COMPUTER FIRE MODELS FOR FIRE INVESTIGATION AND RECONSTRUCTION

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ABSTRACT

Fire modeling can be separated into two broad categories, physical and mathematical fire modeling. Physical fire modeling has been around since the dawn of man and consists of burning objects to evaluate their effects. Study of fire phenomena by utilizing mathematics began in the early 1940's. Mathematical fire modeling can further be arranged into three categories based on the types of calculations performed, including: hand calculations, zone models, and computational fluid dynamics models. A general discussion of each type of modeling is presented in this paper. Computer fire modeling has been used to design and analyze fire protection systems (i.e. sprinkler systems, detection systems), evaluate the effects of fire on people and property, estimate fire risks, and assess postfire reconstruction. This paper focuses on the use of computer fire models for fire investigation purposes and provides a detailed discussion on the input data needed for fire modeling, available education and training, and its application in analyzing fire dynamics. Specifically, the use of computer fire models in validating or refuting an origin hypothesis by comparison of fire patterns was studied.

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HISTORY AND BASICS OF FIRE MODELING

Many in the fire profession would state that the use of mathematics and science as applied to fire-related dynamics began in the early 1940's (Nelson, 2002). As a result of this relatively recent application of math to fire dynamics, most scientists would call the profession/science young and relatively undeveloped. This paper proposes the opposite, that fire is one of the oldest and most studied phenomena of all. The first studies of fire began at the dawn of man when human beings started to develop insight and understanding of what materials could be used for fuel to continue combustion. Surely, cavemen did not quantitatively study the effects of the fuels (i.e. tree bark=100J of energy vs. wood log=50,000J). However, it is obvious that they recognized that dry, greater surface-to-mass fuels were easier to ignite and burned faster than did larger wet fuels. In fact, the study of fire is the basis for all other scientific disciplines. Faraday summarized this best when he discussed the phenomena of fire as it related to a candle burning:

> *"There is no more open door by which you can enter into the study of natural philosophy than by considering the physical phenomena of a candle. There is not a law under which any part of this universe is governed which does not come into play, and is not touched upon, in these phenomena"* (Faraday, 1861, p.1).

Therefore, one type of modeling that can be dated back to the dawn of man is the actual burning of fuels and examining their results. These studies are still being used today as the basis for the fire protection profession. Today standardized tests (i.e. ASTM D1230, D2859, E603) are utilized to illustrate the hazards associated with different fuels. The first major category of modeling fire dynamics is physical fire modeling, which is the testing and demonstration of fire given various fuels and scenarios. These types of tests and demonstrations fall within two broad categories, full-scale tests and small-scale tests. Full-scale tests are replications of a fire scenario by creating a structure or item with similar geometric dimensions and attempting to reproduce fire phenomena. Small-scale tests are replications of a fire scenario by creating a structure or item with a scaled-down geometric dimension and other variables when attempting to reproduce fire phenomena.

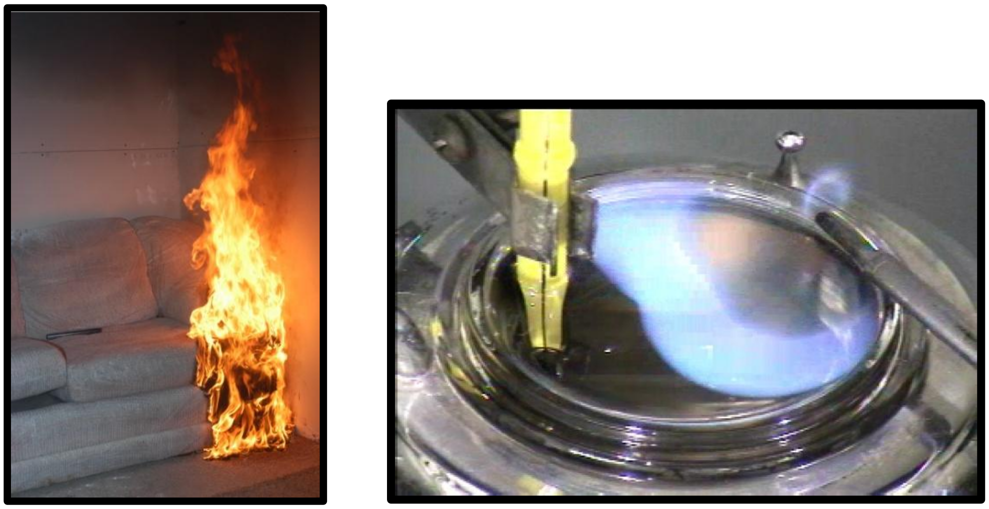

Figure 1: Examples of Physical Fire Modeling – Full-Scale Testing (left); Small-Scale Testing (right)

The physical models lend themselves to the beginning of mathematical models. Mathematical models are sets of mathematical equations that describe the behavior of a physical system (Beyler, et. al, 2008, 3-94). In other words, scientists would observe physical models and attempt to develop equations based on thermal science fundamentals in order to match the observed physical behavior. These mathematical equations range from simple algebraic equations used for predicting basic fire phenomena (i.e. flame height calculations) to complicated partial differential equations used for predicting enclosure fire phenomena. For purposes of this paper, mathematical fire models can be broken into three categories based on their use and level of precision and complexity, which include: hand calculations, zone models, and computational fluid dynamics (CFD), also known as field models.

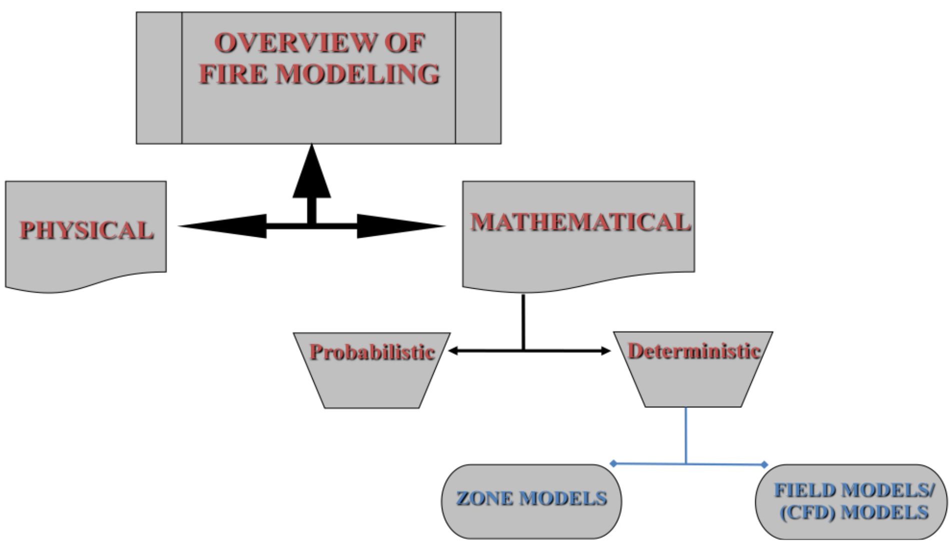

Figure 2: Illustration of the Types of Fire Modeling

TYPES OF MODELS

Basic hand calculations are typically algebraic equations developed principally on experimental correlations utilized to estimate the effects of simple fire phenomena for simple configurations. Even though these calculations are basic, they can often provide a reliable prediction of the fire phenomena. These can provide the user with a quick, *back of the envelope* calculation or estimate for the given scenario. In fact, the upper level mathematical equations found in the more advanced computer fire models (Zone and Field) are similarly based on these hand calculations and experimental correlations. These hand calculations are often implemented into spreadsheet software (e.g. Microsoft Excel) as a collection of calculations for ease of use and repetition. The most popular collection is known as Fire Dynamics Tools (FDTs) which was created and is still supported by the U.S. Nuclear Regulatory Commission.

$$Heskestad: \frac{Z_{0.5}}{D} = 3.7\dot{Q}_D^{*2/5} - 1.02$$

Where: Correlation is based on GENERAL fire in the OPEN

$$0.12 \angle \dot{Q}_D^{*} \angle 1.2x10^4$$

$$D = \text{Area Equivalent} = \frac{\pi D^2}{4} = \text{area of fire source}$$

Figure 3: Heskestad Flame Height Correlation - Example of Basic Hand Calculation

The transition from basic hand calculations to the more-advanced computer software for fire modeling started in 1975 (Nelson, 2002). Zone fire models are a type of computer software utilized for evaluating enclosure fire dynamics. The more common Zone fire models separate the compartment into two zones, commonly referred to as the upper and lower zones or layers. These zones are based on the physics and dynamics of fire inside of an enclosure, which include the fire plume, combustion products and air entrainment. The fire plume and resulting collection of hot gases and combustion products would form one zone, typically referred to as the upper zone (upper layer). The ambient air and entrained air outline the other zone, typically referred to as the lower zone (lower layer). The interface between the two zones constantly changes height based on the increasing collection of hot gases in the upper layer, which subsequently descends the upper layer. Zone models, from a mathematical standpoint, are therefore considered to be separated into two separate control volumes, with the upper zone considered as a control volume that receives both mass and energy from the fire and loses energy by convection or mass movement of gases through openings, by radiation to the floor, and to the surfaces in contact with the upper zone by conduction and radiation.

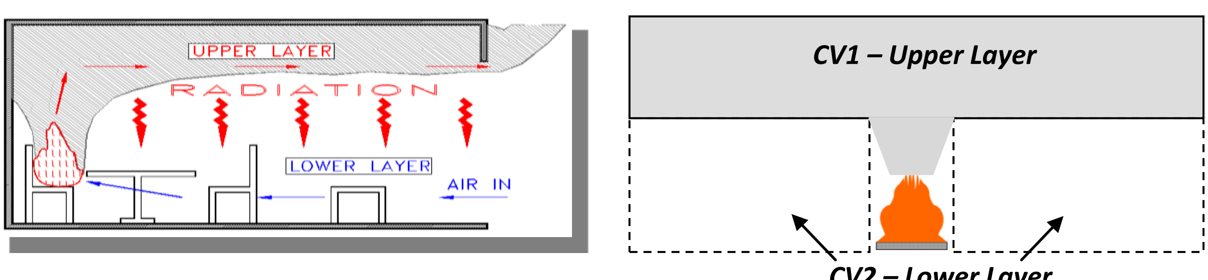

Figure 4: Schematic of Upper and Lower Layer Separation (left); Schematic of Control Volumes and Calculation Principles for Zone Models (right)

The last type of mathematical computer fire model referenced in this paper is the computational fluid dynamics (CFD) model, also known as field models. Field models separate a compartment into hundreds to thousands of tiny cubes or calculation cells based on user inputs. Field models are more calculation intensive than their zone model counterparts. These models calculate each cell using higher level mathematics to specifically relate energy transfer and flow of fluids to each other. The basic laws of mass, momentum, and energy conservation are applied in each cell and balanced with all adjacent cells.

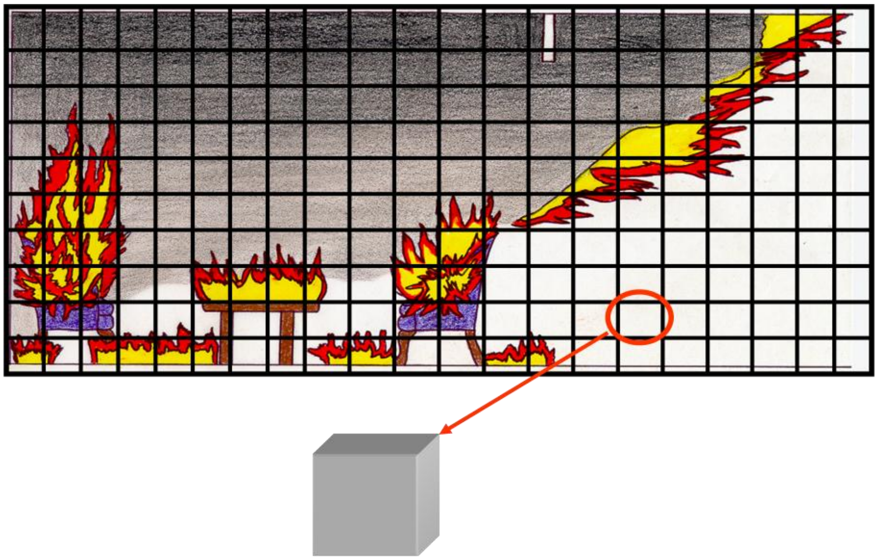

Figure 5: Computational Fluid Dynamics (CFD) or Field Model - Illustration of Computational Cells

Three of the more common fire models utilized today include: Consolidated Model of Fire Growth and Smoke Transport (CFAST), Fire Dynamics Simulator (FDS), and Building Research Association of New Zealand fire (BRANZfire). CFAST was created and released in the early 1980's by NIST (2005b). NIST continues to support this model and just recently released the 6.0.10 version. FDS was officially released in 2000 and is another model that was created and still supported by NIST (2008). Currently, FDS is up to its fifth version. BRANZfire was created and released in 1997 by the Building Research Association of New Zealand (2003).

USE, VALIDATION & VERIFICATION

Since 1975, computer fire modeling has been increasing in its application to solving fire dynamics problems. The primary focus of modeling is to provide mathematical and scientific research into the behavior and problems associated with fire. Since the inception of computer fire models, numerous governmental, university and private laboratories have been assisting with the progression and development of the models to better ensure that the mathematical equations reliably represent real-world fire behavior. Some of these laboratories include: United States National Institute of Standards and Technology (Building and Fire Research Lab), United States Nuclear Regulatory Commission, Sandia National Laboratory, United Kingdom Building Research Establishment (Centre for Fire Safety Engineering), Building and Research Association of New Zealand (BRANZ), Harvard University, University of California-Berkeley, University of Maryland, Worcester Polytechnic Institute, Lund University (Sweeden), and University of Edinburgh.

Computer fire models have many applications, including: design and analysis of fire protection systems (i.e. sprinkler systems, detection systems), evaluation of the effects of fire on people and property, postfire reconstruction and fire risk assessment (Wood, et. al, 2008, 3-112). There is currently widespread use of modeling in the design and evaluation of fire safety of buildings and facilities. Their use is currently being implemented into several United States national building codes and fire safety standards, including: NFPA 1 *Uniform Fire Code*, NFPA 72 *National Fire Alarm Code*, NFPA 101 *Life Safety Code*, NFPA 921 *The Guide for Fire and Explosion Investigations*, NFPA 5000 *Building Construction and Safety Code* and several others (NFPA, 2007). Most notably, the United States Nuclear Regulatory Commission is regularly using computer fire models to assist in their design of enclosures for maximum fire safety protection (NRC, 2006). Postfire reconstruction or fire investigation has also seen an increase in the use of computer fire models. Most notably, the United States government in their analysis of both the World Trade Center fire and the Station Nightclub fire that occurred in West Warrick, Rhode Island utilized FDS and CFAST in evaluating the reason for the spread, behavior, and impact of the fire. NIST was charged with the analysis of both of these national tragedies, as well as many other tragedies around the United States, to evaluate the reasons for the behavior of fire by implementation of computer fire modeling (NIST, 2005a & 2007).

Since the inception of the first computer fire model, hundreds of peer-reviewed technical publications and articles have been written regarding the use, methodology, validity, and reliability of computer fire models. Several textbooks and chapters have been written regarding the use of computer fire models, including: *An Introduction to Mathematical Fire Modeling* (Janssens, 2000); Chapter 3.5 *Introduction to Fire Modeling* and Chapter 3.6 *Applying Models to Fire Protection Engineering Problems and Fire Investigations* published in the Fire Protection Handbook (NFPA, 2008); Chapter 3-5 *Computer Fire Modeling*, Chapter 3-7 *Zone Computer Fire Models for Enclosures*, and Chapter 3-8 *Modeling Enclosure Fires Using CFD* published in the Society of Fire Protection Engineers' Handbook of Fire Protection Engineering (SFPE, 2002). Additionally, there have been several American Society for Testing and Materials' standards that have been produced which standardize the documentation, use and methodology for computer fire models, including: ASTM E603 *Standard Guide for Room Fire Experiments;* ASTM E1355 *Standard Guide for Evaluating the Predictive Capability of Deterministic Fire Models*; ASTM E1472 *Standard Guide for Documenting Computer Software for Fire Models;* ASTM E1591 *Standard Guide for Obtaining Data for Deterministic Fire Models*; and ASTM E1895 *Standard Guide for Determining Uses and Limitations of Deterministic Fire Models*. Each model, in compliance with ASTM E1472, comes with a User's Guide and Technical Reference Manual as well, which provide further explanation and guidance in the use, validation, verification, and reliability of the specific model (NIST, 2005b & 2008; BRANZ, 2003).

Many of the organizations that develop models continue to support these models by performing validation and verification studies. NIST constantly reviews, validates and verifies these models by comparing real-world fire experiments to the data produced from the model. This assists in ensuring the reliability of the models and their application to fire problems. Additionally, a community of model users has been organized to provide consistent feedback to the model creators regarding any issue with the models. NIST also reviews and cooperates with independent researchers to utilize their data from experimental tests within the model. BRANZ, similar to NIST, performs full-scale experiments that are used to continuously validate the mathematical equations contained within the BRANZfire model.

Most recently, the United States Nuclear Regulatory Commission (NRC) has written a 2000+ page series of validation and verification manuals on their analysis of various computer fire models, including CFAST and FDS (NRC, 2006). The objective of this project was to examine the predictive capabilities of selected fire models. NRC ran a series of full-scale laboratory burn tests and ran the data through the various computer fire models. They were specifically analyzing each model's capability and reliability to reproduce the results from the live fire tests. Both CFAST and FDS in specific applications were well validated and verified.

USE FOR INVESTIGATIONS

NFPA 921, The Guide for Fire and Explosion Investigations requires fire investigators to follow a systematic approach in their analysis of the origin, cause and responsibility of a fire. The scientific method has been put forward as this systematic approach. One of the primary steps in the scientific method is to test the hypothesis. Computer fire modeling is a scientifically and generally accepted method to test a hypothesis. Its primary use falls within the testing of one's hypothesis in the scientific method as it pertains to understanding the fire, timeline analysis, occupant survivability, fuels analysis, and analyzing post-fire indicators.

- ***Understanding the fire:*** Computer fire modeling can assist an investigator in understanding how a fire may have evolved. More specifically, computer fire modeling will assist by assessing the relationship of the heat release rate of the burning fuel with other variables (i.e. CO production, radiant ignition). Complex scenarios allow for multiple runs to be performed with a range of ventilation variables, which provides the user with a range of outcomes to analyze their effects. Also provided by the models is the ability to calculate the minimum energy required for a compartment to transition through flashover, as well as the timing issues for flashover and full-room involvement. Modeling may assist in evaluating sufficiency of fuels for flashover and damage that exists after the fire due to the heat flux from a burning object.
- ***Timeline Analysis***: The model can provide a range of timing issues that may assist in understanding eyewitness accounts, the progression of the fire in relationship to other variables, survivability of occupants, possibility of egress, comparison of injuries to fire development, activation and interaction of fire protection elements, and evaluating ignition and time to ignition issues. The use of computer fire models in a timeline analysis will provide an objective analysis to analyze the progression of events.

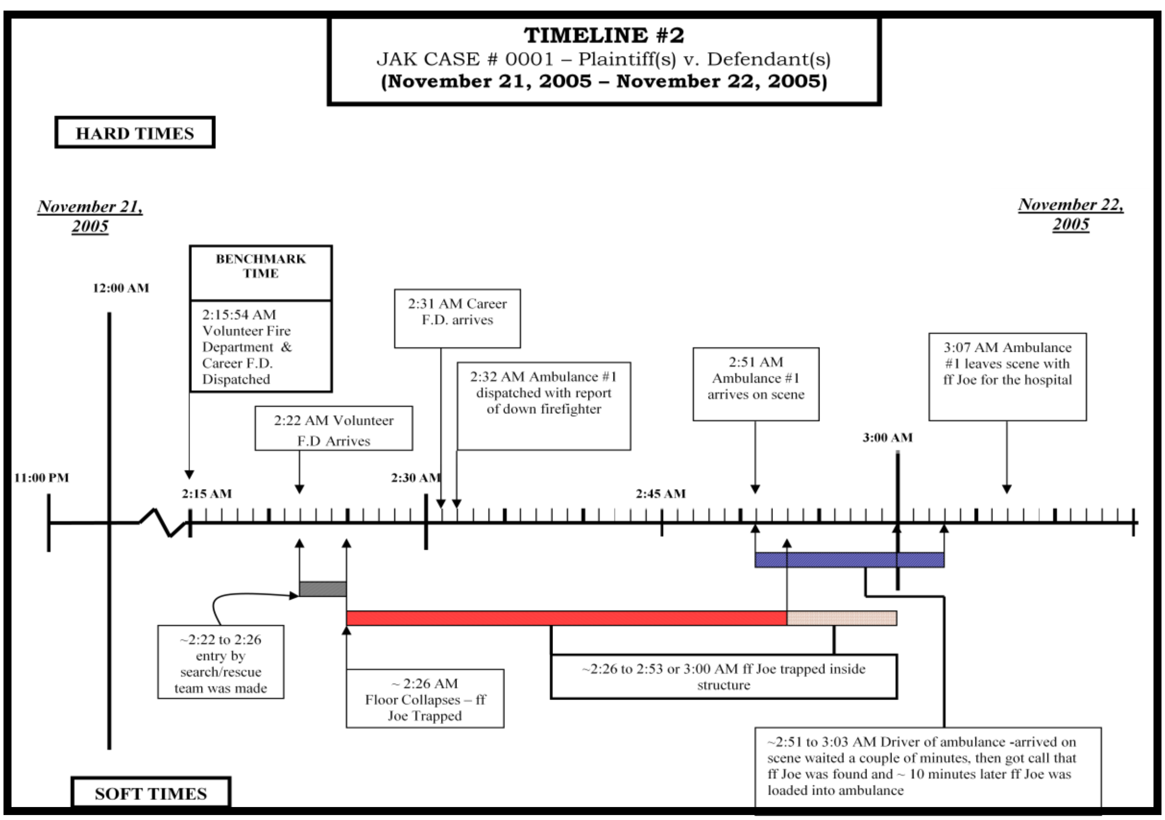

Figure 6: Sample Timeline with Range of Computer Fire Modeling Soft Times

- ***Survivability Analysis:*** People are affected adversely from several different by-products of fire, including: temperature, toxic gases, heat and flame, and visibility reduction. These different by-products have tenability limits and can be analyzed with a computer fire model. Investigators can utilize these models to assist with their analysis of egress and escape issues.
- ***Analyzing Post-Fire Indicators:*** Investigators can utilize computer fire models to compare the post-fire damage or physical evidence to the results of the various models. Many of the models can provide insight into the transfer of heat and the subsequent effects of this transfer on materials. More discussion on this topic is presented later in this paper.

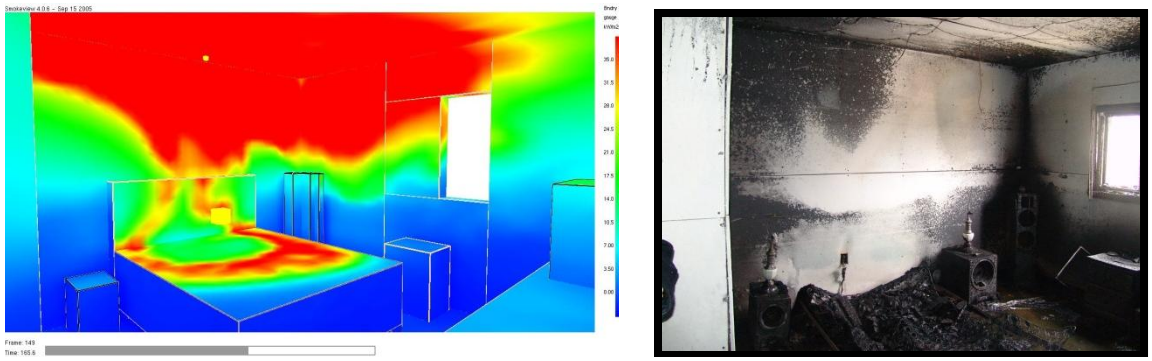

Figure 7: Analyzing Fire Patterns with Computer Fire Modeling Compared to Post-Fire Patterns

- ***Visualization of Fire Phenomena*** – A feature of some of these models is to transfer the mathematical output into three-dimensional computer graphics. FDS and CFAST have companion animation software that will provide an animation of the fire that can be utilized to visualize fire phenomena.
- ***Multiple Hypotheses*** – Computer fire modeling is at the heart of the scientific method. Computer fire models may provide an objective means of testing one's hypothesis. It allows an investigator to test their hypothesis or other's hypotheses for validation or refutation. An example of how to test one's origin hypothesis is provided near the end of this paper.
- An investigator is cautioned when utilizing any of the models for the above purposes to ensure that the models are appropriately chosen and used within their limitations and assumptions.

Computer fire modeling should be utilized as a *tool* in an investigators' analysis of a fire. The use of computer fire modeling for fire investigations is usually an easier task than for design engineering, because there is always other information available such as eyewitness accounts, forensic evidence, fire department reports, etc. A computer fire model in this case is most often used to supplement the other information in demonstrating that a particular hypothesis is or is not plausible.

The accepted and peer-reviewed methodology for using computer fire models is to provide a range of variables to evaluate both the sensitivity of the model and ensure that the variables that are not specifically known are accounted for within the series of models (SFPE, 2002; NFPA, 2008). The use of modeling for fire investigation and reconstruction must follow a similar methodology. The user must input a range of variables based on the scenario, the collected data, and the probable hypotheses. This variation of the input variables will affect the output or outcomes of the model and provide the user a range to utilize in their analysis. If the data collected, probable hypotheses, and/or fire scenarios are too great, then the output will also typically be too vast to provide any valuable assistance with the investigators' analysis.

INPUT DATA NEEDED FOR MODELING

Computer fire modeling is steadily increasing in use for fire investigations and analysis. Typically, fire investigators at the time of performing an on-scene investigation do not realize that a computer fire model will assist at a later point. Therefore, every on-scene investigation should require that investigators obtain the data required for modeling. For this reason, this paper provides the general input data needed for computer fire modeling that must be obtained at the scene.

1. ***Structural dimensions*** – The first and most important aspect of recreating a scenario in computer fire models is to start with an accurate scene diagram. This is more than the typical two-dimensional plan view diagram that most investigators are used to performing. The investigator needs to create a three-dimensional diagram, including the geometry, soffit, sill, heights, widths, etc.. (Figure 8). Additionally, the investigator needs to obtain the locations of furniture and other fuel packages, as well as thicknesses and heights of those pieces of furniture.

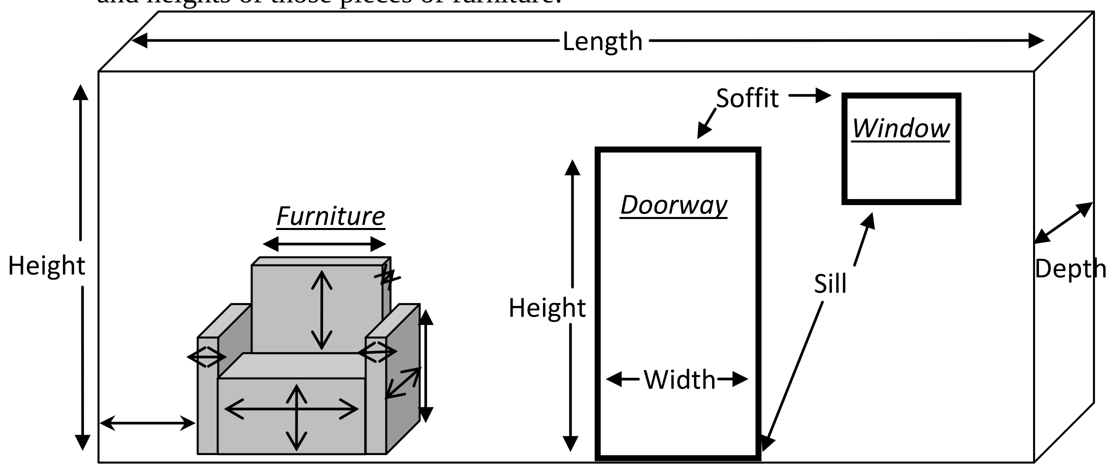

Figure 8: Schematic illustrating needed dimensions for computer fire modeling

2. ***Lining Materials*** – In enclosure fire dynamics, the materials lining the walls, ceiling and floor will play an important role in the transferring of energy out of the compartment. Therefore, investigators need to accurately determine the type of materials (i.e. carpet, gypsum wallboard) and the thickness of those lining materials. It is recommended that investigators collect and preserve samples of these lining materials.
3. ***Fuels and Fire Growth*** – One of the most important variables input into a computer fire model are the types of fuels and their properties. The user of the model will need to input the heat release rate per unit area of the primary and secondary fuels. Additionally, the computer model will require a fire growth rate (HRR over time) to be input. Therefore, the more information regarding the type of fuel, the properties of fuel, size, orientation, and location within the compartment the less error involved in implementing this variable into the computer fire model. Additionally, it is recommended that investigators collect and preserve samples of the fuels for further analysis.
4. ***Ventilation*** – As part of the diagramming section, the investigator will need to locate and document all of the ventilation openings, including heights, widths, soffit, and sill. These include windows, doorways, HVAC, and other mechanical ventilation issues (PPV). The investigator will need to determine the positioning of these ventilation openings (i.e. open/closed, on/off). For any mechanical ventilation the investigator will need to determine the volume and temperature of the air for those vents.
5. ***Fire Protection Elements*** – The investigator will need to locate any and all fire protection elements on their diagram, including heights. One of the biggest problems with fire protection elements is the inaccurate placement of these devices, especially smoke alarms. The investigator can utilize this information in conjunction with computer

fire modeling to evaluate a properly placed fire protection element versus the improperly placed element. Additionally, locating automatic sprinklers may be used for the evaluation of suppression and extinguishment issues.

6. ***Changes during the fire*** – Investigators will also need to determine if and what changes occurred during the progression of the fire and when these changes occurred. This may become very important if changes to the ventilation were done during the progression of the fire. This can often times be obtained through witness interviews and physical evidence.
7. ***Photographic Survey*** – The investigator needs to perform a photographic survey of the scene to capture other elements that may not be preserved on the diagram. Additionally, the photographs will become paramount in analyzing the post-fire indicators.

AVAILABLE TRAINING AND EDUCATION

There are two types of knowledge transfer available for the investigator to obtain additional information regarding computer fire modeling. The two transfers can either be through education or training. Available education includes:

- *Seneca College*-1 semester course solely on Fire Dynamics Simulator and Smokeview.
- *University of Maryland*-1 semester Fire Modeling at the undergraduate level and 1 semester Advanced Computer Fire Modeling Master's level course
- *Worcester Polytechnic Institute*-1 semester Computer Fire Modeling Master's level course

Available training includes:

- *National Fire Academy*-2 week course on Fire Dynamics and Modeling
- *Society of Fire Protection Engineers (SFPE)*-3 day Basic & Advanced FDS course
- *National Association of Fire Investigators (NAFI/NFPA)*–1 day Computer Fire Modeling for Fire Investigations

TESTING OF AN ORIGIN HYPOTHESIS WITH COMPUTER FIRE MODELS

One of the primary uses of modeling is to test one's hypothesis. Hypotheses are developed not only for the cause of a fire, but also and more importantly they are developed for the area of origin (NFPA 921, 2008). The origin hypothesis is more important because the area of origin must first be determined before a cause can properly be evaluated (NFPA 921, 2008). Fire patterns have historically been and continue to be the primary tool used by investigators in determining an area of origin. Use of computer fire modeling is proving to be a tool in validating and/or refuting one's origin hypothesis based on the resulting fire patterns that remain after a fire and the boundary heat flux values calculated within the model when testing different areas of origin and fuel packages. This specific application can be implemented when running a field model that calculates boundary heat fluxes and has a companion animation program, similar to FDS/Smokeview.

Computer fire models are being utilized in conjunction with the Full-Scale Burn Patterns Study that is on-going at Eastern Kentucky University in cooperation with the National Association of Fire Investigators (Gorbett,et al., 2006; Hopkins, et al., 2007; Hicks, et al., 2006). To date, there have been 10 full-scale research burns performed to analyze fire patterns reproducibility and persistence through flashover. Each full-scale test was outfitted with instrumentation, including thermocouples and radiometers. To ensure validation and verification of the models, each have been evaluated against the experimental test results (temperature and heat flux). The first six research burns finalized in March 2006 were intended to analyze reproducibility given similar fuel packages, orientation, and similar origin (i.e. center head of mattress). The last two research burns completed in March 2007 were to evaluate an origin in a small (low heat release rate) fuel package (i.e. night stand) near a larger fuel package (i.e. mattress, high heat release rate) to analyze if the larger fuel package's resulting damage would obscure patterns that would assist in determining an accurate area of origin (Hopkins, 2008).

March 2006 Full-Scale Burn Pattern Study: Origin = Head of Mattress

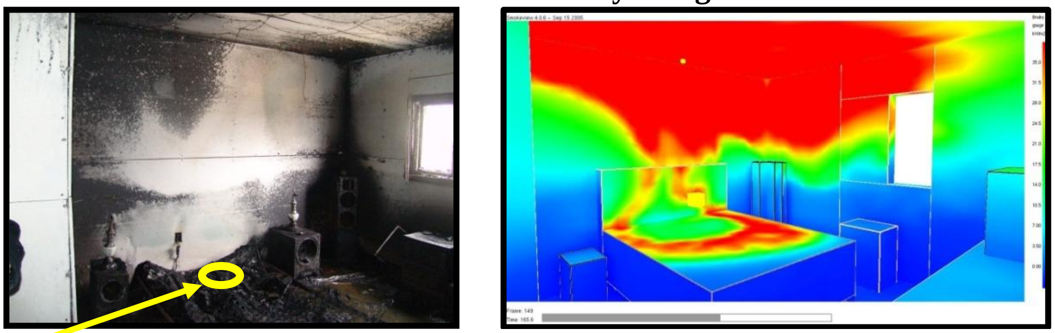

Figure 9: East Wall Actual Damage (left) versus FDS Heat Flux Damage (right)

Origin

March 2007 Full-Scale Burn Pattern Study: Origin = Night Stand

Figure 10: East Wall Actual Damage Cell 1 (left), Cell 2 (middle) versus FDS Heat Flux Calculation (right)

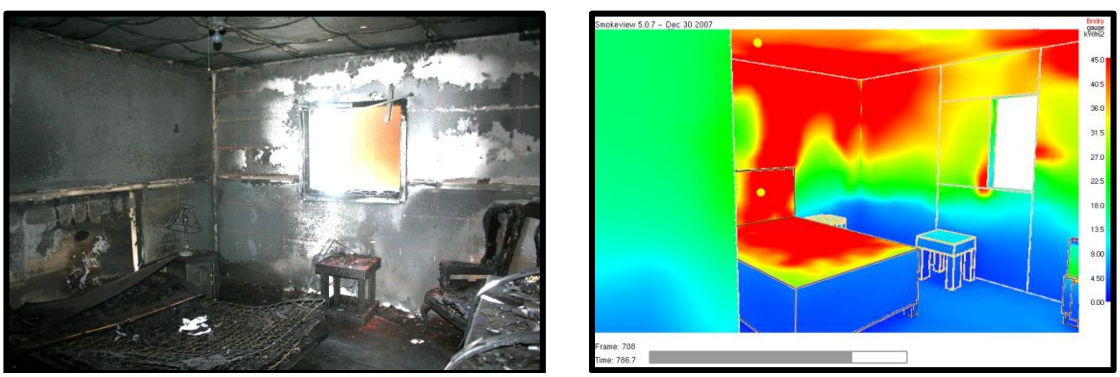

Figure 11: South Wall Actual Damage (left) versus FDS Heat Flux Calculation (right)

The creation of lines of demarcation has been related to the exposure of a witness surface to varying heat flux intensities (Hopkins, et al., 2007). Figure 9 illustrates an example of the resulting *actual* damage from the patterns research burn test compared to a FDS/Smokeview heat flux calculation. These tests were performed with the origin of the fire at the head of the mattress. The resulting *actual* damage reveals the effects of the upper layer, flame plume, and ventilation generated patterns. The calculated heat flux shown by FDS/Smokeview, demonstrated by a color difference (i.e. darker the color, the higher the calculated heat flux), can be considered anticipated damage calculated by the model. It is evident that the FDS/Smokeview heat flux calculation (anticipated damage) was consistent with the *actual* damage.

Figures 10-11 illustrates the actual damage that resulted from the March 2007 test burns compared to the FDS/Smokeview heat flux calculations. This test was performed with the origin of the fire located in the nightstand next to the mattress. The resulting *actual* damage reveals the effects of the upper layer, flame plumes, and ventilation generated patterns. The resulting damage from the initial flame plume (nightstand burning) is present in these burns. Therein, validating the use of patterns for determining an area of origin starting in a smaller fuel package and transferring to a larger fuel package. Additionally, the FDS/Smokeview heat flux calculation (anticipated damage calculated by the model) provides a similar intensity of damage located at the nightstand, which is consistent with the *actual* damage. This intense pattern was not present at smaller surrounding objects in the previous studies. Therefore, it is apparent that FDS/Smokeview can be utilized as a tool in testing an area of origin hypothesis.

CONCLUSIONS

Due to the recent increase in the use of computer fire models for fire investigations, it is imperative that all investigators are aware of the models' capabilities, assumptions, appropriate uses, and limitations. Currently it is an underutilized tool in the fire investigation and analysis profession. Not every case will warrant the use of this tool during an investigators' analysis, but all investigators need to begin collecting the data required at the scene to ensure that if the need arises they have adequately collected the important data. As an analogy, not many investigators can use a GC/MS, but most are aware of the appropriate collection and preservation methods to ensure that samples can be sent into the laboratory for fire debris analysis. The same methodology and knowledge should be passed onto those investigators in the field. The use of modeling should be supported by the investigation community, but should also be constantly monitored to ensure its proper and objective use.

The appropriate uses for computer fire modeling as it relates to investigations include: testing of one's hypothesis, understanding the fire, survivability of occupants, timeline analysis, and validating or refuting post-fire damage. It is not appropriate for someone to utilize a computer fire model to prove causation. Computer fire models will never replace a good on-scene investigation. Investigators need to be very concerned with those that believe that they can perform an investigation by sitting at a computer. It is important for all investigators to remember that computer fire models should be used as a tool to supplement an investigator's on-scene investigation and analysis.

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