NISTIR 6152

Features, Limitations and Uncertainties in Enclosure Fire Hazard Analyses – Preliminary Review

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Prepared for:
U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Washington, DC 20555

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March 1998

NIST

U.S. Department of Commerce
William M. Daley, *Secretary*
Technology Administration
Gary R. Bachula, *Acting Under Secretary for Technology*
National Institute of Standards and Technology
Raymond G. Kammer, *Director*

Prepared for:
U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Washington, DC 20555

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FEATURES, LIMITATIONS AND UNCERTAINTIES IN ENCLOSURE FIRE HAZARD ANALYSES – PRELIMINARY REVIEW

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Abstract

A significant number of fire modeling tools have been developed to analyze the hazards and risks associated with fires in buildings. These tools range from empirical correlations of data suitable for hand calculations, through control volume (zone) models of increasing sophistication, to state-of-the-art computational fluid dynamics (field) models. Properly applied, these tools permit development of a better understanding of the dynamics of building fires and can aid in the fire safety decision-making process. This report presents a review of three fire modeling tools (FIVE, COMPBRN III, CFAST) currently being used in fire safety design and a fourth model (LES) of the field model type which is beginning to be used in fire protection engineering. This review focuses on the application potential for these models in the nuclear power industry.

In view of the uncertainties associated with fire modeling predictions, extreme care must be exercised in the interpretation of fire modeling results. For scenarios where the level of predicted hazard is well below the damage threshold, the results can be used with a high level of confidence provided there is a high level of confidence that all risk-significant scenarios have been considered. For scenarios where the level of predicted hazard is near the damage threshold, the results should be used with caution in view of the uncertainties that exist. In order to address some of the uncertainties in fire modeling, a multi-level approach is proposed which combines professional judgment, correlations, zone models, and field models.

Keywords: compartment fires, computational fluid dynamics, computer models, field models, fire hazards assessment, fire models, hazard assessment, nuclear power plants, nuclear reactor safety, zone models

1. Introduction

The purpose of this report is to provide a preliminary review of the features, limitations and uncertainties associated with the current state-of-the-art of fire modeling. Fire modeling is a technique used to analyze the hazards and risks associated with fires in buildings. This technique typically entails the description of a fire scenario and the calculation of fire conditions resulting from the specified fire scenario. A number of fire modeling tools have been developed to perform these calculations. These tools range from empirical correlations of data suitable for hand calculations, through control volume (zone) models of increasing sophistication, to state-of-the-art computational fluid dynamics (field) models. Properly applied, these tools permit a better understanding of the dynamics of building fires and can thereby aid in the fire safety decision-making process.

The use of fire modeling techniques for fire safety decision-making is limited by a number of uncertainties. These uncertainties include:

- the selection of appropriate fire scenarios;
- the selection of appropriate input parameters for selected fire scenarios;
- the selection of appropriate algorithms for selected fire scenarios; and
- the selection of appropriate decision-making criteria.

Building fires are critical events in that small perturbations in input conditions can sometimes yield large differences in outcomes. Ultimately, the value of a particular fire modeling technique should be measured by its ability to reduce the uncertainties associated with the decisions being made. Any model of a physical system is incomplete by nature; certain assumptions and approximations are always necessary. The questions then are:

- How complete is the model in terms of the phenomena being modeled?
- What is the effect of incomplete phenomenology on the calculated outcomes?
- How sensitive are the calculated outcomes to the input parameters?
- How accurately are the input parameters known?
- What is the uncertainty in the input parameters?
- How do the calculated outcomes affect the decisions being made?
- What is the uncertainty in the calculated parameters?
- What is the uncertainty in the damage criteria?

In theory, models with increasing capabilities should narrow the range of uncertainty, as illustrated conceptually in Figure 1. The question is whether this is true in practice. The purpose of this report is to provide a brief review of the features of selected fire hazard analysis techniques, to address the capabilities and limitations of these techniques, and to identify verification and validation efforts for the techniques. The fire hazard analysis techniques addressed here include the FIVE methodology [1]*, COMPBRN (Version III) [2] and CFAST (FAST Version 3.1.2) [3]. These techniques span a range from relatively simple correlations applied in a one-room, one-layer zone model (FIVE) through a one-room two-layer quasi-steady

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* Numbers in brackets refer to literature references at the end of the report.

zone model (COMPBRN) to a multi-room two-layer transient zone model (CFAST). CFAST is the zone fire model portion of a suite of fire protection engineering tools collective known as FAST. A fourth model referred to as the Large Eddy Simulation (LES) [4] model will also be discussed. This last model is a field model and represents the current state-of-the-art in fire simulation used in fire protection engineering design tools.

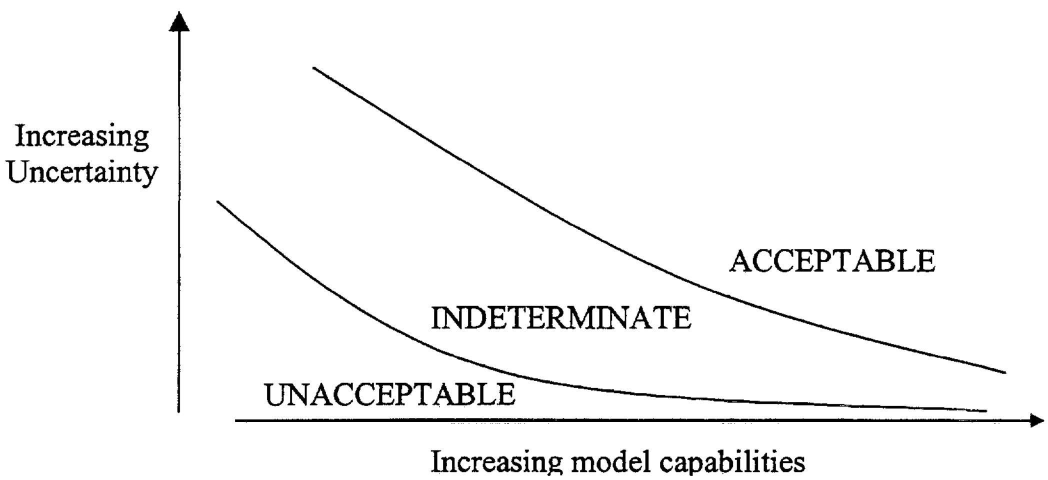


Figure 1. Concept of Reduced Uncertainty as Function of Increasing Model Capabilities

A fire scenario is a description of the significant factors influencing the outcome of a fire. In general, a fire scenario will include a description of:

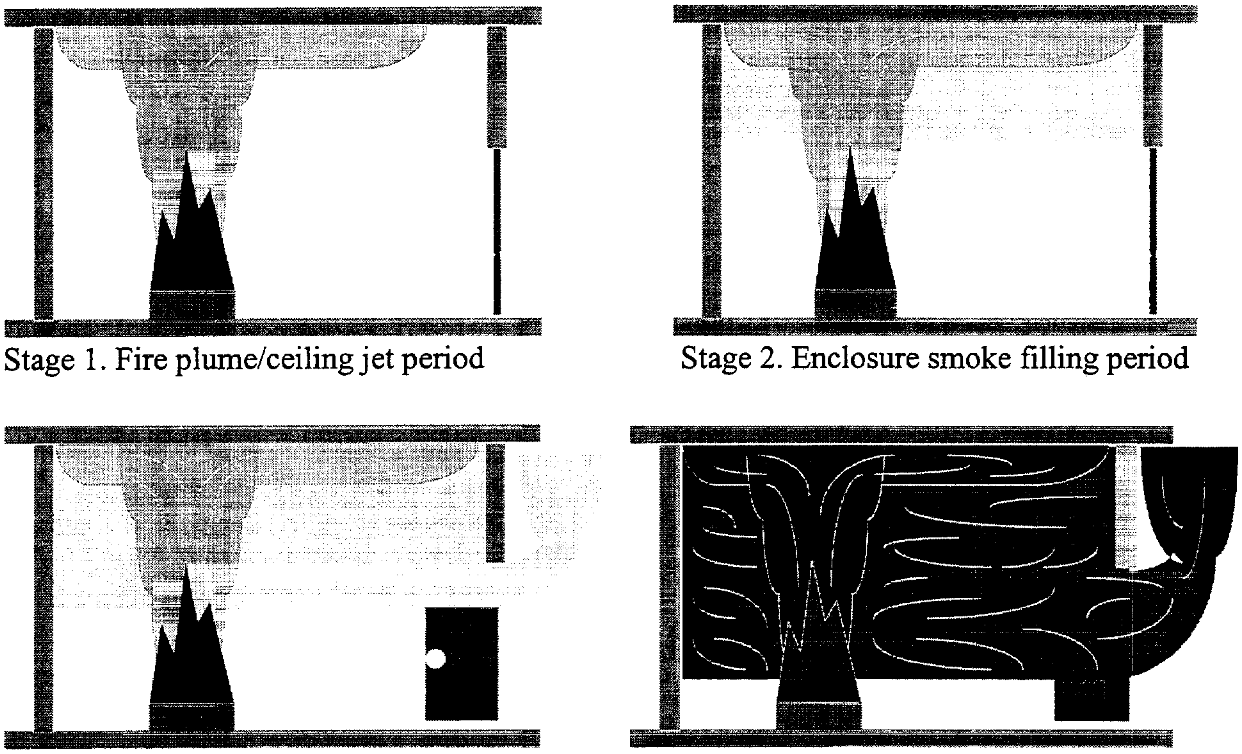
- A fire source, including location, intensity history and duration;
- Additional fuels that might ignite and serve as fire sources (intermediate combustibles);
- Enclosure boundaries, including dimensions and materials;
- Ventilation openings and systems;
- Fire protection devices and systems, including fire detection, alarm and suppression systems; and
- One or more targets, such as people, equipment or fire protection devices.

The level of detail required for a fire scenario description depends on both the sophistication of the model being used and the required output to address the questions being asked.

2. Stages of Enclosure Fires

Conceptually, enclosure fires can be characterized in terms of the stages illustrated in Figure 2:

- Fire plume/ceiling jet period
- Enclosure smoke filling period
- Preflashover vented period
- Postflashover vented period



Stage 1. Fire plume/ceiling jet period

Stage 2. Enclosure smoke filling period

Stage 3. Preflashover vented period

Stage 4. Postflashover vented period

Figure 2. Stages of an Enclosure Fire

The initial stage of enclosure fires beyond ignition and incipient sustained burning is the fire plume/ceiling jet period. During this period, buoyant gases rise to the ceiling in a plume above the fire, then spread radially beneath the ceiling as a relatively thin jet of hot gases. As the plume gases rise to the ceiling, they entrain cool fresh air. This entrainment decreases the plume temperature and combustion product concentrations, but increases the volume of smoke. The plume gases impinge upon the ceiling and turn to form a ceiling jet, which can continue to extend radially until confined by enclosure boundaries or other obstructions at ceiling level, such as deep solid beams.

Once the ceiling jet spreads to reach the full extent of the compartment, the second stage of enclosure fires ensues. This is the enclosure smoke filling period. During this stage, a layer of smoke descends from the ceiling as a result of air entrainment into the smoke layer and gas expansion due to heat addition to the smoke layer. The entrainment of fresh air into the smoke layer tends to dampen this increase.

The duration of this second period depends on the heat release and heat loss histories as well as on the types and locations of ventilation openings in the enclosure. In closed rooms, the smoke layer continues to descend until the room is full of smoke or until the fire source burns out, due to either fuel consumption or oxygen depletion. In ventilated rooms, the smoke layer descends to the elevation where the rate of mass flow into the smoke layer is balanced by the rate of flow from the smoke layer through natural or mechanical ventilation.

The preflashover vented fire period begins when smoke starts to flow from the enclosure. Ventilation may occur naturally through openings in compartment boundaries or be forced by mechanical air handling systems. In either case, the loss of heat by convection affects the energy balance used to describe conditions in the smoke layer. The smoke layer may continue to expand and descend during the preflashover vented period, but this transient factor is normally of negligible consequence compared with the quasi-steady energy and mass flow terms into and out of the smoke layer.

The primary differences between the unventilated and ventilated stages of preflashover enclosure fires relate directly to the ventilation. In the unventilated case, as the smoke layer continues to descend, less cool air is entrained into the plume to dampen the temperature rise. Consequently, higher temperatures can result in the unventilated case. At the same time, however, adequate ventilation is normally needed to permit the growth of an enclosure fire. Fires in unventilated spaces can become oxygen starved resulting in a reduced burning rate and lower, less hazardous temperatures. These conflicting factors make it difficult to generalize regarding which of these stages represents the more significant hazard.

The final stage of enclosure fires, the postflashover vented period, typically represents the most significant hazard, both within the fire compartment and to remote areas of a building. This period occurs when thermal conditions within the enclosure become such that virtually all exposed combustibles ignite, in many cases almost simultaneously, and air flow to the compartment is sufficient to sustain intense burning. During this period, the rate of air flow into the enclosure, and consequently the peak rate of burning within the compartment, become limited. The ventilation is limited by the sizes, shapes and locations of boundary openings for naturally ventilated spaces and by the ventilation rate for mechanically ventilated spaces. With adequate ventilation, flames may fill the enclosure volume. A one zone model has commonly been used to analyze the postflashover period of enclosure fires due to the relatively uniform conditions that have been observed.

The duration and intensity of each stage depend on a number of variables, including:

- The fire heat release rate history;
- The enclosure size;
- The enclosure ventilation; and
- The enclosure construction.

The methods and algorithms used to analyze and simplify the mass and energy balances applicable to each stage differ between models. To a large extent, these differences distinguish the different models.

3. Elements of Enclosure Fires

Regardless of the sophistication of the fire model, some common elements of enclosure fires can be considered. These elements include:

- The fire source;
- The fire plume;
- The ceiling jet;
- The fire plume/ceiling jet sublayer;
- The hot gas layer;

- The lower gas layer;
- Vents (floor, wall, ceiling);
- Ventilation systems (injection, extraction, balanced);
- Enclosure boundaries (floor, walls, ceiling);
- Targets (people, equipment, fire protection devices); and
- Fire protection systems (detection, alarm, suppression).

The sophistication of a model is largely determined by the levels of detail, resolution and uncertainty associated with these elements. Issues related to the bases for and uncertainties inherent in each element are discussed below. The results of this preliminary analysis are summarized in Table 1.

3.1 Fire Source

The fire source is the motive force in enclosure fires and fire models. Despite use of the term "fire model" to describe this class of analytical tools, **the fire itself is not generally predicted or calculated by fire models. Rather, fire models typically calculate the consequences of a specified fire.** Thus, the accuracy of a simulation is directly related to the accuracy with which the user specifies the fire scenario as well as to the accuracy of computational schemes employed. Some models, such as COMPBRN, attempt to predict fire growth and burning rates. These capabilities are rudimentary at best and depend on a number of input parameters obtained from test data. According to reference [2], reasonable agreement is obtained when the input parameters are known. However, the parameters are a function of specific details associated with each fire scenario and are not well known for arbitrary scenarios. The general level of agreement will depend on the accuracy of the input parameters.

Different models can consider various types of fires. Some of the possible types include:

- Gas burner: a programmed mass loss rate independent of environmental conditions;
- Pool fire: a liquid fuel with a horizontal surface, typically of specified diameter or area, where the burning rate depends on heat feedback to the fuel surface;
- Solid fire: a solid fuel of specified properties and geometry, where the burning rate depends on the heat feedback to the fuel surface;
- Wall fire: a fire involving the exposed surfaces of combustible vertical wall finishes; and
- Ceiling fire: a fire involving the exposed surface of combustible ceiling finishes.
- Spray fire: a liquid fuel emitted under pressure through a puncture in a surface.

Some models can track different chemical species. This capability is important for evaluating the impact of the fire on people and equipment. The concentrations of carbon dioxide and carbon monoxide are used to determine when spaces become untenable. Other quantities such as smoke particulates (carbon particles) and hydrogen chloride can be damaging to components and systems used in nuclear power plants.

The available species depend on how a model treats the chemistry of combustion. Typically, zone fire models and existing field models rely on user specification of yield factors, which represent the expected conversion of fuel and air molecules to different products of combustion. Some models, including CFAST, permit specification of yield factors that depend on the ventilation conditions within the fire enclosure. Yield factors are not currently predicted from fundamental principles by any of the zone models or the field models; they are generally determined empirically in laboratory fire experiments.

Representative yield factors for different fuels burning under a range of ventilation conditions have been tabulated from small-scale tests, e.g., by Tewarson [5]. Yield factors are generally used in fire models as a proportion relative to the mass pyrolysis rate of the burning item. Comparison of concentrations of carbon dioxide and carbon monoxide predicted by the CFAST model with data from experiments conducted in a decommissioned nuclear power plant indicates that "gas concentrations are well predicted" [6] by the model. The limited amount of data available concerning nonthermal damage to equipment from smoke and acid gases makes it difficult to estimate the impact under real fire conditions.

As an adjunct to species tracking, some models permit the heat output of a fire to be constrained based on the availability of oxygen. Other models do not address this constraint and thus permit nonphysical heat release rates to be specified. In the CFAST model, the user can specify whether a fire should be constrained by the availability of oxygen for combustion. The basic FIVE methodology does not address oxygen constraint, but a supplementary calculation is available in the FIVE documentation that does address this constraint. The LES model provides a capability to limit combustion based on the available oxygen.

The ignition of secondary fuels is an important element of most serious enclosure fires and consequently of fire hazard analyses. However, the ability to predict the ignition and subsequent burning rate of secondary fuels is currently quite limited. Both CFAST [3] and LES [4] provide capabilities to model heat transfer, ignition, and burning associated with multiple objects. Modeling of target objects is discussed in more detail in a subsequent section of this report.

The uncertainty associated with describing the potential fire is probably the single most significant limitation in the application of fire modeling to fire risk assessment. A number of efforts are underway to address this limitation primarily through the development of "design fires" or "design fire scenarios". The use of design fires has been discussed in the literature by Custer [7]. The National Fire Protection Association [8] and the International Organization for Standardization [9] have prepared guidance documents for the development and application of design fires. The design fire concept should have applicability to nuclear power plants.

3.2 Fire Plume

Hot products of combustion are buoyant relative to the surrounding ambient atmosphere. Consequently, these combustion products ascend through the atmosphere above the fire source in a coherent plume, entraining ambient air in the process. This entrainment process serves to cool the plume as it rises while transporting entrained air and energy released by the fire from the lower layer to the upper layer.

Fire plumes have been investigated extensively, with most investigations focused on the axisymmetric plume. These investigations follow the classic treatment of Morton, Taylor and Turner, who developed the theory for an axisymmetric plume rising from a weak point source of energy (*i.e.*, Boussinesq approximation) [10]. Since real fires are strong area or volume sources rather than weak point sources, some investigations have resulted in adjustment factors, such as virtual origin offsets, to account for differences between theory and reality. Others have divided the fire plume into multiple regions in efforts to account for near- and far-field effects.

3.2.1 Axisymmetric Fire Plumes

Various correlations have been developed by different investigators for the axisymmetric geometry. These correlations are based on the classic work of Morton, Taylor and Turner, but typically have been modified to account for the strong, volumetric sources of real fires. The three zone models reviewed here use three different correlations for axisymmetric plumes.

The FIVE model uses the Heskestad [11] correlation for plume centerline temperature rise. Heskestad refers to experimental work by Kung and Stavrianidis [12] and by George, et al. [13] as the bases for the engineering relations for fire plumes he developed. Kung and Stavrianidis performed a series of ten pool fire tests with pool sizes of 1.22 m, 1.74 m and 2.44 m in diameter using four different fluids, including methanol, heptane, a silicone transformer fluid and a hydrocarbon transformer fluid. These pool fires produced convective heat release rates calculated to range from 170 kW to 4400 kW.

COMPBRN III uses the correlation of Zukoski, et al. [14] for fire plume entrainment. This entrainment correlation is based on experimental measurements by Yokoi [15]. Zukoski, et al. [14] also performed laboratory scale experiments using 0.10 m to 0.50 m diameter porous-bed burners to produce methane-fired diffusion flames with heat release rates ranging from 10 kW to 200 kW. They then compared their experimental results with the Zukoski correlation. In these experiments, they found that aerodynamic disturbances caused by ventilation system operation and wall blockage increased entrainment rates by up to 20% to 40%. They used screens around their test apparatus to dampen out these disturbances. They also investigated wall and corner effects, suggesting the concept of reflection to account for these effects. They note that plume mass fluxes are less than predicted by their simple correlation if the hot gas layer interface lies below the top of the visible flame and rise to or above the predicted values as the interface moves up. Differences of up to 50 percent above or below those predicted by their correlation occurred during their experiments [14].

Cetegen, et al. [16], revisited the Zukoski correlation and developed adjustment factors to address entrainment in the near and far field of fire plumes. To date, these adjustments have not been incorporated in the general Zukoski correlation or in the COMPBRN III implementation of this correlation. COMPBRN III does permit the user to specify an adjustment factor for the Zukoski correlation. With appropriate knowledge, the user could use this feature to explore a range of adjustment factors and their consequences for a given scenario.

CFAST uses the McCaffrey correlation [17] for fire plume entrainment. This correlation is based on laboratory measurements made by McCaffrey above a 0.3 m square porous refractory burner operating on natural gas at heat release rates in the range of 14 kW to 58 kW. The user cannot make adjustments to the McCaffrey entrainment correlation embedded in the CFAST model or specify an alternative plume correlation to use. However, CFAST does limit the entrainment to the hieght at which the plume is still bouyant.

The LES model does not use a plume correlation as such. It calculates plume entrainment using the fundamental equations describing fluid motion. These equations are solved numerically at each time step for each of the tens of thousands or hundreds of thousands of cells that makeup the geometry of interest.

3.2.2 Wall/Corner Fire Plumes

The concept of reflection has been used to describe the influence of adjacent walls and corners on otherwise axisymmetric plumes. This concept suggests that a fire burning along a wall can be treated as a fire in the open burning with twice the intensity, but entraining air around only one-half of its perimeter. Similarly, a fire burning in a corner can be treated as a fire in the open burning with four times the intensity, but entraining air around only one-quarter of its perimeter.

This treatment has produced generally satisfactory results in the limited number of applications where it has been applied. Alpert and Ward [18] suggested use of this approach for the evaluation of fire hazards in unsprinklered industrial facilities. Mowrer and Williamson [19] successfully applied the reflection concept to the analysis of relatively small gas fires (40 kW to 160 kW) on a porous 0.3 m square burner in the standard room fire test method (2.4 m x 3.6 m x 2.4 m high room with a single 0.76 m wide x 2.03 m high doorway). When the adjustment factors were used, the measured and predicted temperature values agreed to within 5 percent versus a 25 percent or greater difference without correction.

The reflection treatment is used in the FIVE methodology and in the COMPBRN model. The CFAST model uses a three dimension coordinate system to implement this concept. When the coordinates of a burning object and the room geometry would place an object adjacent to a wall or corner, the computer program automatically adjusts the rate of entrained air which may have an effect on the heat release rate. In theory, this adjustment factor should not be necessary for the LES model.

3.2.3 Line Plumes

Plumes rising from horizontal fire sources that are much longer in one dimension than in the other can be characterized as line plumes. Recently, Grove and Quintiere [20] have attempted to correlate existing data on line plumes as well as axisymmetric plumes. None of the four models currently specifically address line plumes, although the COMPBRN III model does address cable trays as a linear series of cells.

3.2.4 Window Plumes

Window plumes, or vent plumes, occur when flames and hot gases flow through an opening between two spaces or from an enclosure to the outside. Virtually no experimental measurements have been made for this geometry. CFAST addresses window plumes by treating them as axisymmetric plumes with a virtual origin located to produce the same mass and energy fluxes as the actual window plume. The height over which the entrainment takes place is a function of the layer heights in the compartments.

The wall/corner fire plume is an example of how immediate obstructions lateral from the plume can influence entrainment in fire plumes. Other obstructions in the entrainment flow field will also impose aerodynamic disturbances that will influence fire plume entrainment. For example, Steckler, et al. [21], showed how the location of a fire near a doorway vent will cause the plume to tilt away from the vent as a result of induced airflow through the vent. Zukoski, et al. [14], also observed tilted plumes as a result of close, but not immediate, walls and corners. In general, tilted plumes result in a longer entrainment distance to the hot gas layer interface and consequently in more entrainment, causing plume temperatures to decay more rapidly with height. But at the same time, fires near obstructions tend to be drawn towards the obstruction by preferential airflow from the opposite direction. This could have negative ramifications, as, for instance, in the case of a fire located near an electrical cabinet, which could be drawn to the cabinet.

3.2.5 Plume Obstructions

Obstructions located in the fire plume itself have not been explored extensively. For example, the influence of a cable tray or other solid obstruction on fire plume characteristics has not been investigated. Similarly, the effect of a fire plume on a large obstruction has not been demonstrated, for example in terms of the heat transfer to the obstruction and the potential for ignition.

3.3 Ceiling Jet

When trapped beneath a ceiling, the buoyant gases rising in the fire plume turn and flow away from the fire plume in a ceiling jet, until they reach the vertical boundaries of the enclosure or other obstructions at the ceiling level. Ceiling jet correlations have been developed for only two geometries, both involving relatively smooth horizontal ceilings. The first correlation, developed by Alpert [22] and revised by Alpert and Ward [18], applies to the unconfined ceiling jet that spreads radially in all directions from the plume impingement zone. The second correlation, suggested by Delichatsios [23], applies to the confined ceiling jet that occurs in spaces where the length is much greater than the width, such as corridors.

Alpert's study [22] was "restricted to fire diameters and flame lengths much smaller than the ceiling height." He uses large-scale data from Thompson [24] and small-scale data from Miller [25] to compare his ceiling jet temperature predictions with experimental data. Miller's data spans a range of heat release rates from 35 W (2.0 Btu/min) to 83 W (4.7 Btu/min), a single fire diameter of 0.1 m (0.33 ft) and fire to ceiling heights of 0.5 m (1.6 ft) to 1.25 m (4.1 ft). Thompson's data spans a range of heat release rates from 264 kW (15,000 Btu/min) to 2638 kW (150,000 Btu/min), fire diameters from 0.5 m (1.6 ft) to 1.3 m (4.4 ft), and a single height of 4.6 m (15 ft). Illustrated on a log-log graph (Figure 7 of Alpert [22]), the experimental data for ceiling jet temperatures seem to fit a fairly narrow range, but the nature of the graph tends to suppress the magnitude of the fluctuations, which exceed 50% ((max-min)/max) in some cases.

Some experimental work has been reported for ceiling jet behavior in spaces with sloped [26] or obstructed ceilings [27]. However, the correlations have not been implemented in any models.

3.4 Fire Plume/Ceiling Jet Sublayer

The fire plume correlations and the unconfined and confined ceiling jet correlations discussed above apply to scenarios where a significant hot gas layer has not developed within the enclosure. As a hot gas layer develops, the fire plume and ceiling jet entrain hot gases, rather than cool ambient air, above the hot gas layer interface. This causes the temperatures in the fire plume and ceiling jet to decay less rapidly with height and radial distance, thus stretching the temperature field in the fire plume/ceiling jet sublayer. A number of methods have been developed to address this situation analytically, but few comparisons with experimental data have been pursued or reported.

COMPBRN III addresses heating of a target located in the fire plume, but does not report fire plume or ceiling jet temperatures directly. CFAST has a user-selectable algorithm for calculating heat transfer to the ceiling and walls. Ceiling jet temperatures and velocity are reported at user-specified detector locations. By assuming a target object is located at a detector position, CFAST can be used to predict the ceiling jet properties at that location.

The FIVE methodology addresses the fire plume/ceiling jet sublayer by superimposing the average hot gas layer temperature within the fire enclosure over the fire plume and ceiling jet temperatures based on ambient conditions. This approach tends to be conservative in the fire plume, particularly near the hot gas layer interface, and in the ceiling jet near the fire plume, becoming less conservative farther out in the ceiling jet. Calculations using the FIVE methodology have been shown to agree with experimental data to within 25 percent [1].

3.5 Hot Gas Layer

A key premise of zone models is the development beneath the ceiling of a layer of buoyant fire gases with relatively uniform properties. These uniform properties derive from the turbulent mixing associated with recirculation in the fire plume/ceiling jet sublayer as it penetrates the hot gas layer as well as within the hot gas layer itself. The hot gas layer is treated as a thermodynamic control volume. Heat and mass transfer across the boundaries of this control volume are evaluated to assess the properties of the hot gas layer.

The validity of the uniform property assumption for the hot gas layer has been demonstrated in actual fire experiments for a range of fire scenarios. The validity of this assumption seems to decrease in spaces with significant mechanical ventilation near the ceiling. In such spaces, a virtually linear temperature gradient has been observed, with higher temperatures near the ceiling and lower temperatures near the floor. The conditions under which the uniform property assumption breaks down have not been identified. A layer temperature gradient should not have a significant affect on a field model such as the LES model.

The three zone models addressed here all treat the hot gas layer similarly, yet somewhat differently. The FIVE model assumes constant pressure and a fixed control volume defined as the space between the fire source and the ceiling in order to calculate average conditions within the smoke layer. The COMPBRN model uses a quasi-steady constant pressure treatment that determines the elevation of the smoke layer interface based on quasi-steady heat and mass balances. At each time step, the interface is assumed to instantaneously equilibrate at this elevation. For closed rooms, the COMPBRN model uses the entire space as the control volume, similar to the FIVE methodology. The CFAST model uses a more comprehensive transient pressure and interface position treatment to calculate smoke layer descent and equilibration based on heat and mass balances. Overall, the net effects of these differences is still being explored through comparisons with experimental data, making generalizations difficult at this time.

The FIVE methodology uses a superimposed fire plume/ceiling jet sublayer to account for the higher temperatures observed in the fire plume and ceiling jet sublayer. Comparisons of CFAST Version 1.6 predictions of hot gas layer temperatures with data from experiments conducted in a nuclear power plant indicates the model over estimated the measured temperatures by a few percent to several tens of percent [6]. The other models discussed in this review have not been subjected to this same verification effort. From a damage standpoint, this over estimation would yield conservative results; from the standpoint of fire detector and sprinkler activation, this would underestimate the time to activation.

3.6 Lower Gas Layer

Conditions within the lower gas layer are not generally as severe as in the hot gas layer. Consequently, some models, including the FIVE methodology and COMPBRN III, neglect the lower gas layer, treating it as if it remains at ambient conditions. Others, including CFAST, treat the lower gas layer as a distinct control volume; they use heat and mass balances to evaluate conditions within the lower gas layer.

The primary means by which the lower layer becomes contaminated with smoke, and thereby able to absorb incident radiation, is through mixing of the upper and lower layers at walls and vents and through mechanical ventilation. Wall mixing has been discussed by Jaluria [28], but is not currently incorporated into any fire models. If it proves to be important for decision making, such wall mixing might best be considered in terms of the development of an intermediate layer between the hot gas layer and the lower layer. Vent mixing has been discussed by Quintiere and McCaffrey [29], who developed an empirical correlation to address this phenomenon, which relates to the shear layer that develops between the countercurrent flows in a wall vent. The CFAST model incorporates a vent mixing algorithm, but it has not been verified experimentally.

Stratification caused by mechanical ventilation has been observed experimentally; it seems to be a consequence of the injection of cool fresh air into the developing hot gas layer. This cool air is denser than the surrounding environment, causing it to have negative buoyancy. As this cool air descends, it entrains surrounding hot gases, causing the mixture to achieve an intermediate temperature. The vertical temperature gradient associated with mechanical injection of air near the ceiling is not addressed by any zone model. However, field models should be capable of addressing this condition. The significance of this effect has not been generalized.

3.7 Vents (Floor, Wall, Ceiling)

Natural ventilation is induced by pressure differentials arising from density differences between the fire-induced environment and the ambient environment. Natural ventilation may occur through openings in walls, floors and/or ceilings. Some models address only single wall openings, while others can address multiple wall, floor and ceiling openings.

One mechanism for mixing between the hot gas layer and the lower layer is mixing between counterflowing streams within a vent.

Stack effect, or chimney effect, is the flow induced by pressure differentials arising from differences between inside and outside ambient air temperatures. This effect is most significant in tall buildings at times when the difference between inside and outside temperatures is large. Wind around a building establishes pressure contours on the building envelope that can influence flows within a building under both fire and ambient conditions. Some models, such as CFAST and LES, address these phenomena, while others do not.

3.8 Ventilation Systems (Injection, Extraction, Balanced)

Mechanical ventilation is addressed by some models (e.g., CFAST) in terms of a fan/duct network that includes consideration of fan pressure/flow characteristic curves and duct friction losses, while other models (e.g., COMPBRN III, FIVE) address mechanical ventilation simply in terms of user-specified volumetric flow rates. Mixing caused by air extraction or injection is either not addressed at all or is addressed in a rudimentary way by zone models. As noted above, nearly linear temperature gradients have been observed in some mechanically ventilated enclosure fire experiments. The CFAST model provides an option to model this effect and the effect has been calculated with CFD models such as the LES model.

3.9 Enclosure Boundaries (Floor, Walls, Ceiling)

Heat loss to boundaries and equipment has a significant effect on thermal conditions within an enclosure subjected to fire. During the early stages of enclosure fires, as much as 95-100% of the heat released by a fire is lost to the boundaries. As the boundaries heat up, their ability to absorb additional heat released by a fire diminishes, reducing this heat loss fraction. Most zone models treat boundaries in terms of 1-dimensional heat conduction through a thermally thick slab. These models typically permit radiative and convective boundary conditions to be specified at the boundary surfaces. Such models do not typically account for heat losses to equipment, which can be significant particularly in spaces with much equipment, such as cable trays, located near the ceiling. Heat losses to objects in the hot gas layer can cause the models to over predict hot gas layer temperatures. Since field models predict conditions at discrete points throughout a space, field models like LES have the potential to include this effect.

Some models, such as the FIVE methodology, treat boundary heat loss in terms of a user specified heat loss factor, which represents the ratio of heat transferred to boundaries and equipment to the heat released by the fire. This approach recognizes the inaccuracy inherent in neglecting heat loss to equipment. The basic FIVE methodology uses a heat loss fraction of 70%, which should generally be conservative for fires that do increase ceiling and wall temperatures significantly about ambient. As boundary temperatures increase, the rate of heat transfer to these surfaces will decrease resulting in a smaller heat loss fraction. Most fire models allow the user to track boundary temperatures. This capability can be used during analysis to assess the impact of the changing heat loss. CFAST tracks the temperatures of the ceiling, walls, and floor separately. If desired, the user can have these values reported in the output.

The LES model provides three types of thermal boundary conditions. The user can select from adiabatic, thermally-thick, and thermally-thin walls. In addition, blockage or objects can be defined at any location within the enclosure volume. These object can have thermal properties similar to the walls and can ignite if a user specified ignition temperature is reached.

3.10 Fire Protection Systems (Detection, Alarm, Suppression)

The early work of Alpert [22] was aimed at evaluating the response of ceiling-mounted fire detectors. This work was followed by the work of Heskestad and Delichatsios [30], who investigated the initial convective flow induced by fires, including steady fires and power law growth rate fires. In the meantime, Heskestad and Smith [31] developed a method for evaluating the thermal response characteristics of fire detection devices based on a first order lumped capacity response model. Based on these works, Evans and Stroup [32] developed the DETACT series of models for evaluating the response to quasi-steady and power law growth fires of fire detectors mounted beneath large, unobstructed ceilings.

In recent years, the U.S. Navy has sponsored two series of large-scale fires in aircraft hangars [33] to evaluate current and potential fire protection strategies in such facilities, which are similar in some respect to turbine halls in power plants. Data from these Navy tests have been used for comparison with current fire plume and ceiling jet temperature correlations incorporated in the DETACT model. Overall, the model results "did not correlate" with the experimental data.

In a different series of tests conducted in an aircraft hanger with a ceiling height of 15 m (50 ft) and steady fires of approximately 4 MW, DETACT and LAVENT provided "reasonable predictions of ceiling jet temperatures and somewhat conservative predictions of thermal device temperatures" [34]. The fire protection device activation submodels used in DETACT and LAVENT are the same as those used in FIVE, CFAST, and LES. The LES model includes the capability to model multiple sprinkler activations. In addition, the CFAST and LES models includes algorithms for assessing the impact of the water droplets on the fire growth [35, 36].

3.11 Targets (People, Equipment, Fire Protection Devices)

This section identifies the capabilities of the models with respect to target exposure and response. Targets, which come in a variety of types, may be subjected to radiative and convective heat fluxes from flames, plumes/ceiling jets, hot gas layers and/or other objects. The response of a target will depend on its thermal characteristics as well as on the exposure conditions. In a broad sense, targets can be classified as thermally thin or as thermally thick, depending on the relative resistance the target exhibits to heat transfer to its interior.

The FIVE methodology permits a simplified analysis of the response of both thermally thick and thermally thin targets to imposed heat fluxes. The COMPBRN III and CFAST models as well as the LES model permit more detailed analyses. There has been relatively little work to verify the accuracy of these target heating algorithms by comparison with large-scale experimental data.

4. Verification and Validation Efforts

A number of efforts for fire model comparison, verification and validation have been undertaken. Many of these efforts have involved comparisons between measured and calculated parameters, primarily temperatures, mass flow rates and smoke layer interface positions. Different protocols have been used to evaluate appropriate average data values for zone model comparisons with experimental data. The details are not discussed here, but it should be recognized that reported experimental data has generally been based on different multi-point averaging techniques. Consequently, reported "measured" data is subject to its own level of uncertainty.

Mowrer [1] compared FIVE methodology calculations with data from two series of large scale fire tests: the FM/SNL series [37, 38] and the UL/SNL series [39]. The UL/SNL series has served as the primary basis for the comparison of the different versions of the COMPBRN model with experimental data. Duong [40] used this test series to compare CFAST model predictions with experimental data. Mowrer and Gautier [41] compared calculations of CFAST, COMPBRN III, FIVE and MAGIC with data from the FM/SNL and UL/SNL series as well as a NBS 3-room series [42]. Peacock, et al. [42] also compared CFAST model predictions with data from the NBS 3-room series and they attempted to evaluate the statistical significance of the experimental data.

Nelson and Deal [43] compared a number of fire models, including FIRST9X, FAST, CCFM-VENTS and the Fire Simulator model in FPETool, with experimental data from the one-room PRC tests conducted by McCaffrey and Quintiere [29], while a number of models have been compared with the one-room fire tests conducted by Steckler, et al. [21]. Peacock, et al. [44] describe a number of room fire test series that provide data for room fire model comparisons; they include descriptions of the PRC and Steckler test series. A number of investigators have compared fire model predictions with a series of fire tests performed in the decommissioned HDR nuclear reactor building in Germany [45]. The results of some of these comparisons have been discussed previously.

Currently, the LES model is the subject of a significant validation effort being conducted jointly by the National Institute of Standards and Technology and the National Fire Protection Research Foundation [46]. This effort is focused on the applicability of the model to large industrial warehouse type spaces. The model is being used to examine the interaction of sprinkler, draft curtains and heat/smoke vents. A series of full scale tests have been conducted using two fire sources, a heptane burner and the Group A Standard Plastic Commodity. During the tests, the fire is allowed to grow while multiple sprinklers activate in an effort to control the fire. Temperature, heat flux, and gas concentration data are recorded during the tests. Another effort is underway to examine the use of the LES model for analysis of smoke plume trajectory in the outdoors [47, 48]. While there is very little experimental data for model verification, certain patterns and trends, developed from multiple simulations using the ALOFT model (a specialized personal computer version of the LES model), "instill confidence in the overall methodology" [47]. This model provides "useful results" [47] given the uncertainties associated with experiments and modeling input involving the outdoors.

Currently, a working group under CIB W14 has undertaken an effort to validate fire model predictions through a round robin series of blind fire model predictions [49]. The objectives of the group include:

- Increase confidence in the use of fire models as tools for fire safety engineering;
- Support ISO/TC92/SC4 in its effort to produce a document on assessment and verification of calculation models;
- Consider all aspects of code evaluation, including physics, numerics, documentation, use of the codes, and availability of appropriate data for the selected scenarios; and
- Carry out a round robin project on deterministic numerical fire simulation computer codes and experiments for model evaluation.

The objectives of the evaluation are so great that it will require several years to complete. It is anticipated that at least ten different scenarios will be considered to assess a code to the extent the working group deems necessary for fire safety engineering. Only the first two scenarios, of a single plume under an exhaust hood and a single room with a door opening, have been considered so far. The second scenario is currently being reviewed.

BSI, formerly known as the British Standards Institute, has recently published a Draft for Development, DD 240, Parts 1 and 2, on "Fire safety engineering in buildings."[50, 51] Part 1 is a guide to the application of fire safety engineering principles, while Part 2 is a commentary on the equations given in Part 1. As noted in the Foreword to Part 1,

> "The original intention was to prepare a British Standard on Fire Safety Engineering. However, after considering the comments received on the draft code of practice circulated for public comment, particularly those concerning the current state of knowledge on the use of fire safety engineering, the responsible committee decided that it should be published as a Draft for Development before it could be given the status of a British Standard. It should therefore be applied on a provisional basis, so that information and experience on its practical application may be obtained."

Part 2 of the Draft for Development gives guidance on the limits of applicability and confidence limits for the equations given in Part 1, many of which are the same as in the three zone-type fire models discussed in this paper. To determine the limits of applicability and the confidence limits, a panel of leading international experts in the area of fire science and fire modeling was assembled and for each equation or mathematical treatment, members of the panel were asked to respond carefully to a questionnaire relating to quantification of model confidence. The primary outcomes of this survey were a description of the limits of applicability for each equation and the definition of the bounds for β-factors, which represent the ratio of predicted to measured values for a parameter. Based on this elicitation of expert knowledge, β-factors for most parameters fell within the range of 0.7 to 1.4, with some wider ranges.

5. Uncertainty Issues Associated with Fire Modeling

According to Custer and Meacham [52], uncertainty is inherent in the performance-based analysis and design process. Some of this uncertainty results from the specification of the problem being addressed (fire size, location, exposures, etc.). Limitations associated with the fire models used for problem analysis can produce additional uncertainties. Specifically, limitations in the number of physical processes considered and the depth of consideration can produce uncertainties concerning the accuracy of fire modeling results. Other uncertainties can be introduced due to limitations related to the input data required to conduct a fire simulation. Other sources of uncertain include specification of human tenability limits, damage thresholds, and critical end point identifiers (e.g., flashover).

The uncertainties associated with fire modeling can be addressed in several ways. A primary method for handling modeling uncertainties is the use of "engineering judgment." Among other things, this judgment is reflected in the selection of appropriate fire scenarios, hazard criteria, and fire modeling techniques. A slightly more formal application of engineering judgment is the use of safety factors. These safety factors can be applied in the form of fire size, increased or decreased fire growth rate, or conservative hazard criteria [52]. Experimental data obtained from fire tests, statistical data from actual fire experience, and other experts' judgment can be used improve the "judgment" and potentially decrease the level of uncertainty. However, the data and expert opinions can introduce new uncertainties into the problem. Siu and Apostolakis provide some guidance concerning assessment of uncertain data and expert opinion for nuclear power plant applications [53, 54].

Experimental data used for verification or validation of fire models as well as for input to the models can generate uncertainties. The International Organization for Standardization has drafted a guidance document providing information on assessment and verification of mathematical fire models and discusses the issue of test data uncertainty [55]. Typically, a measurement is only a result of an approximation or estimate of the specific quantity subject to measurement. Therefore, a measurement is not complete unless it is accompanied by a quantitative statement of the uncertainty [56].

Finally, a sensitivity analysis can be conducted to evaluate the impact of uncertainties associated with various aspects of a fire model. A sensitivity analysis should identify the dominant variables in the model, define acceptable ranges of input variables, and demonstrate the sensitivity of the output [55]. From this analysis, areas where extra caution in selecting inputs and drawing conclusions can be determined. A complete sensitivity analysis for a complex fire model is a sizable task. Again, engineering judgment will be required to select an appropriate set of case studies to use for the sensitivity analysis. The American Society for Testing and Materials also has a guide for evaluating the predictive capabilities of fire models [57]. The recommendations in this guide should be reviewed and applied as appropriate when utilizing fire modeling.

6. Conclusions and Recommendation

A limited effort has been made to identify key features, limitations and uncertainties in some current fire models. The range of conditions underlying the bases for the fire model elements have been explored. A number of model comparison and validation efforts have been identified as part of this preliminary undertaking. Such validation efforts are increasing in both number and detail with increasing international interest in performance-based fire safety. Most validation efforts for fire models have addressed relatively straightforward and low hazard fire scenarios. These efforts are worthwhile for exploring the accuracy of the algorithms employed by the models.

Since the fire itself is not generally predicted or calculated by fire models, the uncertainty associated with specification of potential fuels is a critical issue in the application of fire modeling techniques. In addition, uncertainties can result from the model, its other inputs, and the associated test data. Appropriate applications of safety factors and sensitivity analysis can be used to address some portion of the uncertainties. In view of the uncertainty issues, care must be exercised in the interpretation of fire modeling results. For scenarios where the level of predicted hazard is well below the damage threshold, the results can be used with a high level of confidence provided there is a high level of confidence that all risk-significant scenarios have been considered. For scenarios where the level of predicted hazard is near the damage threshold, the results should be used with caution in view of the uncertainties that exist.

The relationship between increasing impact of uncertainty and closeness to potential damage level suggests a multilevel approach to analyzing fire hazard could be a solution. This concept would be an expansion of one proposed by Kazarians, et. al. [58] for nuclear power plants. At the highest level, a grading schedule approach based on event tree or fault tree logic would be used to screen out areas requiring no additional consideration. The next step would be to apply a structured set of simple correlations, similar to the FIVE methodology, to further assess the impact of fire in various part of a nuclear power plant. A zone model would be applied to selected areas to calculate potential damage as a function of time in areas identified as representing significant risk based on the previous two assessments. Finally, a field model (e.g., LES) could be used to determine the fire environment around and resulting damage to specific target items within a space. By applying a four level system, the overlap between analytical methods would serve as an internal check and address some of the modeling uncertainties. The application of multiple models at each stage of the analysis would also be a method to increase confidence in the results.

This tied modeling approach should be accompanied by further experimental work. On one hand, experimental work could be aimed at providing the bases for comparison of modeling and analytical efforts. On the other hand, experimental work could be aimed at improving the understanding of damage mechanisms to safety-related equipment under realistic risk-significant fire scenarios.

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Table 1. Summary of Model Features

Model	FIVE	COMPBRN III	CFAST	LES
General features				
Type of model	Quasi-steady zone	Quasi-steady zone	Transient zone	Transient field
Number of layers	1	1-2	2	Multiple
Compartments	1	1	30	Multiple
Floors	1	1	30	Multiple
Vents	Wall (1)	Wall (1)	Wall (4 per room) Floor (1), Ceiling (1)	Multiple
Number of fires	Multiple	Multiple	Multiple	Multiple
Ignition of secondary fuels	No	Yes	Yes	Yes
Plume/ceiling jet sublayer	Yes	No	Yes	From Conservation Laws
Mechanical ventilation	Yes	Yes	Yes	Yes
Targets	Yes	Yes	Yes	Yes
Fire sources				
Types	1. Gas	1.Gas 2. Pool 3. Solid	1. Gas	No specific type
Combustion factors	1. O_2 constrained (optional) 2. Yields specified	O_2 constrained	1. O_2 constrained (optional) 2. Yields specified	1. O_2 constrained (optional) 2. Yields specified
Other factors		1. Secondary ignition 2. Radiation enhancement	1. Secondary ignition	1. Secondary ignition 2. Radiation enhancement
Fire plumes				
Types	1. Axisymmetric (Heskestad)	1. Axisymmetric (Zukoski)	1. Axisymmetric (McCaffrey)	Fluid Motion Equations
Modification factors	1. Wall/corner	1. Wall/corner 2. Doorway tilt	1. Wall/corner	From Conservation Laws
Ceiling jets				
Types	1. Unconfined (Alpert) 2. Confined (Delichatsios)	NA	Unconfined for Detection	From Conservation Laws
Vents				
Types	Wall	Wall	Wall Floor/ceiling	Wall Floor/ceiling
Method	Bernoulli / Orifice	Bernoulli / Orifice	Bernoulli / Orifice	From Conservation Laws
Modification factors	Flow coefficient	Flow coefficient Shear mixing	Flow coefficient Shear mixing Stack effect Wind effect	From Conservation Laws

Model	FIVE	COMPBRN III	CFAST	LES
Mechanical ventilation				
Types	Injection Extraction	Injection Extraction	Injection Extraction	Injection Extraction
Method	Volumetric flow	Volumetric flow	Fan/duct network (triple connection)	User specified velocity
Boundary heat loss				
Method	Heat loss factor	1-D conduction	1-D conduction	1-D conduction
Boundary conditions	NA	Radiative Convective	Radiative Convective (Floor/Ceiling)	Radiative Convective
Equipment heat loss	No	No	Yes (Targets)	Yes
Targets				
Types	1. Thermally thick 2. Thermally thin	1. Thermally thick	1. Thermally thick 2. Thermally thin	1. Thermally thick 2. Thermally thin 3. Adiabatic
Heating	Radiative Convective	Radiative Convective	Radiative Convective	Radiative Convective
Damage criteria	Temperature	Temperature	Temperature Heat flux Flux-time product	Temperature
Validation				
Room sizes	18m x 12m x 6m 9m x 4m x 3m 9m x 7.6m x 3m	3m x 3m x 2.2m 4m x 9m x 3m	12 m^3, 60,000 m^3 4m x 2.3m x 2.3m, multiroom (100 m^3), multiroom (200 m^3), seven-story building (140,000 m^3)	37m x 37m x 8m Outdoors
Ventilation	Forced, Natural	Natural	Natural, Forced	Natural, natural with wind
Fire sizes	500kW, 800kW, 1MW, 2MW	32kW, 63kW, 105kW, 158kW	<800kW, 4-36MW 2.9MW, 7MW, 100kW, 1MW, 3MW	4.5MW, 410MW, 450MW, 820MW, 900MW, 1640MW, 1800MW
Fire types	Steady, Transient	Steady	Steady, Transient	Steady, Transient
Fuels	Propylene gas, heptane pool, methanol pool, PMMA solid, electrical cables	Methane gas, electrical cables & heptane pool	Furniture, natural gas burner	Crude oil, heptane burner, Group A plastic commodity

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Features, Limitations And Uncertainties In Enclosure Fire Hazard Analyses – Preliminary Review

CONTRACT OR GRANT NUMBER

TYPE OF REPORT AND/OR PERIOD COVERED
Final

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PERFORMING ORGANIZATION (CHECK (X) ONE BOX)
- X NIST/GAITHERSBURG
- NIST/BOULDER
- NIST/JILA

LABORATORY AND DIVISION NAMES (FIRST NIST AUTHOR ONLY)
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SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS (STREET, CITY, STATE, ZIP)
U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, Washington, DC 20555

PROPOSED FOR NIST PUBLICATION

	JOURNAL OF RESEARCH (NIST JRES)		MONOGRAPH (NIST MN)		LETTER CIRCULAR
	J. PHYS. & CHEM. REF. DATA (JPCRD)		NATL. STD. REF. DATA SERIES (NIST NSRDS)		BUILDING SCI. SERIES
	HANDBOOK (NIST HB)		FEDERAL INFO. PROCESS. STDS. (NIST FIPS)		PRODUCT STANDARDS
	SPECIAL PUBLICATION (NIST SP)		LIST OF PUBLICATIONS (NIST LP)		OTHER
	TECHNICAL NOTE (TN)	X	INTERAGENCY/INTERNAL REPORT (NISTIR)		—

PROPOSED FOR NON-NIST PUBLICATION (CITE FULLY): —U.S. FOREIGN—

PUBLISHING MEDIUM: PAPER DISKETTE CD-ROM WWW OTHER

SUPPLEMENTARY NOTES

ABSTRACT (A 2000-CHARACTER OR LESS FACTUAL SUMMARY OF MOST SIGNIFICANT INFORMATION. IF DOCUMENT INCLUDES A SIGNIFICANT BIBLIOGRAPHY OR LITERATURE SURVEY, CITE IT HERE. SPELL OUT ACRONYMS ON FIRST REFERENCE.) (CONTINUE ON SEPARATE PAGE, IF NECESSARY.)

A significant number of fire modeling tools have been developed to analyze the hazards and risks associated with fires in buildings. These tools range from empirical correlations of data suitable for hand calculations, through control volume (zone) models of increasing sophistication, to state-of-the-art computational fluid dynamics (field) models. Properly applied, these tools permit development of a better understanding of the dynamics of building fires and can aid in the fire safety decision-making process. This report presents a review of three fire modeling tools (FIVE, COMPBRN III, CFAST) currently being used in fire safety design and a fourth model (LES) of the field model type which is beginning to be used in fire protection engineering. This review focuses on the application potential for these models in the nuclear power industry.

In view of the uncertainties associated with fire modeling predictions, extreme care must be exercised in the interpretation of fire modeling results. For scenarios where the level of predicted hazard is well below the damage threshold, the results can be used with a high level of confidence provided there is a high level of confidence that all risk-significant scenarios have been considered. For scenarios where the level of predicted hazard is near the damage threshold, the results should be used with caution in view of the uncertainties that exist. In order to address some of the uncertainties in fire modeling, a multi-level approach is proposed which combines professional judgment, correlations, zone models, and field models.

KEY WORDS (MAXIMUM OF 9; 28 CHARACTERS AND SPACES EACH; SEPARATE WITH SEMICOLONS; ALPHABETIC ORDER; CAPITALIZE ONLY PROPER NAMES)
compartment fires, computational fluid dynamics, computer models, field models, fire hazards assessment, fire models, hazard assessment, nuclear power plants, nuclear reactor safety, zone models

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