Analytical Tools in Forensic Fire Investigations

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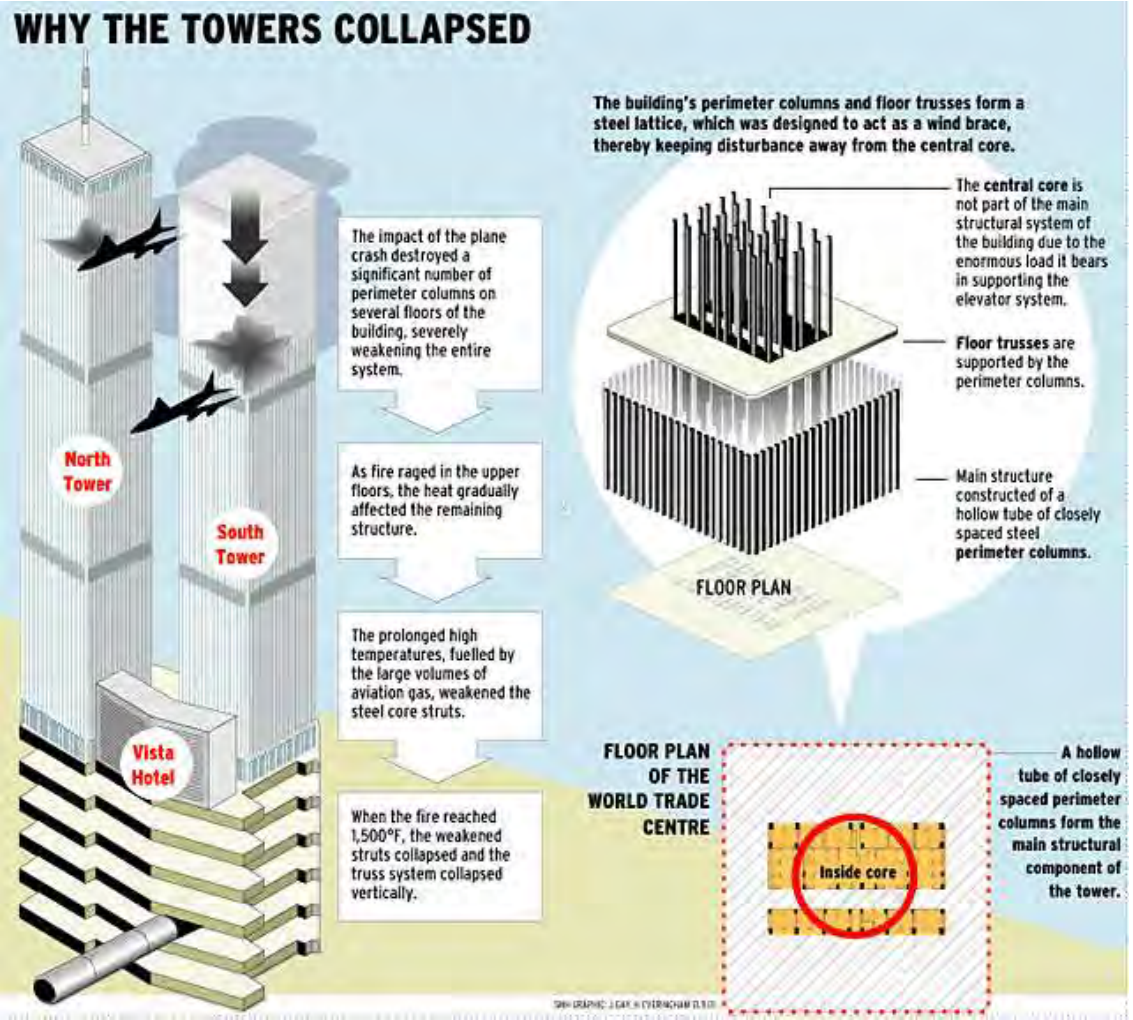
THE UNIVERSITY of TENNESSEE

Definition of Forensic Engineering

- ***Forensic engineering*** is the investigation of materials, products, structures or components that fail or do not operate or function as intended, causing personal injury or damage to property.
- The field also deals with retracing processes and procedures leading to accidents in operation of vehicles or machinery.



National Society of Forensic Engineers (NSPE) Quoted Definition

- ***Forensic Engineering*** is the application of the art and science of engineering in the jurisprudence system, requiring the services of legally qualified professional engineers.
- Forensic engineering activities may include:
  - Investigation of the physical causes of accidents and other sources of claims and litigation
  - Preparation of engineering reports
  - Testimony at hearings and trials in administrative or judicial proceedings
  - Advisory opinions to assist the resolution of disputes affecting life or property.

Qualifications of a Forensic Engineer

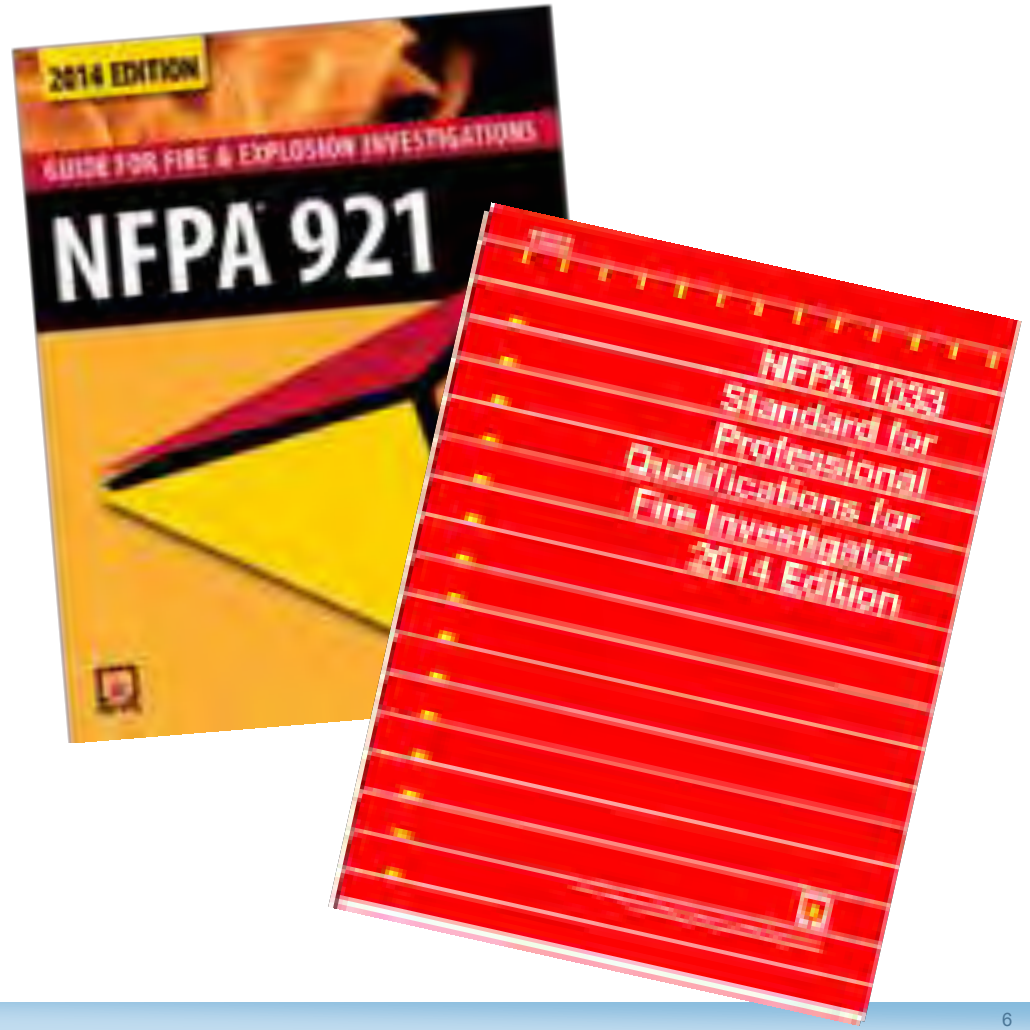
- Technical Competency
- Knowledge of Legal Procedures
- Detective Skills
- Oral and Written Communication Skills
- Personality Characteristics
- Ethical and Professional Responsibilities

Scientific and Professional Journals

- ***Forensic Science International*** (Elsevier Science Publishers, Ireland)
- ***Journal of Forensic Sciences*** (American Academy of Forensic Sciences)
- ***Journal of the National Academy of Forensic Engineers*** (National Academy of Forensic Engineers)

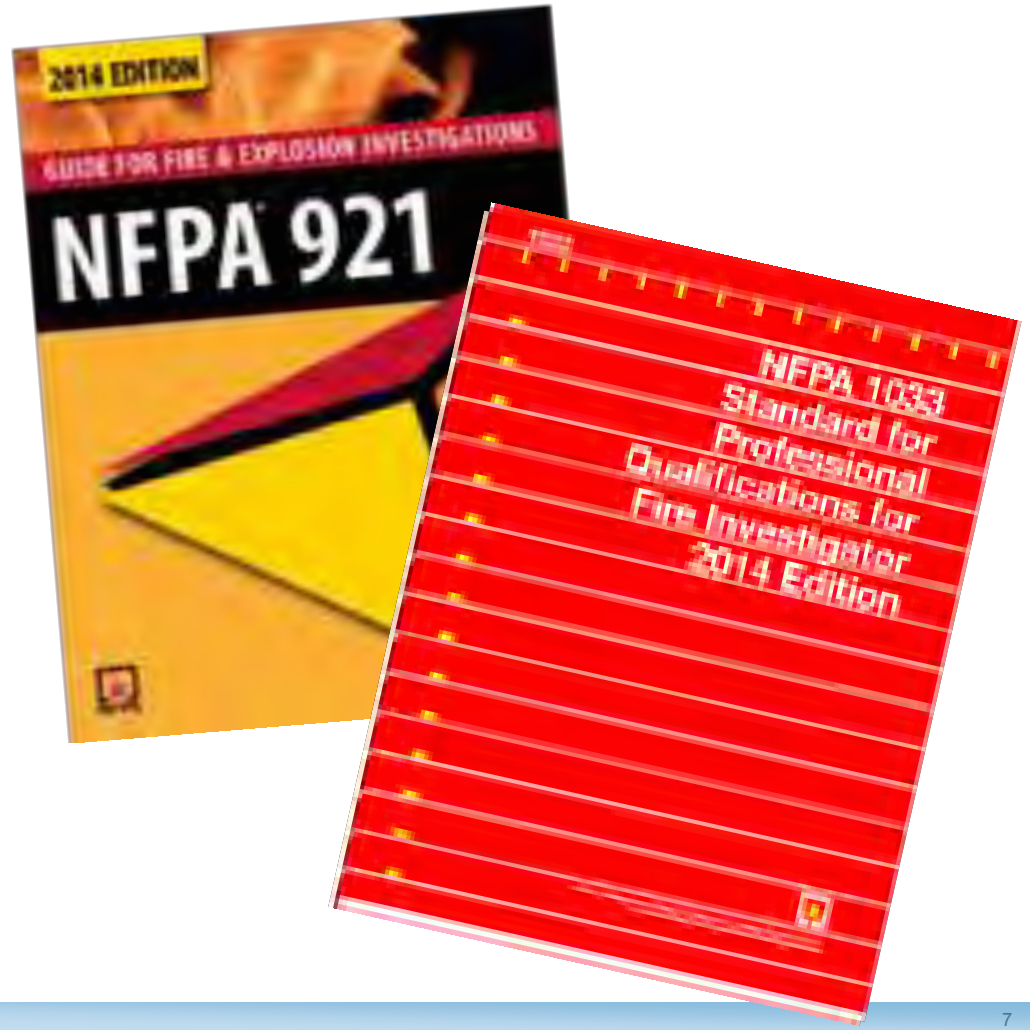
Presentation Goals and Objectives

- Provide an insight into the various analytical tools that can be used in forensic fire scene investigations
- Assist you in meeting the training requirements of *NFPA 1033* (2014 Edition)
- Provide additional areas not presently covered by *NFPA 921* (2014 Edition)



Fire Investigation Standards of Care

- In the fire investigation field, a "*standard of care*" is the formal process an investigator follows when examining a scene and rendering an opinion as to its origin, cause and responsibility
- *NFPA 921* (2014 ed.) and *NFPA 1033* (2014 ed.) are the prevailing standards of care that fire investigation experts use as "*best practices*"



NFPA 1033 (2014) – Adoption and Impact

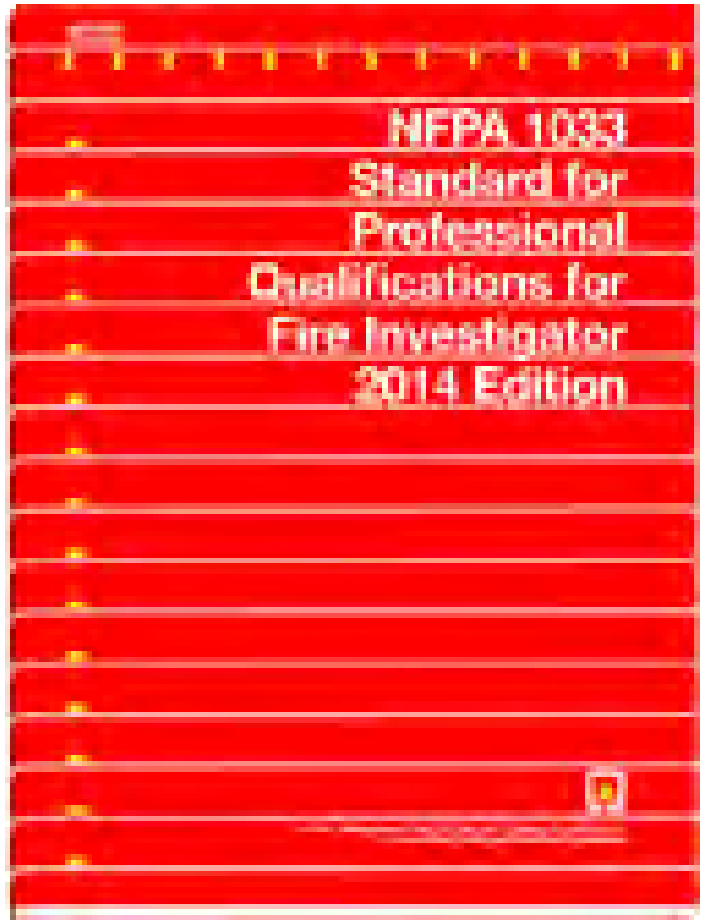
- Approved by the Standards Council on May 28, 2013 with an effective date of June 17, 2013
- The 2014 Edition supersedes all previous editions
- Sets the minimum JPRs to ensure compliance with all scientific standards in collecting and assessing evidence, determining responsibility, and rendering conclusions as to a fire's origin, cause, and development.

NFPA 1033 (2014 Ed.) Requires Maintaining a "*Minimum Knowledge*"

- Fire science
- Fire chemistry
- Thermodynamics
- Thermometry
- Fire dynamics
- Explosion dynamics
- Computer fire modeling
- Fire investigation
- Fire analysis
- Fire investigation methodology
- Fire investigation technology
- Hazardous materials
- Failure analysis and analytical tools (*NFPA 921, Ch. 22*)
- Fire protection systems
- Evidence documentation, collection, and preservation
- Electricity and electrical systems

What You Can You Do To Meet The Job Performance Requirements?

- Track the instruction you receive by the 16 categories broken down by contact hours
- Utilize *CFI Trainer* whenever possible
- Participate in the development of core curricula
- Conduct self-peer review and critiques of your own work
- Use available training materials that exceed *NFPA 921* and *NFPA 1033* content



Available Training Materials

- ❑ Lesson Plans
- ❑ PowerPoint Slides
- ❑ Appendices
- ❑ Case Studies
- ❑ Test Questions

Forensic Fire Scene Reconstruction, 3rd edition

David J. Icove **John D. DeHaan** **Gerald A. Haynes**

This new edition covers engineering calculations, fire modeling and also features several exhaustive case studies which leverage the current technology that is explained in depth throughout the text. Specialized topic areas are also covered, including use of the drone aircraft, forensic and panoramic photography, computer modeling as well as an advanced discussion of tenability. Using historical fire cases and realistic case examples, the authors examine the newest lessons learned and insight into the ignition, growth, development, and outcome of those fires. All documentation in the case examples follows or exceeds the methodology set forth by NFPA 921—Guide for Fire and Explosion Investigations and its companion standard NFPA 1033—Standard for Professional Qualifications for Fire Investigator, 2009 Edition. and Kirk's Fire Investigation .Seventh Edition.

ISBN: 0-13-295620-9 **Copyright: 2013** **$92.00**

Kirk's Fire Investigation, 7th edition

John D. DeHaan **David J. Icove**

As fire investigation continues to evolve, author John DeHaan, a forensic scientist with extensive experience in all phases of fire and explosion, is joined by recognized forensic fire engineering expert David Icove for the 7th edition of *Kirk's Fire Investigation*, the leading and most widely read textbook in the field of fire investigation. With today's investigators being held to higher standards than ever before, this text, written to the FESHE curriculum, details the "need-to-know" investigation skills and includes special topics such as lab analysis, fire deaths, and explosions while offering correlation to both the NFPA 921 and 1033 guidelines.

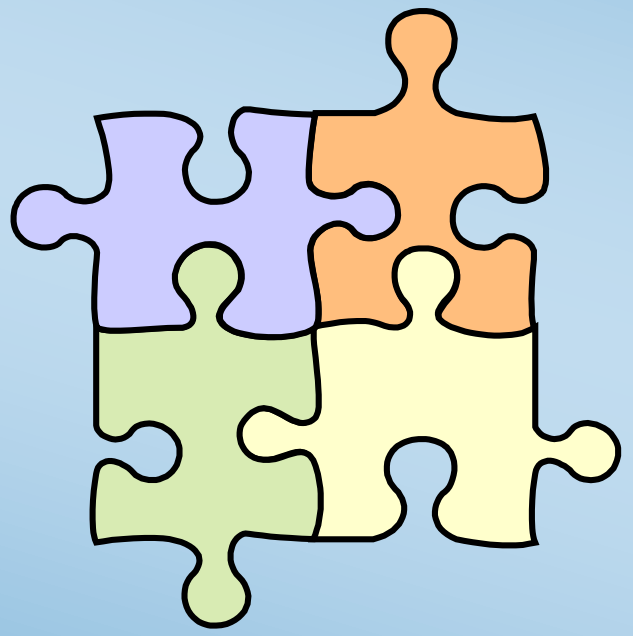
ISBN: 0-13-283001-9 **Copyright: 2012** **$104.40**

Fire Dynamics

Gregory E. Gorbett **James L. Pharr**

Fire Dynamics is Brady's first edition text written to the FESHE baccalaureate curriculum that is a resource for all fire service professionals from the student to the fire investigator. With fourteen chapters and FESHE and NFPA references and guidelines throughout, the text provides a comprehensive approach to fire dynamics with the latest research and experiments from real field experience. Authors, Gregor E. Gorbett and James L. Pharr, bring a real world focus as this book covers principles of fire dynamics and chemistry with a real world application. Fire Dynamics blends both academic information for the student and real world applications for the practicing fire safety professional to become the best in their field.

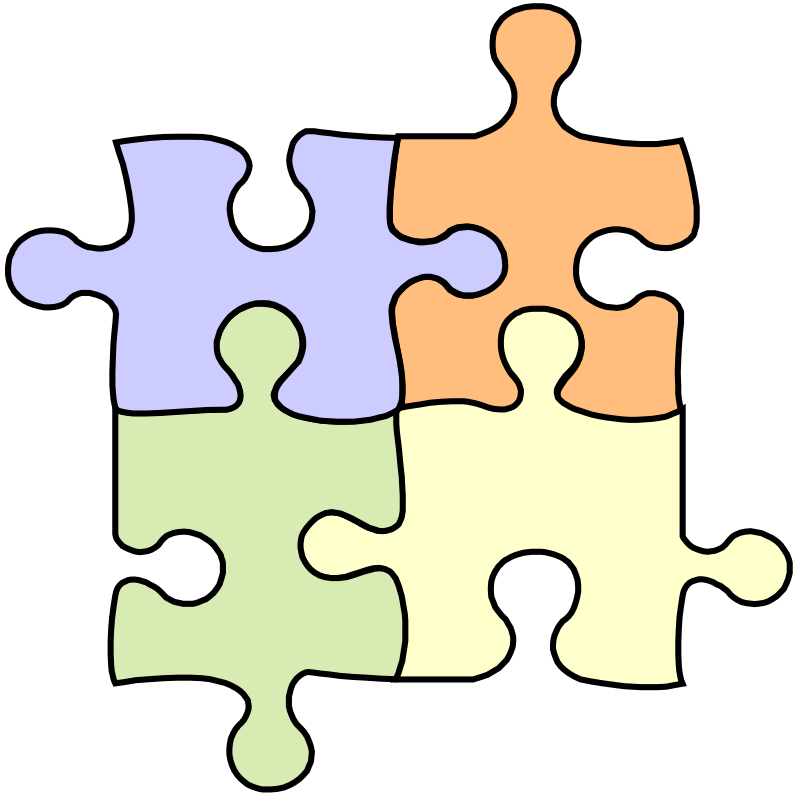
ISBN: 0-13-507588-2 **Copyright: 2011** **$81.20**



NFPA 921 (2014 Edition) – Chapter 22: Failure Analysis and Analytical Tools

NFPA 921 (2014 Edition) – Chapter 22: Failure Analysis and Analytical Tools

- This chapter identifies methods available to assist the investigator in the analysis of a fire/explosion incident.
- In many cases, the methods are used to organize information collected during the documentation of the incident into a rational and logical format.
- Tools used include root cause analysis, timelines, fault trees, and failure mode and effects analysis.



NFPA 921 (2014 Edition) – Chapter 22: Failure Analysis and Analytical Tools

- Identifies methods available to assist the investigator in the analysis of a fire/explosion incident.
- These methods are used to organize information collected during the documentation of the incident into a rational and logical format.
- Tools used include timelines, fault trees, failure mode and effects analysis, and fire modeling.

NFPA 921 (2014 Edition) – Chapter 22: Failure Analysis and Analytical Tools

Addresses:

- 22.1 Introduction
- 22.2 Time Lines
- 22.3 Systems Analysis
- 22.4 Mathematical Modeling
- 22.5 Fire Testing
- 22.6 Data Required for Modeling and Testing

Examples of what it does not thoroughly address:

- Data Analysis of Loss Histories
- Root cause analysis
- Structural analysis to determine area of fire origin
- Matrix analysis (Bilancia Matrix and Cox's Origin Analysis)

A REVIEW OF *NFPA 921* (2014 EDITION) CHAPTER 22

22.1 Introduction

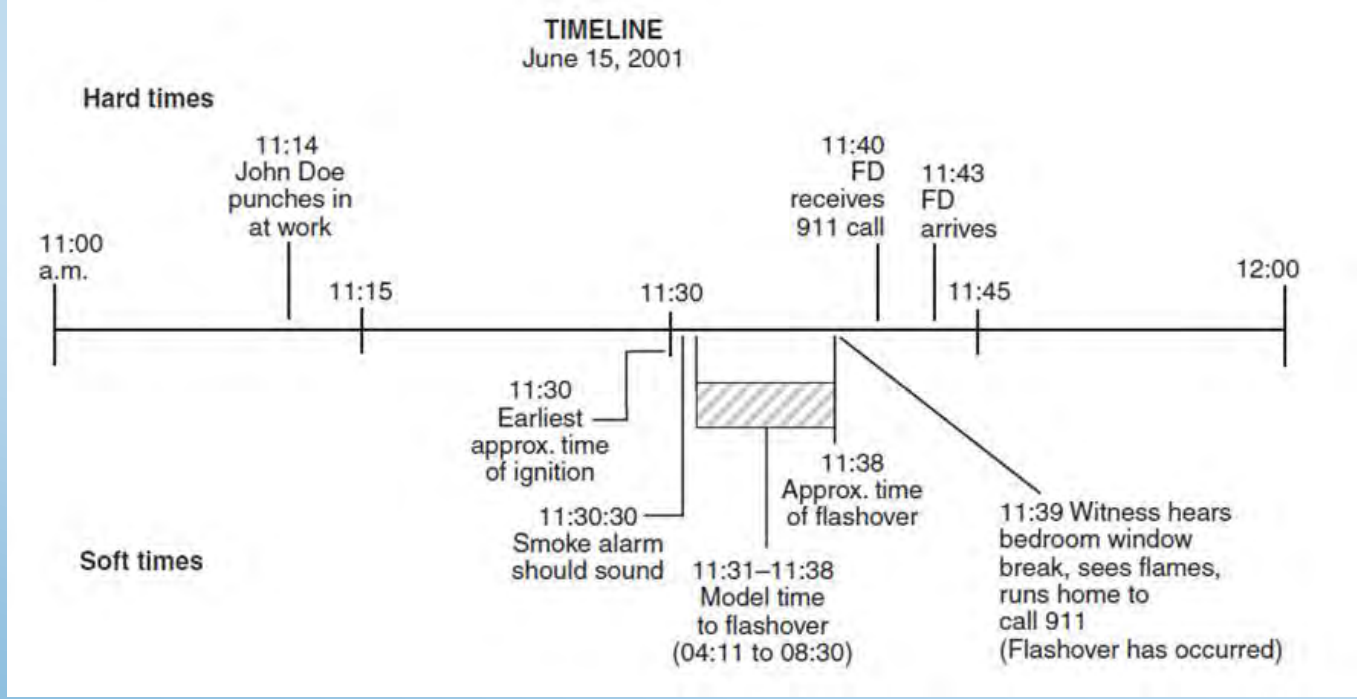
22.2 Time Lines

22.3 Systems Analysis

22.4 Mathematical Modeling

22.5 Fire Testing

22.6 Data Required for Modeling and Testing



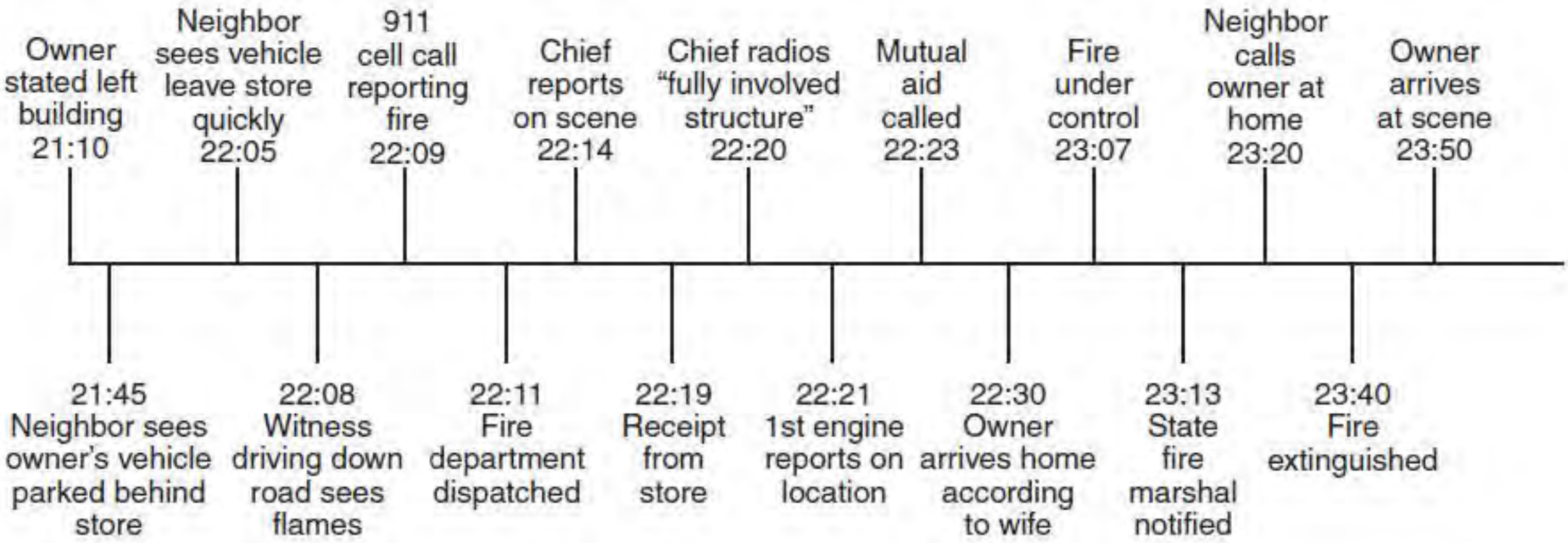
NFPA 921, Pt. 22.2 – Time lines

Pt. 22.2.2 Time Lines (Hard Time-Actual)

- *NPFA 921* Definition: A time line is a graphic or narrative representation of events related to the fire incident, arranged in chronological order.
- *Hard time* (*pt.* 22.2.2) identifies a specific point in time linked to a reliable clock or timing device of known accuracy.
- It is possible to have a time line with no hard times.

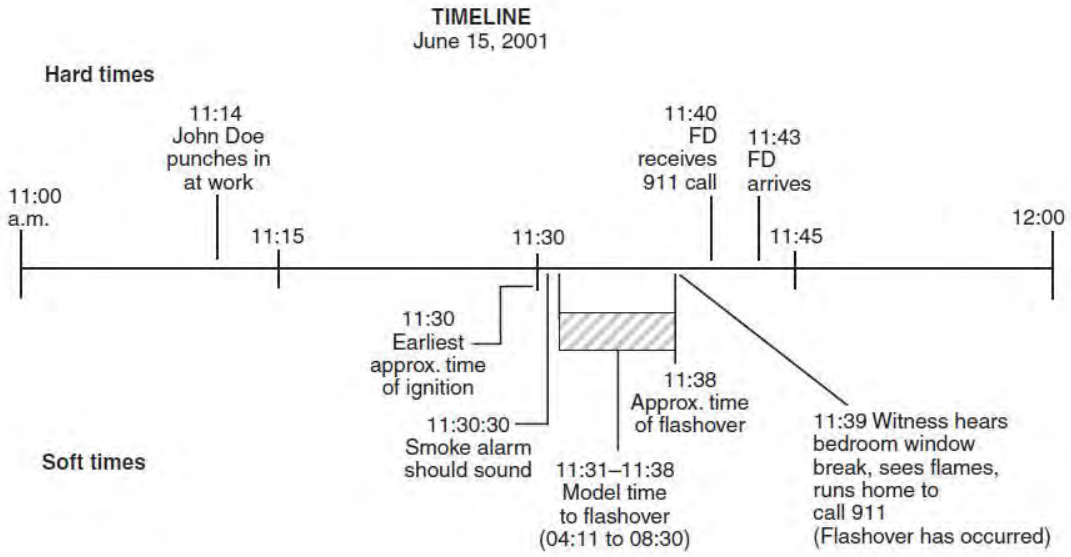
- Fire department dispatch telephone or radio logs
- Police department dispatch and radio logs
- Emergency Medical Service reports
- Alarm system records
- Building inspection report(s)
- Health inspection report(s)
- Fire inspection report(s)
- Utility company records
- Private videos/photos
- Media coverage
- Timers
- Weather reports
- Current and/or prior owner/tenant records
- Interviews
- Computer-based fire department alarms, communications audio tapes, and transcripts
- Building or systems installation permits

See: *NFPA 921* (2014 Edition) for an Example of Hard Timeline

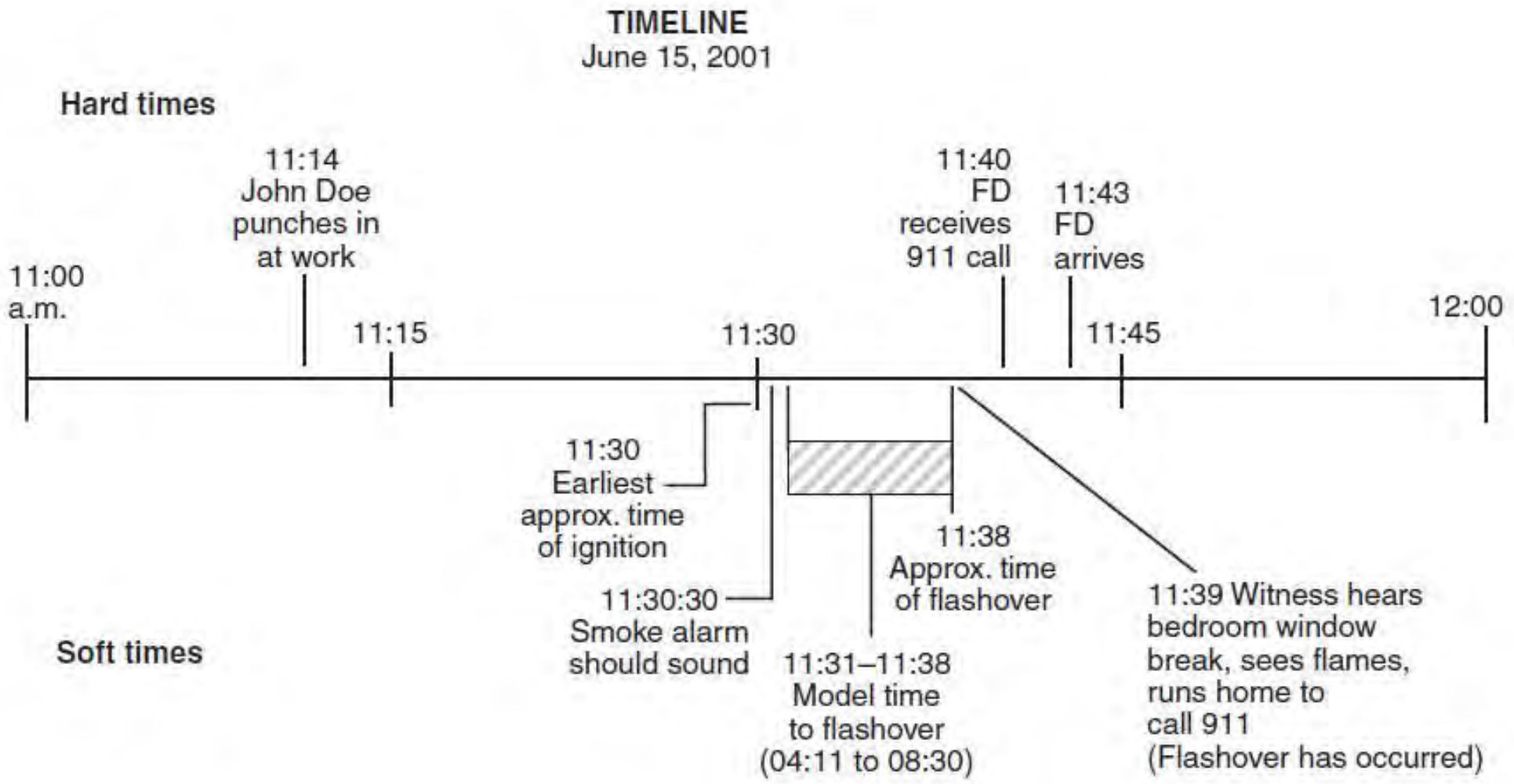


See: *NFPA 921* (2014 Edition) Pt. 22.2.3 for an Example of Soft Time Lines

- Soft time (pt. 22.2.3) can be either *estimated* or *relative* time.
  - *Relative time* is the chronological order of events or activities that can be identified in relation to other events or activities.
  - *Estimated time* is an approximation based on information or calculations that may or may not be relative to other events or activities.

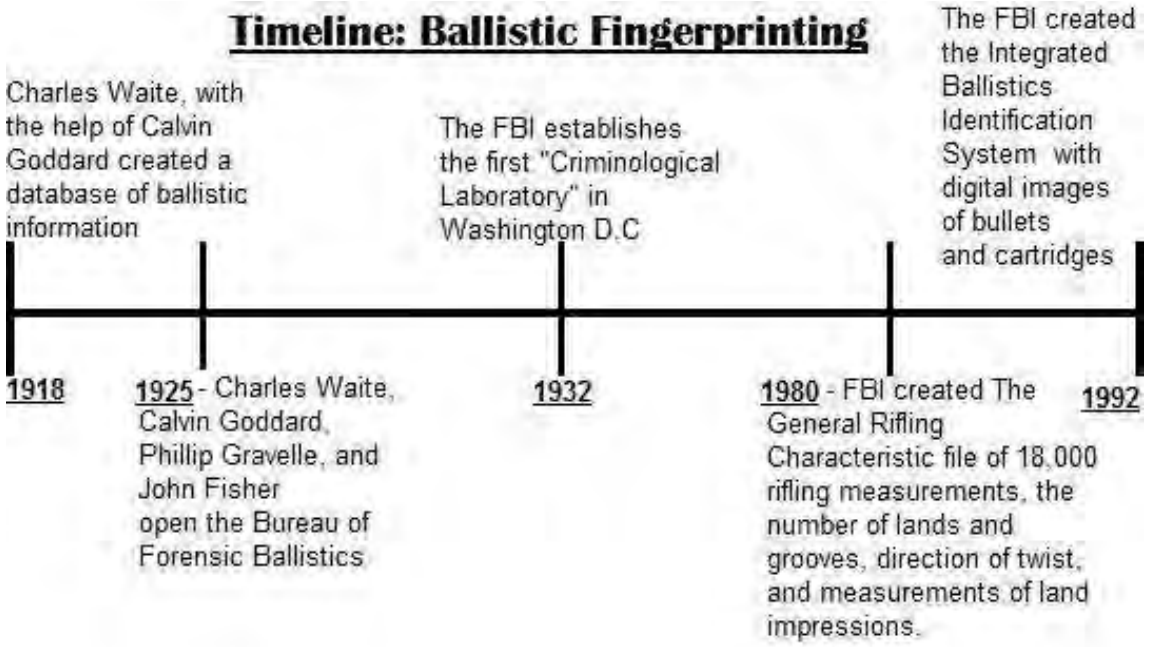


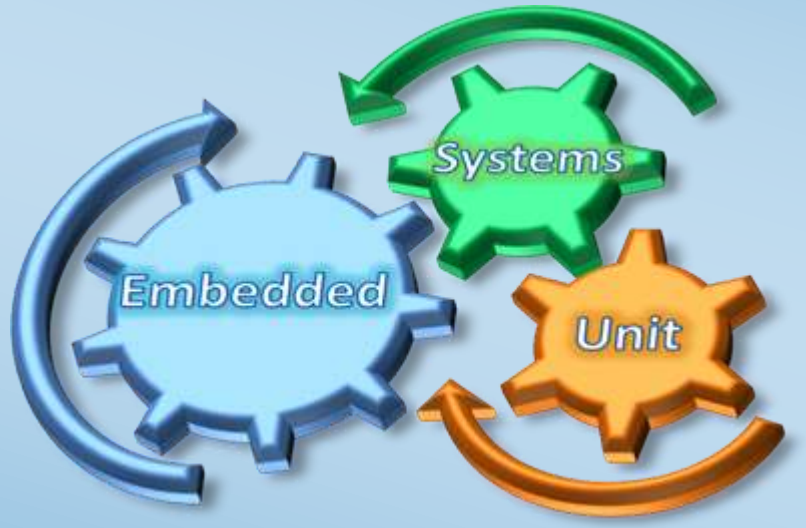
See *NFPA 921* (2014 Edition) for an Example of Scaled Hard and Soft Timelines



Analytical Tools that Assist in Forensic Engineering

- These techniques rely on accurate reporting of failure rates, and precise identification of the failure modes
  - Timeline analysis
  - Failure mode and effects analysis (FMEA)
  - Fault tree analysis

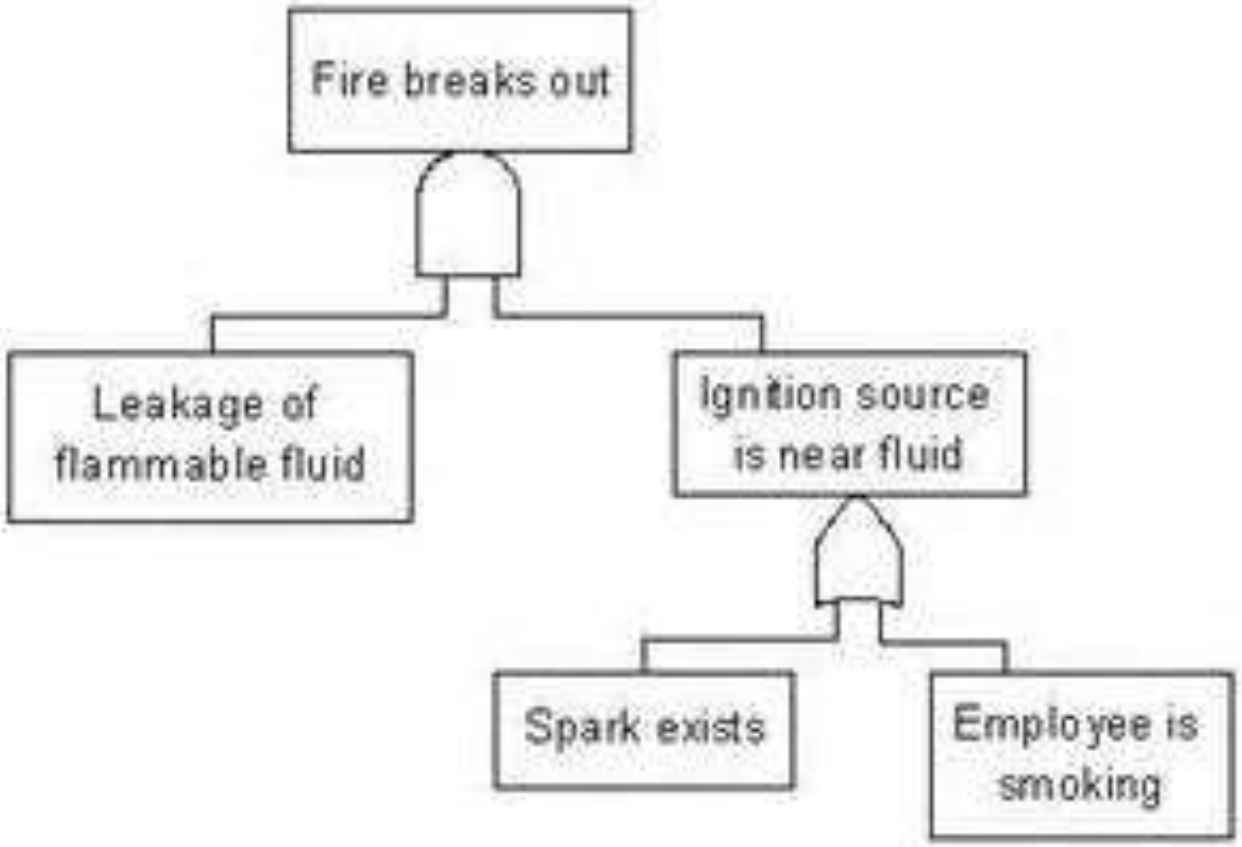




NFPA 921 Pt 22.3 – System Analysis

22.3 Systems Analysis – The Fault Tree

- **NFPA 921 (2014 Edition), pt. 22.3.1. Fault Trees.** A fault tree is a logic diagram that can be used to analyze a fire or explosion. A fault tree is developed using deductive reasoning. The diagram places, in logical sequence and position, the conditions and chains of events
- **22.3.1.4** May be used to estimate the probability of an undesired event by assigning probabilities to the conditions and events.



22.3 Systems Analysis – The Fault Tree

Sources of information

- Operations and maintenance manuals
- Maintenance records
- Parts replacement and repair records
- Design documents
- Experts with knowledge of system
- Examination and testing of exemplar equipment or materials
- Component reliability databases
- Building plans and specifications
- Fire department reports
- Incident scene documentation
- Witness statements
- Medical records of victims
- Human behavior information

22.3 Systems Analysis -- Failure Mode and Effects Analysis

- **NFPA 921 (2014 Edition) Pt. 22.3.2. Failure Mode and Effects Analysis (FMEA)** is a technique used to identify basic sources of failure within a system, and to follow the consequences of these failures in a systematic fashion.
- In fire/explosion investigations, FMEA is a systematic evaluation of all equipment and/or actions that could have contributed to the cause of an incident.

22.3 Systems Analysis -- Failure Mode and Effects Analysis

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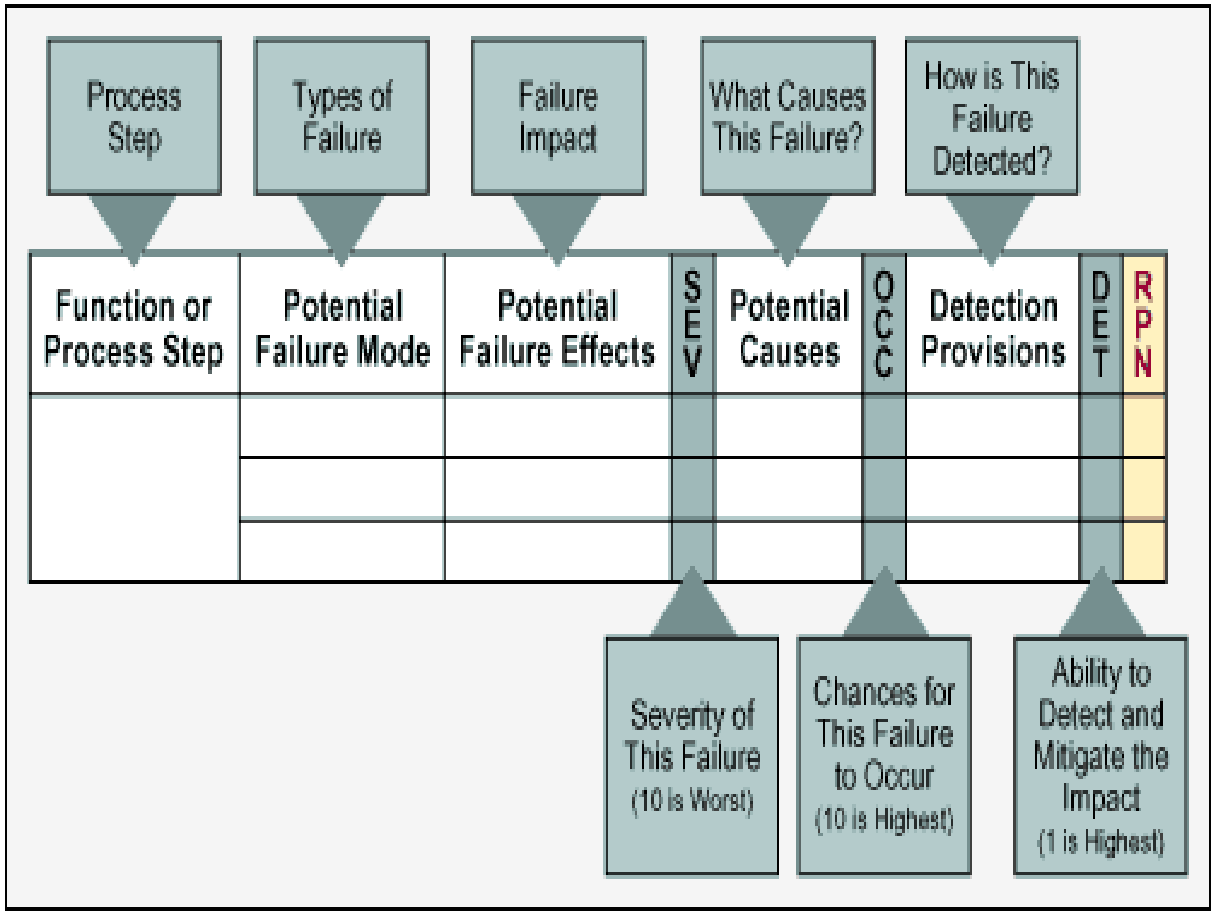
22.3 Systems Analysis -- Failure Mode and Effects Analysis

FUNCTIONAL ASPECTS

- Can help identify potential causes of a fire or explosion
- Can indicate where further analysis could be beneficial.
- Useful in a large or complex incidents
- It can be effective in identifying factors, both physical and human, that could have contributed to the cause of the fire/explosion.



NFPA 921 (2014 Edition) Pt. 22.3.2. Example Failure Mode and Effects Analysis (FMEA)

Table 22.3.2.7 Sample Failure Mode and Effects Analysis for Lunchroom Fire

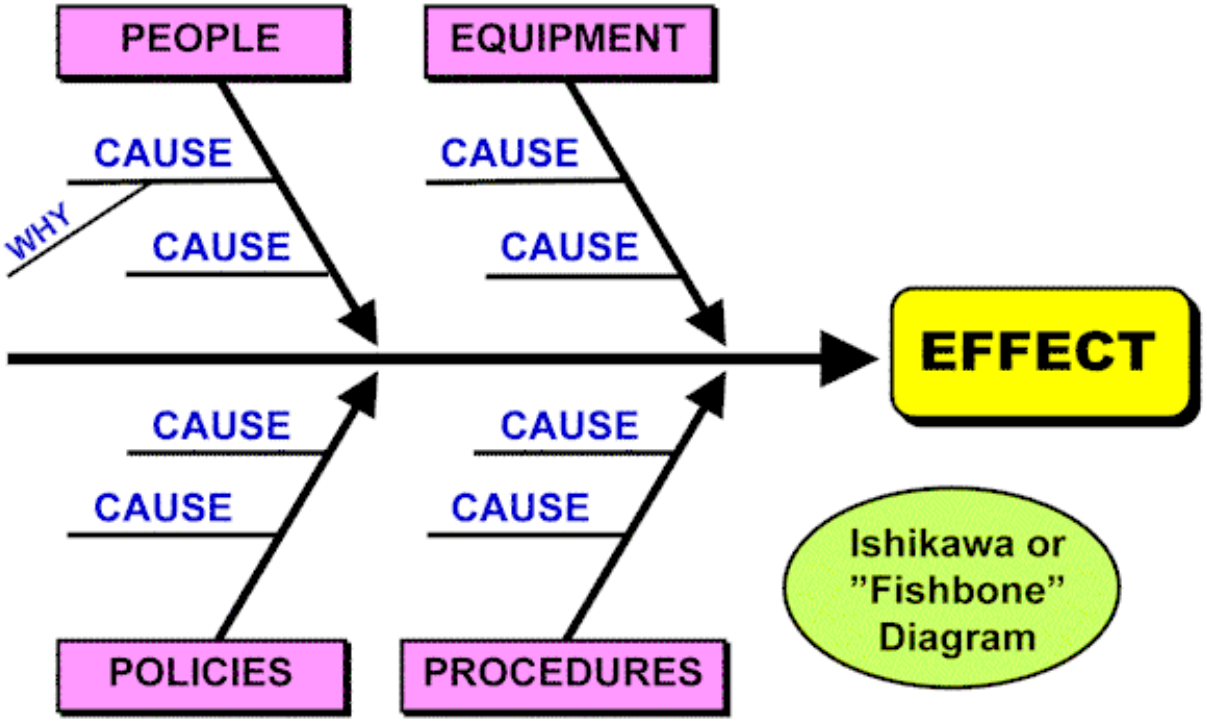
Component Item	Failure Mode	Cause of Failure	Effects of Failure	Hazard Created	Necessary Conditions	Indication of Failure
Coffee maker	Heater current flows without shutoff	Switch left on and controls fail	"Boils" out any water in reservoir; thermal runaway of heating element; local temperature increases above 600°C	Ignition of plastic housing	Power on; switch on or fails closed; thermostat fails in ON position; both thermal fuses fail to open	Melting of aluminum housing around heating element; condensed aluminum at base of maker; thermostat closed circuit; both fuses closed circuit
Range (electric)	Autoignition of cooking oil	Unattended cooking Control failure	Oil temperature raised above autoignition temperature	Burning oil fire and large amount of smoke	Unit on; switch on or fails in closed position; no temperature regulation	Burner control in ON position; melted aluminum pan; oil consumed or spilled on unit; contacts fused or welded

Failure Mode and Effects Analysis (FMEA)

- ***Failure analysis*** usually connotes the determination of how a specific part or component has failed.
- It is usually concerned with material selection, design, product usage, methods of production, and the mechanics of the failure within the part itself.

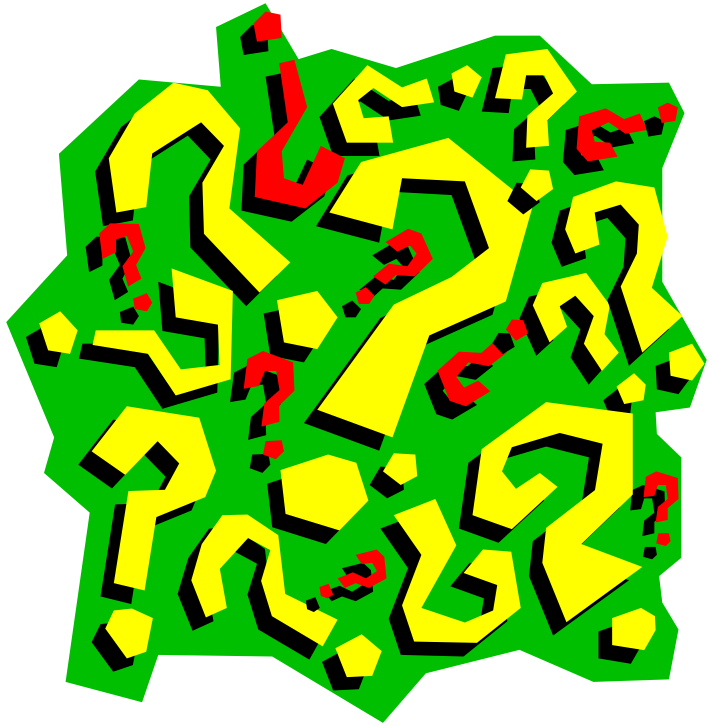
Root Cause Analysis

- ***Root cause analysis*** places more emphasis on the managerial aspects of large system failures.
- Often associated with the analysis of system failures rather than the failure of a specific part, and how procedures and managerial techniques can be improved to prevent the problem from reoccurring.



Why Determine Root Cause?

- Prevent problems from recurring
- Reduce possible injury to personnel
- Reduce rework and scrap
- Increase competitiveness
- Promote happy customers and stockholders
- Ultimately, reduce cost and save money
- Embrace the scientific method



Looking Beyond the Obvious

- Invariably, the root cause of a problem is not the initial reaction or response.
- It is not just restating the “Finding”

Often the Stated Root Cause is the Quick, but Incorrect Answer

For example, a *normal response* is:

- Equipment Failure
- Human Error

Where the *actual issues* may be:

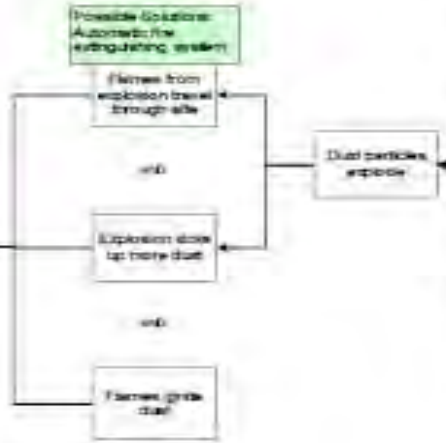
- Process/program/system failure
- Poorly written work instruction
- Lack of training

The initial response is usually the *symptom*, not the root cause of the problem. This is why Root Cause Analysis is a very useful and productive tool.

Dust Explosions: How do we prevent them from happening?

The Chemical Safety Board investigations Manager, Stephen Selk, P.E. gave a briefing on February 17, 2008 to update to the public on the Imperial Sugar Company explosion and to provide a root cause analysis on dust explosions. The speech was very enlightening. One of the things he said was "The Board identified 281 [dust] fires and explosions over a 25-year period that took 119 lives and caused 718 injuries." So, obviously this is a concern. But what to do about it?

When he presented the root cause analysis for dust explosions, he stated that five things were necessary for an explosion: presence of a combustible dust, presence of oxygen, dispersion of the dust into the air, confinement of the particles, and ignition energy. For each of these requirements in the root cause analysis, there is a possible solution - but that possible solution may or may not be effective.



Now we'll examine dispersion of the dust and confinement together. These two requirements almost seem to be mutually exclusive. In reality, the particles are always confined, even if it is only by the building surrounding the processing plant. It's not clear how much confinement, or how much dispersion, is required for an explosion to occur. So, specific solutions here would need to be tailored for each individual plant - and there may not be any that truly work. However, there is one solution that may prevent, or lessen the effects of, follow-on explosions. That is a blast-proof building. This solution, too, would need to be designed specifically for the task at hand, and may be prohibitively expensive.

First, a dust explosion requires the presence of a combustible dust. Unfortunately, the combustible dust is usually a by-product (or the actual product) of the process being performed. So, attempting to remove the combustible gas is probably not worthwhile.

What about the presence of oxygen? Obviously, there has to be oxygen in the refinery itself for the workers to be able to breathe, but it may be possible to remove the oxygen within some of the equipment, possibly by the use of inerting equipment. Inerting equipment using nitrogen to reduce the percentage of oxygen to below combustible levels has been used with some success in various industries.

Eliminating all ignition sources, including static electricity, in a plant filled with electronic equipment and wiring seems like a monumental task indeed. However, this is where the focus on preventing explosions frequently lies. This requires constant and careful inspection of all wiring and potential power sources. Another consideration is that fire is a potential ignition source. If preventing ignition is to be the primary way to avoid dust explosions, automatic fire extinguishing systems should be considered.

Preventing dust explosions is a daunting task. But we see as we examine the statistics - 281 fires and explosions over 25 years, many of them destroying lives and buildings - it is something that must be done. Once we have completed the root cause analysis, we can look for solutions and then set about implementing them.

Cause Map
Detail Level

ThinkReliability

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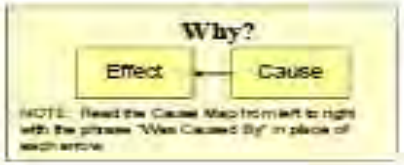
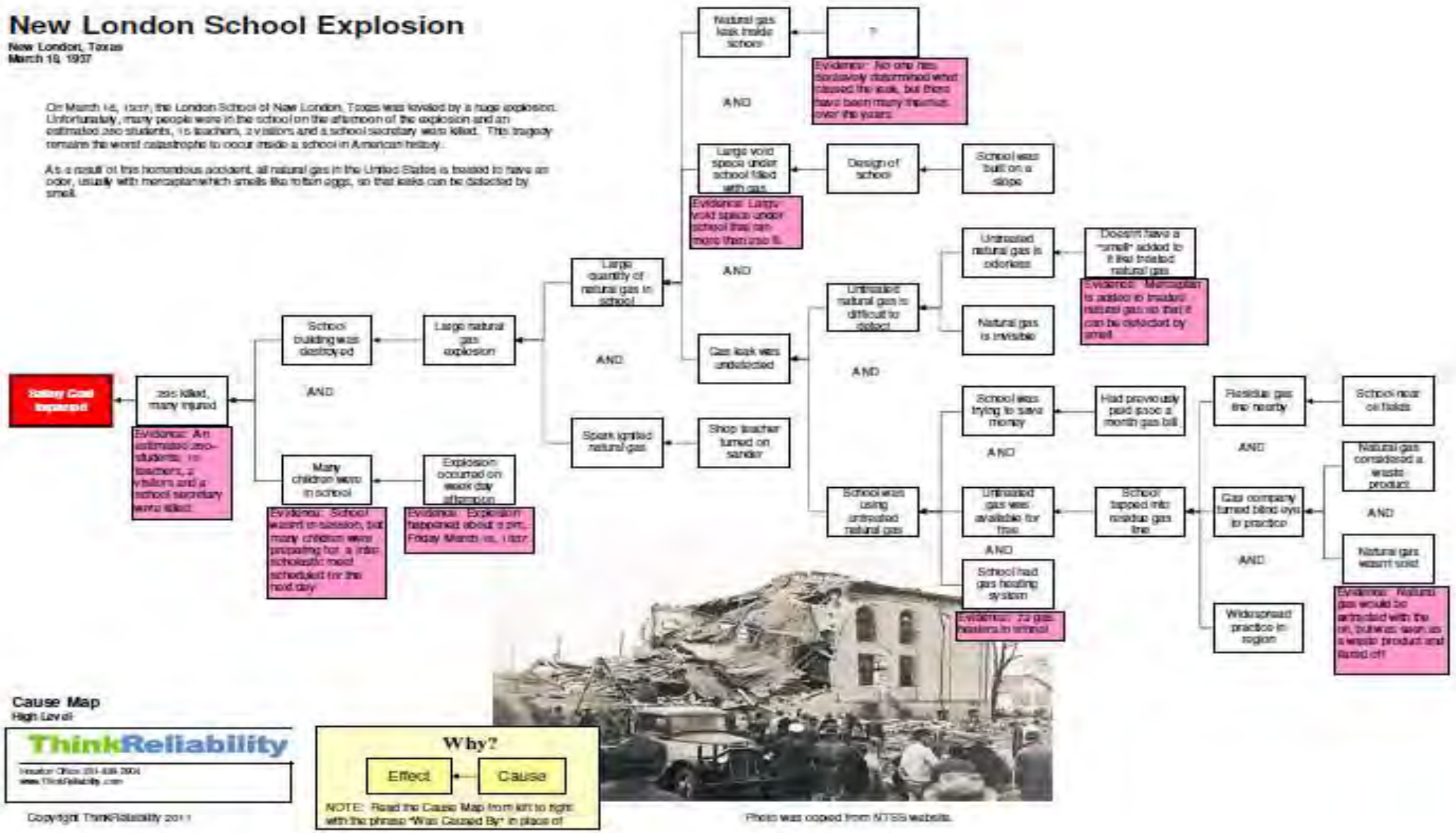


See: ThinkReliability website: http://www.thinkreliability.com/



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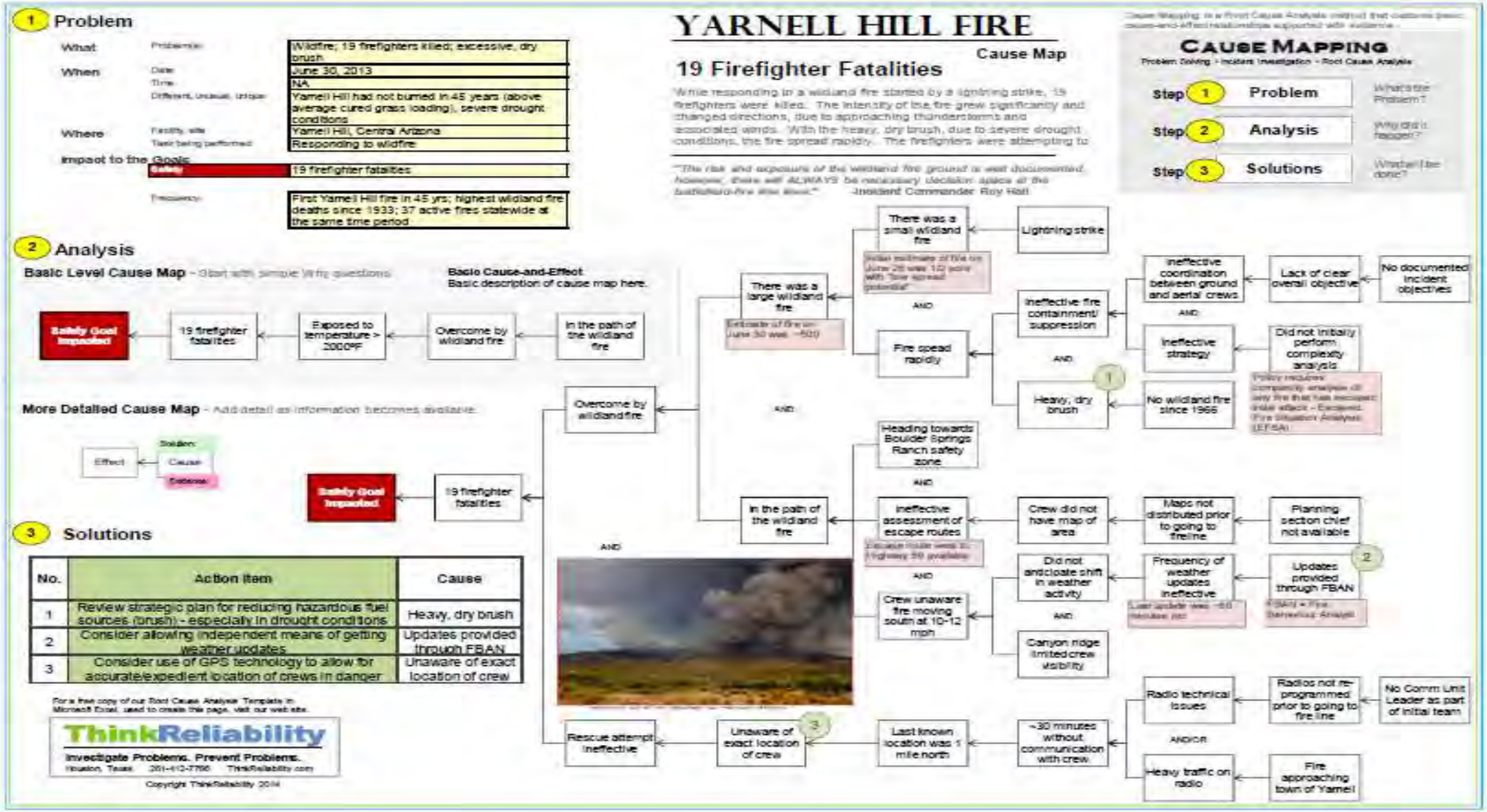

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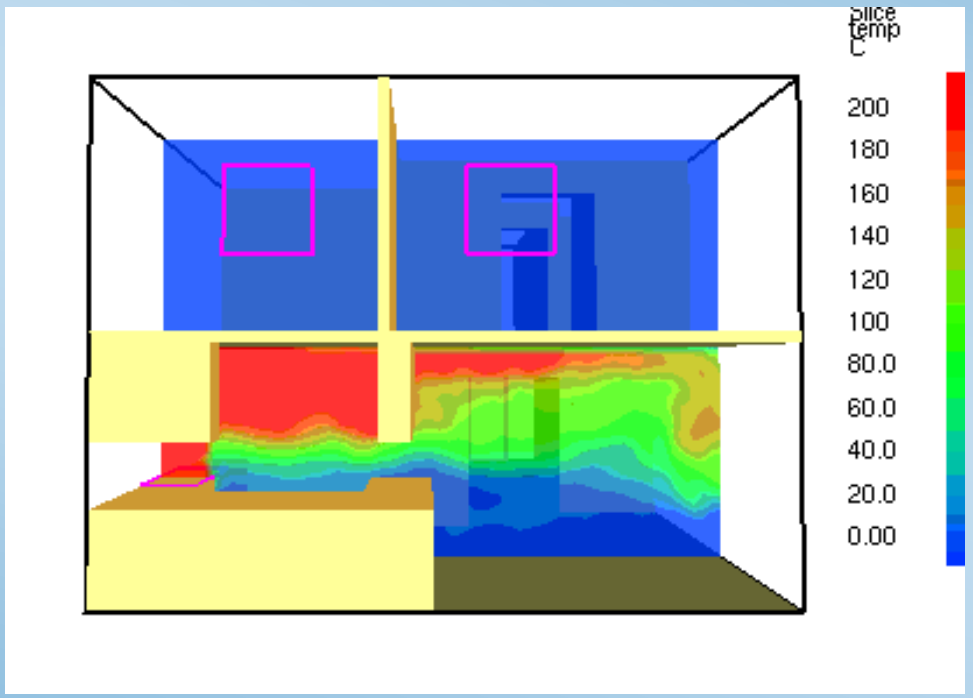
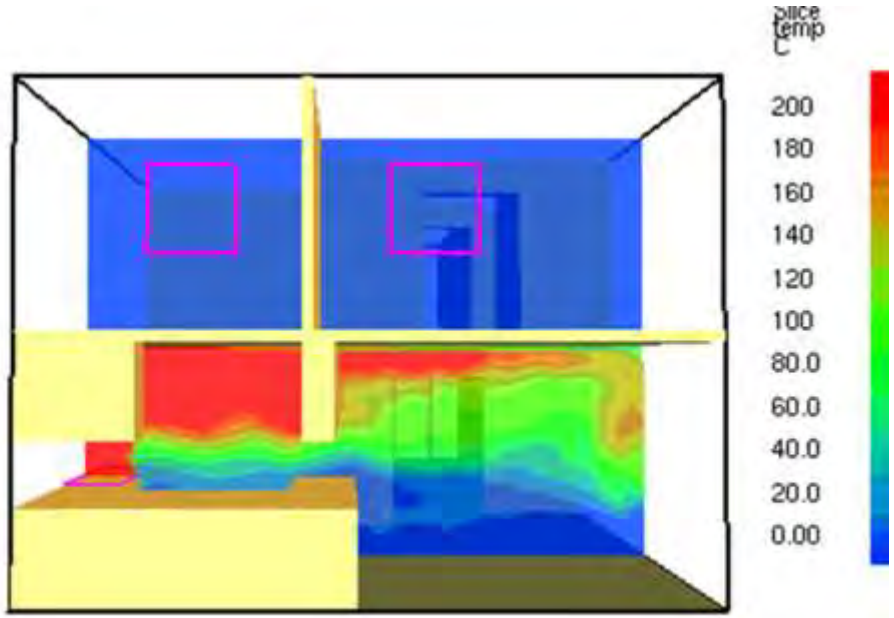


NFPA 921, Pt 22.4 – Mathematical Modeling

22.4 Mathematical Modeling

- **NFPA 921 (2014 Ed.) pt. 22.4.1** Mathematical modeling techniques provide the investigator with *tools for testing hypotheses* regarding the origin and cause of the fire/explosion and the cause of the resulting damage to property or injury to people.
- *Even when the origin and cause are not issues, it is often possible and important to establish the cause of the resulting damage to property or injury to people*.



22.4 Mathematical Modeling – Use Care when Selecting and Applying

***NFPA 921* (2014 Ed) pt. 22.4.1.3 – Limitations of Mathematical Modeling.**

- Mathematical modeling, whether simplified hand calculations or computer fire models, has inherent limitations and assumptions that should be considered.
- Models generally rely upon empirical data and are validated via comparison with other empirical data.
- Care must be taken to assure that the model is being used with due regard for limitations, assumptions, and validation.
- While computational models can be used to test hypotheses, *models should not be utilized as the sole basis of a fire origin and cause determination*.

22.4.2 Heat Transfer Analysis

- **22.4.2.1** Heat transfer models allow quantitative analysis of conduction, convection, and radiation in fire scenarios.
- These models are then *used to test hypotheses regarding fire causation, fire spread, and resultant damage to property and injury to people*. Heat transfer models are often incorporated into other models, including structural and fire dynamics analysis.
- **22.4.2.2** Heat transfer models and analyses can be used to *evaluate various hypotheses*, including those relating to the following:
- (1) Competency of ignition source
- (2) Damage or ignition to adjacent building(s)
- (3) Ignition of secondary fuel items
- (4) Thermal transmission through building elements

Other *NFPA 921* Analysis Techniques

- **22.4.4 Hydraulic Analysis.** Analysis of automatic sprinkler and water supply systems
- **22.4.5 Thermodynamic Chemical Equilibrium Analysis.** Fires and explosions believed to be caused by reactions of known or suspected chemical mixtures
- **22.4.6 Structural Analysis.** Structural analysis techniques can be utilized to determine reasons for structural failure or change during a fire or explosion.
- **22.4.7 Egress Analysis.** The failure of occupants to escape may be one of the critical issues that an investigator needs to address.

Other *NFPA 921* Analysis Techniques

- **22.4.8 Fire Dynamics Analysis.** Fire dynamics analyses consist of mathematical equations derived from fundamental scientific principles or from empirical data. They range from simple algebraic equations to computer models incorporating many individual fire dynamics equations. *Fire dynamics analysis can be used to predict fire phenomena and characteristics of the environment such as the following*:
  - (1) Time to flashover
  - (2) Gas temperatures
  - (3) Gas concentrations (oxygen, carbon monoxide, carbon dioxide, etc.
  - (4) Smoke concentrations
  - (5) Flow rates of smoke, gases, and unburned fuel
  - (6) Temperatures of the walls, ceiling, and floor
  - (7) Time of activation of smoke detectors, heat detectors, and sprinklers
  - (8) Effects of opening or closing doors, breakage of windows, or other physical events

NFPA 921, Pt 22.5 – Fire Testing

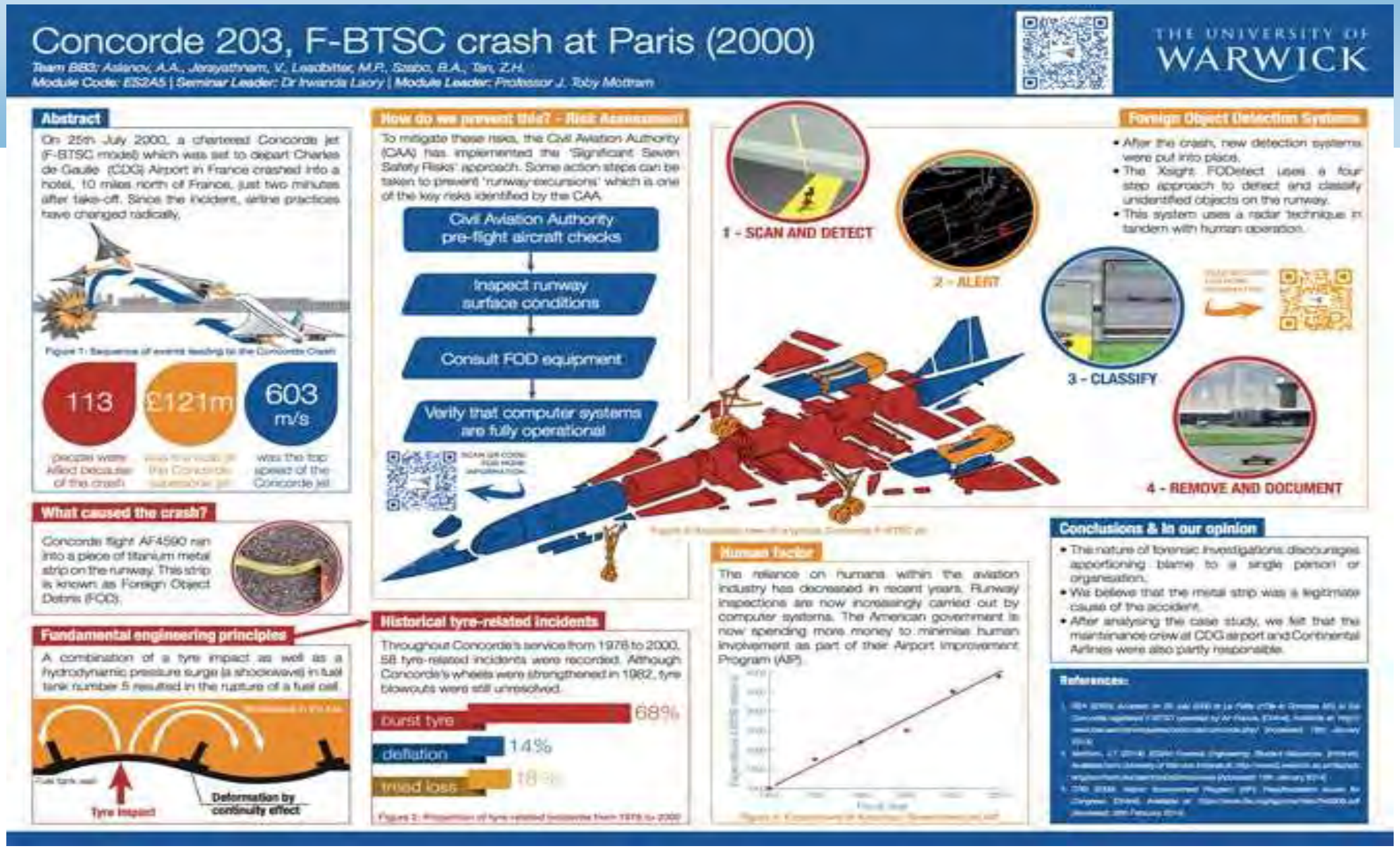
22.5.1. Role of Fire Testing

Fire testing is a tool that *can provide data that complement data collected at the fire scene (see 4.3.3)*, or *can be used to test hypotheses*.

- **22.5.1.1** *Used as a part of data collection*, fire testing can provide insights into the characteristics of fuels or items consumed in the fire, into the characteristics of materials or assemblies affected by the fire, or into fire processes that may have played a role in the fire. This information is valuable in the analysis of data and the formation of hypotheses. *(See also Section 17.10.)*
- **22.5.1.2** *Used as a part of hypothesis testing*, fire testing can assist in evaluating whether a hypothesis is consistent with the case facts and the laws of fire science. In this manner, fire testing is used in much the same way as fire modeling. In addition, fire testing may support modeling by providing input data for models or by providing benchmark data that can be used to assess the accuracy and applicability of a model.

Role of Fire Testing, Modeling, and Ventilation

- **22.5.2* Fire Test Methods.** To the extent possible, fire test methods, procedures, and instrumentation should follow or be modeled after standard tests or test methods that have been reported in the fire science literature.
- **22.5.3 Limitations of Fire Testing.** While fire testing can provide useful information, it is not possible to perfectly recreate all of the conditions of a specific fire that may affect the results of a full-scale test fire.
- **22.6 Data Required for Modeling and Testing.** Scene data required for modeling and testing, typically obtained by the fire investigator, are used to quantify or characterize the physical scene. Relevant scene data include structural dimensions; type of building materials; size, location, and type of contents; and size, location, and type of sources of ventilation.
- **22.6.2 Ventilation.** Understanding ventilation conditions is important to the validity of a fire test or model. The position and condition of doors, windows, skylights, and other sources of ventilation, such as thermostatically controlled exhaust fans, should be determined. Ventilation effects may include wind, fire department ventilation, and HVAC operation and should be considered.


Concorde 203, F-BTSC crash at Paris (2000)
Team BB3: Aslanov, A.A., Jerayathnam, V., Leadbitter, M.P., Szabo, B.A., Tan, Z.H.
Module Code: ES2A5 | Seminar Leader: Dr Irwanda Laory | Module Leader: Professor J. Toby Mottram
THE UNIVERSITY OF WARWICK
Abstract
On 25th July 2000, a chartered Concorde jet (F-BTSC model) which was set to depart Charles de Gaulle (CDG) Airport in France crashed into a hotel, 10 miles north of France, just two minutes after take-off. Since the incident, airline practices have changed radically.
Figure 1: Sequence of events leading to the Concorde Crash
113
£121m
603 m/s
people were killed because of the crash
was the top speed of the Concorde jet
What caused the crash?
Concorde flight AF4590 ran into a piece of titanium metal strip on the runway. This strip is known as Foreign Object Debris (FOD).
Fundamental engineering principles
A combination of a tyre impact as well as a hydrodynamic pressure surge (a shockwave) in fuel tank number 5 resulted in the rupture of a fuel cell.
Fuel tank wall
Tyre impact
Deformation by continuity effect
How do we prevent this? - Risk Assessment
To mitigate these risks, the Civil Aviation Authority (CAA) has implemented the 'Significant Seven Safety Risks' approach. Some action steps can be taken to prevent 'runway excursions' which is one of the key risks identified by the CAA.
Civil Aviation Authority pre-flight aircraft checks
Inspect runway surface conditions
Consult FOD equipment
Verify that computer systems are fully operational
SCAN QR CODE FOR MORE INFORMATION
Historical tyre-related incidents
Throughout Concorde's service from 1976 to 2000, 58 tyre-related incidents were recorded. Although Concorde's wheels were strengthened in 1982, tyre blowouts were still unresolved.
burst tyre 68%
deflation 14%
tread loss 18%
Figure 2: Proportion of tyre-related incidents from 1976 to 2000
1 - SCAN AND DETECT
2 - ALERT
3 - CLASSIFY
4 - REMOVE AND DOCUMENT
Foreign Object Detection Systems
• After the crash, new detection systems were put into place.
• The Xsight FODetect uses a four step approach to detect and classify unidentified objects on the runway.
• This system uses a radar technique in tandem with human operation.
Human factor
The reliance on humans within the aviation industry has decreased in recent years. Runway inspections are now increasingly carried out by computer systems. The American government is now spending more money to minimise human involvement as part of their Airport Improvement Program (AIP).
Conclusions & In our opinion
• The nature of forensic investigations discourages apportioning blame to a single person or organisation.
• We believe that the metal strip was a legitimate cause of the accident.
• After analysing the case study, we felt that the maintenance crew at CDG airport and Continental Airlines were also partly responsible.
References:

The Use of Structural Deformation as a Method of Determining Area of Fire Origin

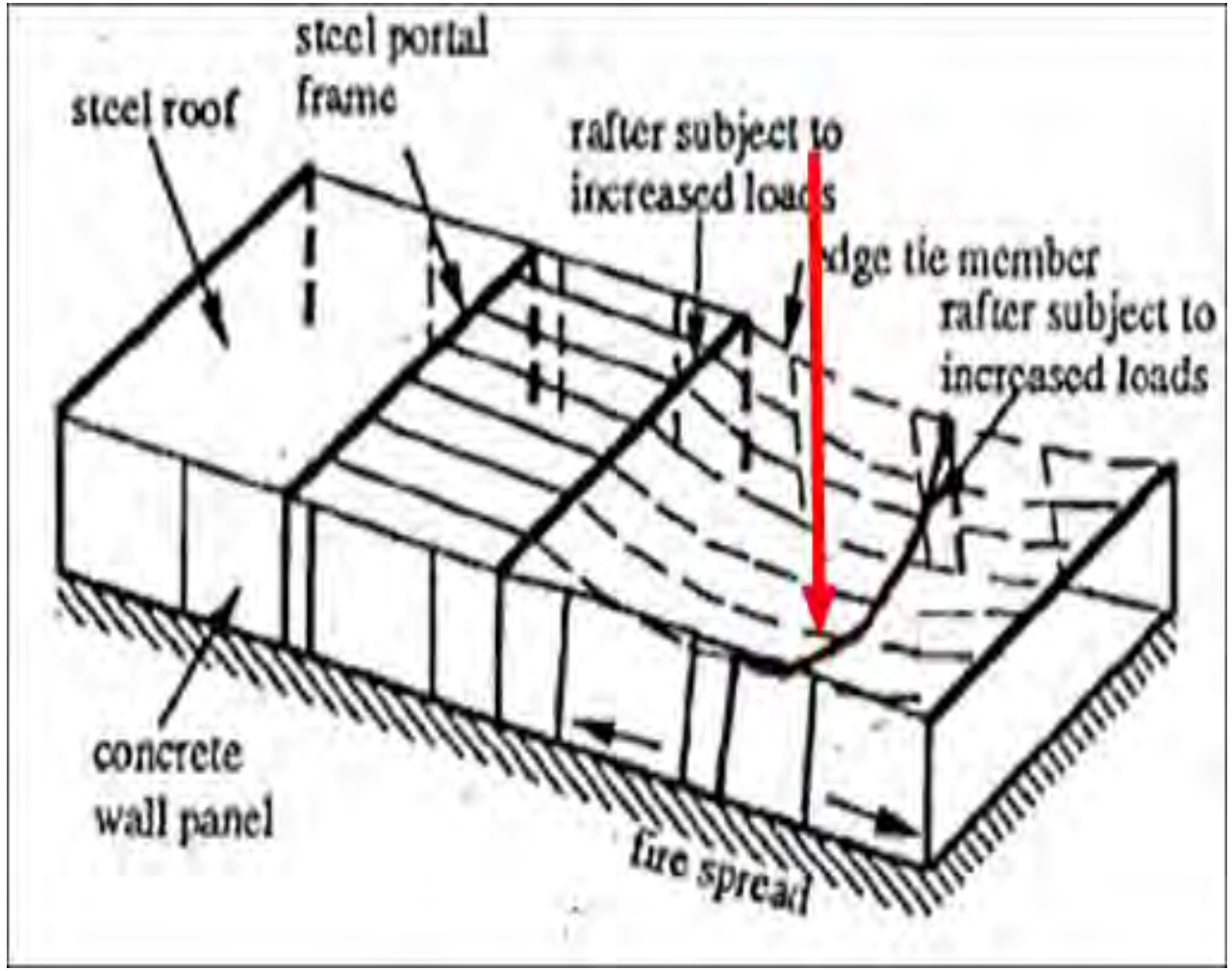
A.T. Tinsley, E.G. Burdette, and D.J. Icove. 2014. ***Structural Deformations as an Indicator of Fire Origin***. Journal of Performance of Constructed Facilities. Volume 28, Issue 3 (June 2014).

Common Causes of Structural Failures in Buildings

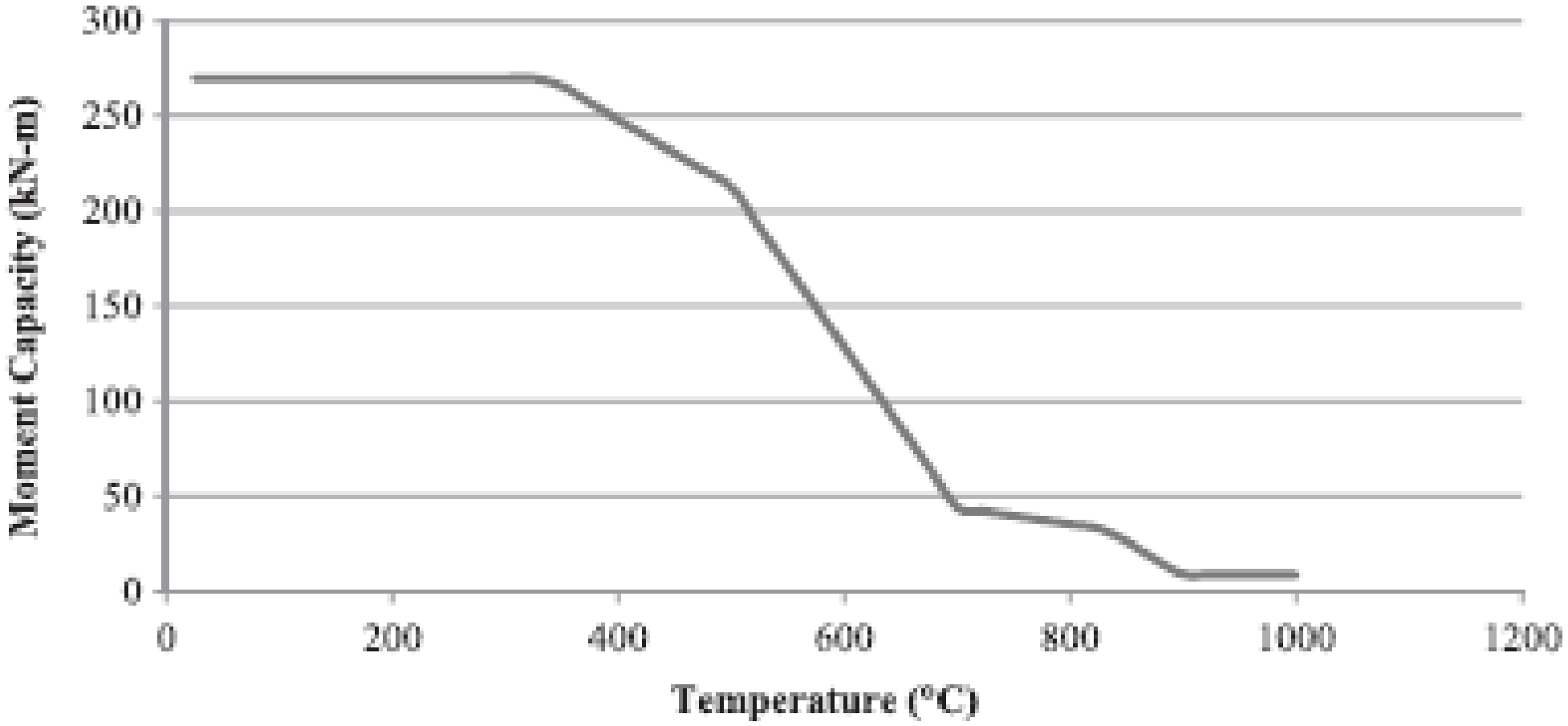
- 1. *Site Selection and Site Development Errors:*
  - Land-use planning errors, insufficient or nonexistent geotechnical studies, unnecessary exposure to natural hazards.
- 2. *Programming Deficiencies:*
  - Unclear or conflicting client expectations, lack of clear definition of scope or intent of project.
- 3. *Design Errors:*
  - Errors in concept, lack of redundancy, failure to consider a load or combination of loads, connection details, calculation errors, misuse of computer software, detailing problems including selection of incompatible materials or assemblies which are not constructible, failure to consider maintenance requirements and durability, inadequate or inconsistent specifications for materials or expected quality of work.
- 4. *Construction Errors:*
  - Nonconformance to design intent, excavation and equipment accidents, excessive construction loads, improper sequencing, premature removal of shoring and formwork, inadequate temporary support.
- 5. *Material Deficiencies:*
  - Material inconsistencies, premature deterioration, manufacturing or fabrication defects.
- 6. *Operational Errors:*
  - Alterations to structure, change in use, negligent overloading, inadequate maintenance.

Textbook Documentation of Deformation based upon Fire Spread

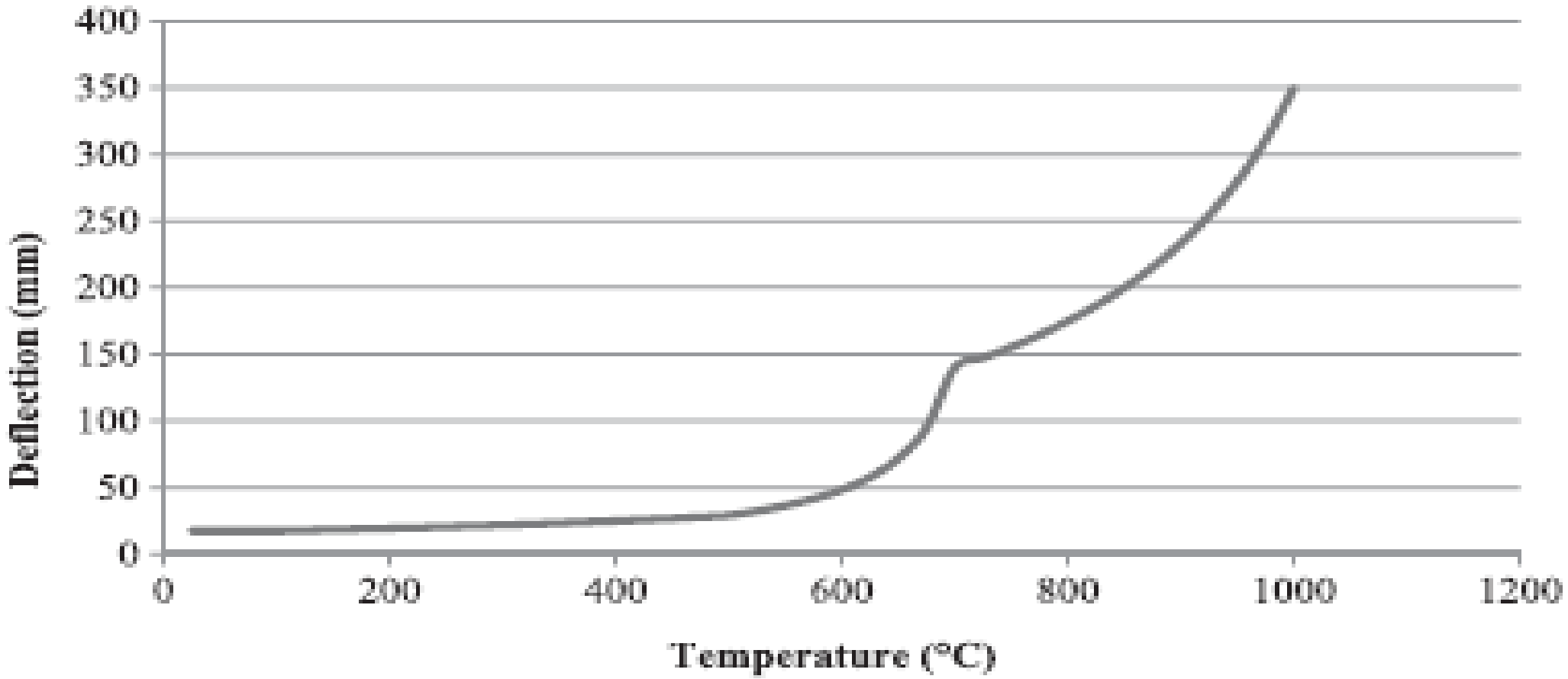
- Assessment of structural steel fire protection (ASTM 119 or NFPA 251)
- Critical temperature is1000°F (538°C)
- See: Buchanan, A. H. (2001). *Structural Design for Fire Safety*. Chichester, England ; New York, Wiley.



Moment Capacity versus Temperature



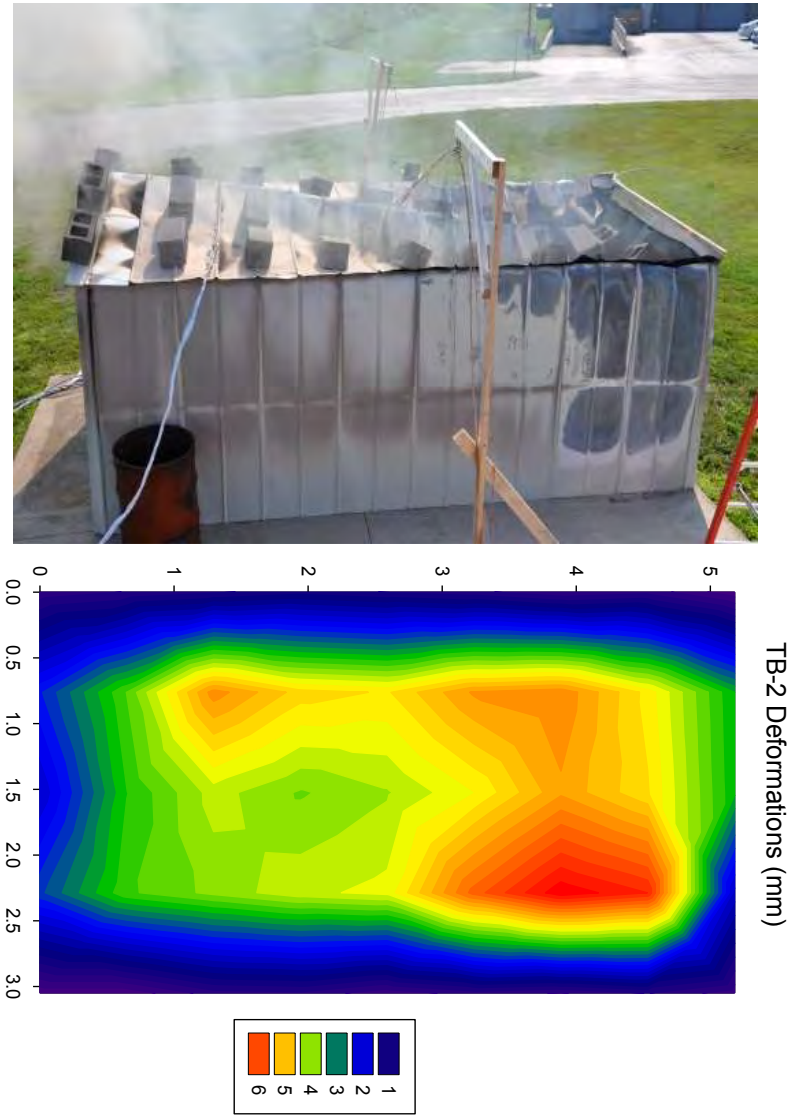
Deflection versus Temperature



Hypothesis: When structural failures occur during fires in large buildings, can the area of fire origin be located?

- Current methodologies of fire origin investigation have yet to include the structural deformations witnessed in steel buildings as a viable indicator of the area of fire origin.
- Research has shown that, when properly applied, this is a valid and reliable technique for fire investigation.

- A series of full scale burn tests were conducted to validate the proposed methodology.
- While it did not turn out that the greatest magnitude of deflection was always indicative of the precise area of origin ---- the tests did show that the deflections can be used as important indicators of the area of origin.



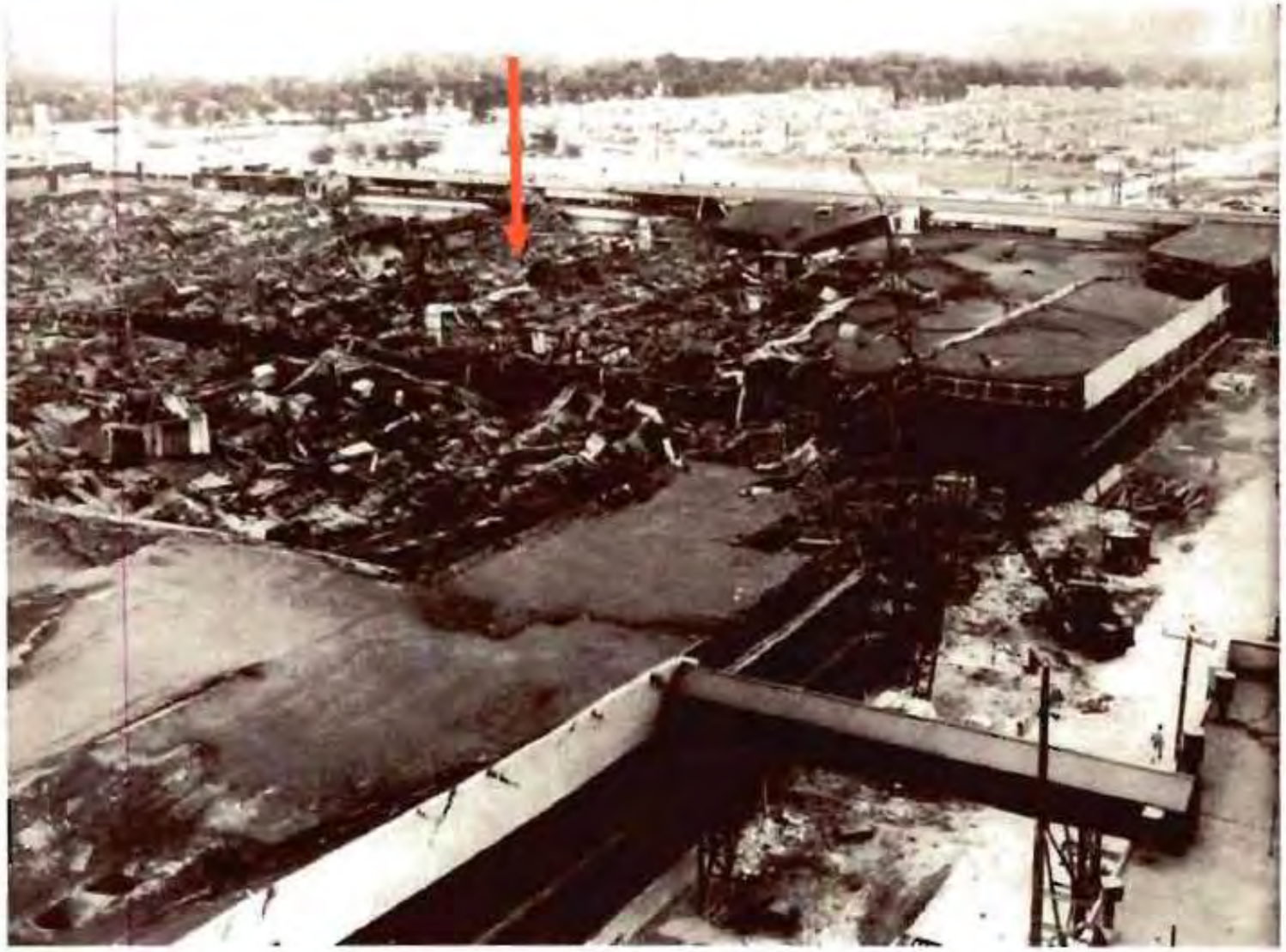
Common Enclosure Fire Dynamics

- As a smoke plume reaches the ceiling, it spreads horizontally over the ceiling area.
- In the early stages of the fire, this smoke plume will generate the most intense temperatures in the area of the building nearest the origin of the fire.
- As the fire continues to develop the temperatures will not equalize throughout the room limiting the rate of heat transfer to other members within the structure.
- When the fuel spreads to additional fuel packages, the difference in temperature between the plume and now elevated temperatures of the upper layer is much smaller than when the fire was started.
- Thus, a smaller amount of heat flux will be received at later points in the fire.
- <u>The area nearest the origin of the fire appears to sustain the highest intensity and longest duration of thermal degradation</u>.

Test Burn: (9-inch diameter heptane pool fire)

Historical Example: McCormick Place Fire Collapse and Confirmed Area of Origin

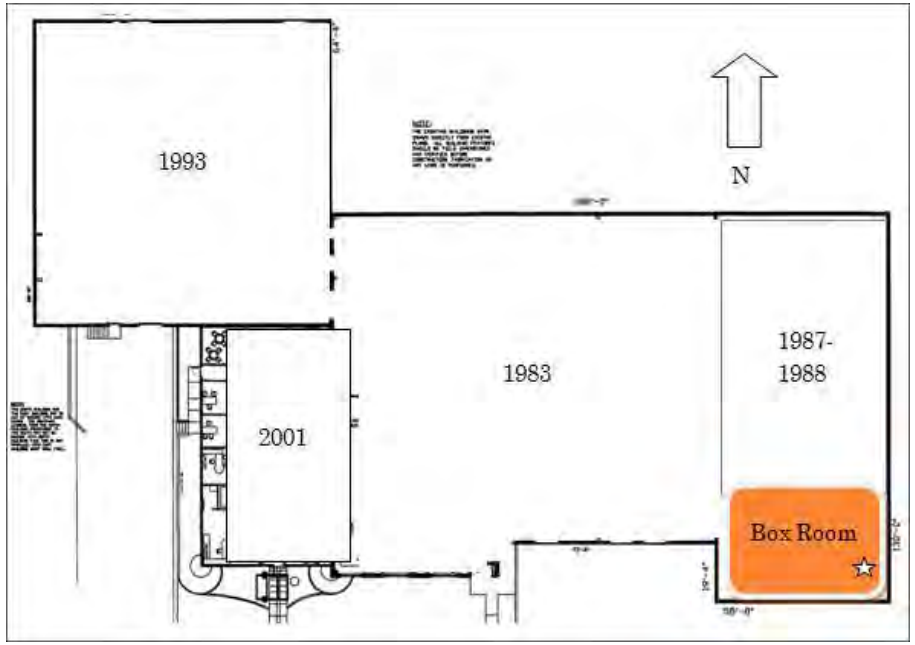
Historical Example: Livonia Transmission Plant Fire Collapse and Confirmed Area of Origin



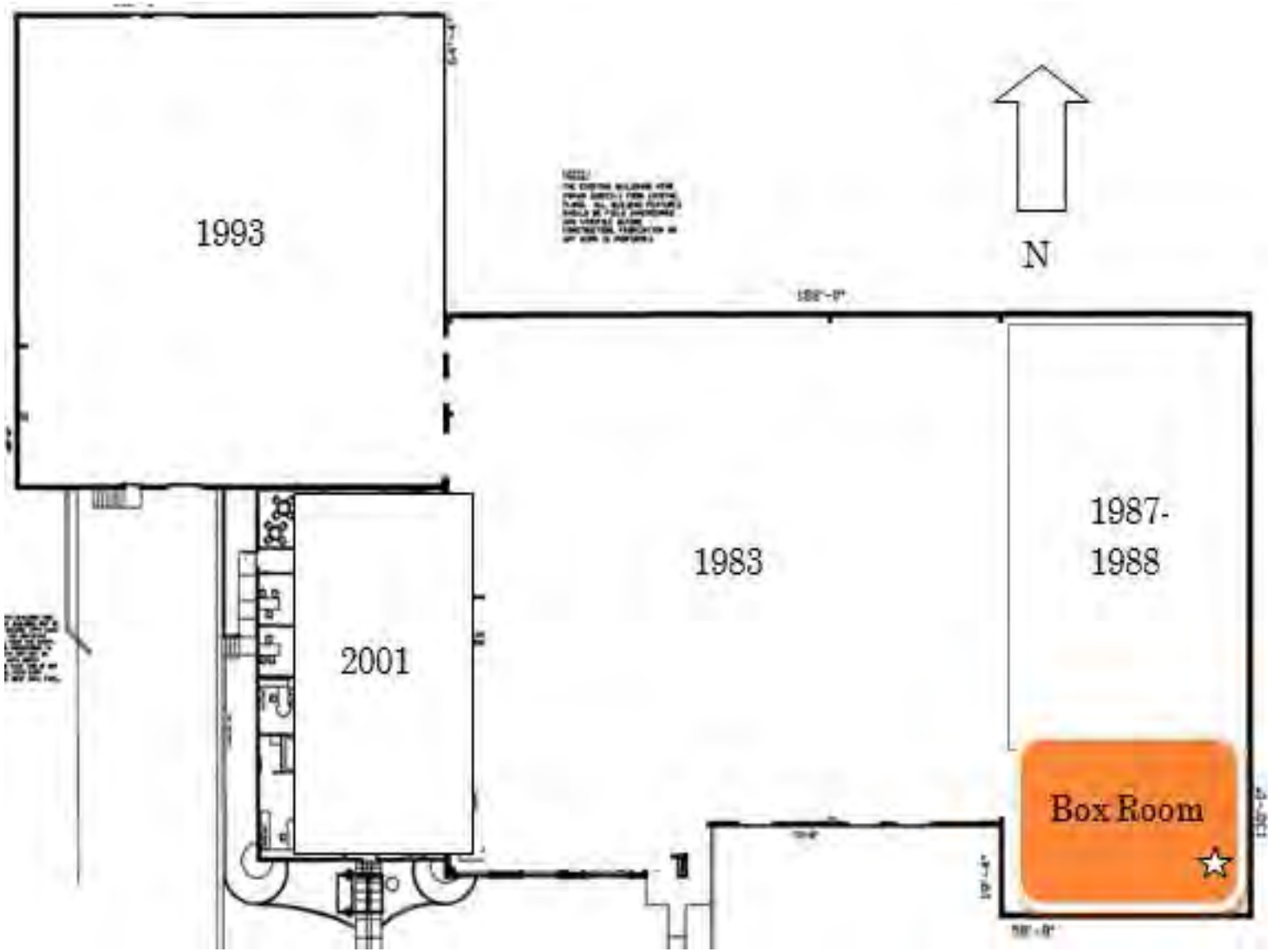
Case Study: Warehouse Predicted Structural Roof Collapse by Fire Engineering Analysis

Warehouse Storage Arson

- Fire set by an arsonist to pallets of corrugated cardboard boxes in storage room
- Building had three major expansions
- Facility had no fire sprinkler coverage in the box storage room
- No local “enforceable fire code”



Fire Scene Area/Point of Origin

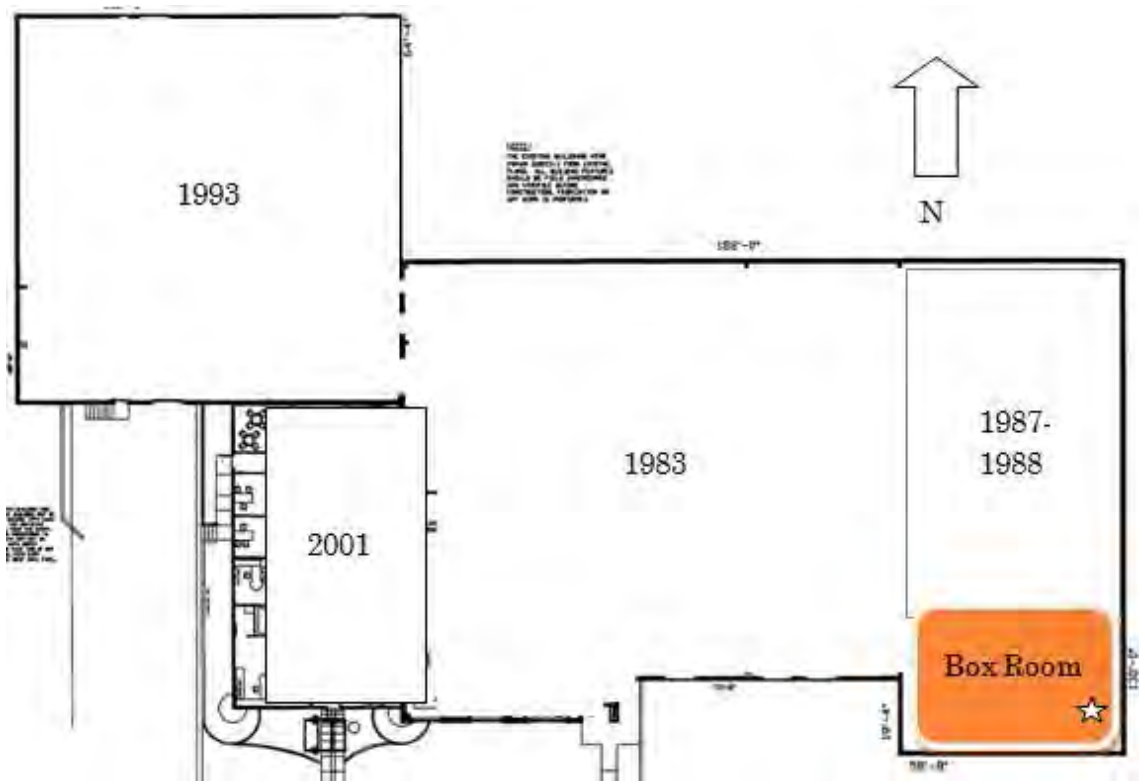


NFPA 921 (2014 Edition) Chapter 22.4.2 Heat Transfer Analysis

- **22.4.2.1** Heat transfer models allow quantitative analysis of conduction, convection, and radiation in fire scenarios.
- These models are then used to test hypotheses regarding fire causation, fire spread, and resultant damage to property and injury to people.
- Heat transfer models are often incorporated into other models, including structural and fire dynamics analysis.
- **22.4.2.2** Heat transfer models and analyses can be used to evaluate various hypotheses, including those relating to the following:
- (1) Competency of ignition source
- (2) Damage or ignition to adjacent building(s)
- (3) Ignition of secondary fuel items
- (4) Thermal transmission through building elements

Problem Statement

- Need to determine:
  1. Nature of materials ignited
  2. Exposed storage area
  3. Burning duration
  4. Upper gas layer temperature
  5. Time to Flashover
  6. Structural collapse
  7. Should we us a Fire Model?
  8. What is the appropriate U.S. NRC FDT spreadsheet to use?



1. Determine Nature of Materials (Fuels)

<u>Inventory the type of materials in room</u>

- Pallets of folded corrugated cardboard boxes
- Wood pallets
- Plastic rolls

1. Determine Nature of Materials (Con't.)

Item	Type of Material	Exposed Unit Floor Areas	Estimated Total Exposed Floor Area	
			ft^2	m^2
Pallet of 500 folded boxes	Corrugated cardboard	22	352	32.7
Pallets	Wood	1	16	1.49
Plastic rolls	Polyethylene	6	96	8.9

2. Calculate Exposed Surface Area

Box Type	Pallet Dimensions (in)			Floor Area (W)(D)		Volume (W)(D)(H)		Density* (D)	Mass (V)(D)	
	W	D	H	ft^2	m^2	ft^3	m^3	kg/m^3	lb	kg
Country Style Hashbrowns	40.0	57.5	31.1	16.0	1.48	41.3	1.17	76	196	88.8
Shredded Potatoes	46.0	50.0	39.5	16.0	1.48	41.3	1.17	76	250	113.2

*Ryu, et al. 2007. "Ignition and Burning Rates of Segregated Waste Combustion in Packed Beds," Waste Management 27 (2007) 802-810.

3. Estimate Burning Duration

$$t_{solid} = \frac{m_{fuel}\,\Delta H_c}{\dot{Q}''\,A_{fuel}}$$

Box Type	Mass of combustible fuel (22 pallets) (kg)	Effective heat of combustion (MJ/kg)*	Heat release rate per unit floor area (kW/m^2)**	Exposed floor area of fuel (m^2)	Burning duration (sec)
Country Style Hash browns	88.8 x 22=1953	15.7	176	32.7	5327 (88.8 min)
Shredded Potatoes	113.2 x 22=2490	15.7	176	32.7	6792 (113 min)

3. Calculate Burning Duration

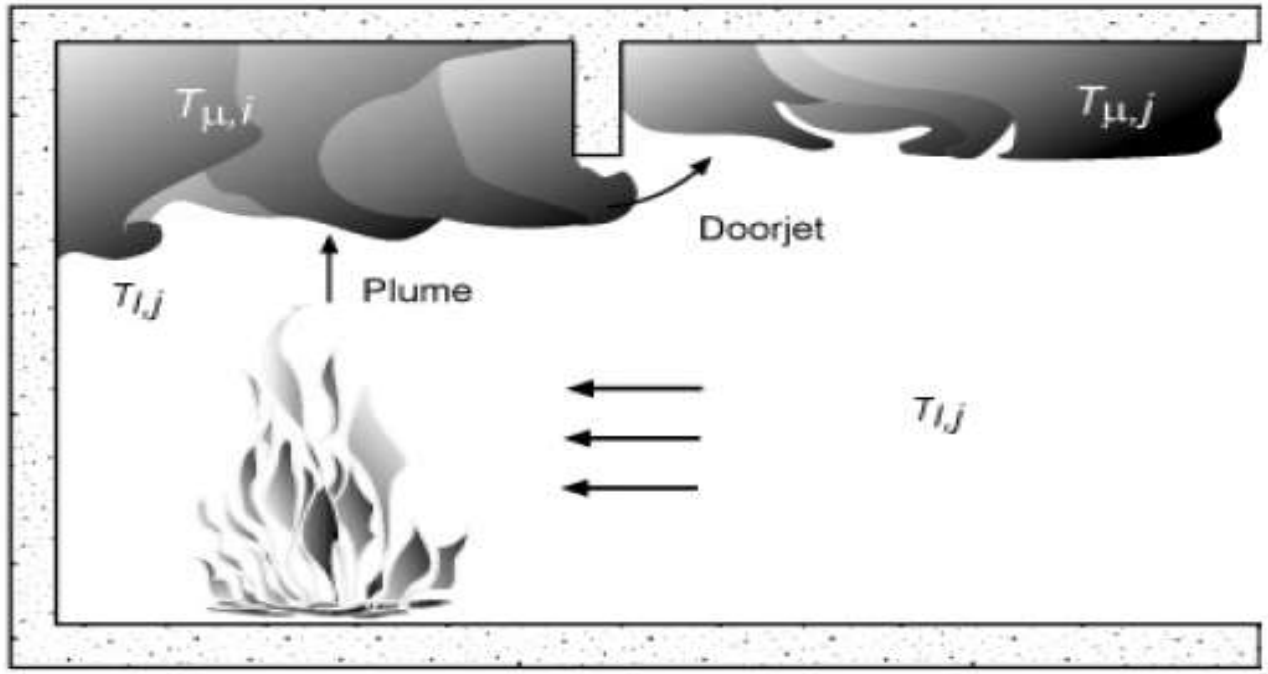
- Finally, the heat release rate of the fire can also be calculated by multiplying the area of the exposed fuel surface times the heat release rate per unit floor area. In this case,

$$(176\ kW/m^2)\ (32.7\ m^2) = 5775\ kW \text{ or } 5.78\ MW$$

- In this case if other combustible materials in the room are considered, it would be fair to state that the fire may easily reach approximately 6000 kW or 6 MW.

4. Calculate Upper Gas Layer Temperature

$$\Delta T_g = 6.85\left[\frac{\dot{Q}^2}{\left(A_v\sqrt{h_v}\right)\left(A_T h_k\right)}\right]^{1/3}$$



Time After Ignition (t)		Upper layer gas temperature (T_g)	
(min)	(sec)	(°C)	(°F)
0	0	25	77
1	60	227.16	440.89
2	120	251.92	485.45
3	180	267.78	514.01
4	240	279.71	535.47
5	300	289.36	552.84
10	600	321.73	611.12
15	900	342.48	648.46
20	1200	358.07	676.53
25	1500	370.69	699.24
30	1800	381.36	718.44
35	2100	390.63	735.13
40	2400	398.86	749.95
45	2700	406.27	763.29
50	3000	413.02	775.44
55	3300	419.24	786.63
60	3600	425.00	796.99

5. Estimate Time to Flashover

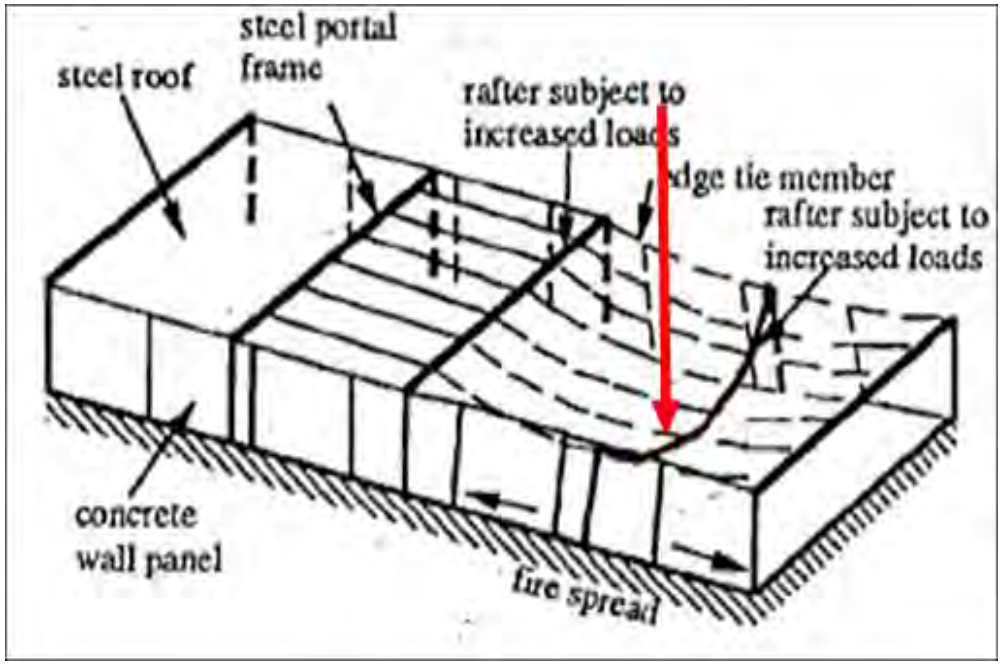
- The actual construction having the 8 x 8 ft (2.44 x 2.44 m) door opening, along with a 2.5 in x 60 ft (0.0635 x 18.3 m) opening above the steel beam, and a 2 x 60 ft (0.609 x 18.3 m) opening below the beam from the box room into the freezer. Assume a 22 ft (6.71 m) ceiling.
- Use Babrauskas and Thomas formulas

$$\dot{Q}_{FO} = 750 A_V \sqrt{h_v} = 750 \cdot 18.3 \sqrt{1.17} = 14145\, kW = 14.1\, MW$$

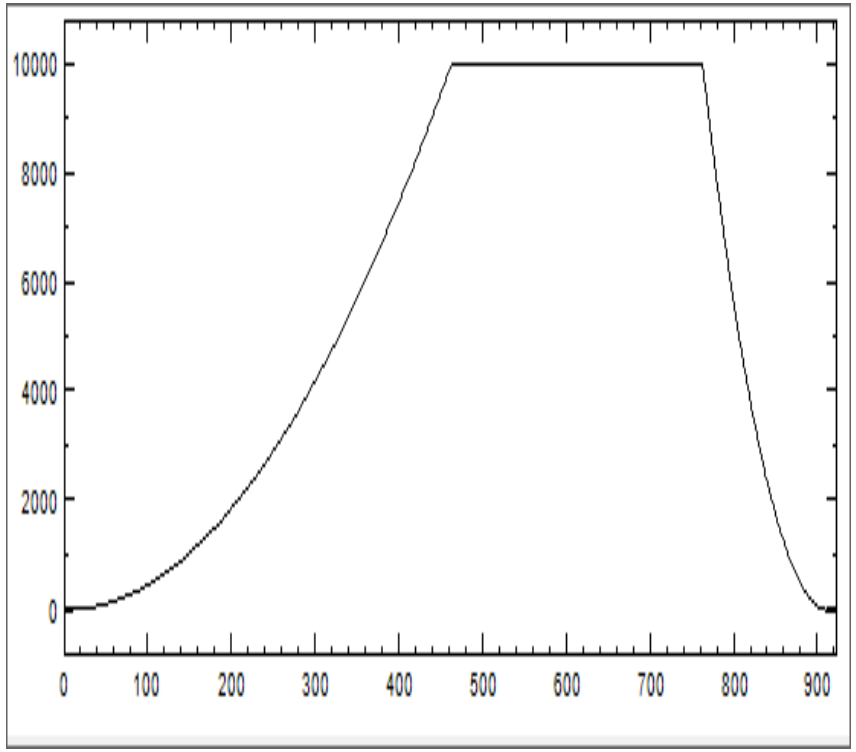
$$\dot{Q}_{FO} = 7.8 A_T + 378 A_V \sqrt{h_v} = 7.8 \cdot 836 + 378 \cdot 18.3 \sqrt{1.17} = 14003\, kW = 14\, MW$$

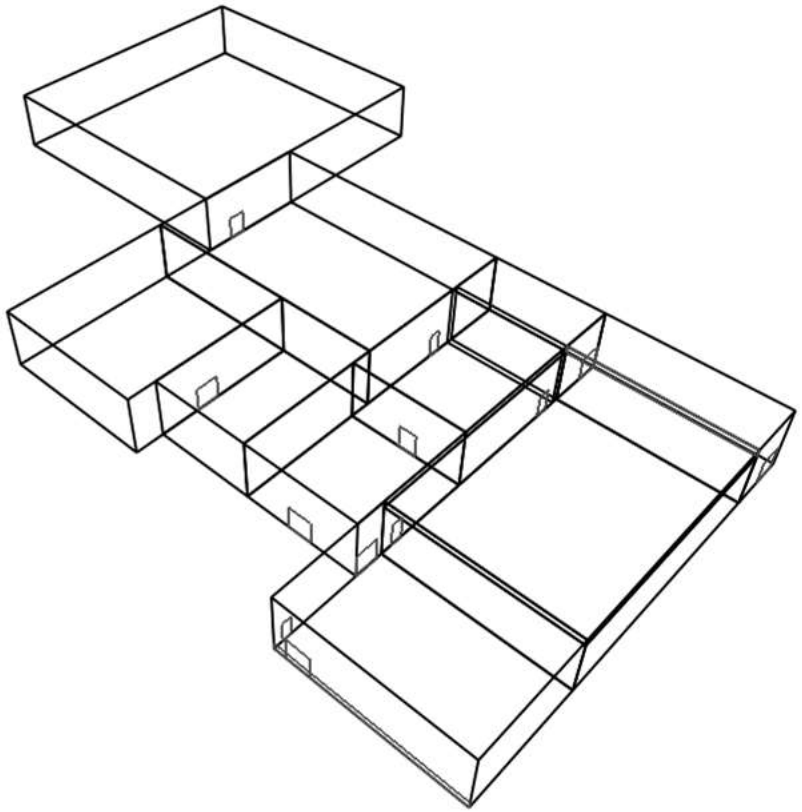
6. Confirm Structural Collapse

- Assessment of structural steel fire protection (ASTM 119 or NFPA 251)
- Critical temperature is 538°C or 1000°F
- See: Buchanan, A. H. (2001). Structural Design for Fire Safety. Chichester, England ; New York, Wiley.



7. How to Select the Appropriate Fire Model?

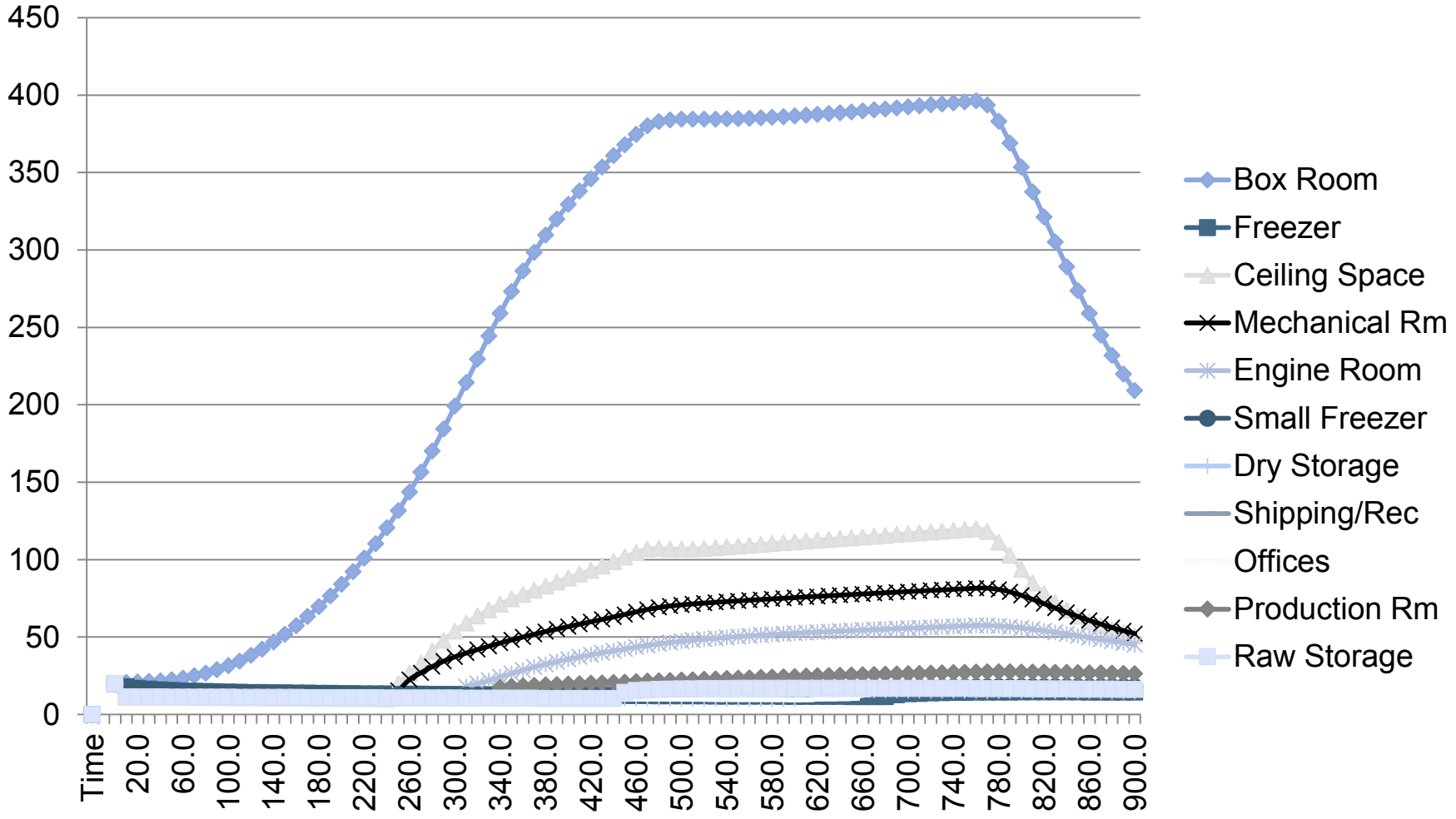




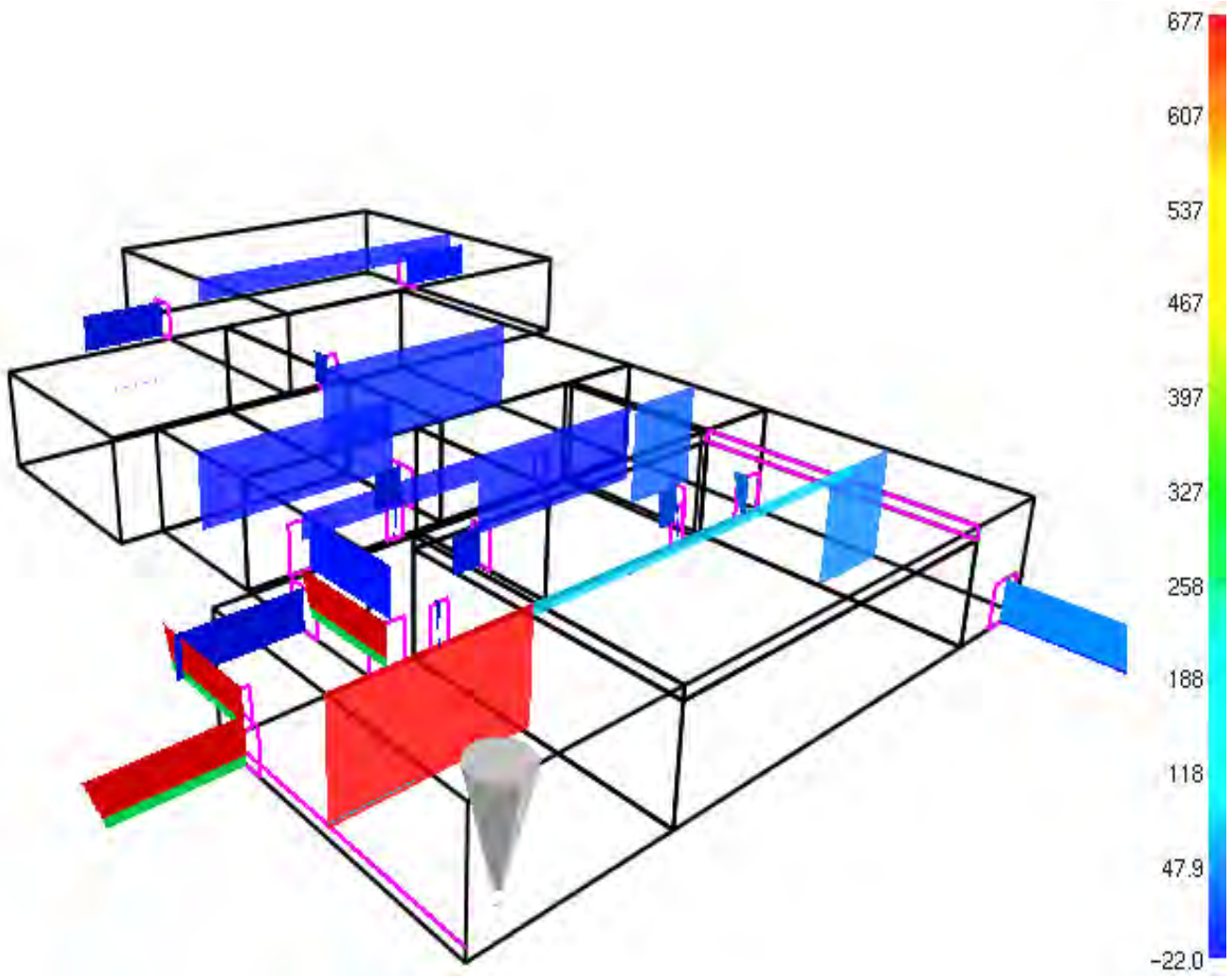
SFPE (2011): ***Guidelines for Substantiating a Fire Model for a Given Application***. In SFPE (Ed.). Bethesda, MD: Society of Fire Protection Engineers.

Mowrer, F.W. (2002). ***The Right Tool for the Job***. Fire Protection Engineering, Society of Fire Protection Engineers, Bethesda, MD, Winter 2002, pp. 39-44.

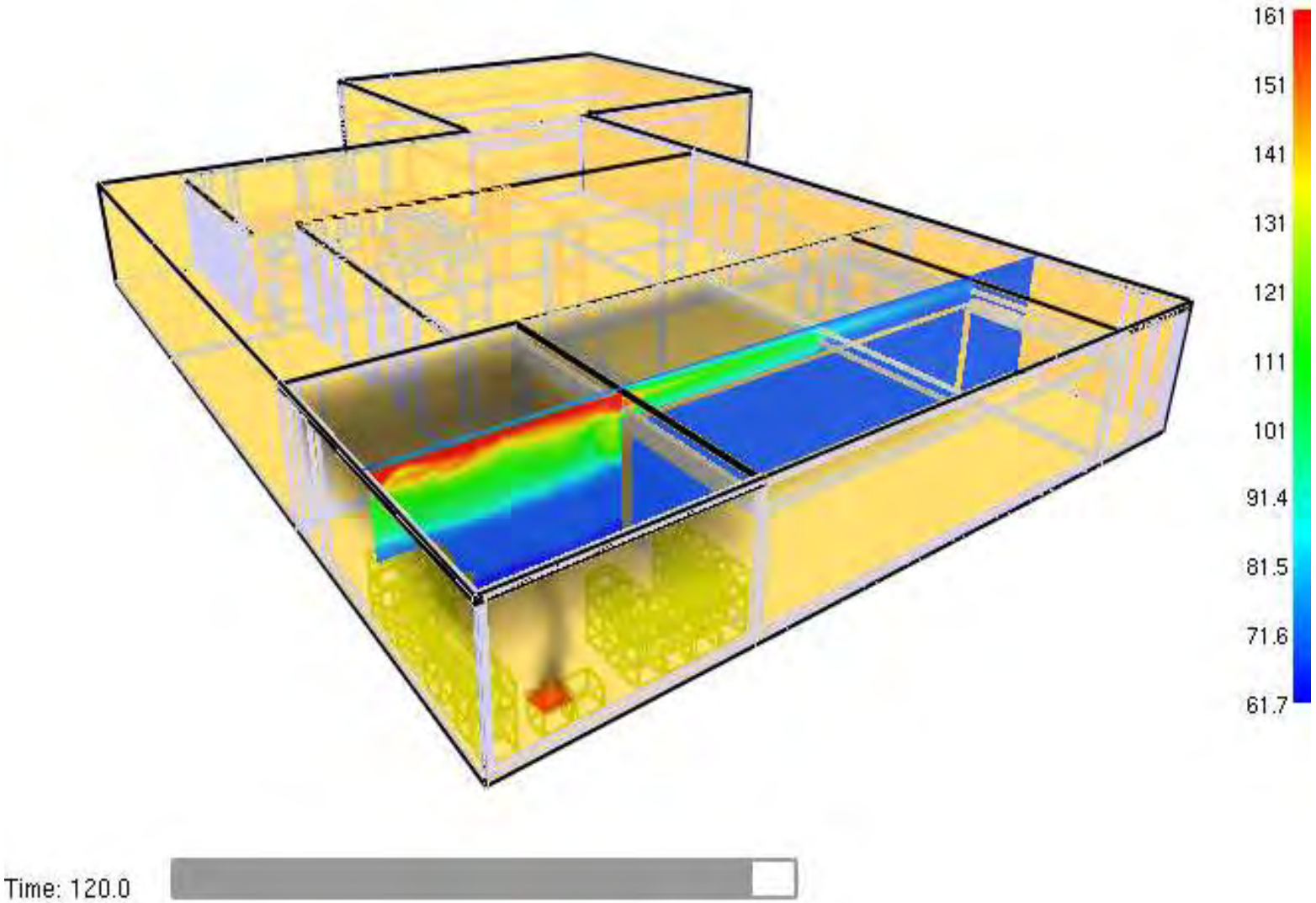
Consolidated Model of Fire Growth and Smoke Transport (CFAST)



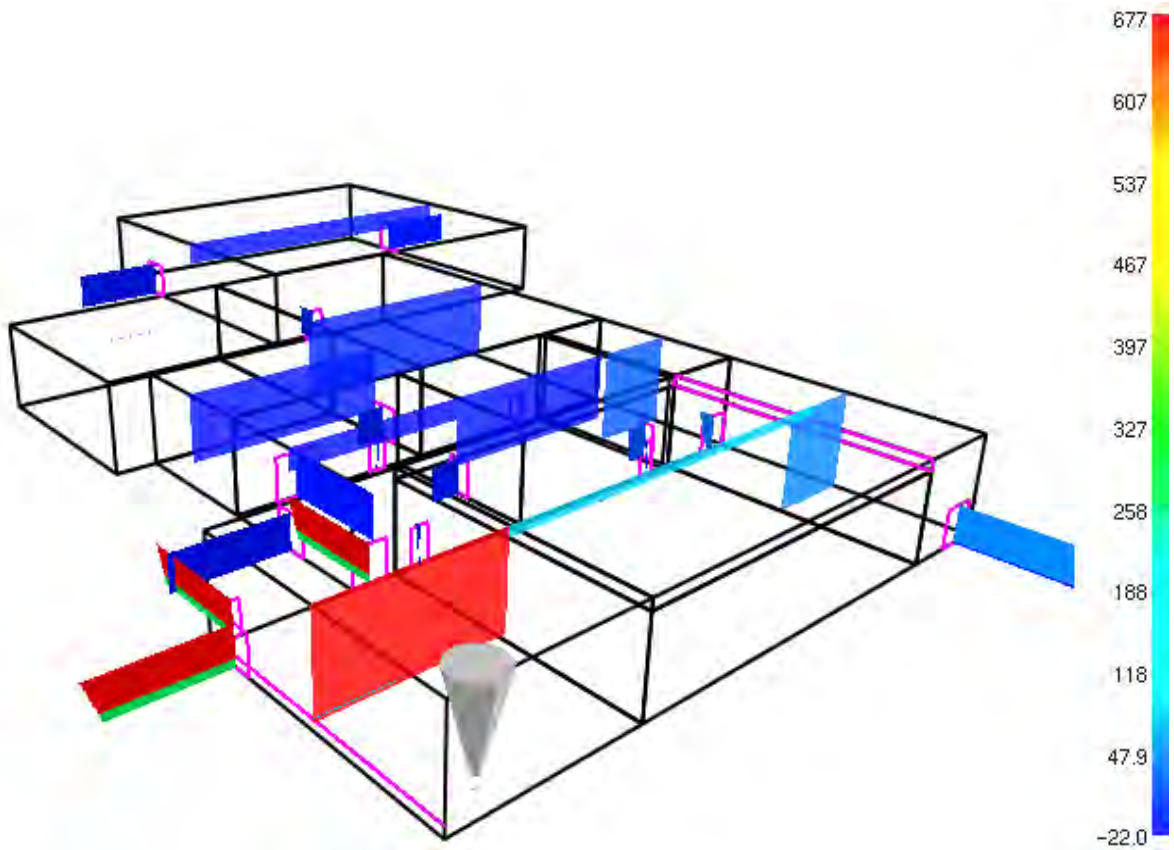
CFAST Fire Modeling Results

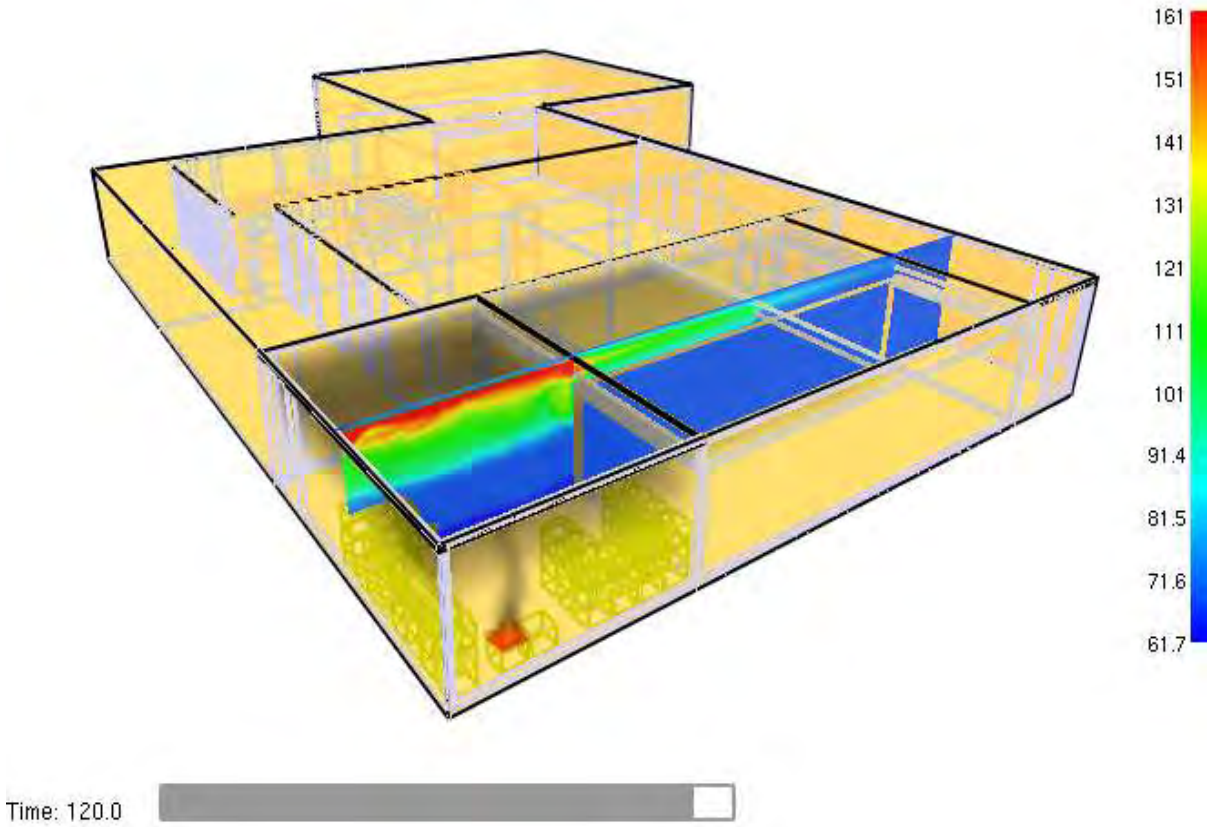


Fire Dynamics Simulator (FDS)



So, Does it Matter Which Fire Models?



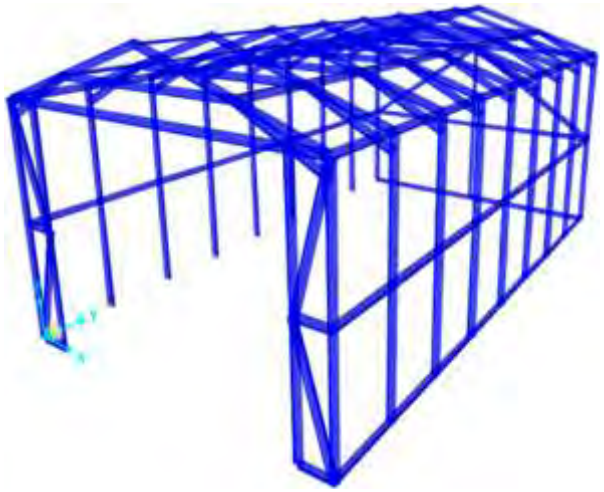


Present and Future Research Questions

- This research was started to provide the fire investigation industry with scientific validity relating to the use of deformations in origin determination and, in turn, investigative protocols for the use of this type of analysis.

<u>The research questions are</u>:

- 1. Can the magnitude of structural deflections be used to adequately support or discount an investigator's origin hypothesis?
- 2. If so, what are the appropriate protocols for the use of such an analysis technique?



Case Study: Modeling of Structural Collapse of Roofs to Prehistoric Structural Fires at Chevelon Pueblo

Reference: D J. Icove, H.E. Welborn, A.J. Vonarx, E.C. Adams, J.R. Lally, T.G. Huff. ***Scientific Investigation and Modeling of Prehistoric Structural Fires at Chevelon Pueblo***, International Symposium on Fire Investigation Science and Technology, Cincinnati, Ohio, June 26-28, 2006.

Overall Goal of Exercise

- Hypothesis Modeling of prehistoric structural fires at Chevelon Pueblo
  - CFAST Zone Model
  - FDS Field Model
- Comparison with test data
- Explore variations on fire source, heat release rate, and roof vent opening
- Explore tenability issues

Exploring Hypotheses

- Research testing and modeling concerned forensic fire science and archaeologists on the origin and cause of structural fires at prehistoric pueblos
- Hypotheses:
  - Accidental
  - Intentionally set during ritual abandonment
  - Fires related to conflict or warfare

Questions asked by Researchers

1. What are the physical dimensions of the compartment?
2. How was the structure used by inhabitants?
3. How was the structure ventilated? Were specific shafts open or closed at the time of the fire and how would changes in ventilation influence the fire's growth and behavior?
4. What is the expected fuel load of the compartment?
5. Are the observed thermal alterations consistent or inconsistent with the assumed use and expected fuel load of that room or compartment?
6. What signatures of fire origin and direction of spread exist, if any?
7. What competent sources of ignition were present?

Typical Structures

Live Fire Testing Results

- Adobe filled completely with brush and fire set
- Roof structure failed within 15 minutes

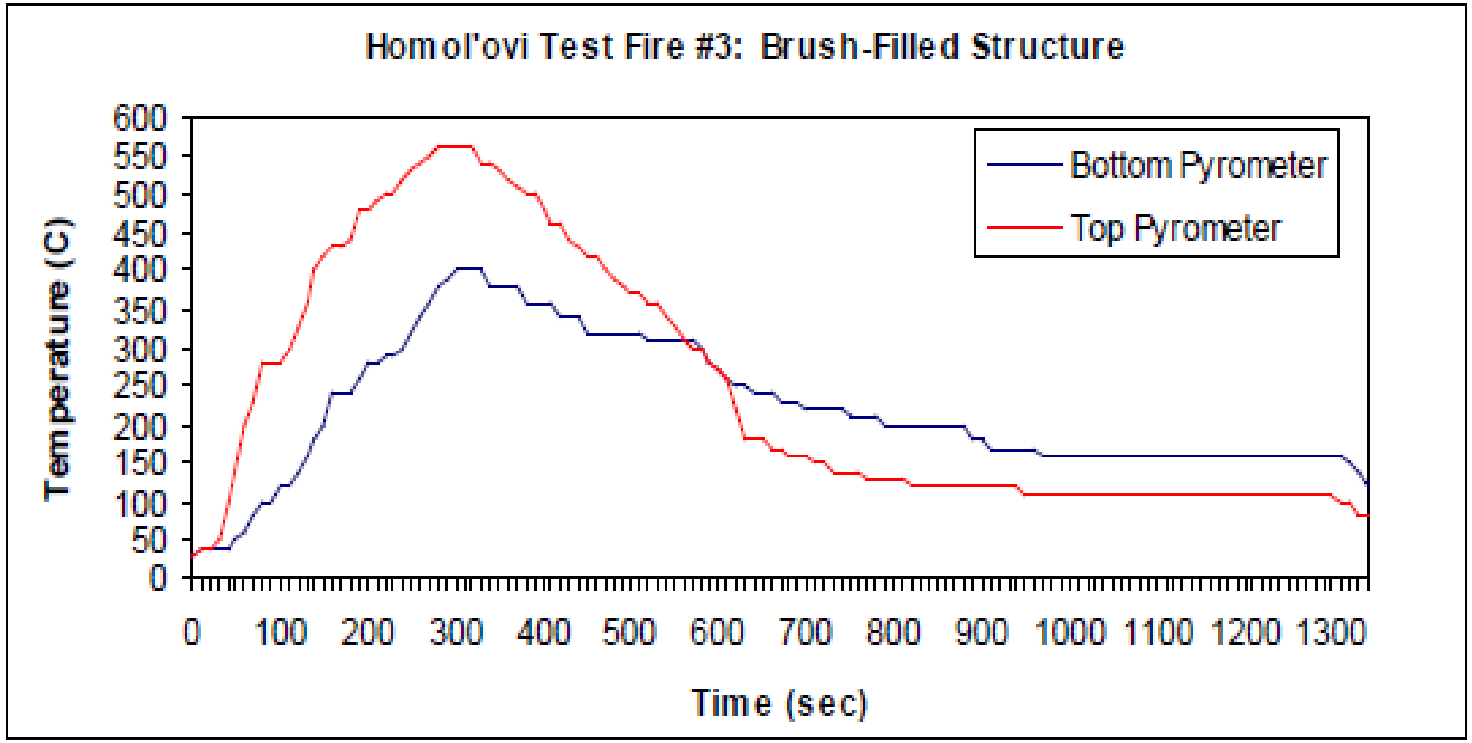
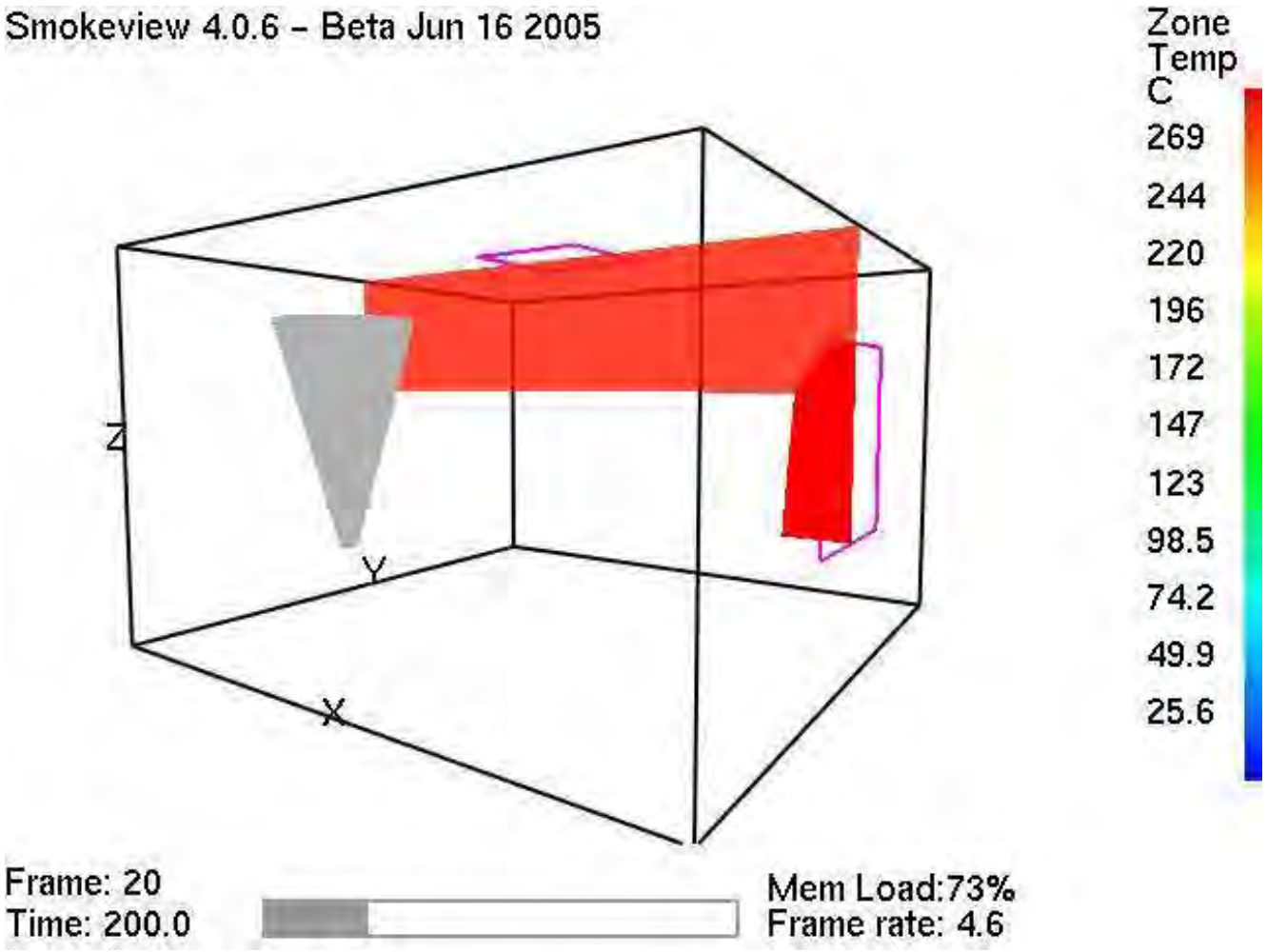
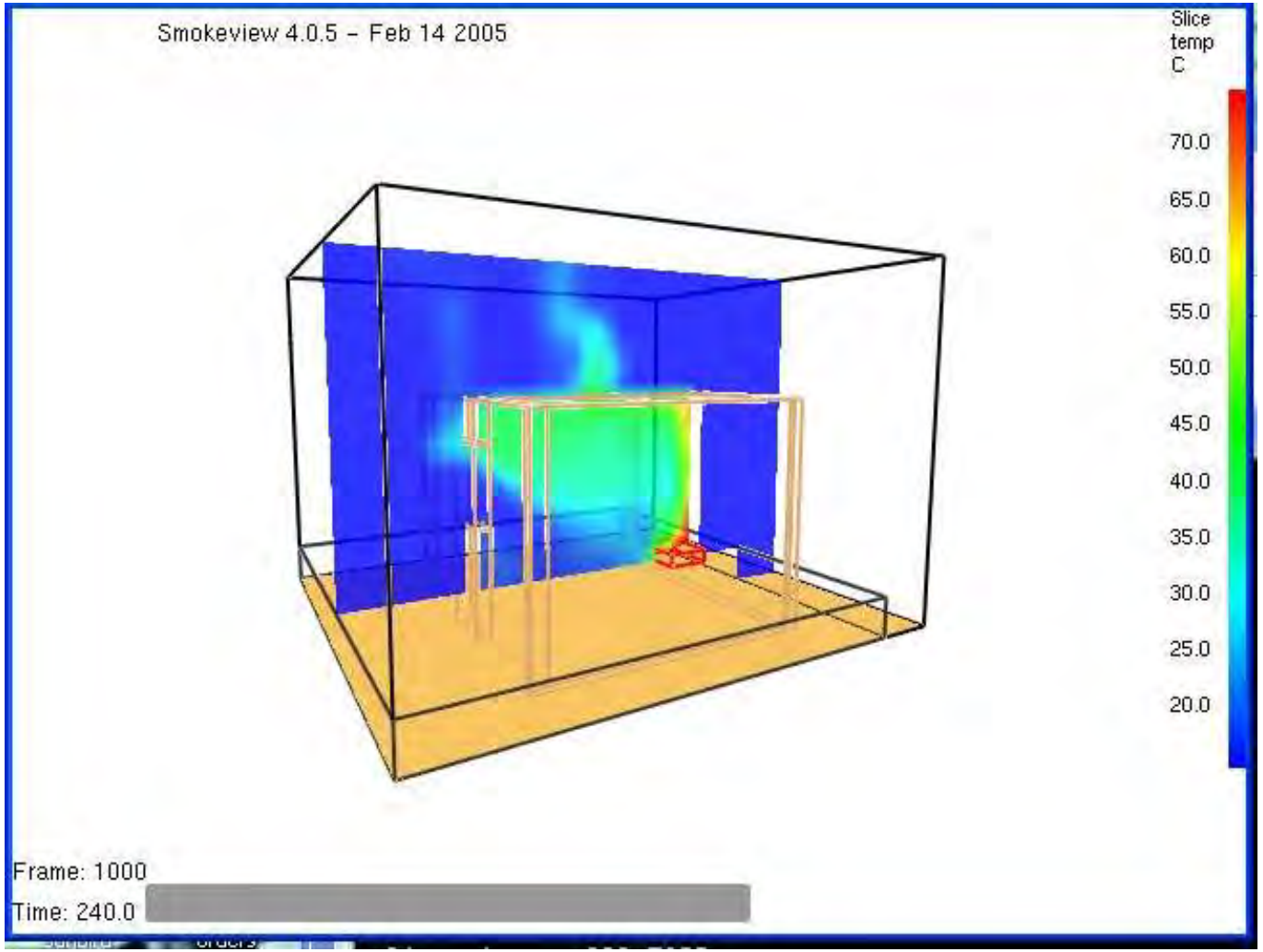


Figure 6. Time-Temperature Plot of Vonarx's third test fire in 2005.

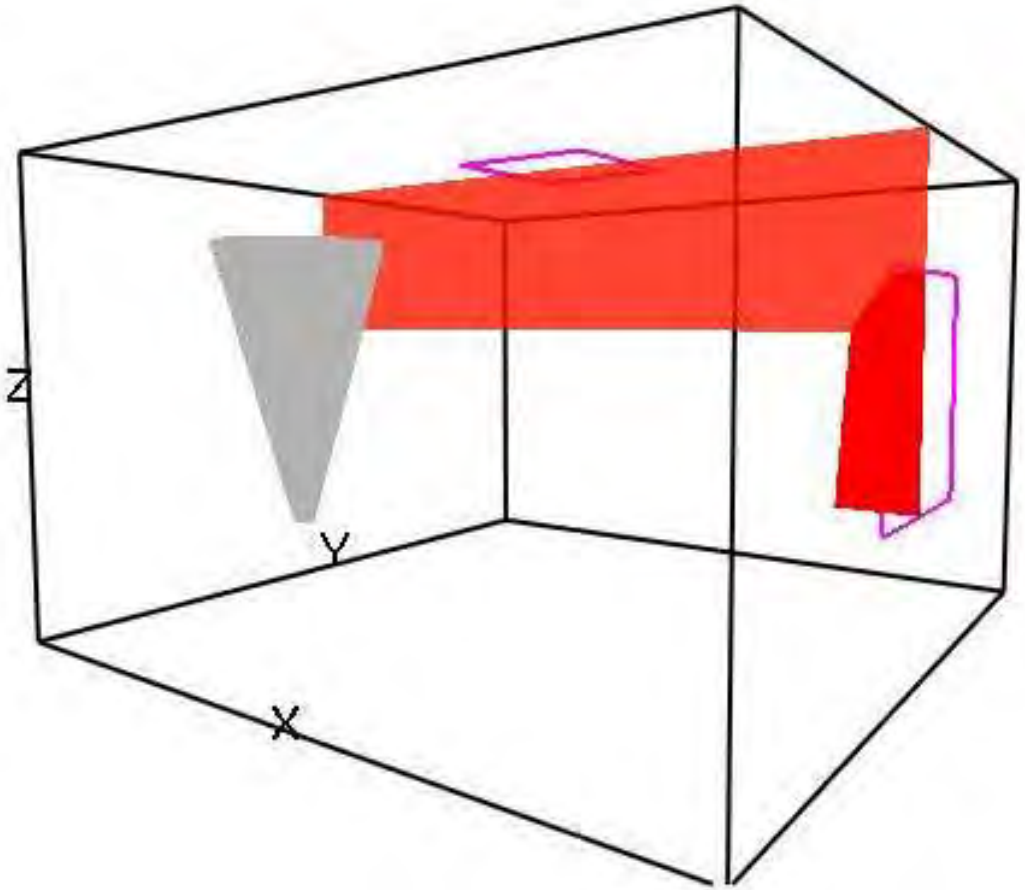
Fire Modeling - Zone

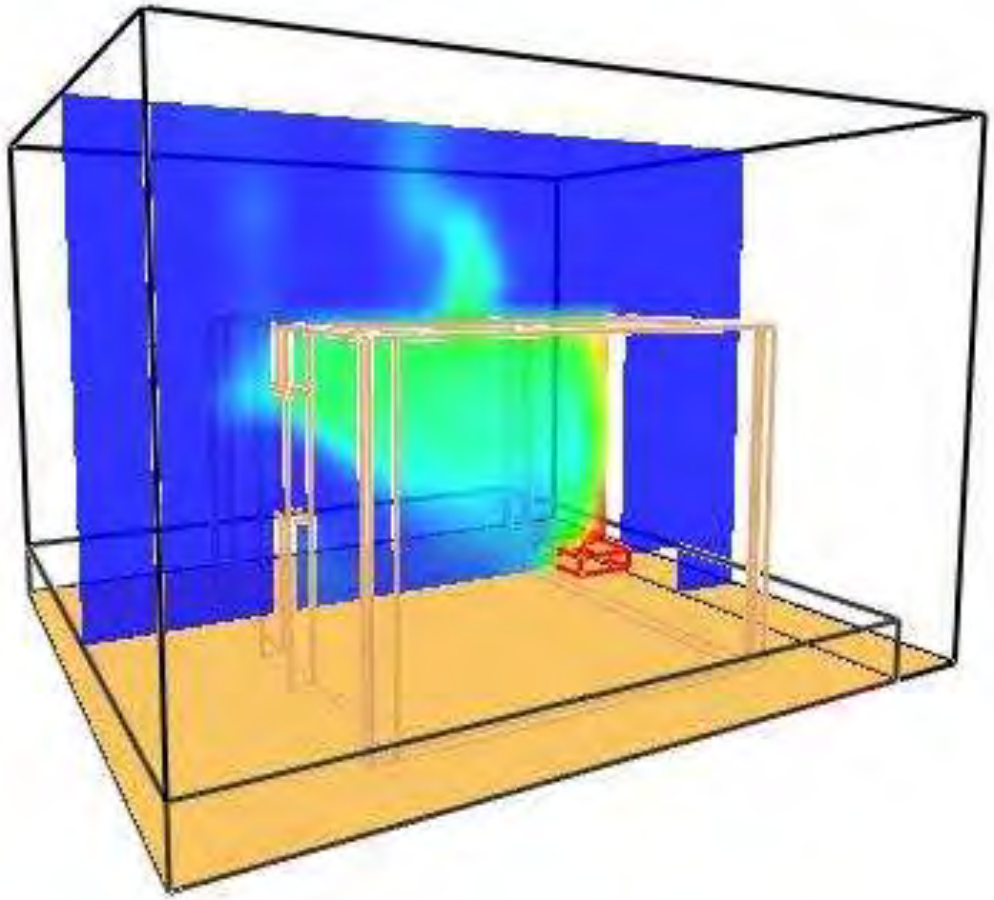


Fire Modeling - Field



Close Agreement with Zone and Field Fire Models





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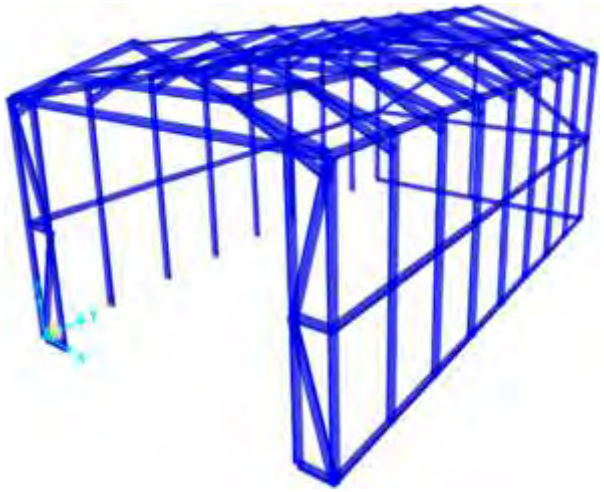

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