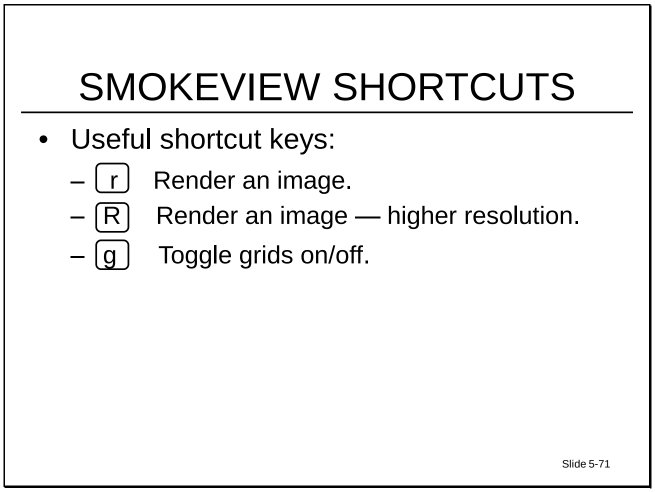
SMOKEVIEW NAVIGATION (cont'd)

- Motion/View:
  - This offers another way of looking at the scene if you do not have a mouse.
- **Stereo**:
  - Allows for 3-D viewing with a cathode ray tube (CRT) monitor (or fast flat screen) or 3-D glasses.

Slide 5-70

5. Motion/View offers another way of looking at the scene if you do not have a mouse.

6. **Stereo** allows for 3-D viewing with a cathode ray tube (CRT) monitor (or fast flat screen) or 3-D glasses.

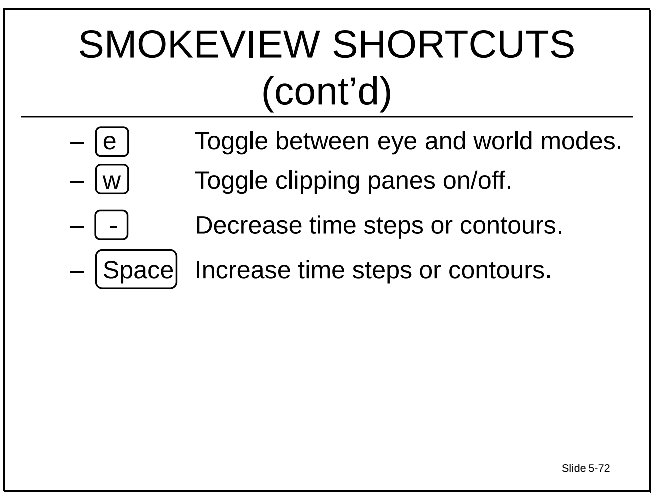


7. Useful shortcut keys.

   a. [r] — render an image.

   b. [R] — render an image in higher resolution.

   c. [g] — toggle grids on/off.



   d. [e] — toggle between eye and world modes.

   e. [w] — toggle clipping panes on/off.

   f. [–] (minus) — decrease time steps or contours.

   g. [space] — increase time steps or contours.

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ACTIVITY 5.2

CFAST Model for Howard County

Purpose

To use the input file provided by instructor (e.g., geometry, ventilation openings and fire size) for CFAST to build and execute a zone model and interpret and analyze results using SmokeView and output data.

To use CFAST to test hypotheses derived from other methods by inputting data including hypothesized location of fuel and fire origin.

Directions

1. Follow the instructor's directions and guidance to locate and open the input files for the Howard County, Maryland, Investigation Project.

2. Input the required data into CFAST, including the fire's location and size, based on your hypothesis.

3. Run the model scenario to produce output, with the instructor's guidance as necessary.

4. Document your results in your notebook.

5. Compare the model results to the hypothesis to draw initial conclusions about the location of fire and fire origin.

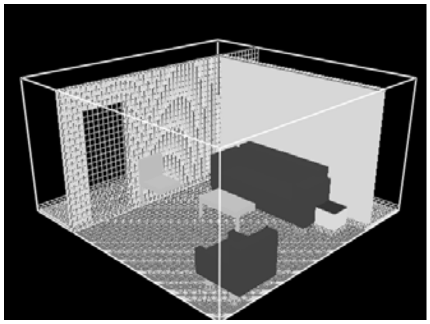
6. Respond to the prompt, "Are the results consistent with the scenario? Why or why not?"

7. Discuss comparisons as a class.

ACTIVITY 5.2 NOTES

V. COMPUTATIONAL FLUID DYNAMICS FIELD MODELS

CFD FIELD MODELS



Slide 5-74

FIELD MODELS

- Field models are a class of computer models known as CFD models.
  - Field models typically divide scenarios into more zones than zone models do.
    - -- Zone models typically have two or three zones.
    - -- Field models designed for the same space can have hundreds of thousands of zones.

Slide 5-75

A. Field models are a class of computer models known as CFD models.

1. The principle difference between zone and field models is the number of zones in which a scenario is subdivided.

2. Zone models typically have two or three zones.

3. Field models designed for the same space can have hundreds of thousands of zones.

FIELD MODELS (cont'd)

- The modeler decides how many "volumes" to divide the space into.
- Much like a zone model, a field model performs calculations in each of the "volumes" and compares the energy levels and species concentrations in each.

Slide 5-76

4. The modeler decides how many "volumes" to divide the space into.

5. Much like a zone model, a field model performs calculations in each of the "volumes" and compares the energy levels and species concentrations in each.

DEGREE OF ACCURACY

- Though FDS models usually contain far more calculation zones than a zone model, they still should not be expected to be more accurate than the physical world they attempt to represent.
- As with zone models, no field fire model can conclusively re-create a fire scenario to 100 percent accuracy.

Slide 5-77

B. Degree of accuracy.

1. Though FDS models usually contain far more calculation zones than a zone model, they still should not be expected to be more accurate than the physical world they attempt to represent.

2. As with zone models, no field fire model can conclusively re-create a fire scenario to 100 percent accuracy.

FDS SETUP

- Setting up a FDS file is done in one of two ways.
  - Either a CAD-based graphical user interface (GUI) is used, such as PyroSim, or an input text file is written in **Fortran** code.
  - The code is used to define obstructions, vents, the fire, chemical reaction specifics, etc.

Slide 5-78

C. FDS setup is done in one of two ways.

1. Either a CAD-based graphical user interface (GUI), such as PyroSim, is used or an input text file is written in **Fortran** code.

2. The code is used to define obstructions, vents, the fire, chemical reaction specifics, etc.

DOMAIN SETUP

- The first thing a modeler does is to define the size of the calculation domain.
- Next, the specific layout is defined.
  - Exact sizes of the domain, vents and obstructions, down to the millimeter level, are not needed. The model will only calculate down to the size of the smallest mesh.

Slide 5-79

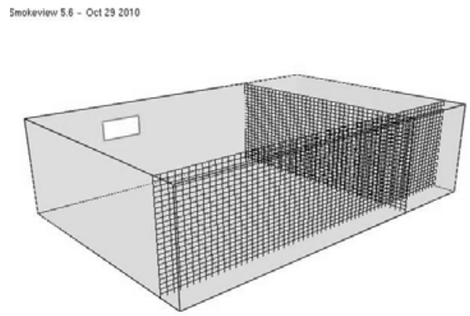
D. Domain setup.

1. The first thing a modeler does is to define the size of the calculation domain.

2. Next, the specific layout is defined.

3. Exact sizes of the domain, vents and obstructions, down to the millimeter level, are not needed. The model will only calculate down to the size of the smallest mesh.

DOMAIN



Slide 5-80

OBJECT CONSTRUCTION FORMAT

- Objects are constructed based upon a rectilinear format.
  - Objects in a scenario, or “obstructions,” are built from series of blocks, each assigned material properties.
  - Simple furniture items, like chairs, often consist of several such blocks, each requiring a separate line of code.

Slide 5-81

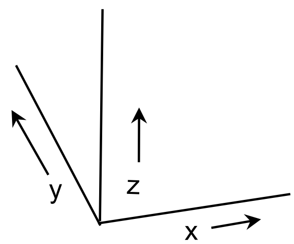
E. Objects are constructed based upon a rectilinear format.

1. Objects in a scenario, or “obstructions,” are built from a series of blocks, each assigned material properties.

2. Simple furniture items, like chairs, often consist of several such blocks, each requiring a separate line of code.

BUILDING OBJECTS

FDS uses a rectangular coordinate system based on the Cartesian coordinate system.



Slide 5-82

3. When building objects, FDS uses a rectangular coordinate system based on the Cartesian coordinate system.

FIRE SPECIFICATION

- Like with other fire models, FDS does not calculate how fast or big a fire gets.
  - It is the job of the modeler to specify the fire's size and growth rate.
  - The model, in essence, calculates the response of the surroundings to the defined fire.

Slide 5-83

F. Fire specification.

1. Like with other fire models, FDS does not calculate how fast or big a fire gets.

2. It is the job of the modeler to specify the fire's size and growth rate.

3. The model, in essence, calculates the response of the surroundings to the defined fire.

OUTPUT

- As with CFAST, FDS outputs its data through a visualization program known as SmokeView.
  - SmokeView can display visual renditions of various values captured in preprogrammed slice files or boundary files.
  - Modelers specify what output data they want to capture and display.

Slide 5-84

G. Output.

1. As with CFAST, FDS outputs its data through a visualization program known as SmokeView.

2. SmokeView can display visual renditions of various values captured in preprogrammed slice files or boundary files.

3. As with inputs, modelers specify what output data they want to capture and display.

OUTPUT INFORMATION

- Slice files (&SLCF).
- Boundary files (&BNDF).
- Devices (&DEVC).
  - Thermocouples.
  - Carbon monoxide sensor.
  - Radiometers.
  - Sprinklers.
  - Oxygen sensors.

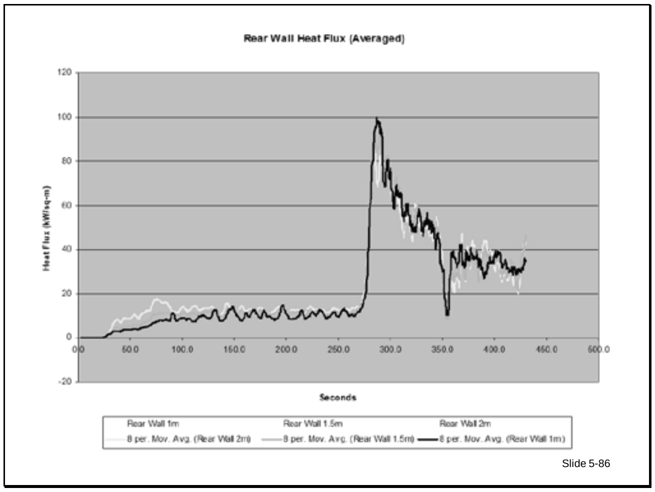
Slide 5-85

a. Data can be displayed in various ways including:

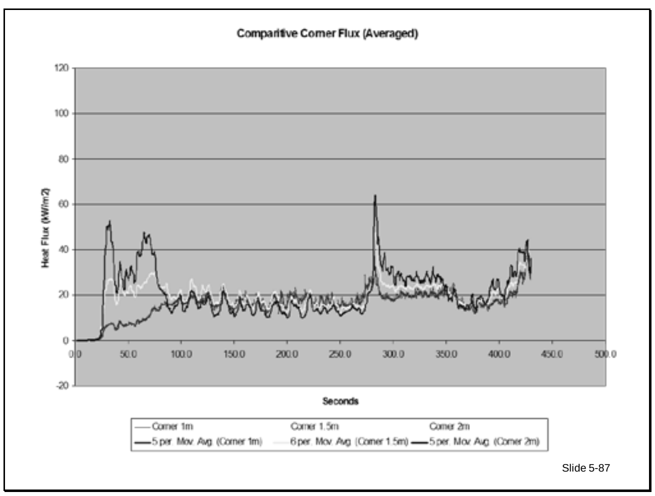
- Slice files — colorful planes arranged through the model that depict values based upon colors.

- Boundary files — estimations of values at the model's boundaries and on surfaces, again based upon color differences.

- Device data is often output in spreadsheet format for evaluation using standard Excel-type reviews.



b. This is the example of how the calculated output of a series of devices placed at a certain place in a scenario can be tracked with time using Excel.



c. This is another example of how FDS can estimate heat flux at point locations.

VI. PYROSIM: MODEL CONSTRUCTION TOOL FOR FIRE DYNAMICS SIMULATOR

PYROSIM: MODEL CONSTRUCTION TOOL FOR FDS

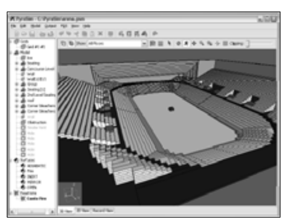
Graphical fire modeling built around the FDS from the NIST.

Slide 5-88

A. PyroSim provides graphical fire modeling built around the FDS from NIST.

USES OF PYROSIM

- Create large, complex fire models.
- You can develop advanced simulation models in a small fraction of the time required to manually create FDS input files.



Slide 5-89

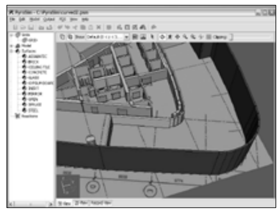
B. Uses of PyroSim.

1. It can be used to create large, complex fire models.

2. It can be used to develop advanced simulation models.

USES OF PYROSIM (cont'd)

- Accurately sketch model geometry using background images.
- You can quickly create fire model geometry directly from floor plan data without repetitive coordinate entry.



Slide 5-90

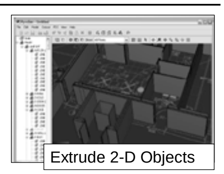
3. It also can be used to accurately sketch model geometry by way of:

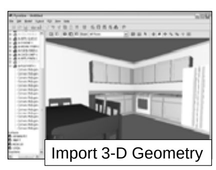
    a. Background images.

    b. Floor plans.

IMPORT GEOMETRY

- Import geometry from AutoCAD DXF files.
- PyroSim can import 2-D and 3-D geometry files.
- Geometry can be used as a background guide and extruded to create walls.





Slide 5-91

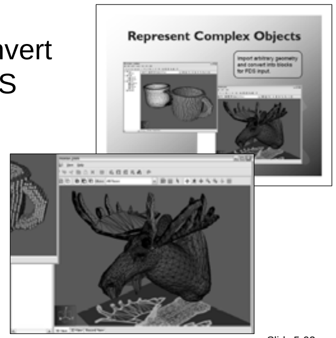
4. Geometry can be imported for use from:

    a. AutoCAD DXF files.

    b. 2-D and 3-D geometry files.

IMPORT GEOMETRY (cont'd)

- Import arbitrary geometry and convert into blocks for FDS input.

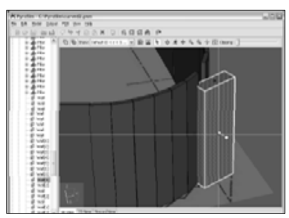


Slide 5-92

c. Arbitrary designs that will be converted into blocks for FDS input.

INTERACTIVE DRAWING TOOLS

- Graphical tools for drawing geometry in 2-D and 3-D let you quickly create objects with the help of instant visual feedback.
- A variety of different tools are available for fast creation and editing of geometry with full undo/redo capability.

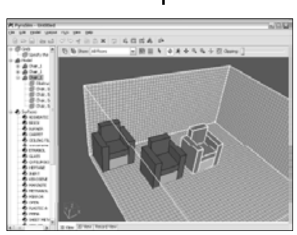


Slide 5-93

5. Geometry can be represented in 2-D or 3-D.

MOVE AND COPY OBJECTS

- Save time by moving and copying objects to new locations.
- You can move, copy, scale and replicate all geometry in your model to quickly accomplish repetitive tasks and leverage existing models.

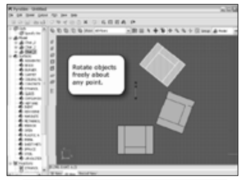


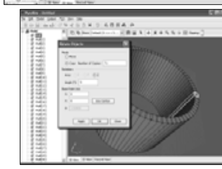
Slide 5-94

6. Objects from models can be moved, copied, scaled or replicated.

ROTATE OBJECTS

You can also rotate geometry in PyroSim to quickly arrange geometry and create circular shapes.



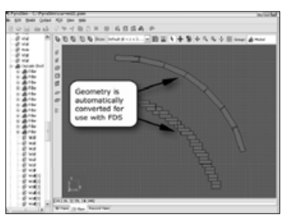


Slide 5-95

7. Geometry can be rotated or arranged to create circular shapes.

AUTOMATIC GEOMETRY DECOMPOSITION

PyroSim automatically breaks up complex diagonal and curved geometry into the grid-aligned blocks required for FDS input.



Slide 5-96

8. Complex diagonal and curved geometry is automatically broken into grid-aligned blocks for FDS input.

MODEL ORGANIZATION

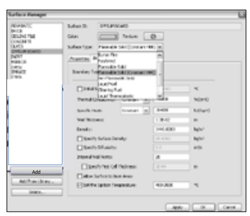
Save time and simplify edits to your large models with tools to group similar geometry and manage multiple floors.

Slide 5-97

9. Similar geometry can be grouped for easier management.

SIMPLIFIED FDS INPUT

Organized inputs simplify the specification of fire and material properties and significantly reduce errors.

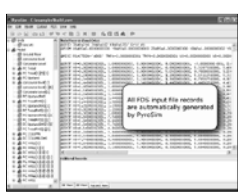


Slide 5-98

10. Input forms are used to specify properties.

AUTOMATIC FDS FILE CREATION

All FDS input records are automatically generated from the PyroSim model, so you do not have to remember FDS input file syntax or spend time entering hundreds of thousands of lines of text.

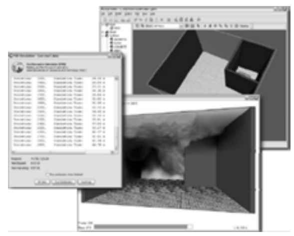


Slide 5-99

11. FDS input records are automatically generated from the PyroSim model.

INTEGRATION WITH FDS

Run FDS seamlessly from within the PyroSim user interface and quickly interpret results using PyroSim and SmokeView.

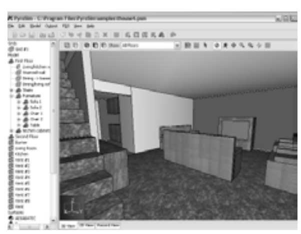


Slide 5-100

12. FDS can be run from within the PyroSim interface.

HIGH QUALITY GRAPHICS

Create realistic presentation graphics with support for textures, advanced shading, and fly-through modes.



Slide 5-101

13. Realistic graphics can be created.

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ACTIVITY 5.3

Build Ventilation Model for Burn Cell in FDS Using PyroSim

Purpose

To use input parameters (e.g., geometry, ventilation openings and fire size) to build and execute a CFD model and interpret and analyze results using SmokeView and output data.

To compare the results derived from the model to the observations obtained from the live compartment fire exercise and results obtained from the CFAST model output and other calculations.

Directions

1. Read the background information and observations from the live burn that was previously conducted (Burn Cell Data Handout).

2. Observe the instructor's demonstration on creating a floorplan to scale, using PyroSim, compartment geometry, number and locaton of ventilation openings, and location and HRR of fire.

3. Observe as the instructor inputs output parameters, including gas temperature, HRR, smoke obscuration, heat flux and surface temperature.

4. Observe the instructor's demonstration of running the FDS model to produce output in SmokeView.

5. Participate in a discussion focusing on how the model output compared to the observations documented from the live fire burn cell exercise and results from CFAST model exercise to include **peak temperature**, **time to flashover**, **heat flux to target**, **target fuels**, **HRR curve**, **visibility**, **gas and solid temperatures**, and **areas of uncertainty.**

ACTIVITY 5.3 NOTES

ACTIVITY 5.4

Analyze Output From FDS Model for Living Room and Hallway for Howard County, Maryland, Investigation Project

Purpose

To use the output file provided by instructor to interpret and analyze results using SmokeView and output data.

To compare all of the collected results to their proposed hypothesis to determine whether the hypothesis was correct.

Directions

1. Observe instructor's demonstration of locating and opening the FDS SmokeView file(s) for the Howard County, Maryland, Investigation Project.

2. With the instructor's guidance, analyze the output through SmokeView.

3. Document your results in your notebook.

4. Compare model results to the data collected from the various tools to identify convergence of the data.

5. In your notebook, respond to the prompt, "Are the results consistent with the scenario? Why or why not?"

6. Be prepared to discuss consistency with the class.

ACTIVITY 5.4 NOTES

“HOWARD COUNTY
FIRE MODEL AND VIDEO”

Slide 5-104

VII. SUMMARY

SUMMARY

- Introduction to modeling.
- Zone models (CFAST).
- General hints for using CFAST and SmokeView.
- CFD field models.
- PyroSim FDS GUI.
- V&V.

Slide 5-105

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APPENDIX A

PEAK HEAT RELEASE RATES FOR COMMON OBJECTS

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Peak Heat Release Rates for Common Objects

Burning cigarette	5 W
Burning match	50 W
Candle	50-80 W
Burning coffeemaker	40 kW
Wastepaper basket	50 kW
Office wastepaper basket with paper	50-150 kW
Small trash can, trash bag fires	50-300 kW
Pillow, latex foam	117 kW
Small chair (some padding)	150-250 kW
TV set	290 kW
Armchair (modern)	350-750-1,200 kW
Recliner (synthetic padding and covering)	500-1,000 kW
Christmas tree	650 kW
Pool of gasoline (2 qt.)	1,000 kW
Christmas tree (dry)	1,000-2,000-5,000 kW
Sofa (synthetic padding and covering)	1,000-3,000 kW
Burning upholstered chair	80 kW-2,500 kW
Burning upholstered sofa	3,000 kW
Living or bedroom (fully involved)	3,000-10,000 kW

Source: Derived from Babrauskas (SFPE 2002b,sec.3-1) and DeHaan,35. Permission "Forensic Fire Scene Reconstruction, Page 67"

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APPENDIX B

REFERENCE SHEET

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Reference Sheet

Online Metric Conversions

AskNumbers
http://www.asknumbers.com

Online Scientific Calculators

EEWeb
http://www.eeweb.com/toolbox/calculator

Web2.0 calc
http://web2.0calc.com/

Holt Scientific Calculator
http://my.hrw.com/math06_07/nsmedia/tools/Sci_Calculator/Sci_Calculator.html

Other Interesting Websites

NIST Fire Investigation
http://www.nist.gov/fire

Overholt's YouTube Channel for Fire Dynamics
http://www.youtube.com/playlist?list=PL00868AACCF4BFD32

CFAST Online
http://www.cfastonline.com

Ignition Handbook and Ignition Handbook Database on CD
http://www.doctorfire.com

Nuclear Regulatory Commission (NRC) Fire Dynamics Tools (Spreadsheets)
http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1805/

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APPENDIX C

FIRE DYNAMICS REFERENCE TABLE

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Fire Dynamics Reference Table

NOMENCLATURE	REPRESENTATION	NOTES
A	Absorptivity	
A_o	Area of an opening (m^2)	
A_f	Fuel bed area (m^2)	
A_t	Total internal surface area of a compartment, including ventilation openings (m^2)	
A_T	Total area of the compartment enclosing surfaces (m^2)	
A_{floor}	Area of compartment floor (m^2)	
$A_{openings}$	Area of compartment openings (m^2)	
A_{wall}	Area of compartment walls (m^2)	
h	Enthalpy; heat transfer coefficient	
h_c	Convective heat transfer coefficient	
Δh_c	Effective heat of combustion of the fuel (kJ/kg)	Represents the chemical energy released per unit mass of vaporized fuel that is reacted. It tends to be the highest for gas and liquid fuels and least for char formers.
H_o	Height of an opening (m^2)	
k	Thermal conductivity of the wall (kW)	The property of matter that represents the ability to transfer heat by conduction.
l	Flame height or length	
$\dot{m}$	Mass loss rate (g/s)	Fuel supplied in a fire.
$\dot{m}''$	Burning rate per unit area or mass burning flux (kg/s)	Fuel reacted with oxygen. Burning rate depends on the fuel properties, its orientation and configuration, and the area involved.

NOMENCLATURE	REPRESENTATION	NOTES
$\dot{q}$	Rate of heat transfer (W or kW)	
$\dot{Q}$	Total heat (energy) release rate (kW) – The size of the fire	The power of the fire measured in kilowatts. It is directly related to flame height and the radiant heat flux surrounding the fire.
Re	Reynolds Number	The Reynolds number expresses the ratio of **inertial** (resistant to change or motion) forces to **viscous** (heavy) forces.
X_r	Radiative loss fraction	
GREEK	**SYMBOLS**	**NOTES**
δ	Thickness of walls (m)	
ε	Emissivity	The property that gives the fraction of energy emitted relative to a perfect radiator (measured from 0 to 1). For gases or flames, ε depends on the thickness of the flame.
ρ	Density of a wall (kg/m^3)	
σ	Stefan-Boltzmann constant	5.67×10^{-11} kW/m^2
SUPERSCRIPTS		
.	Per unit time	
x'	Single prime (signifies ‘per unit width’)	
x'	Double prime (signifies ‘per unit area’)	
x''	Triple prime (signifies ‘per unit volume’)	
SI QUANTITIES		
Force	N (Newton)	
Mass	Kg (kilogram)	
Time	s (second)	
Length	m (meter)	

SI QUANTITIES		
Temperature	°C or K	
Energy	J (joule)	
Power	W (watt)	
Thermal conductivity	W/m – °C	
Heat transfer coefficient	W/m^2 – °C	
Specific Heat	J/kg – °C	
Heat Flux	W/m^2	
CONVERSION	**FACTORS**	**SYMBOLS**
Length	1 m = 3.2808 ft	l
Area	$1\ m^2 = 10.7639 ft^2$	A
Density	$1\ kg/m^3 = 0.06243\ lb/ft^3$	ρ
Energy	1 kJ = 0.94783 Btu	Q
Heat	1 kJ = 0.94783 Btu	q
Heat flow rate	1 W = 3.4121 Btu/hr	$\dot{q}$
Energy release rate	1 W = 3.4121 Btu/hr	$\dot{Q}$
Heat flow rate per unit area, heat flux	$1\ W/cm^2 = 0.317\ Btu/hr\text{-}ft^2$ $1\ W/cm^2 = 10\ kW/m^2$	$\dot{q}'$
Specific heat	1 kJ/kg -°C = 0.23884 Btu/lb - °F	c
Thermal conductivity	1 W/m - °C = 0.5778	k
Thermal diffusivity	$1\ m^2/s = 10.7639\ ft^2/s$	α
HEAT RELEASE	**RATES**	**NOTES**
Glowing cigarette	**5 W**	
Kitchen match (candle flame)	**50 W**	
Small wastebasket	**50 to 150 kW**	
Small upholstered chair	**150 to 250 kW**	
Upholstered (foam) chair	**350 to 750 kW**	
Recliner (PU foam/synthetic)	**500 to 1000 kW**	**1 megawatt**
Sofa	**1000 to 3000 kW**	**1 to 3 megawatts**
Gasoline pool on concrete	**1000 kW**	**1 megawatts**

HEAT FLUX	VALUES (kW/m^2)	NOTES
Sun	**1**	
2nd degree burns	**4 to 6**	
Wastebasket fire	**50**	
Post-flashover fire	**120 to 150**	
CRITICAL RADIANT FLUX FOR IGNITION	**20**	**Most objects will ignite at 10 to 20 kW/m^2.**
EQUATIONS	**FORMULAS**	
Conduction heat transfer from a moving fluid (gas or solid) to a solid surface. *(Principles of Fire Behavior, Chapter 3, Page 49)*	$\dot{q} = kA(T_2 - T_1)/l$	Where *k* is the **thermal conductivity,** *A* is the **area** through which the heat is transferred. T_2 and T_1 are the respective **temperatures** of the wall faces; *l* is the **wall thickness.**
Convective heat transfer *(the ability of heat to be transformed from a moving fluid to a solid surface).* *(Principles of Fire Behavior, Chapter 3, Page 53)*	$\dot{q}' = h(T_2 - T_1)$	Where *h* is the **convective heat transfer coefficient,** T_2 is the **air stream temperature** (e.g., 30^oC). T_1 is the **surface temperature** (e.g., 0^oC). *See Principles of Fire Behavior, Chapter 3, Page 54 (Table 3-2) for typical h values*
Radiant heat transfer *(electromagnetic energy consisting of electric and magnetic fields).* *(Principles of Fire Behavior, Chapter 3, Page 55-58)*	$\dot{q}' = \sigma T^4$ *(maximum possible output of radiation due to temperature expressed in terms of heat flux)* $q' = \dfrac{X_r \dot{Q}}{4\pi c^2}$	Where T is the **object's temperature** expressed in Kelvin (K), and σ is the **Stefan-Boltzmann constant** [$5.67 \times 10^{-11} kW/m^2\text{-}K^4$]. Where $\dot{Q}$ is the **energy release rate** of the fire (kW), and X_r is the **fraction of energy radiated** relative to the total energy released. [See *Principles of Fire Behavior, Chapter 3, Page 59, Tables 3.3 and 3.4 for typical X_r values*]

EQUATIONS	FORMULAS	NOTES
Energy Release Rate (*the power of the fire measured in kilowatts*). Denoted by the symbol $\dot{Q}$. Represents the size of the fire and its potential for damage *(Principles of Fire Behavior, Chapter 6, Page 107)*	$\dot{Q} = \dot{m}' \, A \Delta H_c$	Where A is the **area burning in m²** ΔH_c is the **effective heat of combustion** [Note: The effective heat of combustion of wood is approximately 13 kJ/g for the flaming period and approximately 30 kJ/g for the smoldering phase of the char]. *See Principles of Fire Behavior Page 111, Table 6-3 for typical values*
Heat Release Rate for Flashover (HRR_{fo}) – (NFPA 921) *(NFPA 921, Chapter 5, Page 921-27)*	HRR_{fo} (kW) = $(750A_o)(h_o)^{0.5}$ Where HRR_{fo} is the heat release rate for flashover, A_o is the Area of the opening in m^2 h_o is the height of the opening in m.	The minimum size fire that can cause a flashover in a given room is a function of the ventilation provided through an opening. This function is known as the **ventilation factor** and is calculated as the area of the opening (A_o) times the square root of the height of the opening (h_o).
Average Flame (Plume) Height *(Principles of Fire Behavior, Chapter 7, Page 138)*	$L_f = 0.23\dot{Q}^{2/5} - 1.02D$ [Heskestad Formula]	Where $\dot{Q}$ is the **energy release rate of the fire,** D is the **base diameter of the fire.** Note: $\dot{Q}^{2/5}$ represents a characteristic combustion length of the fire and is directly related to the flame length. *See Principles of Fire Behavior, Chapter 7, Pages 142-143 for average flame heights for most common fuels.*

EQUATIONS	FORMULAS	NOTES
Flame Height – (NFPA 921) *(NFPA 921, Chapter 5, Page 921-29)*	$H_f = 0.174(k\dot{Q})^{0.4}$ If the flame height is known, the HRR can be estimated using the following formula: $\dot{Q} = \frac{79.18 H_f^{5/2}}{k}$ Where H_f = flame height in meters k = wall effect factor $\dot{Q} =$ fuel release rate in kilowatts	The height of flames above the surface of burning fuels is directly related to the heat release rate (HRR) of the fire. For a given fuel, the HRR is related to the amount of surface burning. If the flame height of the fire is known or can be estimated, the approximate HRR can be determined. Note: The value of *k* to be used is as follows: *k* = 1 when there are no nearby walls *k* = 2 when the fuel package is at a wall *k* = 4 when the fuel package is in a corner

APPENDIX D

UNIT CONVERSION TABLE

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Unit Conversion Table

Dimension	Metric	Metric/English
Acceleration	1 m/s^2 = 100 cm/s^2	1 m/s^2 = 3.2808 ft/s^2 1 ft/s^2 = 0.3048 m/s^2
Area	1 m^2 = 10^4 cm^2 = 10^6 mm^2	1 m^2 = 1550 in^2 = 10.764 ft^2; 1 acre = 43,560 ft^2 1 yd^2 = 0.836 m^2 1 ft^2 = 144 in^2 = 0.0929 m^2; 1 acre = 4046.86 m^2
Density	1 g/cm^3 = 1 kg/L = 1,000 kg/m^3	1 g/cm^3 = 62.428 lbm/ft^3 = 0.036127 lbm/in^3 1 lbm/in^3 = 1,728 lbm/ft^3 1 kg/m^3 = 0.06243 lbm/ft^3
Energy, heat, work, internal energy, enthalpy	1 kJ = 1,000 J = 1,000 N · m = 1 kPa · m^3 1 kJ/kg = 1,000 m^2/s^2 1 kWh = 3,600 kJ 1 cal = 4.184 J 1 IT cal = 4.1868 J 1 kcal = 4.1868 kJ	1 kJ = 0.94782 BTU 1 BTU = 1.05506 kJ = 5.40395 psia · ft^3 = 778.169 lbf · ft 1 BTU/lbm = 25.037 ft^2/s^2 = 2.326 kJ/kg 1 kJ/kg = 0.430 BTU/lbm 1 kWh = 3,412.14 BTU 1 therm = 10^5 BTU = 1.055 x 10^5 kJ (natural gas)
Force	1 N = 1 kg · m/s^2 = 10^5 dyne 1 kgf = 9.80665 N	1 N = 0.22481 lbf 1 lbf = 32.174 lbm · ft/s^2 = 4.44822 N
Length	1 m = 100 cm = 1,000 mm = 10^6 um 1 km = 1,000 m	1 m = 39.370 in = 3.2808 ft = 1.0926 yd 1 ft = 12 in = 0.3048 m 1 mile = 5,280 ft = 1.6093 km 1 in = 2.54 cm
Mass	1 kg = 1,000 g 1 metric ton = 1,000 kg	1 kg = 2.2046226 lb 1 lbm = 0.45359237 kg 1 ounce = 28.3495 g 1 slug = 32.174 lbm = 14.5939 kg
Power, heat transfer rate	1 W = 1 J/s 1 kW = 1,000 W = 1.341 hp 1 hp = 745.7 W	1 kW = 3,412.14 BTU/h = 737.56 lbf · ft/s 1 hp = 550 lbf · ft/s = 0.7068 BTU/s = 42.41 BTU/min = 2,544.5 BTU/h = 0.7457 kW; 1 BTU/h = 1.055056 kJ/h
Pressure	1 Pa = 1 N/m^2 1 mmHg = 0.1333 kPa 1 kPa = 10^3 Pa = 10^{-3} Mpa 1 atm = 101.325 kPa = 1.01325 bars = 760 mm Hg at 0 °C = 1.03323 kgf/cm^2	1 Pa = 1.4504 x 10^{-4} psia = 0.020886 lbf/ft^2 1 psi = 144 lbf/ft^2 = 6.894757 kPa 1 atm = 14.696 psia = 29.92 in Hg at 30 °F 1 in Hg = 3.387 kPa
Specific heat	1 kJ/kg · °C = 1 kJ/kg · K = 1 J/g · °C	1 BTU/lbm · °F = 4.1868 kJ/kg · °C 1 BTU/lbmol · R = 4.868 kJ/kmol · K 1 kJ/kg · °C = 0.23885 BTU/lbm · °F = 0.23885 BTU/lbm · R

ACRONYMS

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ACRONYMS

ANSI	American National Standards Institute
ASTM	American Society for Testing and Materials
ATF	Bureau of Alcohol, Tobacco, Firearms and Explosives
Btu	British thermal unit
CFAST	Consolidated Model of Fire Growth and Smoke Transport
CFD	computational fluid dynamics
CFI	Certified Fire Investigator
CFR	Code of Federal Regulations
CHF	critical heat flux
CRT	cathode ray tube
DOA	dead on arrival
FDS	fire dynamics simulator
FDTs	fire dynamics tools
FHAs	fire hazards analyses
FMRC	Factory Mutual Research Corporation
FSI	flame spread index
GUI	graphical user interface
HRR	heat release rate
HVAC	heating, ventilating and air conditioning
IAAI	International Association of Arson Investigators
ICS	Incident Command System
IG	Instructor Guide

kg/s	kilograms per second
kJ	kilojoule
kJ/kg	kilojoules per kilogram
kρc	thermal inertia
kW	kilowatt
kW/m^2	kilowatts per meter squared
LFL	lower flammable limits
LIFT	lateral ignition and flame spread test
LNG	liquefied natural gas
LODD	line-of-duty death
MLR	mass loss rate
mm	millimeter
MPEG	Moving Picture Experts Group
MQH	McCaffrey, Quintiere and Harkleroad
MW	megawatt
NETC	National Emergency Training Center
NFA	National Fire Academy
NFPA	National Fire Protection Association
NIST	National Institute of Standards and Technology
NRC	U.S. Nuclear Regulatory Commission
NUREG	Nuclear Regulatory Guide
PIA	Post-Incident Analysis
PPV	positive-pressure ventilation

PU	polyurethane
RTI	response time index
SFPE	Society of Fire Protection Engineers
SM	Student Manual
STP	standard temperature and pressure
SwRI	Southwest Research Institute
UL	Underwriters Laboratories
UFL	upper flammable limits
V&V	verification and validation
W/cm^2	watt per centimeter squared