Chapter 7

# Fire Hazard Analysis Techniques

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Available methods to estimate the potential impact of fire can be divided into two categories: risk-based and hazard-based. Both types of methods estimate the potential consequences of possible events. Risk-based methods also analyze the likelihood of scenarios occurring, whereas hazard-based methods do not. Fire risk analysis is described more fully in Section 3, Chapter 8, "Fire Risk Analysis." Section 3, Chapter 9, "Closed Form Enclosure Fire Calculations," provides simple fire growth calculation methods.

The goal of a fire hazards analysis (FHA) is to determine the expected outcome of a specific set of conditions called a fire *scenario.* The scenario includes details of the room dimensions, contents, and materials of construction; arrangement of rooms in the building; sources of combustion air; position of doors; numbers, locations, and characteristics of occupants; and any other details that have an effect on the outcome of interest. This outcome determination can be made by expert judgment, by probabilistic methods using data from past incidents, or by deterministic means such as fire models. "Fire models" include empirical correlations, computer programs, full-scale and reduced-scale models, and other physical models. The trend today is to use models whenever possible, supplemented if necessary by expert judgment. Although probabilistic methods are widely used in risk analysis, they find little direct application in modern hazard analyses. Probabilistic models are discussed in Section 3, Chapter 5, "Introduction to Fire Modeling." Typically, when the potential impact of fire is estimated, a hazard basis is used. When probabilities or frequencies are considered, it is usually in the context of determining whether or not a scenario is sufficiently likely to warrant further analysis.

Hazard analysis can be used for one of two purposes. One is to determine the hazards that are present in an existing or planned facility. The other use is for design, where trial design strategies are evaluated to determine whether they achieve a set of fire safety goals. Hazard analysis can be thought of as a component of risk analysis. That is, a risk analysis is a set of hazard analyses that have been weighted by their likelihood of occurrence. The total risk is then the sum of all of the weighted hazard values. In the insurance and industrial sectors, risk assessments generally target monetary losses, since these dictate insurance rates or provide the incentive for expenditures on protection. In the nuclear power industry, probabilistic risk assessment has been the basis for safety regulation. Here the risk of a release of radioactive material to the environment is commonly examined, ranging from a leak of contaminated water to a core meltdown.

Available fire hazard calculation methods range from relatively simple equations that can be performed with a hand calculator to complex methods that require powerful computers, and many methods that fall between.

See also Section 2, Chapter 1, "Physics and Chemistry of Fire"; Section 3, Chapter 4, "Use of Fire Incident Data and Statistics"; Section 3, Chapter 5, "Introduction to Fire Modeling"; Section 3, Chapter 8, "Fire Risk Analysis"; Section 3, Chapter 9, "Closed Form Enclosure Fire Calculations";

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**Key Terms**

bounding condition, design fire curve, design fire scenario, fire hazard analysis, fire model, fire scenario, performance-based design, *t*-squared fire

Section 3, Chapter 10, "Performance-Based Codes and Standards for Fire Safety"; and Section 3, Chapter 11, "Overview of Performance-Based Fire Protection Design."

# PERFORMING A FIRE HAZARD ANALYSIS

## Steps of a Fire Hazard Analysis

Performing an FHA is a fairly straightforward engineering analysis. The steps include the following:

1. Selecting a target outcome
2. Determining the scenario(s) of concern that could result in that outcome
3. Selecting an appropriate method(s) for prediction of growth rate of fire effects
4. Calculating the time needed for occupants to move to a safe place
5. Analyzing the impact of exposure of occupants or property to the effects of the fire
6. Examining the uncertainty in the hazard analysis
7. Documentation of the fire hazard analysis process, including the basis for selection of models and input data

Fire hazard analysis can also be used as part of the performance-based design process. For more information on performance-based design, see Section 3, Chapter 10, "Performance-Based Codes and Standards for Fire Safety," and Section 3, Chapter 11, "Overview of Performance-Based Fire Protection Design."

## Selecting a Target Outcome

The target outcome most often specified is avoidance of occupant fatalities in a building. Another might be to ensure that fire fighters are provided with protected areas from which to fight fires in high-rise buildings. The U.S. Department of Energy (DOE) requires that FHAs be performed for all DOE facilities.[1] Their objectives for such FHAs, as stated in DOE 5480.7A, include the following:

- Minimizing the potential for the occurrence of fire
- No release of radiological or other hazardous material to threaten health, safety, or the environment
- An acceptable degree of life safety to be provided for DOE and contractor personnel and no undue hazards to the public from fire
- Critical process control or safety systems are not damaged by fire
- Vital programs are not delayed by fire (mission continuity)
- Property damage does not exceed acceptable levels (e.g., $150 million per incident)

An insurance company might want to limit the maximum probable loss to that on which the insurance rate paid by the customer is based; a manufacturer might want to avoid failures to meet orders to avoid erosion of its customer base; and some businesses might want to guard their public image of providing safe and comfortable accommodations. Any combination of these outcomes could be selected as appropriate for an FHA.

# DEVELOPING FIRE SCENARIOS AND DESIGN FIRE SCENARIOS

## Fire Scenario and Design Fire Scenario Defined

Determining the fire source is one of the most important parts of performing a fire hazard analysis. To determine the fire source, a design fire scenario must be developed. A *fire scenario* is a set of conditions that defines the development of fire and the spread of combustion products. Fire scenarios comprise three sets of features: building characteristics, occupant characteristics, and fire characteristics. Building characteristics describe the building features that could affect fire development and the spread of combustion products. Occupant characteristics describe the state(s) of occupants at the time of the fire. Fire characteristics describe the ignition and growth of the fire. A *design fire scenario* is a set of conditions that defines the critical factors for determining the outcomes for trial fire protection designs of new buildings or modifications to existing buildings.[2] Design fire scenarios are the fire scenarios that are selected to analyze a trial design. They are generally a subset of the fire scenarios.

The design fire scenario is based on a fire that has a reasonable likelihood of developing from a series of events. Fire scenarios need to be based on reality and should be developed accordingly. For example, the occupancy, the purpose for which the design is being developed, the fuel load, potential changes in the property, the presence of sprinklers and fire detection, the presence of alarm and notification systems, and smoke management should be considered. Design fire scenarios differ by occupancy and should be based on reasonably expected fires and worst-case fires. Although this chapter deals with hazard-based approaches, some risk must be included in the analysis when developing design fire scenarios. For instance, if a fire may be technically plausible but is extremely unlikely, that scenario may not be necessary to include in the design fire scenarios.

## Determining the Scenario(s) of Concern

Records of past fires, either for the specific building or for similar buildings or class of occupancy, can be of substantial help in identifying conditions to be avoided. Statistical data from NFPA or from the National Fire Incident Reporting System (NFIRS) on ignition sources, first items ignited, rooms of origin, and the like can provide valuable insight into the important factors contributing to fires in the occupancy of interest. (See also Section 3, Chapter 4, "Use of Fire Incident Data and Statistics.") Anecdotal accounts of individual incidents are interesting but might not represent the major part of the problem to be analyzed.

Murphy's Law ("if anything can go wrong, it will") applies to major fire disasters; that is, significant fires seem to involve a series of failures that set the stage for the event. Therefore, it is important to examine the consequences of things not going according to plan. In DOE-required FHAs, one part of the analysis is to assume both that automatic systems fail and that the fire department does not respond. This is used to determine a worst-case loss and to establish the real value of these systems. The 2006 edition of NFPA *101*®, *Life Safety Code*®, includes a performance-based design option containing a basic set of design fire scenarios. Scenario 8 is a common fire that starts while either the fire alarm system or the sprinkler system (in turn) is rendered ineffective. Given the normal high reliability of these systems, it is not required for the performance objectives to be met fully under these conditions, but stakeholders should feel that the resulting losses are not catastrophic or otherwise unacceptably severe. In a risk assessment, the consequences of such failures would be weighted by the probability of failure and added into the total risk. In a hazard analysis, the objective is hazard avoidance, so the contribution of low probability events is more subjective. Scenarios must be translated into design fires for fire growth analysis and occupant evacuation calculation. See the discussion in the Quantification of Design Fire Scenarios section later in this chapter.

## NFPA *101* Design Fire Scenarios

NFPA *101* provides eight design fire scenarios that should be considered in the development of a performance-based design. Briefly, these design fire scenarios are as follows:

1. An occupancy-specific design fire scenario that is representative of a typical fire for the occupancy
2. An ultrafast-developing fire in the primary means of egress, with interior doors open at the start of the fire (for a discussion of fire development, see Section 2, Chapter 4, "Dynamics of Compartment Fire Growth")
3. A fire that starts in a normally unoccupied room that may endanger large numbers of occupants
4. A fire that originates in a concealed wall or ceiling space adjacent to a large occupied room
5. A slowly developing fire, shielded from fire protection systems, in close proximity to a high-occupancy area
6. The most severe fire resulting from the largest possible fuel load characteristic of the normal operation of the building
7. An outside exposure fire
8. A fire originating in ordinary combustibles with each passive or active fire protection system individually rendered ineffective; this scenario is not required where it can be shown that the level of reliability and the design performance in the absence of the system are acceptable to the authority having jurisdiction (AHJ)

Although only eight scenarios are listed in the performance option of NFPA *101,* more than eight scenarios will be developed and analyzed. For most building designs, for example, there will usually be far more than a single scenario that is representative of a typical fire in a given occupancy.

## Applying NFPA *101* Design Fire Scenarios

For a typical building, what happens when each of these eight general scenarios is applied to what might occur as a reasonable design fire in that building? For the purposes of this illustration, a multistory hotel building with some meeting rooms on lower floors is considered. The following fires might be used as design fires in meeting the eight-scenario criteria of NFPA *101:*

1. A typical fire based on the occupancy might include a patron smoking in bed, or a sterno-initiated fire in a meeting room or restaurant area.
2. An ultrafast fire in a primary means of egress would likely mean a flammable liquid fire in the corridor near one of the exit doors.
3. Fire in a normally unoccupied room would likely include a fire in a janitor's closet, started by oily rags or ignition of some cleaning fluid.
4. Fire in a concealed space, particularly if the hotel were of combustible construction, might occur in the drop ceiling above the bathroom. This would likely be an electrical fire.
5. A shielded fire near occupied space might be in a maid's cart or under a display table in a meeting room.
6. The most severe fire from the largest fuel load typical to the building might occur during remodeling or might occur due to storage of furniture in one room or storage of chairs in a meeting room.
7. The outside exposure fire could include other buildings, skylights in the roof of a low-rise building nearby, or a wildland fire. This fire would be specific to the occupancy and building being considered.
8. Failure of a system would need to include looking at rated walls, rated floors, as well as sprinkler and fire alarm systems. When looking at these systems, one should consider what might fail rather than failure of the entire system. For instance, failure of a sprinkler system might mean failure of the entire water supply or it might mean failure of a single sprinkler to react when expected. By providing redundancy into water supply and fire pumps, and monitoring main valves, failures could be limited as a part of this evaluation.

## Bounding Conditions

During development of the fire scenarios and design fire scenarios, the allowable future changes in the facility must also be considered. The extent of the changes that are considered by the design become bounding conditions for the analysis and subsequent use of the building. One can expect that a design fire scenario is not exactly what will happen and that the building as originally designed and anticipated will not remain exactly as analyzed. Therefore, as one develops design fire scenarios and one calculates the expected fire response, some amount of change in those scenarios must also be considered.

When conducting a hazard analysis, it is important to consider the types of changes that may occur. If the hazard analysis only considered a specific set of initial conditions, then it would be necessary to revise the fire hazard analysis any time changes were made in the future. The range of changes that will be considered by the hazard analysis is a judgment call between the designers and the owner.

For example, a hotel room floor might become a meeting room floor; a meeting room area might become an exposition center; occupant loads could be greater than expected or calculated; movable walls could create simultaneous use when nonsimultaneous use was expected; or the space between a ballroom ceiling and the floor above might be used for storage. All of these events are reasonably foreseeable, but some may fall outside of the bounding conditions. Bounding conditions must be clearly identified because changes in the building may occur.

Other situations that might occur on a more general basis, for any occupancy, include the response of a fire department and cutbacks in fire department funding or unwanted alarms causing deactivation of a system. Some of these bounding assumptions can be addressed specifically—for instance, maximum fuel load or occupant characteristics.

## Implied Risk

Although this chapter addresses fire hazard analysis, there is some implied risk in any such analysis. The primary risk factors involved are included in the design fire development. The design fires described for the hotel building did not include such accidents as gasoline tanker trucks crashing into the side of the building or bombs ignited at the base of the building. There is always the risk that these events could happen, but the engineer must evaluate the likelihood of these events. For example, buildings are typically not designed to survive the impact and ensuing fire of a missile strike. If this were to occur, achievement of the design goals and objectives might not be expected. Similarly, it is conceivable that simultaneous fires could occur, although prescriptive building codes such as NFPA *101* explicitly exclude such an event. These might be limitations described in the fire strategy report to clarify what is covered and what is not.

When proposing to exclude a scenario from further consideration, it is important to ensure that stakeholders understand the implications of excluding the scenario. For example, if the fire scenario associated with a gasoline tanker truck crashing into the side of the building is dismissed, and the building is located on a highway leading to a major oil refinery, stakeholders would need to understand and accept that if a gasoline tanker truck did crash into the side of the building, goals and objectives might not be met.

## Data Sources

In developing design fire scenarios, it is useful to have data on which to base future quantification. Members of the NFPA *Life Safety Code* Technical Committees developed the design fire scenarios based on statistical analyses prepared by the NFPA Fire Analysis and Research Division and also on past fires that have occurred in different occupancy types.

The NFPA One Stop Data Shop provides much information regarding fire statistics and results. Other sources addressing typical fires in occupancies include Factory Mutual data, state or local jurisdiction data for various occupancies, the National Fire Incident Reporting System, or past fire history published in the *NFPA Journal.* Other possibilities include fire test results (many of which can be found on the National Institute of Standards and Technology Fire Internet site), manufacturers' data regarding specific fire performance of materials, or listings of materials by recognized test labs. It can be reasonably expected that the amount of data to develop a design fire will not be sufficient to exactly predict what will happen in all cases.

## Overall Example

The following example develops scenarios for a large exhibit hall at a convention center and describes some of the work that might be done using the scenarios that have been developed.

The first step is to investigate potential fires that might occur so that the design fire scenarios can be chosen. Based on the scenarios from NFPA *101,* the scenarios examined for a typical convention center might be as follows:

1. The occupancy-specific design fire scenario might include a fire in an exhibit booth or a fire in auditorium seating.
2. The ultrafast fire might involve a fire in a plastic boat display located near the main exit.
3. A fire in a normally unoccupied room could occur in the storage of stacked chairs in an exhibit hall next to the exhibit hall being considered. There could be a show in one exhibit hall with large numbers of people, and the adjacent hall might be used as temporary storage during that event.
4. A fire in a concealed space is unlikely in Type 1 construction but could occur in electrical or insulation areas.
5. A shielded fire could occur in the plastic boat previously mentioned or in a covered exhibit space. More and more jurisdictions are requiring automatic sprinklers in covered exhibit spaces, but that is not yet universal.
6. The most severe fire to be considered would likely be the boat fire previously mentioned.
7. An outside exposure fire would typically not be considered for this occupancy because convention centers are generally surrounded by parking lots and other open areas. However, if the loading dock is considered outside, the scenario might involve fire in a truck waiting to unload at the convention center.
8. A typical fire with failure might include failure of the sprinkler or fire alarm system or perhaps failure of the smoke control system.

If the purpose of the example is to perform an egress analysis, the worst-case fire may be all that is necessary for evaluation. The worst-case fire would likely be the shielded boat fire at peak rate of heat release. To quantify the fire, users might look at the fuel load and estimate the rate of burning, they might look at plastic fires and extrapolate, they might look at fast or ultrafast fires and assume the fire peaks at the estimated sprinkler response time, they might assume the fire is shielded on the inside of the boat and so not have the fire peak at the estimated sprinkler response time, or they might specify sprinklers inside the boat and limit the fire size. The user would likely try a combination of these factors to see the effects.

Once the fire scenario is developed, smoke-filling calculations can be performed to determine the clear height of a smoke layer over time. Those calculations would be compared to the timed evacuation analysis. Both calculations would likely start without suppression or smoke control to see whether the evacuation can occur without those two systems. If so, the analysis is simplified.

Finally, the user would identify bounding conditions via a sensitivity analysis. For instance, is the size of the boat important? How about the materials of the boat? Has the fuel been removed from the boat? If smoke control is necessary to make the design work, that smoke control needs to be identified as a critical system. Similarly, the occupant load, the exit sizes, the number of disabled persons, and the availability of an alarm system as well as its audibility must all be considered in the sensitivity analyses.

Once all of these factors have been considered and dealt with, the hazard-based analysis is complete. The documentation of the analysis is the next important part and cannot be omitted from any fire hazard analysis. The assumptions, bounding conditions, scenarios considered, and limitations should be identified to the AHJs, the owner, and other interested parties. See Section 3, Chapter 11, "Overview of Performance-Based Fire Protection Design," for more details on documentation requirements.

## QUANTIFICATION OF DESIGN FIRE SCENARIOS

Quantification of design fire scenarios involves two steps. The first step is to develop the design fire curve for the design fire scenario or portion of the design fire scenario of interest. The design fire curve represents the heat release rate over time for the fire in question. Once the design fire curve is estimated, the second step, predicting the fire effects, is then possible.

The purpose of the design fire is similar to the assumed loading in a structural analysis—that is, to answer the question of whether the design will perform as intended under the assumed challenge. Keeping in mind that the greatest challenge is not necessarily the largest fire (especially in a sprinklered building), it is helpful to think of design fires in terms of their growth phase, steady-burning phase, and decay phase (Figure 3.7.1).

### Design Fire Curves

The design fire curve is a description of the intensity (heat release rate) of a fire as a function of time. The design fire curve can be divided into four phases: ignition, growth, steady-burning, and decay. Because there is not a single framework for developing the entire design fire curve, each step is typically developed separately and then brought together as a single curve.

It is not always necessary to quantify each phase of a design fire curve, depending on the goals of the analysis. For example, to predict when a fire detection or suppression system would activate, it might only be necessary to quantify the growth phase. For sizing a smoke control system, only the maximum heat release rate might be needed. A structural analysis might need the peak burning rate and the duration of peak burning. Performing an evacuation analysis might require quantification of the growth and fully developed stages.

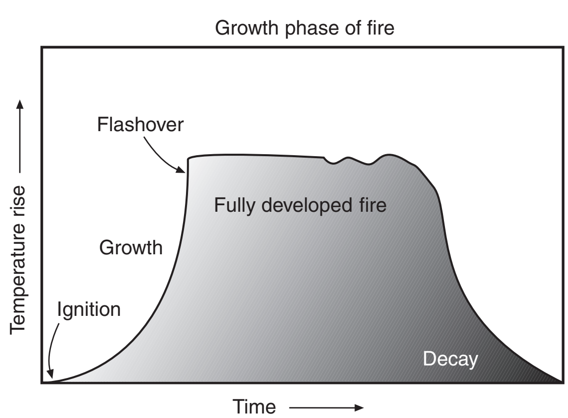


**FIGURE 3.7.1** Design Fire Structure

**Ignition.** The design fire curve starts at ignition. A simple approach to developing a design fire curve is to assume that an ignition source of sufficient intensity is available to instantaneously ignite the initial fuel package to establish burning. However, if the heat transfer to a combustible object or the temperature of the object is known, calculations can be performed to predict whether the object will ignite. Calculations to determine whether ignition occurs depend on the state of the fuel: solid, liquid, or gas.

Ignition can be divided into two categories: piloted and nonpiloted. In the case of piloted ignition, a "pilot" such as a spark or flame initiates flaming. For nonpiloted ignition, flaming occurs spontaneously as a result of heating in the absence of flame or spark.[3] Except for piloted ignition of gases and liquids that are at a temperature above their flashpoint, all materials must first be heated before ignition can take place.[3]

*Solids.* With the exception of smoldering combustion, for a solid to ignite it must first be heated sufficiently to release flammable vapors. Flammable vapors can be given off either by pyrolysis or by melting and subsequent vaporization. Pyrolysis occurs when a material is heated and decomposes, releasing vapors known as *pyrolyzates.* Unlike melting and vaporization, in which no molecular changes occur, the vapors given off are different from the material that was originally heated.[4] The process of pyrolysis can be viewed as "thermal cracking," in which larger molecules are broken into smaller molecules.

Piloted ignition occurs if the concentration of pyrolysis gases is above the lower flammable limit and a "pilot" is present. For nonpiloted ignition to occur, the pyrolysis gases must be at a concentration above the lower flammable limit and they must be above their autoignition temperature. Because of this, it requires less energy for piloted ignition to occur than for nonpiloted ignition.[4]

Methods of predicting ignition of solid materials exposed to thermal radiation differ depending on whether a solid is thermally thin or thermally thick. A thermally thick material is one in which a temperature rise will not be perceived on the unexposed surface when the material is heated. Wood is a typical example of a thermally thick material, whereas sheet metal is a good example of a thermally thin material.

An engineering guide[4] published by the Society of Fire Protection Engineers (SFPE) focusing on piloted ignition contains six methods for predicting the piloted ignition of solid materials under radiant exposure as follows.

For thermally thin materials, the method of Mikkola and Wichman can be used:

$$t_{ig} = \rho L_0 c \frac{(T_{ig} - T_0)}{(\dot{q}''_r - \dot{q}''_{crit})} \qquad (1)$$

where

$T_{ig}$ = Ignition temperature (°C)

$T_0$ = Initial temperature (°C)

$t_{ig}$ = Time to ignition (sec)

$\rho$ = Density of the material (kg/m$^3$)

$c$ = Specific heat of the material (kJ/kg·C)

$L_0$ = Thickness of the material (m)

$\dot{q}''_r$ = External heat flux (kW/m$^2$)

$\dot{q}''_{crit}$ = Critical heat flux for ignition (kW/m$^2$)

For thermally thick materials, the following methods can be used:

- Mikkola and Wichman

$$t_{ig} = \frac{\pi}{4} k\rho c \frac{(T_{ig} - T_0)^2}{(\dot{q}''_r - \dot{q}''_{crit})^2} \tag{2}$$

  where $k$ is thermal conductivity (W/m·K).

- Tewarson

$$t_{ig} = \frac{\pi}{4} \frac{(TRP)^2}{(\dot{q}''_r - \dot{q}''_{min})^2} \tag{3}$$

  where $TRP$ is thermal response parameter (kW·sec$^{1/2}$/m$^2$) and $\dot{q}''_{min}$ is minimum heat flux for ignition (kW/m$^2$).

- Quintiere and Harkleroad

$$t_{ig} = \left(\frac{\dot{q}''_{min}}{b \cdot \dot{q}''_r}\right)^2 \qquad \text{for } t \le t_m \tag{4}$$

  where b is a constant related to $k\rho c$ (sec$^{-1/2}$) and $t_m$ is characteristic time to reach thermal equilibrium (sec).

- Janssens

$$t_{ig} = 0.563 \left(\frac{k\rho c}{h_{ig}^2}\right)\left(\frac{\dot{q}''_r}{\dot{q}''_{crit}} - 1\right)^{-1.83} \tag{5}$$

  where $h_{ig}$ is heat transfer coefficient at ignition, which incorporates both the radiative and convective components (W/m$^2$·C).

- Toal, Silcock, and Shields

$$t_{ig} = \frac{(FTP_n)}{(\dot{q}''_r - \dot{q}''_{crit})^n} \tag{6}$$

  where $FTP_n$ is flux time product and $n$ is flux time product index is greater than or equal to 1.

See SFPE's engineering guide[4] for additional information on applying these methods as well as the appropriateness of these methods for different situations.

*Liquids.* For a liquid to ignite, it must be at a temperature that is equal to or greater than its flashpoint. NFPA 30, *Flammable and Combustible Liquids Code,* defines flashpoint as "the minimum temperature of a liquid at which sufficient vapor is given off to form an ignitable mixture with air, near the surface of the liquid or within the vessel used."

A number of test methods can be used to measure the flashpoint of a liquid. Flashpoint is not a physical property and is instead a model of physical phenomena associated with vaporization of a sufficient quantity of fuel to establish a gaseous mixture that is at the lower flammable limit at a distance above the fuel surface and therefore can change with the test method employed.[3]

Ignition of a liquid at its flashpoint is analogous to piloted ignition of a solid, in that for ignition to occur, a pilot must be present. The analogy for nonpiloted ignition of liquids would be ignition at the autoignition temperature. Values for flashpoints and autoignition temperatures for some common materials can be found in NFPA 497, *Recommended Practice for the Classification of Flammable Liquids, Gases, or Vapors and of Hazardous (Classified) Locations for Electrical Installations in Chemical Process Areas.*

*Gases.* For ignition of a flammable gas to occur, it must be mixed with a sufficient quantity of oxygen for a reaction to take place. Concentrations where this occurs are represented by a flammability range, which corresponds to gas/air concentrations that are at or above the lower flammable limit and not exceeding the upper flammable limit. Flammability limits for a variety of gases can be found in NFPA 497.

For mixtures of flammable gases, Le Chatelier's principle can be used to determine the lower flammable limit.[3] Le Chatelier's law states that

$$L_m = \frac{100}{\sum_i \frac{P_i}{L_i}} \tag{7}$$

where

$L_m$ = Lower flammability limit of the mixture

$P_i$ = Volume fraction of gas $i$

$L_i$ = Lower flammable limit of gas $i$

For more information, see Section 6, Chapter 10, "Gases."

**Fire Growth.** Following ignition, a fire might grow as it develops on the first item ignited or spreads to additional items. To determine whether spread would occur to adjacent items, the problem can be approached from the perspective of whether or not these items would ignite. For growth involving a single item, the fire could spread to unignited portions of the item. This could either lead to the entire item burning, or earlier ignited portions might burn out before the fire spreads to involve the entire item, such that the entire item is never fully involved.

## Prediction of Fire Effects

The primary importance of the appropriate selection of the design fire's growth is in obtaining a realistic prediction of detector and sprinkler activation, time to start of evacuation, and time to initial exposure of occupants. In 1972, Heskestad first proposed that for the early fire growth period the assumption that fires grow according to a power law relation works well and is supported by experimental data.[5] He suggested fires of the form

$$Q = \alpha t^n \tag{8}$$

where

$Q$ = Rate of heat release (kW)

$\alpha$ = Fire intensity coefficient (kW/sec$^n$)

$t$ = Time (sec)

$n$ = 1, 2, 3

Later, it was shown that for most flaming fires (except flammable liquids and some others) $n = 2$, the so-called $t$-squared growth rate.[6] A set of specific $t$-squared fires labeled slow, medium, and fast, with fire intensity coefficients such that the fires reached 1000 Btu/sec (1055 kW) in 600, 300, and 150 seconds, respectively, were proposed for design of fire detection systems.[7] Later, these specific growth curves and a fourth called "ultrafast,"[8] which reaches 1055 kW in 75 seconds, gained favor in general fire protection applications.

This set of $t$-squared growth curves is shown in Figure 3.7.2. The slow curve is appropriate for fires involving thick, solid objects (e.g., solid wood table, bedroom dresser, or cabinet). The medium growth curve is typical of solid fuels of lower density (e.g., upholstered furniture and mattresses). Fast fires are thin, combustible items (e.g., paper, cardboard boxes, draperies). Ultrafast fires are some flammable liquids, some older types of upholstered furniture and mattresses, or materials containing other highly volatile fuels.

These $t$-squared curves represent fire growth starting with a reasonably large, flaming ignition source. With small sources, there is an incubation period before established flaming, which can influence the response of smoke detectors. During this incubation period, the fire may not significantly grow in size, although smoke would still be produced in quantities potentially sufficient to activate smoke detectors.

This specific set of fire growth curves has been incorporated into several design methods, such as that for the design of fire detection systems in *NFPA 72®, National Fire Alarm Code®*. They are also referenced as appropriate design fires in several international methods for performing alternative design analyses in Australia and Japan and in a product fire risk analysis method published in this country.[9] Although in the Australian methodology the selection of growth curve is related to the fuel load (mass of combustible material per unit floor area), this is not justified, since the growth rate is related to the form, arrangement, and type of material and not simply its quantity. Consider 22 lb (10 kg) of wood arranged in a solid cube, as sticks arranged in a crib, and as a layer of sawdust (Figure 3.7.3). These three arrangements would have significantly different growth rates although representing identical fuel loads.

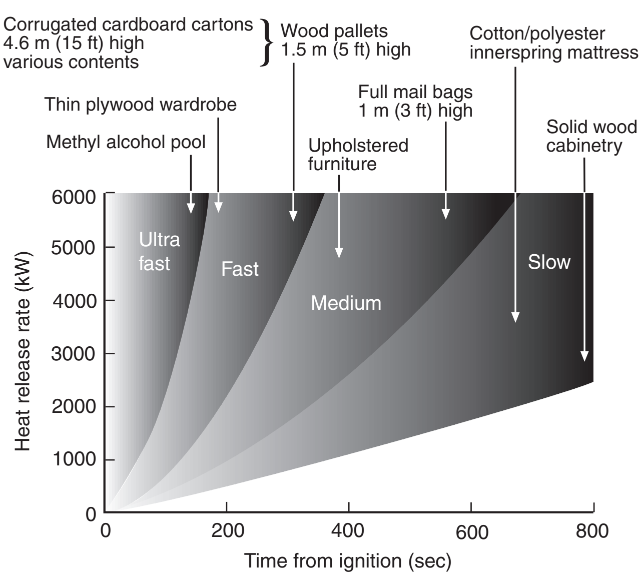


**FIGURE 3.7.2** Set of $t$-Squared Growth Curves

**Steady Burning.** Where a fire scenario involves a fire in an enclosure, fire growth might continue until all the combustible items within the room are involved. Once this occurs, the rate of burning is influenced by one of two factors: (1) the available ventilation or (2) the available fuel. Calculation of fire temperatures within the room is easily accomplished by use of simple algebraic equations. Although computer models are frequently used in hazard analyses, they are generally no more accurate (and indeed may be less accurate) than simple hand calculations for prediction of temperature and burning rate during fully developed burning.[10] For example, for postflashover fires, hand calculation methods are generally used to estimate compartment temperatures.[11]

SFPE's engineering guide[11] on fire exposures of structural elements provides calculation methods for predicting fire temperatures and burning rates in fully developed compartment fires. Some of these methods are based on an assumption of ventilation-limited burning, and others model fuel-controlled conditions. For most cases, the method developed by Law was found to provide bounding predictions when the "Ψ" factor was not used and the predicted burning duration was increased by a factor of 1.4.

Law's method is as follows:

$$T = T_{gm}(1 - e^{-0.05\Psi})(°C) \tag{9}$$

$$T_{gm} = 6000 \left( \frac{1 - e^{-0.1 \frac{A}{A_o \sqrt{H_o}}}}{\sqrt{\frac{A}{A_o \sqrt{H_o}}}} \right) (°C)$$

$$\dot{m}_f = 0.18 A_o \sqrt{H_o} \left( \frac{W}{D} \right) \left( 1 - e^{-0.036 \frac{A}{A_o \sqrt{H_o}}} \right) (\text{kg/sec})$$

where

$T_{gm}$ = Maximum compartment temperature (°C)

$A$ = Surface area of interior of enclosure ($m^2$)

$A_o$ = Area of ventilation opening ($m^2$)

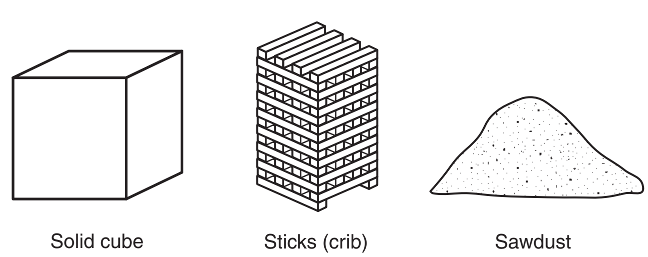


**FIGURE 3.7.3** Dependence of Fire Growth on Fuel Form and Arrangements

$H_o$ = Height of ventilation opening (m)

$$\Psi = \frac{m_f}{\sqrt{A \times A_o}}$$

$m_f$ = Mass of fuel (kg)

$\dot{m}_f$ = Mass burning rate of fuel (kg/sec)

$W$ = Width of wall containing ventilation opening (m)

$D$ = Depth of compartment (m)

Law reports that the correlation for predicting burning rate is valid for

$$\frac{\dot{m}_f}{A_o\sqrt{H_o}}\left(\frac{D}{W}\right)^{1/2} < 60$$

In some cases, it may only be desired to predict whether flashover is possible for a given fire scenario involving a fire in an enclosure. In such cases, the approach described in the section Prediction of Flashover can be used.[12]

**Decay.** All fires eventually decrease in size. A fire can decay for one of three reasons: consumption of available fuel, oxygen depletion, or suppression. Because the hazards posed during the decay phase are typically insignificant in comparison to the hazards posed during the fully developed phase, decay is typically omitted from analysis. An exception is in calculations involving structural fire resistance of concrete or insulated steel. Where test data are available, they might include decay.

If decay occurs due to the exhaustion of fuel, Table 3.7.1 shows the expected temperature change as fuel is depleted.[11] For fires with a predicted duration of less than 60 minutes, a decay rate of 10°C/min can be used. In other case, a decay rate of 7°C/min can be used.

Decay could also occur in the event that a sprinkler system is present and activated. A simple assumption is that the fire immediately goes out, but this is not conservative. A National Institute of Standards and Technology (NIST) study documents a (conservative) exponential diminution in burning rate under the application of water from a sprinkler (Figure 3.7.4).[13] Since the combustion efficiency is affected by the application of water, the use of values for soot and gas yields appropriate for post-flashover burning would represent the conservative approach in the absence of experimental data.

**Prediction of Flashover.** Flashover occurs when a fire grows to such a size that it involves all combustible items within an enclosed room. Although occurrence of flashover is not a hazard in itself, flashover would affect the occurrence of other hazards as described in the next section. Several correlations are available to predict the minimum heat release rate necessary for flashover to occur in a room. The time at which flashover occurs can be estimated by determining when the fire is predicted to reach this minimum size. The following methods can be used to predict the minimum heat release rate necessary for flashover.[12]

**TABLE 3.7.1** Rate of Decrease in Temperature

| *Temperature Decay (°C/min)* | *Restrictions* |
|---|---|
| 10 | Duration < 60 minutes |
| 7 | Duration > 60 minutes |

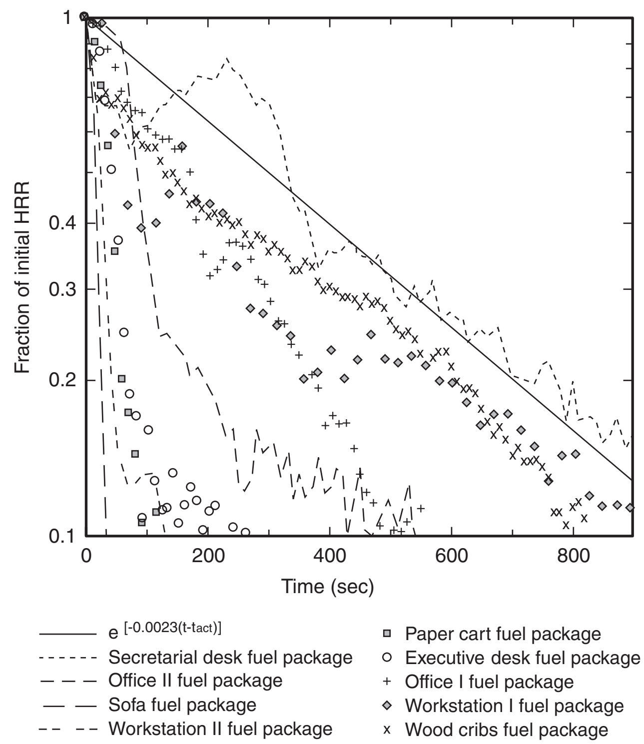


**FIGURE 3.7.4** Decay Rates for Various Fuels

- Method of Babrauskas

$$\dot{Q} = 750A_o\sqrt{H_o} \quad (9)$$

where

$\dot{Q}$ = Minimum heat release rate required for flashover (kW)

$A_o$ = Area of opening into compartment (m$^2$)

$H_o$ = Height of opening into compartment (m)

- Method of McCaffrey, Quintiere, and Harkleroad

$$\dot{Q} = 610(h_k A_T A_o\sqrt{H_o})^{1/2} \quad (10)$$

where

$$h_k = \frac{k}{\delta}$$

$k$ = Thermal conductivity of compartment surface (kW/m·K)

$\delta$ = Thickness of compartment surface (m)

$A_T$ = Total area of compartment surfaces (m$^2$)

- Method of Thomas

$$\dot{Q} = 7.8A_T + 378A_o\sqrt{H_o} \quad (11)$$

where the variables are as defined above.

## PREDICTION OF HAZARDS

Fire is a dynamic process of interacting physics and chemistry, so predicting what is likely to happen under a given set of circumstances is daunting. The simplest predictive methods are algebraic equations. Computer models are used to automate fire hazard calculations and are particularly useful where many repeated calculations must be performed.

### Simple Fire Hazard Calculations

Once the design fire curve has been developed, it is then possible to predict the hazards that would result. The types of hazards that might be of interest include the following:

- Radiant heat flux, which affects the potential for ignition of materials or thermal injury to people
- Smoke production, which dictates the volume of smoke produced
- Fire plume and ceiling jet temperatures and velocities, which could cause weakening of exposed structural elements
- Species production, which affects the rate at which an untenable environment could be created
- Depth of upper layer, which can be used as a surrogate for an untenable environment

As was the case with the stages of design fire curves, it is not always necessary to quantify all of the hazards that result from a design fire scenario. The hazards that are quantified are a function of the goals of the analysis. For example, if the purpose of the analysis is to determine whether a thermally activated detection or suppression system activates, only the plume and ceiling jet temperatures and velocities might be determined. For analysis of a smoke control system, only the smoke production rate might be determined. A structural analysis might only require calculation of the heat transfer to the structure. An evacuation analysis might require quantification of all of the hazards listed.

**Radiant Heat Flux.** Radiant heat flux is a measure of the rate of radiative heat transfer per unit area. An example of radiant heat transfer is the heating that can be felt from exposure to the sun on a hot day (although the intensity of thermal radiation in sunlight is too small to be of concern from a fire standpoint). The radiant heat flux from a single burning item can be predicted as a function of the distance from the item in accordance with Equation 18 of Section 3, Chapter 9, "Closed Form Enclosure Fire Calculations." For radiant heat fluxes resulting from fire gases, such as in a compartment fire, the radiant heat flux can be calculated if the gas temperature and the temperature of the target object are known by applying the following equation:

$$\dot{Q}_r = \varepsilon\sigma(T_1^4 - T_2^4) \tag{12}$$

where

$\dot{Q}_r$ = Rate of radiant heat transfer (kW)

$\varepsilon$ = Emissivity of gas (0–1) (—)

$\sigma$ = Stephan-Boltzmann constant ($5.67 \times 10^{-11}$ kW/m$^2$·K$^4$)

$T_1$ = Temperature of gas (K)

$T_2$ = Temperature of target (K)

The equation is only applicable for instantaneous calculations, as the temperature of the target will rise as a function of the thermal radiation that it receives.

**Smoke Production.** When calculating smoke production rates, *smoke* is usually defined as the products of combustion and the air entrained into the fire plume. Therefore, the amount of smoke produced is a function of the height above the fire. Section 3, Chapter 9, "Closed Form Enclosure Fire Calculations," provides a number of equations that can be used to predict smoke production.

**Fire Plumes and Ceiling Jet Temperatures and Velocities.** A fire will produce a plume of hot gas that will rise and contact the ceiling of a compartment, forming a ceiling jet. The temperature and velocity of a plume can be calculated as described in Section 3, Chapter 9, "Closed Form Enclosure Fire Calculations." Similarly, the temperature and velocity of a ceiling jet can be calculated in accordance with the following equations:[14]

$$\text{For } 0.18 \geq \frac{r}{H} \qquad \Delta T = \frac{16.9\dot{Q}^{2/3}}{H^{5/3}} \tag{13}$$

$$\text{For } \frac{r}{H} > 0.18 \qquad \Delta T = \frac{5.38(\dot{Q}/r)^{2/3}}{H} \tag{14}$$

$$\text{For } 0.15 \geq \frac{r}{H} \qquad U = 0.96\left(\frac{\dot{Q}}{H}\right)^{1/3} \tag{15}$$

$$\text{For } \frac{r}{H} > 0.15 \qquad U = \frac{0.195\dot{Q}^{1/3}H^{1/2}}{(r/H)^{5/6}} \tag{16}$$

where

$\Delta T$ = Temperature rise over ambient (°C)

$U$ = Ceiling jet velocity (m/sec)

$H$ = Height above fire (m)

$r$ = Horizontal distance from fire centerline (m)

$\dot{Q}$ = Total heat release rate (kW)

When using these equations, it must be cautioned that they are only valid for horizontal, unobstructed ceilings where there is no smoke layer present. In cases where a layer forms, higher temperature rises can be expected.

**Species Production.** Fires can create a number of products of combustion that can be toxic or corrosive, including carbon dioxide ($CO_2$), water vapor ($H_2O$), carbon monoxide (CO), and many others that vary with the fuel and burning conditions. Species production rates can be calculated from the following equation:[15]

$$\dot{G}_j = y_j \frac{\dot{Q}}{\Delta H_c} \tag{17}$$

where

$\dot{G}_j$ = Smoke production rate of species $j$ (kg/sec)

$y_j$ = Yield fraction of species $j$ (–)

$\dot{Q}$ = Heat release rate (kW)

$\Delta H_c$ = Heat of combustion of fuel (kJ/kg)

Yield fractions for several fuels are available in the *SFPE Handbook of Fire Protection Engineering.*[15]

**Depth of Upper Layer.** As smoke is produced in a compartment, it forms a layer that descends as a function of time. This is analogous to filling a bowl of water. Section 3, Chapter 9, "Closed Form Enclosure Fire Calculations," provides an equation that can be used to estimate the velocity of descent of the smoke layer. However, when applying this equation, it should be noted that the mass production rate of smoke is not constant, since as the layer descends, the smoke production rate decreases due to the reduced vertical distance available to entrain air into the plume. (See the equations for predicting smoke production rate in the same chapter.)

**Toxicity.** Toxic gases produced by a fire can incapacitate or kill people who are exposed to them. A commonly used approach to determine whether the fire-induced environment is potentially harmful to people exposed is the "fractional effective dose" (FED) model developed by Purser.[16] This can be expressed as follows:

$$F_{IN} = [(F_{I_{CO}} + F_{I_{CN}} + FLC_{irr}) \times VCO_2 + FED_{I_O}] \text{ or } F_{I_{CO_2}} \tag{18}$$

where

$F_{IN}$ = Fraction of an incapacitating dose of all asphyxiating gases

$F_{I_{CO}}$ = Fraction of an incapacitating dose of CO

$F_{I_{CN}}$ = Fraction of an incapacitating dose of HCN

$FLC_{irr}$ = Fraction of irritant dose

$VCO_2$ = Multiplication factor for $CO_2$-induced hyperventilation

$FED_{I_O}$ = Fraction of an incapacitating dose of low-oxygen hypoxia

$F_{I_{CO_2}}$ = Fraction of an incapacitating dose of $CO_2$

Purser gives the following equations for calculation of the individual fractional effective doses:[16]

$$F_{I_{CO}} = \frac{8.2925 \times 10^{-4} \times [CO]^{1.036}}{30} \tag{19}$$

where [CO] is the concentration of CO, expressed in parts per million.

$$F_{I_{CN}} = \frac{\exp\,(CN/43)}{220} \tag{20}$$

where

CN = The concentration of HCN in parts per million added to the concentration of other nitriles minus the concentration of $NO_2$

$FLC_{irr}$ = The fraction of the incapacitating dose from all incapacitating products (HCl, HBr, etc.)

$VCO_2 = \exp\left(\frac{[CO_2]}{5}\right)$, where $[CO_2]$ is the concentration of carbon dioxide in percent

$FED_{I_O} = \{\exp[8.13 - 0.54(20.9 - [O_2])]\}^{-1}$, where $[O_2]$ is the concentration of oxygen in percent

$F_{I_{CO_2}} = \{\exp[6.1623 - 0.5189[CO_2]]\}^{-1}$, where $[CO_2]$ is the concentration of $CO_2$ in percent

It should be noted that the equations for FED and the components of FED are based on a one minute exposure. For exposures to constant concentrations of fire products, the FED can be determined by multiplying the value determined using the previous equations by the exposure time in minutes. For exposures where the concentrations vary with time, the total FED can be calculated by discretizing the exposure (determining the average exposure at each one minute interval and summing the FED determined for each one minute interval).

It should be noted when applying the previous correlations that some populations are more susceptible than others to fire products (e.g., asthmatics, the old, and the young). Additionally, no single FED value for design has been widely agreed on even for "average" populations. A report by the National Institute of Standards and Technology investigates this subject in detail.[17]

**Egress Calculations.** Evacuation calculations are sometimes simple enough to be done by hand. The most thorough presentation on this subject (and the one that is most often used in alternative design analysis) is that of Nelson and Mowrer.[18] See also Section 4, Chapter 2, "Calculation Methods for Egress Prediction."

## Simple Analytical Solution Techniques

Simple computer programs and spreadsheets can be used to perform simple fire hazard calculations. In the case of the equations listed previously or referenced in other chapters, this is a relatively straightforward task. However, many fires and fire effects are not steady state. An example is smoke filling within an enclosure. The smoke production rate is a function of the smoke layer height, so the rate of smoke layer descent is not constant. In such instances, spreadsheets can be used to develop solutions to differential equations for which developing an exact solution is nontrivial.

For a differential equation of the following form:

$$\frac{dy}{dt} = f(y, t) \tag{21}$$

where the initial value $y(t = 0)$ is $y_0$.

The Euler method is a numerical technique for solving differential equations of this form, and can be stated as

$$y_{n+1} = y_n + hf(y_n, t_n) \tag{22}$$

where

$y_n$ = Value of equation $y$ at time step $n$

$y_{n+1}$ = Value of equation $y$ at time step $n + 1$

$h$ = Time step size

This process can be iterated over the desired length of time to obtain the desired solution. Since the Euler method determines the value of equation $y$ at time step $n + 1$ based on the value at time step $n$ and the slope of the tangent to $y$ at time step $n$, errors can be introduced based on the nonlinearity of equation $y$. There are methods available to reduce this error, such as the improved Euler method.

However, another method of reducing the error is to reduce the size of the time step, recognizing that as the size of the time step approaches zero, the difference between the predicted value of $y$ and the actual value of $y$ also approaches zero. The computational power offered by modern computers allows very small time steps to be used and to still get a solution rapidly.

It should be noted that the default for many spreadsheets is to not permit iterative calculations. (The spreadsheet views the "circular reference" as an error.) Spreadsheets for which this is the case would need to be configured to allow iteration. The spreadsheet's user's manual or help function can be consulted for assistance.

**EXAMPLE.** *Thermal detector response can be used to illustrate application of the Euler method to a fire protection problem.* This example uses an algorithm similar to that used by the computer fire model DETACT-QS[19] to predict the time to activation of a thermal detector for a heat release rate that follows a power law curve. Two calculations will be performed. First, the instantaneous ceiling jet velocities are calculated in accordance with Equations 13 through 16. A quasi-steady assumption is made, which means that transport delays from the fire to the detector are ignored. Then, based on the temperature and velocity of the ceiling jet and the thermal response characteristics of the sensor (response time index), the temperature change at the detector will be calculated. See Section 16, "Water-Based Fire Suppression Equipment" for more information. The change in temperature of the detector can be expressed as[20]

$$\frac{dT_d}{dt} = \frac{\sqrt{U_g}(T_g - T_d)}{RTI} \qquad (23)$$

where

$T_d$ = Temperature of detector (°C)

$U_g$ = Ceiling jet velocity at detector (m/sec)

$T_g$ = Ceiling jet temperature at detector (°C)

$t$ = Time (sec)

$RTI$ = Detector response time index ($m^{1/2} \times sec^{1/2}$)

A Euler solution to this expression can be expressed as

$$T_{d_{n+1}} + T_{d_n} + \Delta t \frac{\sqrt{U_g}(T_g - T_{d_n})}{RTI} \qquad (24)$$

where

$T_{d_{n+1}}$ = Temperature of detector at time step $n + 1$ (°C)

$T_{d_n}$ = Temperature of detector at time step $n$ (°C)

$\Delta t$ = Size of time step (sec)

Equation 24 could easily be programmed into a spreadsheet or simple computer program, along with the ceiling jet temperature and velocity correlations expressed in Equations 13 through 16, to calculate $U_g$ and $T_g$. It is also necessary to include a method of calculating the heat release rate at each time step.

The following example illustrates the use of this method in estimating thermal detector response. A heat detector is located on a 3 m high ceiling, 2 m away from a fire located on the floor with a constant heat release rate of 1000 kW. The room has an ambient temperature of 20°C and is sufficiently large that a smoke layer will not form quickly. The heat detector has a temperature rating of 75°C and an RTI of 50 $m^{½}sec^{½}$. When would the detector operate? Using Equation 24 and Equations 13 through 16, the solutions in Table 3.7.2 are obtained when different time steps are used.

## Computer Models

**Fire Models.** A survey[21] documented available models and calculation methods that could be applied to FHA. The key to determining which are appropriate to a given situation and which are not is a thorough understanding of the assumptions and limitations of the individual model or calculation and how these relate to the situation being analyzed. Single-room models are appropriate where the conditions of interest are limited to a single, enclosed space. Where the area of interest involves more than one space, and especially where the area of interest extends beyond a single floor, multiple-compartment models should be used. This is because the interconnected spaces interact to influence fire development and flows.

Many single-compartment models assume that the lower layer remains at ambient conditions (e.g., ASET).[22] Since there is little mixing between layers in a room (unless there are mechanical systems), these models are appropriate. However, significant mixing can occur in doorways, so multiple-compartment models should allow the lower layer to be contaminated by energy and mass (Figure 3.7.5).

The model should include the limitation of burning by available oxygen. This is straightforward to implement (based on the oxygen consumption principle) and is crucial to obtaining an accurate prediction for ventilation-controlled burning. For multiple-compartment models, it is equally important for the model to track unburned fuel and allow it to burn when it encounters sufficient oxygen and temperature. Without these features, the model concentrates the combustion in the room of origin, overpredicting conditions there and underpredicting conditions in other spaces.

**TABLE 3.7.2** Time Step(s) Predicted Activation Time(s)

| *Time Step(s)* | *Predicted Activation Time(s)* |
|---|---|
| 1 | 24.000 |
| 0.1 | 24.200 |
| 0.01 | 24.230 |
| 0.001 | 24.229 |

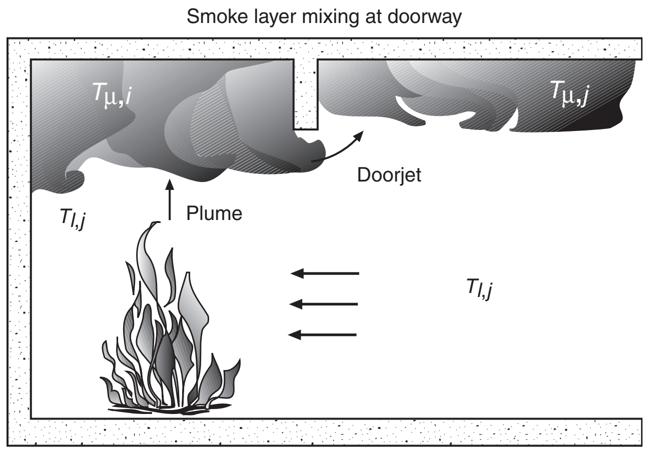


**FIGURE 3.7.5** Assumption of Zone Models That Fire Gases Collect in Internally Uniform Layers

Heat transfer calculations take up a lot of computer time, so many models take a shortcut. The most common is the use of a constant "heat loss fraction," which is user-selectable (e.g., ASET or CCFM[23]). The problem is that heat loss can vary during the course of the fire.

Another problem can occur in tall spaces, for example, atria. The major source of gas expansion and energy and mass dilution is entrainment of ambient air into the fire plume. It can be argued that in a very tall plume, this entrainment is constrained. However, most models do not include this constraint, which can lead to an underestimate of the temperature and smoke density and an overestimate of the layer volume and filling rate—the combination of which may give predictions of available safe egress times that are either greater or less than the correct value. In the model CFAST,[24] this constraint is implemented by stopping entrainment when the plume temperature drops to within 1°C of the temperature just outside the plume, where buoyancy ceases.

**Documentation.** Only models that are rigorously documented should be allowed in any application involving public health, safety, or welfare, such as in code enforcement or litigation. This means that the model should be supplied with a technical reference guide that includes a detailed description of the included physics and chemistry, with proper literature references; a listing of all assumptions and limitations of the model; and estimates of the accuracy of the resulting predictions, based on comparisons to experimental data. Public exposure and review of the exact basis for a model's calculations, internal constants, and assumptions are necessary for it to have credibility in a regulatory application.

ASTM publishes a *Standard Guide for Documenting Computer Software for Fire Models,* ASTM E1472-05.[25] Documentation for any model used in a regulatory application should comply with this guide. Although it may not be necessary for the full source code to be available, the method of implementing key calculations in the code and details of the numerical solver used should be included. This documentation should be freely available to any user of the model, and a copy should be supplied with the analysis as an important supporting document.

**Input Data.** Even if the model is correct, the results can be seriously in error if the data that are input to the model do not represent the condition being analyzed. The FHA should include a listing of all data values used, their source (i.e., what apparatus or test method was employed and what organization ran the test and published the data), and some discussion of the uncertainty of the data and its result on the conclusions. The National Institute of Standards and Technology's (NIST) website contains a section of well-documented data for use in calculations, called *Fire on the Web* (http://fire.nist.gov). A much larger database, called FASTDATA, is available from NIST on a CD-ROM (see the URL above for information). (See also the subsection entitled "Accounting for Uncertainty" later in this chapter.)

**Egress Models.** The prediction of the time needed by the building occupants to evacuate to a safe area can be performed and compared to the predicted available safe egress time. Whether the evacuation calculation is done by model or hand calculation, it must account for several crucial factors. First, unless the occupants see the actual fire, time is required for detection and notification *before* the evacuation process can begin. Next, unless the information is compelling (such as seeing the actual fire), it takes time for people to decide to take action. The action they choose may or may not be evacuation. Finally, the movement begins. All of these factors require time, and that is the critical factor. No matter how the calculation is done, *all* of the factors must be included in the analysis to obtain a complete picture. An excellent discussion of this topic is found in SFPE's *Engineering Guide—Human Behavior in Fire.*[26]

The process of emergency evacuation of people follows the general concepts of traffic flow. A number of models perform such calculations and may be appropriate for use in certain occupancies. Most of these models do not account for behavior and the interaction of people (providing assistance) during the event. The literature reports incidents of providing assistance to disabled persons, again especially in office settings.[27] If such behavior is expected, it should be included, as it can result in significant delays in evacuating a building.

Crowded conditions, as well as smoke density, can result in reduced walking speeds.[28] A person's walking speed decreases in dense smoke until he or she moves as if blindfolded (Figure 3.7.6). Care should be exercised in using models relative to how they select the path (usually the *shortest* path) that the person travels. Some models are *optimization* calculations that give the best possible performance.

## Analyzing the Impact of Exposure

In most cases, the exposure will be to people, and the methods used to assess the impacts of exposure of people to heat and combustion gases involve the application of combustion toxicology models. The HAZARD I software package contains the only toxicological computer model, called TENAB,[29] that is based on research at NIST on lethality to rats and by Purser on incapacitation of monkeys. TENAB accounts for the variation

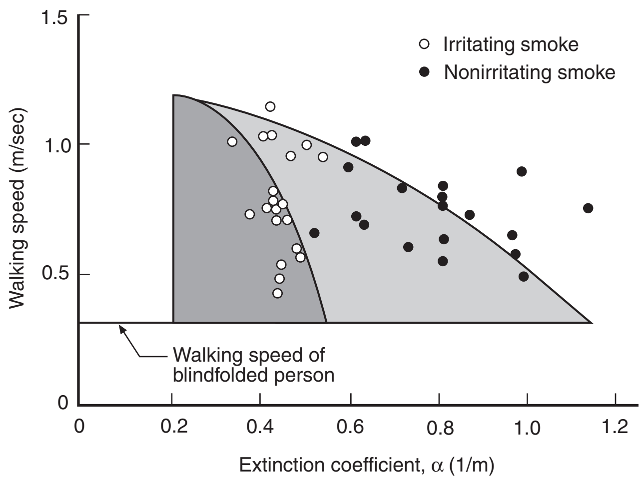


**FIGURE 3.7.6** Reduced Walking Speeds Resulting from Crowded Conditions and Smoke Density

in exposure to combustion products as people move through a building, by reading the concentrations from the fire model in the occupied space during the time the person is in that space. If the person moves into a space with a lower concentration of carbon monoxide, the accumulated dose can decrease. Details such as these ensure that the results are reasonable.

Assessing the impact of exposure to sensitive equipment is more difficult, since little data exist in the literature on the effects of smoke exposure on such equipment. Of particular importance here is the existence of acid gases in smoke, which are corrosive and especially harmful to electronics. Fuels containing chlorine (e.g., polyvinyl chlorides) have been studied. However, unless the equipment is close to the fire, acid gases, especially HCl, deposit on the walls and lower the concentration to which the equipment may be exposed. CFAST in the HAZARD I package contains a routine that models this process and the associated diminution of HCl concentration.

## Accounting for Uncertainty

Uncertainty analysis refers to dealing with the unknowns and variation inherent in any prediction. In the calculations, this uncertainty is derived from assumptions in the models and from the representativeness of the input data. In evacuation calculations, there is the added variability of any population of real people. In building designs and codes, the classic method of treating uncertainty is with safety factors. A sufficient safety factor is applied such that, if all of the uncertainty resulted in error in the same direction, the result would still provide an acceptable solution. In the prediction of fire development/filling time, the intent is to select design fires that provide a *worst likely* scenario. Thus a safety factor is not needed here, unless assumptions or data are used to which the predicted result is very sensitive.

The FHA report should include a discussion of uncertainty. This discussion should address the representativeness of the data used and the sensitivity of the results to data and assumptions made. If the sensitivity is not readily apparent, a sensitivity analysis (i.e., varying the data to the limits and seeing whether the conclusions change) should be performed. This is also a good time to justify the appropriateness of the model or calculation method. For more information, see Section 3, Chapter 10, "Performance-Based Codes and Standards for Fire Safety."

## Final Review

If a model or calculation produces a result that seems counterintuitive, there is probably something wrong. Cases have been seen in which the model clearly produced a wrong answer (e.g., the temperature predicted approached the surface temperature of the sun), and there have been others in which it initially looked wrong but was not (e.g., a *dropping* temperature in a space adjacent to a room with a growing fire was caused by cold air from outdoors being drawn in an open door). Conversely, if the result is consistent with logic, sense, and experience, it is probably correct. This is also a good time to consider whether the analysis addressed all of the important scenarios and likely events. Were all the assumptions justified and were uncertainties addressed sufficiently to provide a comfort level similar to that obtained when the plan review shows that all code requirements have been met?

# SUMMARY

Quantitative fire hazard analysis is becoming the fundamental tool of modern fire safety engineering practice and is the enabling technology for the transition to performance-based codes and standards. (For more information on performance-based codes, see Section 3, Chapter 10, "Performance-Based Codes and Standards for Fire Safety.") The tools and techniques described in this chapter provide an introduction to this topic and the motivation for fire protection engineers to learn more about the proper application of this technology.

Predicted fire hazards are a function of the design fire scenarios analyzed. Therefore, when performing a fire hazard analysis, it is important to select design fire scenarios that are challenging enough to represent a realistic "worst case," but not so challenging that the likelihood of occurrence is too remote.

There are many fire hazard calculations that can be performed with a hand calculator, a simple spreadsheet, or a computer program. In some cases, these simple methods would not be sufficient, for example, in cases where compartment geometry is complex, where it is desired to optimize cost/benefit, or where predicted hazard values are very close to acceptable limits. However, even in these types of cases, simple methods can be used for initial predictions or as a reality check of results from more complex models.

In any engineering analysis, it is incumbent on the user to understand the application and limitation of any methods used. This chapter has outlined a number of simple fire hazard calculation methods, but the applicability and limitations of the methods were not included. Users are referred to the documents referenced in the text for information regarding the applications and limitations of any of the methods included in this chapter.

## ACKNOWLEDGMENT

James R. Quiter, P.E., wrote portions of the discussion of design fire scenarios, which originally appeared in the "Simple Fire Hazard Calculations" chapter in the 19th edition of this handbook.

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### NFPA Codes, Standards, and Recommended Practices

*Reference to the following NFPA codes, standards, and recommended practices will provide further information on fire hazard analysis techniques discussed in this chapter. (See the latest version of* The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 30, *Flammable and Combustible Liquids Code*
*NFPA 72®, National Fire Alarm Code®*
NFPA *101®*, *Life Safety Code®*
NFPA 497, *Recommended Practice for the Classification of Flammable Liquids, Gases, or Vapors and of Hazardous (Classified) Locations for Electrical Installations in Chemical Process Areas*