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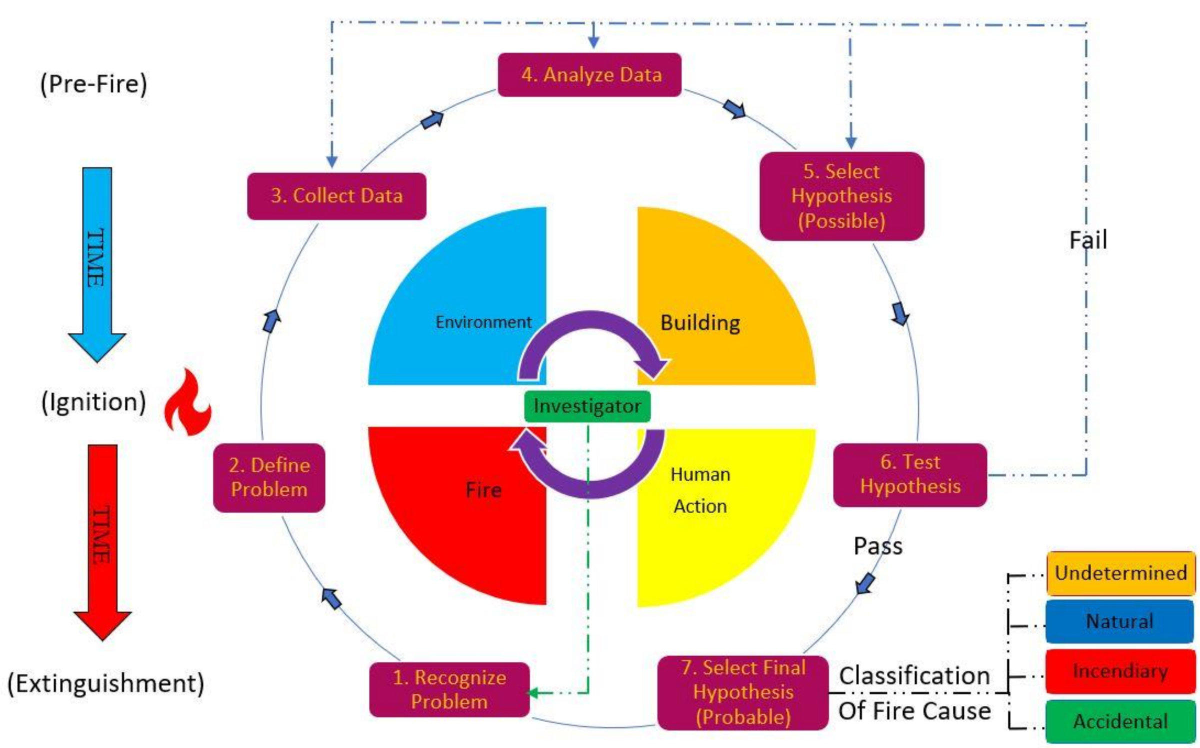
By: Joseph M. Ellington, CFI

The forensic analysis of a fire involves the credible evaluation of information about the environment, the building and its contents, the fire, and elements of human interaction that together as a system, shape and influence the development of a fire over time and determine its outcome. As an observer and participant in this system, the investigator plays a crucial role in the process. Data is often unknown or incomplete and elements of human interaction that influence changes in the environment are frequently ambiguous or contradictory.

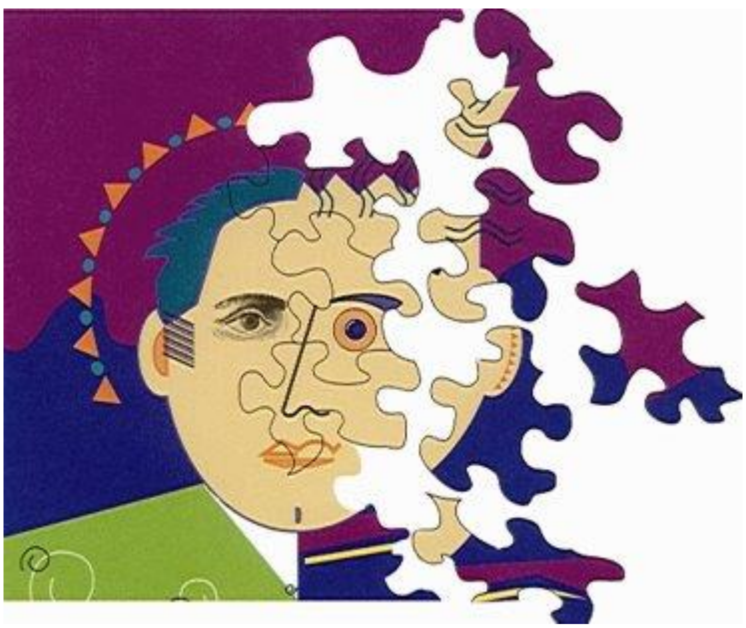
The systems approach is not a new concept and is based on the premise that breaking down a complex concept into simple easy to understand units helps in better understanding its complexity. The approach concentrates on the holistic entity of the system without neglecting its components and attempts to understand the role of each component while simultaneously understanding the activity of the whole system. The figure below visually describes the systems approach and its application to fire investigation.

A Systems Approach to Fire Investigation



In the past, fire investigation was described as an art[1] and emphasis was placed on the skill and experience of the investigator rather than on sound methodology and knowledge grounded in a systematic and scientific approach. The final outcome of an investigation depended largely on witness descriptions and the experience, often perceived rather than actual, of the investigator. Fire dynamics analysis and modeling have evolved as tools for investigating fire related issues fueled by demands for a systematic and scientific approach to investigations rather than reliance on an experienced based one.

While the investigator may have difficulty articulating the process, the concept(s) of performing a fire dynamics analysis or applying a model is not new to fire investigation. During processing and documenting a fire scene, the investigator is, in fact, performing a fire dynamics analysis by constructing an abstract model of the fire and mentally applying a body of knowledge and principles accumulated through education, training, and experience.



The investigator's model is conceptual, an internal abstraction or mental image of a system that seldom involves actual quantitative analysis or mathematical calculations, but rather is the sum of what the investigator has learned, been taught, or internalized through experience concerning what is normal or abnormal about the basic interaction of fire with structures and materials (i.e. fire dynamics[2]).

[1] The Science & Art of Fire Investigation – Firepoint Magazine – Journal of Australian Fire Investigators – Sept. 1998, by Tony Café - Art is about creativity and fire investigators are not at fire scenes to ponder creativity but are there to physically find and interpret the evidence which will indicate the cause of the fire. Fire investigators who believe in art are often found at the fire scene, or worse in court, talking about the fire as if they were actually present during the fire. They are using their imagination rather than the part of their brain which controls logic and reasoning.

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[2] **NFPA 921 - 3.3.70** - Fire Dynamics is the detailed study of how chemistry, fire science, and the engineering disciplines of fluid mechanics and heat transfer interact to influence fire behavior.

While processing the scene, the investigators actually engage in a form of perceptual shorthand better described as *more than mere intuition but less than a full-blown analysis*, comparing their observations against this conceptual model with respect to key elements of fire phenomena, ignition, heat transfer, combustion, and materials response, noting similarities and differences. The investigator's conclusions are *shaped* by the thoroughness of his or her procedures, powers of observation, and depth of analytical reasoning. The *validity* of the investigator's internal conceptual model, however, ultimately determines whether the conclusions are right or wrong.

If the knowledge, training and experience that underlies the fire investigator's conceptual fire dynamics model is valid (i.e. based on sound principles), the process systematic, the methodology sound, the logic reasonable, and attention to detail, the conclusions will be accurate. Otherwise, the fabric of the conclusions will begin to unravel when subjected to the reasonable examination of others. A way of demonstrating the accuracy and reliability of the investigator's conclusions is by performing a forensic (i.e. formal) fire dynamics analysis and documenting that the guidelines and procedures recommended by NFPA 921 – Guide for Fire & Explosion Investigations, were applied in reaching them[3].

NFPA 921 recognizes fire dynamics analysis and modeling as methods available to assist the investigator in the analysis of a fire. NFPA 1033 – Standard for Professional Qualifications for Fire Investigator requires the investigator to have and maintain an up-to-date basic knowledge of fire dynamics.

The goal of both a fire investigation and a fire dynamics analysis are an output that accurately represents a <u>model</u> of the fire event being investigated <u>within identifiable and acceptable limits of error</u>. Despite its inclusion in NFPA 921, both fire investigators and the courts have been relatively slow to accept fire modeling either as a reliable tool or uniformly and routinely apply its methodology <u>in the investigative process</u>. Reasons for this include their difficulty in learning and applying the methodology, a lack of understanding with respect to its limitations, and misuse and misapplication of its procedures. The reluctance is particularly interesting in light of the almost universal application and acceptance of other methods of determining the origin and cause of fires (e.g. interpretation of burn patterns, arc mapping, etc.) whose error rates are difficult to confirm or quantify.

Fire models cannot <u>directly</u> predict where a fire originated or identify its source of ignition because their input is defined by the user. For this reason, fire models are referred to as *Deterministic.* Model results,

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[3] **NFPA 921 - 1.3 Application** These procedures represent the judgment developed from the NFPA consensus process system that if followed can improve the probability of reaching sound conclusions.

however, can be compared to physical and eye-witness descriptions to support or refute a hypothesis or identify an alternative hypothesis that more appropriately fits existing data. Coupled with reconstruction of the fire scene, however, a forensic fire dynamics analysis using a fire model can be a valuable resource to evaluate hypotheses concerning the fire.

Importantly, a fire model cannot replace a fire investigation or repair an otherwise flawed investigation. It can, however, make a significant difference in the outcome of an investigation by clarifying issues that were not considered or fully investigated during the initial investigation or establish the justification and economic basis for decisions to expend resources and money toward additional investigation. In the courtroom, a fire model can help clarify and help visualize the complex processes underlying a fire that are relevant to establishing a basis for resolving contested fire related issues involving property damage and injuries or death resulting from a fire.

Examples of fire related issues are (1) the timing, performance and impact of the operation or non-operation of fire detection, alarm, and protection systems or components (2) the contribution of the building's geometry and design, its construction materials, and its contents with respect to flame spread and smoke propagation (3) tenability conditions over the course of a fire including time to flashover, gas temperatures, gas species concentrations (O2, CO, CO2,) flow rates of smoke, gases and unburned fuel, and temperatures of walls, ceilings, and floor with respect to ASET[4] (Available Safe Egress Time) and (4) the impact of human activities with respect to the fire's development (e.g. doors and windows opening or closing, fire department response and fire ground operations. The figure below[5] from NFPA 921 is an example of the detail that might be examined through application of a fire model.

[4] **Available Safe Egress Time** (ASET) in enclosure fires is defined as the time between fire detection and the onset of conditions which are hazardous to continued human occupancy.

[5] **NFPA 921 - FIGURE 5.6.3.1(c)** Actual Temperature Measurements from a Test Fire That Became Underventilated and Then Became Ventilated by the Opening of the Door

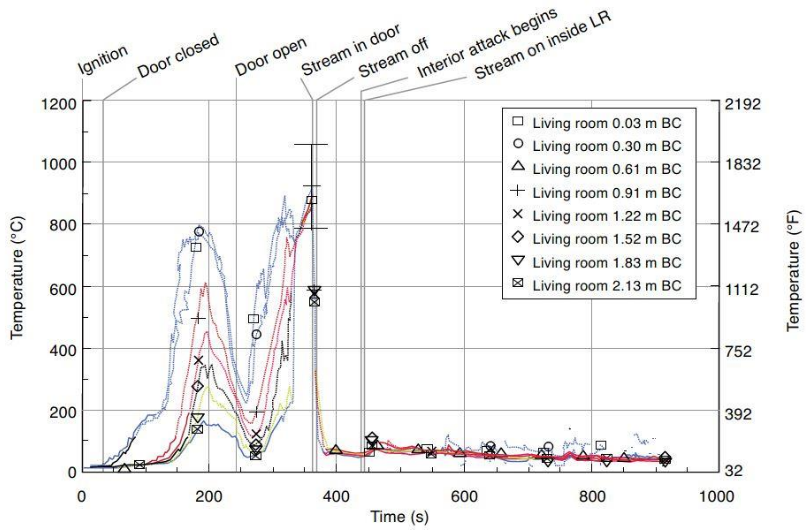

FIGURE 5.6.3.1(c) Actual Temperature Measurements from a Test Fire That Became Underventilated and Then Became Ventilated by the Opening of the Door.

Crucial to understanding fire models and how they function is an understanding of what a model fundamentally is. A model is simply an idealized version of a physical system too complex to analyze easily or in full without simplification. If, for example, we attempt to analyze the motion of a baseball thrown through the air we find it quite complicated. The ball is neither spherical nor perfectly rigid. It has raised seams and spins as it moves through the air. Wind and air resistance influence its motion. The ball rotates and so does the earth beneath it. The balls weight varies a little as its distance from the center of the earth changes and so on.

If we try to include all of these small things the analysis gets pretty tangled. Instead we invent a simplified version of the problem We neglect the size and shape of the ball representing it as a point. We neglect air resistance and make the ball move in a vacuum. We also ignore the earth's rotation and make the weight exactly constant. Mathematically, the ball is in essence a particle moving along a parabolic path. With these simplifications we have a problem simple enough to deal with but still meaningful and reasonably accurate with respect to predicting the balls' path once it is thrown. These same principles can be applied to bullets, artillery shells and nuclear warheads to deliver them with accuracy.

Like the motion of a baseball with its perceived simplicity, fire investigation is a complex endeavor and requires an understanding of materials and processes that take place within an environment of numerous and difficult to predict variables that require simplification before the problem can be reasonably approached. Similar to the problem of predicting the baseball's motion, the goal of fire modeling is to uncover laws governing the behavior of fire, to reduce and express these in mathematical terms, and to visualize the results in a model. Out of intense complexities, intense simplicities emerge! [6]

A criticism that is often leveled with respect to fire models is that they are animations that simulate a fire and do not represent the actual fire. The criticism fails to differentiate between an animation and a simulation or consider that fact that although technically all models are wrong some are useful [7]. An animation is not linked to predictive data but programmed by a person with knowledge of the event who explains what is being presented. Conversely, a simulation has far more science involved, requiring expert testimony with respect to its underlying basis. The witness will have to explain how the simulation was created.

Unlike an animation, a model simulates a real-world system and allows the user to manipulate variables to observe or study the resulting changes. Importantly, the user can ask 'what if' questions with respect to variables that either cannot be controlled in a real system, or the time and expense are unrealistic.

Fire models are mathematical and can be a single equation, a procedure (i.e. group or collection of equations), or a full-scale model. The user's choice of an individual equation, procedure, or full-scale model depends upon the issues to be examined, the degree of preciseness required, the level of detail needed and, importantly, the capability of the person applying these procedures. All may be applied in a sequential manner as a basis for input in the next step in the process of analysis.

Single Equation Models

Scientifically sound equations and other empirically derived engineering relationships exist that permit reasonably quantitative approximations of the development of hazardous conditions (e.g. temperature, smoke, toxic products) from fire in a single room or several rooms. Simplified equations (basic hand calculations) are typically algebraic equations developed principally from experimental correlations and designed to solve a single, narrowly focused question. These equations may provide rough but reliable predictions relating to fire phenomena without the use of a full-scale model.

Typically, single equations require much less data for input to run than a full-scale fire model and may be performed on a hand calculator. A reference source for equations related to basic fire science, fire

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[6] Winston Churchill

[7] In 1976, a British statistician named George Box wrote the famous line, "All models are wrong, some are useful."

dynamics, hazard calculations, design calculations, and fire risk analysis is the SFPE (Society of Fire Protection Engineers) Handbook of Fire Protection Engineering.

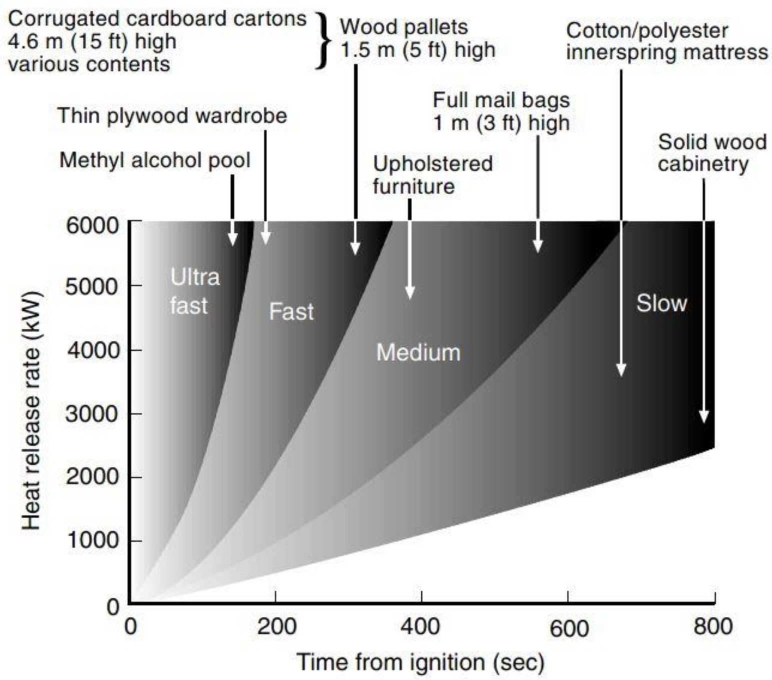
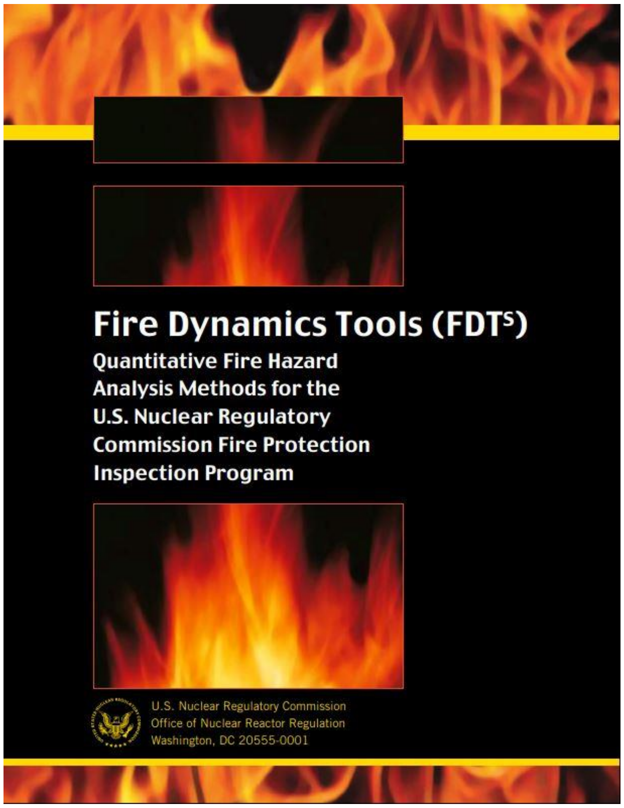


FIGURE 3.7.2 Set of *t*-Squared Growth Curves

An example of a single equation model is where the energy release rate for growing fires in solid fuels is characterized by a relationship where the fire grows as a function of the square of time, expressed as $Q\ (t) = \alpha t^2$. Within the equation Q = Heat release rate at a given time (kW), α = Fire growth constant (kW/sec^2) , t = Time. The equation gives rise to a set of specific t-squared fires labeled slow, medium, fast, and ultrafast with fire intensity coefficients such that the fires reach 1000 Btu/sec in 600, 300, 150, and 75 seconds and were proposed for the design of fire detection systems.

<u>Procedures</u>

A procedure is a group of equations incorporated into a single application. The procedures used are based on sound physics or established <u>correlations</u>. Simplicity, applicability, and computation speed have been emphasized with some sacrifice of mathematical rigor. Procedures are useful in performing first-order approximations, rather than exactly predict, fire conditions. Users often have limited experience with computers, fire dynamics, and fire modeling. Procedures are a good choice for quick calculations to ‘frame problems” that do not require a high level of accuracy and detail. They can be used as a basis for decisions to continue the inquiry or investigation or use more complex models.



Fire Dynamics Tools[8] developed by the U.S. Nuclear Regulatory Commission Fire Protection Inspection Program incorporate equations into Excel spreadsheets. The spreadsheets and supporting documentation are useful to assist in quantitative fire hazard analysis.

Full-Scale Models

Full-scale models primarily use quantitative data and arithmetic expressions manipulated by a computer to describe the processes that go on during a fire. More complex models use multiple equations that must all be solved simultaneously using numerical methods. This requires a computer, as well as the ability to describe the structure and its contents on a three-dimensional grid and manipulation of large quantities of complex data with accuracy and speed.

The underlying basis for most computer fire models is the room or enclosure fire that most fire investigators have the greatest experience and familiarity with and are based on the impact of important and complex, interdependent relationships between the mass burning rate, the rate of heat release, and the available air (i.e. oxygen) on the course and development of the fire.

CFAST (Consolidated Model of Fire and Smoke Transport)

[8] Fire Dynamics Tools (FDTs) Quantitative Fire Hazard Analysis Methods for the U.S. Nuclear Regulatory Commission Fire Protection Inspection Program (NUREG-1805 Volumes 1 & 2)

CFAST, developed by NIST (National Institute of Standards & Technology), is perhaps the best-known model. CFAST is a multi-room, two-zone fire model used to calculate and predict the evolving distribution of smoke, fire gases and temperature throughout compartments of a building during a user specified fire.

CFAST simplifies an enclosure fire by idealizing the compartment as consisting of two regions: An upper layer filled with hot combustion gases and a lower layer filled with essentially cool air. Each layer is assumed (i.e. simplification) to have uniform temperatures. The gas concentrations and the interface dividing the layers moves vertically during a fire. Eventually the mass and energy flowing out of doors or windows is lost from the room. If, however, it flows into another space, it becomes the source of the fire problem in that space. Zone models view an enclosure fire much like a bathtub that can only hold so much water before spilling over. These simplifications allow the fire modeling problem to be tractable, but at the same time, produce meaningful results. Comparison of zone model results show reasonable, but not exact, correlation with experimental results.

FDS (Fire Dynamics Simulator)

FDS[9], a more complex fire modeling program, was also developed by NIST, is based on CFD[10] (Computational Fluid Dynamics.) Unlike CFAST, that divides the space into two distinct layers, FDS divides the fire space, referred to as a computational domain, into many small cells defined by the user.

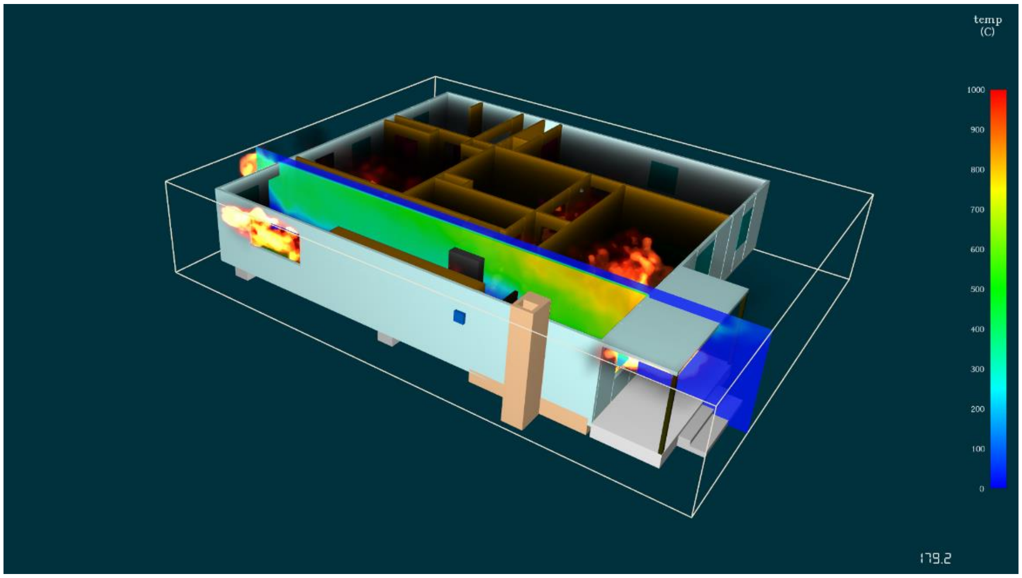
FDS calculates temperature, pressure, species concentration, and flow field in relationship to a prescribed fire in much greater detail than a zone model can. FDS requires vastly more raw computing power, memory, and faster processors. FDS requires more time to set up and run and a higher level of expertise to make the decisions required in setting up the problem and interpreting the results.

FDS, and other CFD (computational fluid dynamics) models, are better suited to situations where space or fuel configuration is irregular, turbulence is a critical element, finer detail is sought, and the hardware and software computing power are available. The model is particularly suited for tracking the movement of

[9] FDS is a Fortran program that reads input parameters from a text file, computes a numerical solution to the governing equations, and writes user-specified output data to files. Smokeview is a companion program that reads FDS output files and produces animations on the computer screen. Smokeview has a simple menu-driven interface, while FDS does not. However, there are various third-party programs that have been developed to generate the text file containing the input parameters needed by FDS.

[10] Computational fluid dynamics (CFD) is a branch of fluid mechanics that uses numerical analysis and data structures to analyze and solve problems that involve fluid flows. numerical solution techniques for the above system of coupled partial **differential** equations

hot gases and smoke. FDS can also be used to track the movement and concentration of fugitive gases (e.g. propane and natural gas leaks) not associated with combustion.



Fire, smoke, and temperatures conditions predicted by FDS during a residential fire at 179.2 seconds after ignition.

Application

The choice and application of a particular model is dependent on the questions to be answered and the issues to be examined. The input data requirement of fire models is more extensive than what many fire investigators gather at a fire scene. Greater attention must be paid to detail during the initial scene investigation to identify, document, and preserve the required raw data required for the model's input. Necessary data includes information about the fire, the building and its contents and systems, the environment, and human activities (witnesses, occupants, first responders) related to the fire's ignition, development, and extinguishment.

Once the data needed for the analysis and to build the model is compiled, the geometry and computational domain is constructed, a fire scenario (i.e. user specified fire) is defined either by entering the thermo-physical properties of each of the fuels and allowing the model to attempt to calculate and predict a fire growth rate or a user defined heat release rate based on a standardized t-squared fire curve. A source of ignition and its location is defined by the user. The location of the ignition source usually coincides with the point of the fire's origin as identified by witness description or determined by the fire investigator.

The user typically specifies and defines "virtual devices" and places them in the model to monitor, record (thermocouples, heat and smoke detectors, sprinkler heads, etc.) and/or to control objects (doors, windows, etc.) based on the state of that device or human activity (the actions of occupants or others).

The model is run, and the results of its calculations stored as raw numerical data in various output files. During this process, CFAST and FDS allow the user to monitor and view the model's progress without interrupting the model and, if needed, make corrections to errors that may not have been obvious when constructing it. When complete, the raw data files can also be imported into a spreadsheet and the data analyzed and graphed to better visualize and interpret its significance. A post-processor application such as Smokeview[11] may be used to open and view the fire's development from the perspective of an observer from any vantage point and at any point in time over the course of the fire.

When interpreting the results of a model's analysis, users should consider the following: Was the data arbitrary or are they correct for the scenario in question? What default values the model inserts if data is not available and what difference these values make with respect to the model's output? What assumptions were made to fill in the gaps? What is the model's error rate with respect to the issue(s) being examined? A sensitivity analysis[12] should be performed with respect to the variables under examination.

The accuracy with which FDS predicts temperatures and heat release rates has been validated with large-scale tests and has been used to reconstruct a number of large, well known fires. FDS temperature predictions are generally within 15% of the measured temperatures, and heat release rates are within 20% of measured values. Model results are often presented as 'ranges' to account for uncertainty.

The error rate associated with modeling fire spread is potentially higher, sensitive to both numerical and physical input parameters, and requires a higher level of user knowledge and judgment with regard to combustion and fire dynamics. When used for this purpose, the user must have an understanding of basic fire science within the context of the fire scene being examined and the development and testing of hypothesis regarding the origin and cause of fires.

[11] SMV (Smokeview) – A visualization program that is used to display the output of FDS and CFAST simulations.

[12] Sensitivity analysis - The study of how the uncertainty in the output of a mathematical model or system (numerical or otherwise) can be divided and allocated to different sources of uncertainty in its inputs.

If properly applied, a forensics fire dynamics analysis and model can assist the investigator in examining issues and testing hypotheses with respect to a fire’s origin, cause, and responsibility and improve the probability of reaching sound conclusions; the stated purpose of NFPA 921.