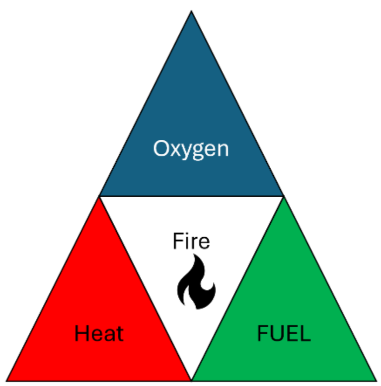
Fire Modeling - A Tool in Fire Death Investigation

Introduction

A case study in fire modeling is presented to demonstrate how a fire model is applied to a fire investigation involving injury and death to simulate an actual fire in the real world and arrive at a solution. The study consists of a fire that occurred in a residence and resulted in the deaths of two occupants. The study highlights the importance of constructing the model, running the simulation, and interpreting the results correctly according to NFPA 921. The goal of the case study is to assess whether a properly installed and operating smoke alarm could have detected the fire early enough to save the lives of the occupants who perished

The 2024 edition of NFPA 921—Guide for Fire and Explosion Investigations [1] requires that an investigator's opinions and conclusions stand the *reasonable examination of others* and that a *reasonable fire investigation certainly* is achieved when investigators have properly applied all of the steps of the scientific method to reach a unique and reliable final hypothesis. [1] The term *Scientific Method* [2] refers to the principles and procedures used for the systematic pursuit of knowledge.



Contrary to many fire investigators' belief, fire modeling is familiar to fire investigation. While processing a scene, for example, a fire investigator performs an *informal* fire dynamic analysis, whether articulating it or not, by applying knowledge and principles accumulated through education, training, and experience. The investigation of fire has moved from a simplistic approach based on the fire triangle [3] and understanding fire from *first principles.* [4], to one of anayzing fire using a systems approach.

Figure 1- The Fire Triangle

[1] NFPA 921 – Section 4.5.2 – Fire Investigation Certainty - Fire investigators achieve reasonable fire investigation certainty when they have properly applied all of the steps of the scientific method to reach a unique and reliable final hypothesis.
[2] NFPA 921 – Section 3.3.171 Scientific Method**.** The systematic pursuit of knowledge involves the recognition and definition of a problem; the collection of data through observation and experimentation; analysis of the data; the formulation, evaluation, and testing of hypotheses; and, where possible, the selection of a final hypothesis.
[3] Fire Triangle – A simple model that explains the necessary ingredients of most fires and graphically illustrates the three criteria required for a fire. That is fuel, heat, and an oxidant (e.g., usually atmospheric oxygen.)
[4] First principles – A first principle is a basis proposition or assumption that cannot be deduced from any other proposition or assumption.

The *systems approach* [5] is the forensic analysis of a fire that involves evaluating information about the environment, the building, the fire, and the elements of human interaction that, together as a system, shape and influence the fire over time and determine its impact and outcome.

Even if an investigator never uses modeling, there is an ever-increasing probability that an investigator's opinions and findings will eventually be evaluated against a modeling analysis. Models force investigators to conduct a *formal* fire dynamics analysis and demonstrate what facts and evidence were relied on to reach their conclusion(s), define their uncertainty, and, therefore, how accurate they are. Whether simplified models (e.g., single equations performed by hand calculations) or full-scale computer fire models are used, modeling has inherent limitations and assumptions that should be considered.

In the example presented in this article, tenability data is extracted from the output of FDS (Fire Dynamics Simulator), and an analysis is plotted as a timeline against important benchmark events gleaned during the fire investigation. ISO 13571:2012 [6] Life-threatening components of fire — Guidelines for Estimating Time to Compromised Tenability in Fires [2] and the SFPE Guide to Human Behavior [7] [3] estimate when individuals can experience compromised tenability during a fire.

Of significant interest is the fire's ignition, when the fire was discovered, the time of sprinkler or smoke alarm activation, the time the fire department received the alarm, the time the fire department arrived, and the time the fire department began the fire ground operations. By default, FDS assumes that the smoke from a fire is generated in direct proportion to the heat release rate. FDS does not explicitly track smoke; smoke is a function of the combustion products. In summary, FDS combines fluid transport modeling, empirical data validation, and smoke detector lag corrections to estimate smoke detector activation during fires.

A timeline comparison of actual events against when predicted threshold tenability conditions were exceeded (e.g., ASET/RSET [8])[4] is a powerful tool for visualizing and reinforcing whether an occupant who perished in a fire could have escaped within the available safe egress time predicted by the analysis.

For survivability considerations, ASET (Available Safe Egress Time) is considered a 'worst-case' scenario for a building. Concerning an individual's life and death, ASET is determined by tenability (i.e., the fire and its effluents) but is influenced by the individual and environment. *Simply put, ASET is the time needed to survive and is driven by fire.*

---

[5] Systems Approach—Forensic Fire Dynamics Analysis & Fie Modeling, Jan 2020, Fire & Arson Investigator, Journal of the International Arson Association, Joseph M. Ellington, Pages 18—23,

[6] ISO 13571 – Life-threatening components of fire – Guidance for estimating time to compromised tenability in fires.

[7] SFPE – Society of Fire Protection Engineers

[8] ASET/RSET – A Standard fire safety engineering tool that focuses on the comparison of two critical parameters during a fire incident.

RSET (Required Safe Egress Time) is the time needed to evacuate from a building or structure. It is driven by human behavior if not heavily influenced. Evacuation models sometimes predict whether an individual can evacuate in time. Fire models aim to determine if ASET is greater than RSET plus a safety factor. The main reason for a safety factor is to account for uncertainty.

The Guidelines for Substantiating a Fire Model for a Given Application (2010), published by the Society of Fire Protection Engineers (SFPE), provides valuable insights into evaluating and selecting fire models for specific fire protection applications. ASTM E 1355, "Standard Guide for Evaluating the Predictive Capabilities of Deterministic Fire Models," and ISO 16730 provide frameworks for evaluating the predictive capabilities of fire models. These standards emphasize validation, verification, and fire model assessment to ensure accuracy and reliability.

A single text-based input file controls FDS simulations. It is typically given a name that helps identify the particular case and ends with the file extension .fds. This input file can be written directly with a simple text editor or with the help of a third-party graphical user interface (GUI) such as Pyrosim.

The importance of the .fds file cannot be overemphasized as it contains the input or entire code and values from which the model or simulation is run. As such, opposing investigators need the file to peer review the simulation's conclusions, verify the assumptions on which it is based, and duplicate the model's output.

Assuming a proper and NFPA 921-compliant investigation has already been conducted, there are three steps to applying a fire model to a fire investigation. The steps presented in this article were followed in the case example included with this article.

Three steps are followed by the fire investigator when applying FDS (i.e., any fire model.)

1. **Construct the model** – During this phase, the investigator builds both the structure, contents and the fire, assigning thermo-physical properties to each and the property and duration of the fire, which determines the model's output. FDS is a Fortran program that reads input parameters from a text file, computes a numerical solution to the governing equations, and writes its output to various user-specified files.
2. **Run the simulation**. FDS runs the model or simulation, solving equations that describe the evolution of fire and its predicted impact on its computational domain (i.e., the structure and its contents (including its occupant(s)).
3. **Interpret the results**. - The model user interprets and visualizes the output data. With FDS, this is usually done in Smokeview or PYROSIM using RESULTS. Smokeview is a companion program provided with FDS that reads FDS output files and produces animations on the computer screen. RESULTS, a third-party application within PyroSim, expands the power of Smokeview and allows users to visualize results from PyroSim/FDS

Step 1—Constructing the model.

The first step is gathering the information and data needed to construct a model and perform the analysis.

The Facts of the Case

Multiple inspections had already been performed on the scene and the fire-damaged residence by the AHJ (Authority Having Jurisdiction), fire department, State Fire Marshal's office, experts representing the owner's property insurer, and other experts retained by the plaintiff, and this expert. These investigations focused primarily on the issues of origin and cause. The scene was reexamined in greater detail to confirm dimensional measurements and the thermo-physical properties of construction elements and contents. The diagram below reflects the general outline of the building and the location of the occupants/victims based on the facts documented during previously described activities.

The fire occurred in the early morning hours and resulted in the deaths of two of the four occupants inside the residence. A young mother and small daughter were asleep inside a hall bedroom and awakened by her young son (age 8), who reported a fire. The small boy "disappeared' after waking his mother and reporting the fire. His body was later recovered in the bedroom of his grandmother by firefighters responding to the fire.

The mother went down the hall to investigate and observed a *small fire with flames less than 6 inches* on the arm of a sofa in the living room in front of the residence. She returned to her bedroom, retrieved her small daughter (2 years old), and exited through the hall and dining room at the rear of the house, passing the master bedroom where her elderly and disabled mother slept.

Once outside with her daughter, the mother attempted to break the back window of the master bedroom where the elderly grandmother was confined to her bed before going next door to a neighbor who called 911 and reported the fire. Arriving firefighters began fire ground and search and rescue operations. During these operations, fire department personnel found the young boy, along with his grandmother, inside the main bedroom where the disabled woman was sleeping. Both perished in the fire. A folded-up wheelchair was found near her bed.

The grandmother was confined to bed at the time of the fire. Previous amputation of her left leg below the knee less than a year before required assistance for everyday activities (e.g., using the bathroom or getting in or out of bed). The medical examiner's report indicated that the grandmother was using both prescription and nonprescription drugs (THC) [9] At the time of her death.

Based on interviews and deposition testimony of the mother, the young boy who perished in the fire had a habit of staying up late at night playing video games on the computer in the living room. The mother was also treated after the fire for smoke inhalation and an injury to her right forearm

---

[9] Unlike alcohol, blood concentrations of THC and its metabolites are not sufficient to prove impairment. Testimony about additional signs of impairment is necessary to prove impairment.

that required seven stitches. A portable cigarette lighter was recovered near the couch where the fire was first observed, and investigators determined the fire originated.

The fire department reported that the front door was locked, and flames were inside the living room when they made forcible entry through the front door to enter the house. The body of the grandmother and a young boy were found prostrate inside the master bedroom. Smoke alarms were not found during the reconstruction of the fire event, and despite agreement on the fire's origin (the sofa inside the living room), neither public nor private investigators could determine the cause of the fire.

The mother brought a suit against the homeowner that, among other things, alleged a properly inspected, maintained, and operable smoke alarm installed in the residence in accordance with applicable codes, standards, statutes, and alarm manufacturers would have detected the fire at an earlier point in time than that testified to by the occupant and thereby prevented the deaths of the two occupants.

In this instance, it is assumed that the fire originated in the SE corner of the living room. The cause was undetermined by the original investigators, who failed to recover any evidence of smoke alarm components in the debris. The fire would not have destroyed these components.

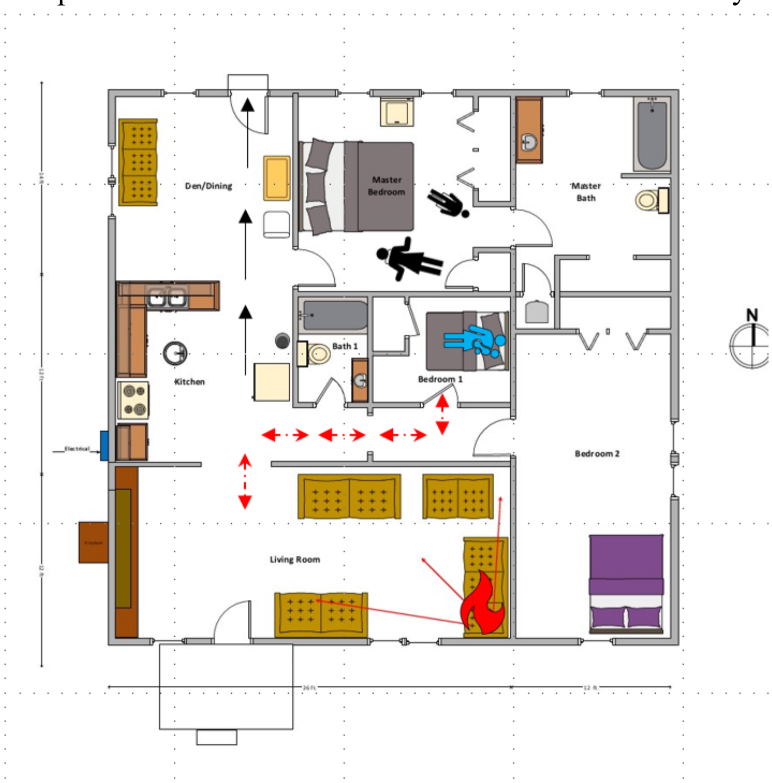


Figure 2 – Floorplan

Figure 3 – Frontal (A & B sides) view of residence after the fire.

Figure 4– Exterior side and rear view (B & C) of residence after the fire.

Figure 5 – Exterior rear view (Side C) of the residence after the fire where the mother exited from.

Figure 6 – Exterior rear view (Side C) of the residence after the fire.

Figure 7 – Interior view of the living room where the fire was first observed.after the fire

Figure 8 – End of sofa and arm where a small fire was first observed.

Figure 9 – The arm of the sofa where the fire was first observed. A portable lighter was

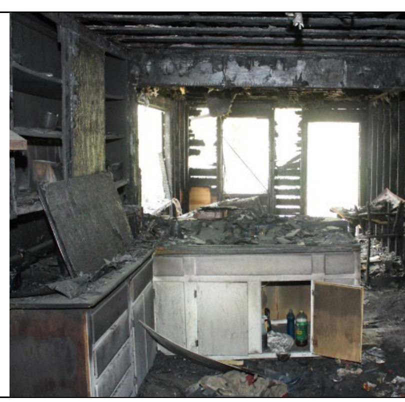


Figure 10 – View through kitchen and dining to the door that mother exited from at the back of the residence.

Figure 11 – Rear door exit inside dining room.

noted in debris on the floor in front of the couch.		
		
Figure 12– Wall separating dining from the master bedroom in the background.	**Figure 13** – Interior view of the master bedroom room where grandmother and young boy perished.	**Figure 14**– Exterior view of the master bedroom window at the rear that the occupant tried to break to save the victims inside the master bedroom.

Once collected, the previous data was used to construct the structure's geometry, its contents, and the location and movement of its occupants. [10]. It was also used to define the fire scenario within the structure. This phase is typically the most labor-intensive and time-consuming part of the process. It requires a higher level of user knowledge, skill, and judgment than the average beginning fire investigator, as well as fire modeling and FDS training.

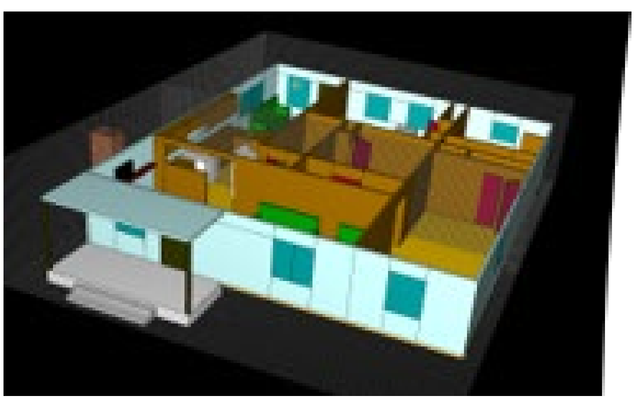


Figure 15 – Computational Domain of the model and Geometry of the residence created using PyroSim, a third—party pre and post-processor.

---

[10] Computational Domain - The entire space within which a model performs calculations including the structure (interior and exterior) and its contents. All calculations in fire dynamics must occur within this computational domain, which consists of rectilinear volumes called meshes.

While a single text-based file controls and runs the entire simulation, a graphical interface may be used to construct the model. The input file within FDS becomes the most important and contains the complete and only source of information about the simulated case.
While the actual simulation is run in FORTRAN[11], the input to the model is based on a single ASCII [12] text file containing parameters organized into namelist [13] Groups. This single input file provides FDS with the necessary information to describe the scenario (i.e., builds the geometry and the fire). The input file is saved with a name such as job_name.fds, where job_name is any character string that helps to identify the simulation.

Adjusters and attorneys sometimes fail to realize the importance of this single text file within FDS, which someone independently evaluating the simulation can use to identify and determine where the correct values were used to reach the results or conclusion(s) the simulation purports. The file can also be used to re-run the simulation and achieve the same results or run alternative simulations to test the models' sensitivity to different parameters. In other words, to play ‘what if?”

```
       CRITICAL_FLAME_TEMPERATURE=1327.0,
       CO_YIELD=0.042,
       SOOT_YIELD=0.198/

&PROP  ID='Cleary Photoelectric P1',
       QUANTITY='CHAMBER OBSCURATION',
       ALPHA_E=1.8,
       BETA_E=-1.0,
       ALPHA_C=1.0,
       BETA_C=-0.8/
&PROP  ID='Cleary Ionization I1',
       QUANTITY='CHAMBER OBSCURATION',
       ALPHA_E=2.5,
       BETA_E=-0.7,
       ALPHA_C=0.8,
       BETA_C=-0.9/
&CTRL ID='BreakWin1', FUNCTION_TYPE='ALL', LATCH=.FALSE., INITIAL_STATE=.TRUE., INPUT_ID='latch'/
&CTRL ID='latch', FUNCTION_TYPE='ALL', LATCH=.TRUE., INPUT_ID='THCPWin1'/
&CTRL ID='BreakWin2a', FUNCTION_TYPE='ALL', LATCH=.FALSE., INITIAL_STATE=.TRUE., INPUT_ID='latch2'/
&CTRL ID='latch2', FUNCTION_TYPE='ALL', LATCH=.TRUE., INPUT_ID='THCPWin2a'/
&CTRL ID='BreakWin2b', FUNCTION_TYPE='ALL', LATCH=.FALSE., INITIAL_STATE=.TRUE., INPUT_ID='latch3'/
&CTRL ID='latch3', FUNCTION_TYPE='ALL', LATCH=.TRUE., INPUT_ID='THCPWin2b'/
&CTRL ID='BreakWin9', FUNCTION_TYPE='ALL', LATCH=.FALSE., INITIAL_STATE=.TRUE., INPUT_ID='latch4'/
&CTRL ID='latch4', FUNCTION_TYPE='ALL', LATCH=.TRUE., INPUT_ID='THCPWin9'/
&CTRL ID='BreakWin10', FUNCTION_TYPE='ALL', LATCH=.FALSE., INITIAL_STATE=.TRUE., INPUT_ID='latch5'/
&CTRL ID='latch5', FUNCTION_TYPE='ALL', LATCH=.TRUE., INPUT_ID='THCPWin10'/
&CTRL ID='BreakWin11', FUNCTION_TYPE='ALL', LATCH=.FALSE., INITIAL_STATE=.TRUE., INPUT_ID='latch6'/
&CTRL ID='latch6', FUNCTION_TYPE='ALL', LATCH=.TRUE., INPUT_ID='THCPWin11'/
&DEVC ID='GasLayerLivingRoom->HEIGHT', QUANTITY='LAYER HEIGHT', XB=2.5,2.5,2.0,2.0,0.1,2.4/
&DEVC ID='GasLayerLivingRoom->LTEMP', QUANTITY='LOWER TEMPERATURE', XB=2.5,2.5,2.0,2.0,0.1,2.4/
&DEVC ID='GasLayerLivingRoom->UTEMP', QUANTITY='UPPER TEMPERATURE', XB=2.5,2.5,2.0,2.0,0.1,2.4/
&DEVC ID='GasLayerDiningRoom->HEIGHT', QUANTITY='LAYER HEIGHT', XB=2.0,2.0,10.0,10.0,0.1,2.4/
&DEVC ID='GasLayerDiningRoom->LTEMP', QUANTITY='LOWER TEMPERATURE', XB=2.0,2.0,10.0,10.0,0.1,2.4/
```

Figure 16 – What an FDS input file used to create a simulation looks like.

For this reason, model users sometimes produce only the simulation results and their interpretation and hide, withhold, or do not produce this file unless asked explicitly during litigation. Those who are unaware or ignorant of this fact never see it.

Describing the fire and the fuels

After creating the geometry, a source of ignition and its location were defined, and a fire scenario (i.e., user-specified fire) was created by entering the thermo-physical properties of the fuels involved and allowing the model to calculate and predict a fire growth rate. [5] Alternatively, a user can define a heat release rate over time (frequently based on a standardized T2 fire curve.) The location of the fire and the thermo-physical characteristics of the fuels involved must be defined.

[11] FORTRAN – A high-level programming language used especially for scientific computation.
[12] ASCII – American Standard Code for Information Interchange. 256 characters make up the standard ASCII text.
[13] A *namelist* is a Fortran input record.

Fuel Packages and Values

Material Property Database					
Material	Ignition Temperature (C)	Thermal Conductivity (W/ m K)	Density (kg/m3)	Specific Heat (kJ/ kg k)	Heat of Combustion (kJ/kg)
Brick		0.36 – 0.45	1600	0.84	
Carpet (Nylon)	405	0..33	1169	.87	22300
Concrete		1.8	2280	1.04	
Polyester Fabric	407	0.2	1345	.15	1500
Glass		0.96	2803	0.84	
Gypsum		0.48	1440	0.84	
Polyester	407	0.05	525	1.1	20300
Pine (White)	350	0.11	435	2.5	18500
Polyurethane Core		0.02	30	1.4	24000
Polyurethane/Cotton		0.02	1570	1.42	24000
Foam Polyurethane (C6.3,H7.1,H,O2.1)	280	0.02	575	1.4	24200

Figure 17 – Compilation of databases showing thermophysical properties of materials used in the simulation.

The properties in the present case were obtained from the following existing databases of materials tested and documented through cone calorimeter testing of similar materials.

1. Fire Protection Handbook
2. The Ignition Handbook
3. UMD Burning Materials Database [6]

Differences in values of the same materials may be averaged. Testing actual materials or exemplars collected from the scene can also be used.

Defining virtual devices

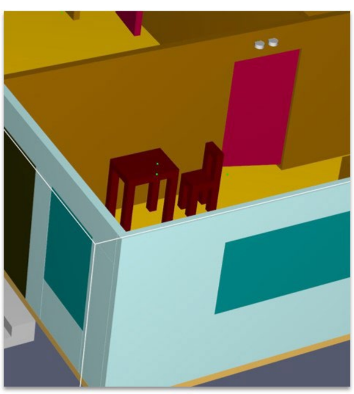


Figure 18– Virtual devices (smoke alarms) used in the simulation.

Next, virtual devices (smoke detectors, etc.) were defined and placed inside the structure (i.e., in the model to monitor) to record and control objects (doors, windows, etc.) based on the state of that device or human activity (e. g., the actions of occupants or others). The purpose of these devices is to simulate real ones or ones that should or could have been present and to ***predict their response*** or action. [7]

The process is not unlike previous investigations and analyses of fires, where a duplicate physical model (at a more significant expense) was built to reconstruct an original structure and simulate an actual fire. The physical model was equipped with thermocouples, gas sensors, and cameras to measure and record data throughout the fire's development. Today, it is accomplished digitally through fire modeling.

Virtual smoke alarms (not found or recovered during the earlier reconstruction of the fire) were placed at various locations within the model to simulate whether a properly inspected, maintained, and operable smoke alarm was installed in the residence in accordance with applicable codes. [14], standards, statutes, and alarm manufacturers could have detected the fire at an earlier point in time than that testified to by the occupant and prevented the deaths of the two occupants.

Measuring the fire's development

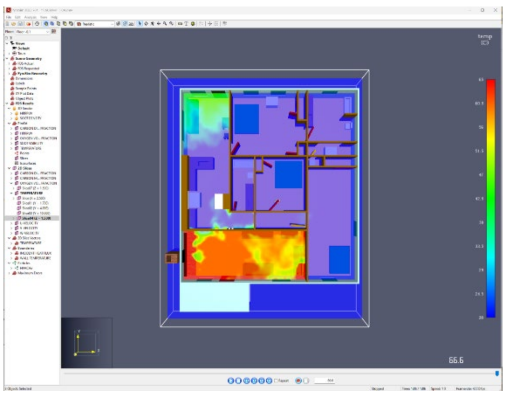


Figure 19 – View of a 'slice file' that shows temperature at 1.5 meters in height throughout the residence at 66.6 seconds during the simulation.

The last step in the construction of the model was to add sensors (point), slices (2D), or volumes (3D) to capture and record changes in the fire environment over time as the fire moved from ignition through extinguishment. After the simulation is run, these can be viewed as 'snapshots in time' or videos in slowed or real-time that reflect the changes the simulation is predicting and the sensor, slices, or volumes are measuring. Typically, these include soot, visibility, heat flux, temperature, pressures, velocity, O2, CO, CO2, and HCN.

<u>Step Two - Running the model!</u>

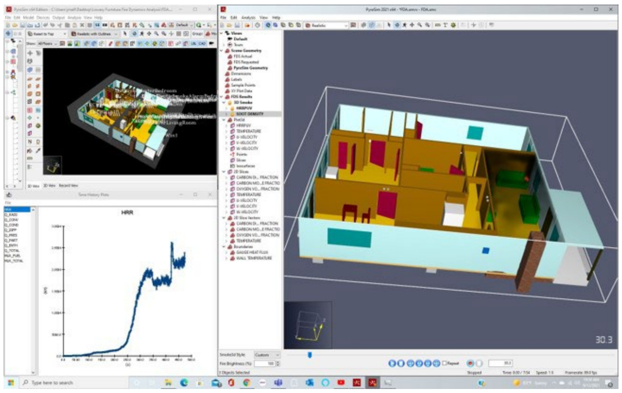
The simulation was then run, and its calculations were stored as raw numerical data in output files. It was started directly via the command prompt or PYROSIM, which acts as a GUI (Graphical User Interface). [15]). In turn, FDS uses the input file to run the analysis and generate the output files needed to evaluate and display its results.

---

14 NFPA 72 - National Fire Alarm and Signaling Code provides guidelines for the placement of smoke alarms in homes to enhance fire safety.

15 FDS can be run without using Pyrosim, or any other pre or post processor using a CLI (Command Line Interface) directly from within DOS.

While current desktop or laptop computers can run FDS, the processor speed, memory, and storage requirements of an analysis of any complexity realistically require either a dedicated system, multiple computers on a network, or cloud computing resources. The file's structure and specific language must comply with the requirements of the FDS software version.



Current versions of FDS and Smokeview (SMV) bundles may be downloaded and run on Windows, MacOS, or Linux systems at [FDS-SMV Downloads (nist.gov)]

Figure 20– Screen views observed at 30.3 seconds during the simulation.

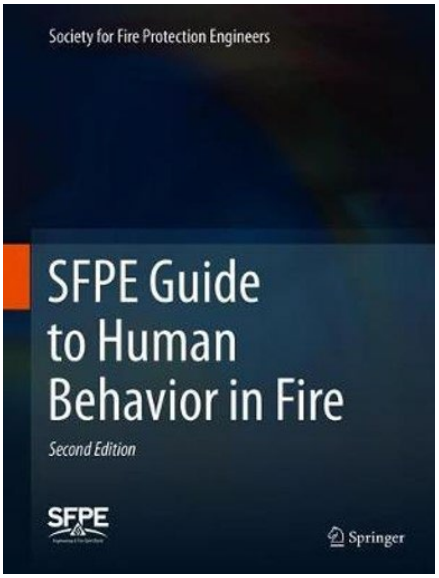
The user can monitor and view the model's progress without interrupting the model and, if needed, make corrections to errors that may not have been obvious when constructing it.
The program will check for errors when it opens the file to run the model and will fail to run if it detects an error. The most common mistakes in FDS are due to mistyped input statements that, when run, result in the immediate halting of the program.

The post-processor provided with FDS (i.e., Smokeview) and Pyrosim (i.e., Results) was then used to open and visualize the model results. Visualization can be a snapshot taken at any discrete point throughout the fire or a 'video' shown in slowed or real-time as viewed from an observer from any vantage point inside or outside the structure and within the computational domain.

Step Three – Interpreting the Results!

Time-dependent concentrations of fire effluents and the thermal environment of fire are determined by the rate of fire growth, the yields of the various fire gases produced from the involved fuels, the decay characteristics of those fire gases, and the ventilation patterns that occur throughout a fire. These and the reaction times of fire protection devices (heat detectors, sprinkler heads, smoke alarms, etc.) are predicted by constructing the model (and fire) and running the simulation.

How these effluents affect the occupant must be interpreted by applying previously established standards against the model results. Once determined, the methodology presented in ISO 13571:2012 can be used to estimate the time at which individuals can be expected to experience compromised tenability.



Along with the SFPE Guide to Human Behavior in Fire, ISO 13571:2012 establishes procedures to evaluate the life-threatening components of fire hazard analysis regarding the status of exposed human subjects at discrete time intervals. It makes it possible to estimate the time occupants can experience compromised tenability. It enables the estimation of a compromised tenability endpoint for each fire effluent component, with the most critical endpoint being the earliest to occur.

Together with the SFPE Guide to Human Behavior in Fire (Society for Fire Protection Engineers), the international ISO standard can, with care, provide guidance when applied to estimating the time limit for rescuing people who are immobile due to injury, medical condition, etc.

Figure 21 –SFPE Guide to Human Behavior in Fire.

The SFPE Guide to Human Behavior in Fire also provides an overview and summary of diverse topics that underline how occupant characteristics influence the response, reactions, and movement of occupants in a fire.

Newly released versions of FDS often drop or change parameters, forcing you to re-examine and revise old input files. Because the software evolves and changes, if involved in later litigation, the simulation output files and the version of model software used to create it must be saved.

In the current example, raw data were imported into an Excel spreadsheet, analyzed, and graphed to visualize its relationship to other data and significance to benchmark events over time. Temperature and radiant heat data were plotted to reveal when threshold limits were reached during the fire's development.

Benchmark Events on the spreadsheet are labeled and charted against the tenability criteria described earlier.

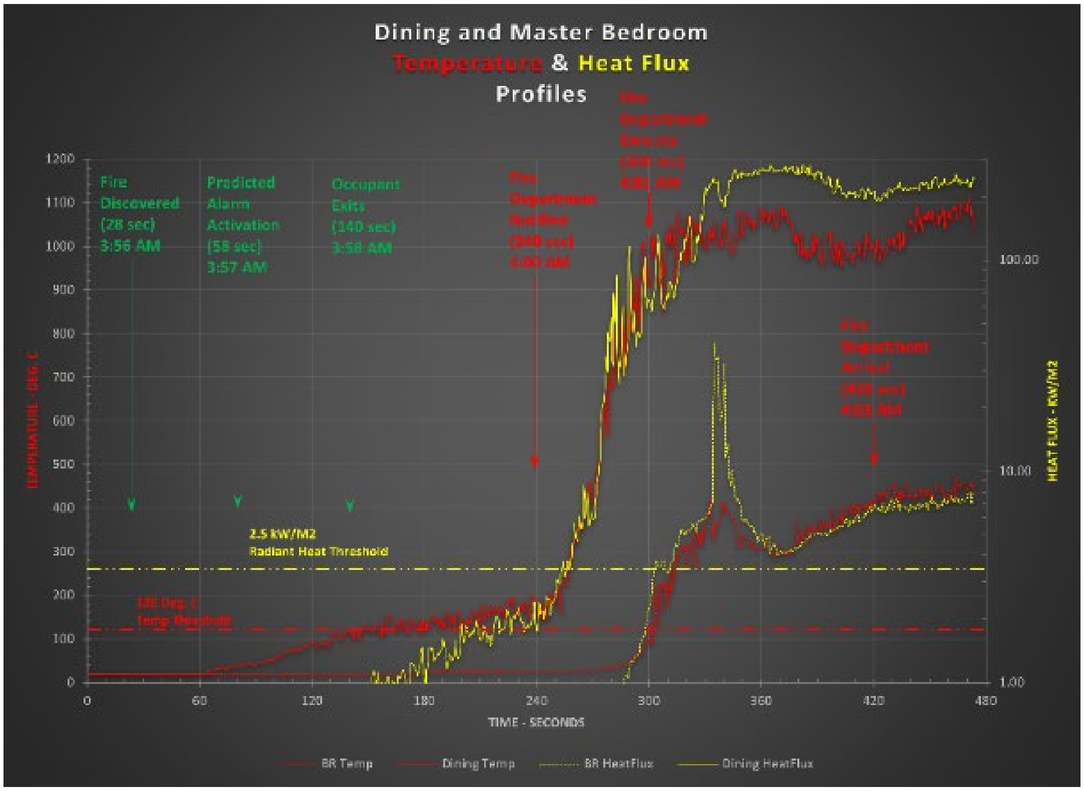


Figure 22 – Benchmark Events plotted from the simulation.

Fire Initiated (0 Seconds)
Fire Discovered (28 Seconds)
Smoke Alarm Activation (58 Seconds)
Opening of a door or window (140 Seconds)
Time of fire department notification (240 Seconds)
ASET Time of egress through Dining Room (260 seconds)
ASET Time inside Master Bedroom (340 Seconds)
Time of fire department arrival. (420 seconds)
Time fire ground operations commenced. (480 Seconds)

The customarily accepted tenability criteria for temperature is 120 deg. C (250 deg. F)
The customarily accepted threshold for tolerance to radiant heat is 2.5 kW/m^2. For small enclosures, this may be reached when upper hot layer temperatures rise above 200 deg. C.

Summary and Analysis

After being awakened and going to investigate, the mother observed a small fire, approximately one ft. in height, on the arm of a sofa in the southeast corner of the living room, returned to her bedroom to retrieve her daughter and exited through the kitchen and dining room from the back door (accounted for in the model at 120 seconds (3:58 a.m.)

While the mother's description of the time interval is ambiguous, the conditions of tenability predicted by the analysis indicate that temperature, oxygen, carbon monoxide, and carbon dioxide levels and concentrations were below threshold limits that allowed egress from the residence. The exception to this is visibility, which deteriorated rapidly before their exit. The nature of the fuels involved at this fire stage (i.e., polyester and nylon fabric and polyurethane foam comprising the couch) would have been the primary contributing factor to smoke production, not a lack of ventilation or available oxygen.

Not all individuals exhibit the same sensitivity to fire effluents; impairment factors inherent to an individual unrelated to the fire may also be present. Given the grandmother's age, medical condition, and impairment, it is unlikely she could have self-evacuated from the main bedroom, irrespective of when she became aware of the fire. Differences in age, mental capacity, physical handicaps, medication, and drug usage can all affect individual responses to fire. Threshold criteria of tenability developed through research and relied on for building design and the development of codes can provide the investigator with guidelines to assess why a fatality occurred in a particular fire.

The son, age 8, who reported the fire earlier, had no known medical impairments, was aware of the fire, and was physically capable of self-evacuating. The psychological behavior and response of children to fire, however, is more complex and less predictable than that of adults. Whether attempting to escape the fire, out of panic, fear, and either a desire to help or not abandon his grandmother, he remained inside the main bedroom, where conditions eventually became untenable, and he was later found with his grandmother. This fact demonstrates that despite the physiological impact of the fire, there is a psychological or *behavioral component* in the decision-making process.

What is clear is that while conditions inside the main bedroom remained tenable for some time, conditions inside the dining room, the only remaining path of egress, deteriorated rapidly after the mother exited the dwelling. Aided by the rear door being left open, minimum threshold levels of visibility and temperature were exceeded quickly, blocking re-entry into the structure or egress.

The mother broke the back window of the main bedroom shortly after her exit before going next door to a neighbor who called 911 and reported the fire. Her blood was recovered from the edge of the fractured glass of the window, and she was treated at a nearby hospital for smoke inhalation. She did not return to the structure after she exited it. Conditions inside the main bedroom remained tenable but exceeded tentability when firefighters were dispatched to the scene and entered the master bedroom.

The department's response time was reported as 3 minutes. Given the distance from the responding fire department, approximately 3 miles, and NFPA 1710 [16], [8] this estimate was probably inflated. The fire department reported that the front door was locked, and flames were inside the living room when they made forcible entry through the front door to enter the house. What is clear is

[16] In 2001, the NFPA 1710 standard, established by NFPA, required a 240-second travel time requirement for first-due engines. A survey conducted by the IAFF (International Association of Fire Fighters) of the fifty most populous cities revealed that 34 % do not meet this standard.

that by the time the firefighters arrived, conditions inside the structure had deteriorated beyond tentability. An individual's ability to escape is measured when their environment remains survivable. If an occupant is delayed, trapped, or becomes incapacitated, conditions during a fire can deteriorate rapidly and reach lethal levels.

The reliability of FDS with respect to predicting heat, temperature, and gas flow is often quoted in the range of 15-20 percent of measured values. Model results are usually presented in ranges to account for uncertainty. The error rate regarding fire spread is potentially higher and sensitive to numerical and physical input parameters [9]

Studies of FDS with respect to predicting smoke alarm performance, coupled with experience, could be better. Studies show that Fire Dynamics Simulator (FDS) simulations involving ASD (Air sampling or aspirating smoke detecting) systems generated quite a high performance prediction accuracy in those tested scenarios. At the same time, significant inconsistencies exist between the experimental and simulation results for conventional point-type smoke detectors (e.g., photoelectric (optical) and ionization types).

In the testing, the smoke levels observed at the time of alarm of the photoelectrical detectors exceeded the manufacturer's nominal sensitivities by more than 220 to 580%. The simulated average alarm times of the point detectors are between 30 and 56% of those tested. This outcome is close to the probability level (50%) required by NFPA 921 to express an expert opinion and level of certainty (i.e., a preponderance of the evidence) in all civil courts to prevail with regard to an issue in dispute. [10]

This realization brings home the fact, as users of FDS and other fire models are warned, that *they are intended for use only by those competent in fluid dynamics, thermodynamics, heat transfer, combustion, and fire science and only to supplement the informed judgment of the qualified user*. In the end, NFPA 921 requires an investigator's opinions and conclusions to *stand the reasonable examination of others*, and that reasonable fire investigation certainly is achieved when they have correctly applied all of the steps of the scientific method to reach a unique and reliable final hypothesis to a problem or issue in dispute.

Given the predicted timeline of the fire and its development, when it was discovered, and the response time of the fire department, even under the best fire ground conditions, firefighters unlikely could have forced entry through the residence's front door, controlled the fire, and located the occupants inside the main bedroom in less than a minute. By the time they did, tenability (e.g., heat and temperature) conditions inside the main bedroom had since transitioned from threshold incapacitation levels to lethal levels (i.e., exceeded ASET), resulting in the death of the occupants inside the main bedroom.

Based on experience, knowledge, and training, our review of the materials provided, and the fire dynamics analyses performed with FDS, we may reasonably conclude that an adequately inspected, maintained, and operable smoke alarm installed in the residence by applicable codes, standards, statutes, and alarm manufacturer's recommendations, would not have detected the fire at an earlier point in time than that testified to by the occupant nor prevented the deaths of the two occupants. In accordance with the recommended guidelines of NFPA 921, the conclusion is expressed *with reasonable certainty* as *probable*.

References

1. NFPA, "NFPA 921: Guide for Fire and Explosion Investigations, National Fire Protection Association 2024).
2. ISO 13571:12 - Life-threatening components of fire — Guidelines for estimating time to compromised tenability in fires.
3. SFPE Guide to Human Behavior in Fire – 2nd ed. – 2019, Society of Fire Protection Engineers, Gaithersburg, MD, 2019.
4. NFPA, "NFPA 72: National Fire Alarm and Signalling Code 2022," National Fire Protection Association.
5. Fire Dynamics Simulator User's Guide – National Institute of Standards and Technology, Special Publication 1019 – Sixth Ed., McGrattan, Hostikka, Floyd, McDermott, Vanella, Mueller
6. The SFPE Handbook of Fire Protection Engineering, 4th. Ed. 2008, Society of Fire Protection Engineers Burning Item Database. 1st edition. A. James, Clark School of Engineering, 3rd Floor, J.M., Peterson Bldg, College Park, MD 20740; University of Maryland; 2009. http://www.firebid.umd.edu/
7. PyroSim User Manual, Version 2023-3, Thunderhead Engineering, Manhattan, Kansas
8. NFPA, "NFPA 1710: Standard for the Organization and Deployment of Fire Suppression Operations, Emergency Medical Operations to the Public by Career Fire Departments," National Fire Protection Association
9. Examination of Fire Dynamics Analysis Techniques: Assessment of Predictive Fire Algorithms, Models, 2021, Underwriters Laboratories, McKinnon, Willi, and Madrzykowski
10. Smoke Detection Performance and FDS Modeling for Full-Scale Fire Tests, 2023, Xtralis, Jiang, Yun, 582 (xtralis.com)