FIRE HAZARD ANALYSIS

by

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Revised by Richard W. Bukowski

Historically, most fire safety regulation has been on the basis of fire hazard analysis, where such assessments were based on the judgment of "experts." Today formal, scientifically based fire hazard analysis (FHA) is common and increasingly being required as a means to avert certain outcomes, regardless of their likelihood. This chapter will discuss the differences between hazard and risk analysis, the process of performing an FHA, and resources available to assist in this process.

HAZARD *VS.* RISK

The goal of an FHA is to determine the expected outcome of a specific set of conditions called a *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 will have an effect on the outcome of interest. This outcome determination can be made by expert judgment; by probabilistic methods using data on past incidents; or by deterministic means, such as fire models. The trend today is to use models wherever possible, supplemented where necessary by expert judgment. While probabilistic methods are widely used in risk analysis, they find little direct application in modern hazard analyses.

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 they most often examine the risk of a release of radioactive material to the environment, from anything ranging from a leak of contaminated water to a core meltdown.

FHA performed in support of regulatory actions generally look at hazards to life, although other outcomes can be examined as long as the condition can be quantified. For example, in a museum or historical structure, the purpose of an FHA might be to avoid damage to valuable or irreplaceable objects or to the structure itself. It would then be necessary to determine the maximum exposure to heat and combustion products that can be tolerated by these items before unacceptable damage occurs.

PERFORMING AN FHA

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

1. Selecting a target outcome
2. Determining the scenario(s) of concern that could result in that outcome
3. Selecting design fire(s)
4. Selecting an appropriate method(s) for prediction
5. Performing an evacuation calculation
6. Analyzing the impact of exposure
7. Accounting for uncertainty

Selecting a Target Outcome

The target outcome most often specified is to avoid fatalities of occupants of 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:

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

In Boston, MA, the Office of the Fire Marshal[2] has established a set of objectives for FHAs performed in support of requests for waivers of the prescriptive requirements of the applicable code. These include:

1. Limit the probability of fatalities or major injuries to only those occupants intimate with the fire ignition.
2. Limit the probability of minor injuries to only those in the dwelling unit of origin.

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3. No occupant outside of the dwelling unit of origin should be exposed to the products of combustion in a manner that causes any injury.
4. Limit the probability of flame damage to the dwelling unit of fire origin (this includes taking into account the possibility of flame extension up the exterior of the building).
5. Limit the probability of reaching hazardous levels of smoke and toxic gases in the dwelling unit of fire origin before safe egress time is allowed. At no time during the incident should the smoke conditions in any compartment, including the compartment of origin, endanger persons in those compartments or prevent egress through those compartments.
6. Limit the incident to one manageable by the Boston Fire Department without major commitment of resources or excessive danger to fire fighters during all phases of fire department operation; i.e., search and rescue, evacuation, and extinguishment.

An insurance company might want to limit the maximum probable loss (MPL) to that which is the basis for the insurance rate paid by the customer; a manufacturer wants to avoid failures to meet orders resulting in erosion of its customer base; and some businesses must guard their public image of providing safe and comfortable accommodations. Any combination of these outcomes may be selected as appropriate for FHAs, depending on the purposes for which they are being performed.

Determining the Scenario(s) of Concern

Once the outcomes to be avoided are established, the task is to identify any scenarios that may result in these undesirable outcomes. Here, the best guide is experience. 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 leading to the outcome(s) to be avoided. Statistical data from the National Fire Incident Reporting System (NFIRS) on ignition sources, first items ignited, rooms of origin, etc., can provide valuable insight into the important factors contributing to fires in the occupancy of interest. (See also Chapter 3, "Use of Fire Incident Data and Statistics," in this section.) Anecdotal accounts of individual incidents are interesting, but may not represent the major part of the problem to be analyzed.

Murphy's Law (anything that can go wrong, will) is applicable to major fire disasters; i.e., all significant fires seem to involve a series of failures that set the stage for the event. Thus, 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 protective systems. If nothing else, such assumptions can help to identify the factors that mean the difference between an incidental fire and a major disaster so that appropriate backups can be arranged.

Scenarios must be translated into design fires for fire growth analysis and occupant assumptions for evacuation calculation.

Selecting Design Fire(s)

Choosing a relevant set of design fires with which to challenge the design is crucial to conducting a valid analysis. The purpose of the design fire is similar to the assumed loading in a structural analysis; i.e., 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 the design fires in terms of their growth phase, steady-burning phase, and decay phase. (See Figure 11-7A.)

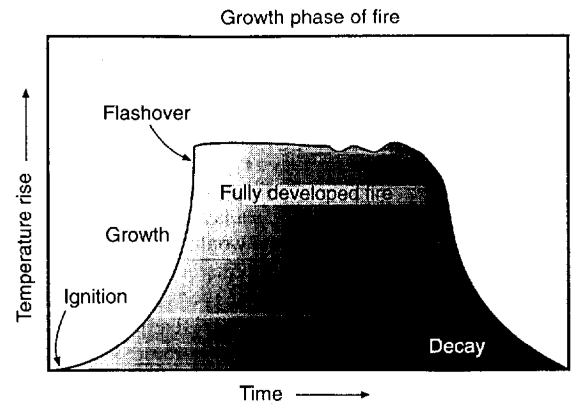

FIG. 11-7A. Design fire structure.

Growth: 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 these early times, the assumption that fires grow according to a power law relation works well and is supported by experimental data.[9] He suggested fires of the form:

$$Q = \alpha t^n$$

where

Q = rate of heat release (kW)
α = fire intensity coefficient (kW/s^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.[10] A set of specific t-squared fires labeled slow, medium, and fast, with fire intensity coefficients (α) such that the fires reached 1,055 kW (1,000 Btu/sec) in 600, 300, and 150 sec, respectively, were proposed for design of fire detection systems.[11] Later, these specific growth curves and a fourth called "ultra-fast,"[12] which reaches 1,055 kW in 75 sec, gained favor in general fire protection applications.

This set of t-squared growth curves is shown in Figure 11-7B. 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). Ultra-fast fires are some flammable liquids, some older types of upholstered furniture and mattresses, or other highly volatile fuels.

In a highly mixed collection of fuels, selecting the medium curve is appropriate as long as there is no especially flammable item present. It should also be noted that 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 (resulting in an underestimate of time to detection). This can be simulated by adding a slow, linear growth period until the rate of heat release reaches 25 kW.

This specific set of fire growth curves has been incorporated into several design methods, such as for the design of fire detection systems in NFPA 72, *National Fire Alarm Code*.[13] 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.[14] While 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 10 kg (22 lb) of wood: arranged in a solid cube, sticks arranged in a crib, and as a layer of sawdust. (See Figure 11-7C.) These three arrangements would have significantly different growth rates while representing identical fuel loads.

Steady burning: Once all of the surface area of the fuel is burning, the heat release rate goes into a steady burning phase. This may be at a sub-flashover or a post-flashover level; the former will be fuel controlled and the latter ventilation controlled. It should be obvious from the model output (for oxygen concentration or upper layer temperature) in which condition the fire is burning.

Most fires of interest will be ventilation controlled; and this is a distinct advantage, since it is easier to specify sources of air than details of the fuel items. This makes the prediction relatively insensitive to both fuel characteristics and quantity, since adding or reducing fuel simply makes the outside flame larger or smaller. Thus, for ventilation-controlled situations: (1) the heat release rate can be specified at a level that results in a flame out the door, and (2) the heat released inside the room will be controlled to the appropriate level by the model's calculation of available oxygen. If the door flame is outside, it has no effect on conditions in the building; if in another room it will affect that and subsequent rooms. For the much smaller number of fuel-controlled scenarios, values of heat release rate per unit area at a given radiant exposure (from the ASTM E1354, *Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter*[15]) can be found in handbooks, and used with an estimate of the total fuel area.

Decay: Burning rate declines as the fuel is exhausted. In the absence of experimental data, an engineering approximation specifies this decline as the inverse of the growth curve; this means that fast-growth fuels decay fast and slow decay slow. It is often assumed that the time at which decay begins is when 20 percent of the original fuel is left. While these are assumptions, they are technically reasonable.

This decay will proceed even if a sprinkler system is present and activated. A simple assumption is that the fire immediately goes out; but this is not conservative. A recent National Institute of Science and Technology (NIST) study documents a (conservative) exponential diminution in burning rate under the application of water from a sprinkler. (See Figure 11-7D.)[16] Since the combustion efficiency is affected by the application of water, the use of values of soot and gas yields appropriate for post-flashover burning would represent the conservative approach in the absence of experimental data.

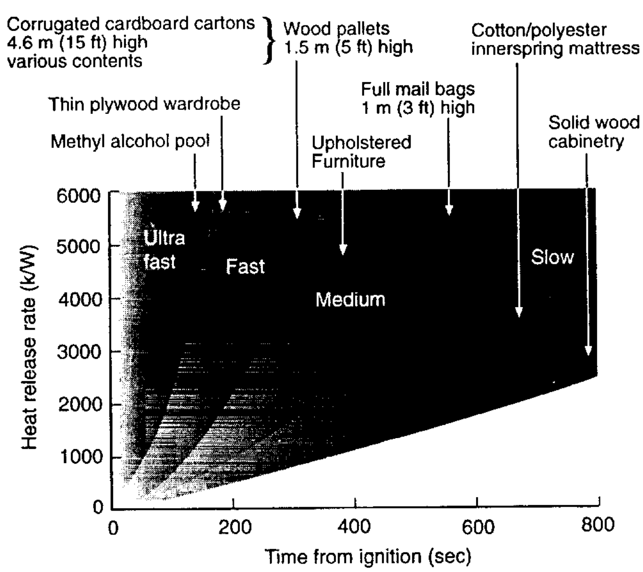

FIG. 11-7B. Set of t-squared growth curves.

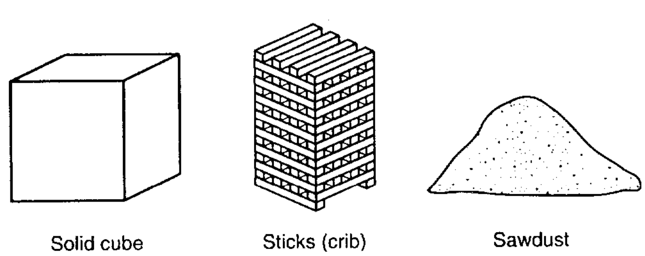

FIG. 11-7C. Fire growth depends on fuel form and arrangements. 10 kg (22 lb) of wood represent identical fuel loads but produce vastly different rates of heat release in a room.

Selecting an Appropriate Method(s) for Prediction

Fire models: A recent survey[3] documented 62 models and calculation methods that could be applied to FHA. Thus, the need is to determine which ones are appropriate to a given situation and which

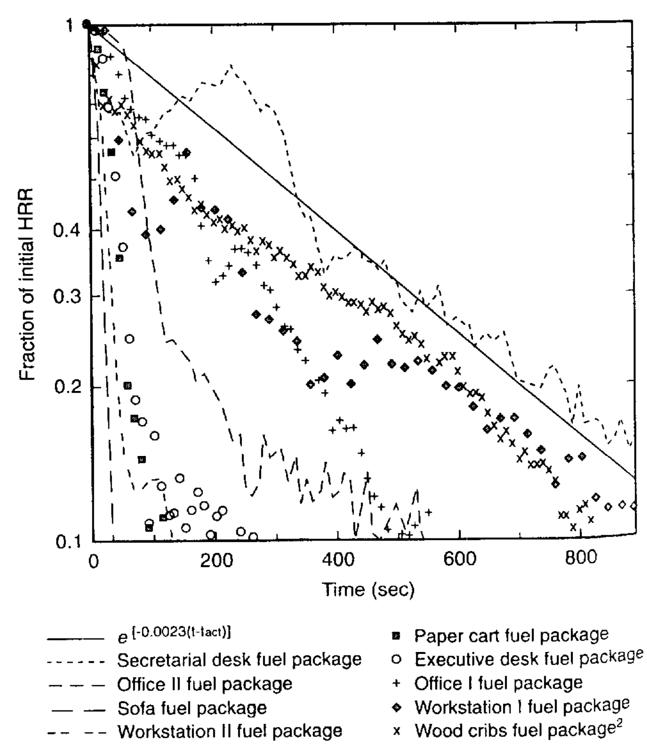

FIG. 11-7D. Decay rates for various fuels under fire sprinkler spray.

are not. The key to this decision is a thorough understanding of the assumptions and limitations of the individual model or calculation and how these relate to the situation being analyzed.

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 of predictive methods are the (algebraic) equations. Often developed wholly or in part from correlations to experimental data, they represent, at best, estimates with significant uncertainty. Yet, under the right circumstances, they have been demonstrated to provide useful results, especially where used to assist in setting up a more complex model. For example, Thomas' flashover correlation[4] and the McCaffrey/Quintiere/Harkleroad (MQH) upper layer temperature correlation[5] are generally held to provide useful engineering estimates of whether flashover occurs and peak compartment temperatures.

Where public safety is at stake, it is inappropriate to rely solely on such estimation techniques for the fire development/smoke filling calculation. Here, only fire models (or appropriate testing) should be used. 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 the fire development and flows.

Many single-compartment models assume that the lower layer remains at ambient conditions (e.g., ASET[6]). 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. (See Figure 11-7E.)

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.

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[7]). The problem is that heat losses vary significantly during the course of the fire. Thus, in smaller rooms or spaces with larger surface-to-volume ratios where heat loss variations are significant, this simplification is a major source of error. In large, open spaces with no walls or walls made of highly insulating materials, the constant heat loss fraction may produce acceptable results; but, in most cases, the best approach is to use a model that does proper heat transfer.

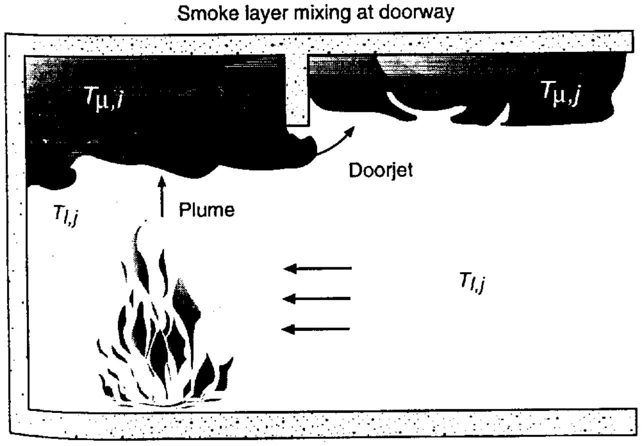

FIG. 11-7E. Zone models assume that fire gases collect in layers that are internally uniform.

Another problem can occur in tall spaces, e.g., 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; but most models do not include this. This 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 egress times available that are either greater or less than the correct value. In the model CFAST[8] this constraint is implemented by stopping entrainment when the plume temperature drops to within one degree (Kelvin) of the temperature just outside the plume, where buoyancy ceases.

Documentation: Only models that are rigorously documented should be allowed in any application involving legal considerations, such as in code enforcement or litigation. It is simply not appropriate to rely on the model developer's word that the physics is proper. 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.

While 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 utilized 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 input to the model does not represent the condition being analyzed. Proper specification of the fire is the most critical, and was addressed in detail in the preceding subsection on selecting the design fire(s).

Next in importance is specifying sources of air supply to the fire, i.e., not only open doors or windows, but also cracks behind trim or around closed doors. Most (large) fires of interest quickly become ventilation controlled, making these sources of air crucial to a correct prediction. The most frequent source of errors by novice users of these models is to underestimate the combustion air and underpredict the burning rate.

Two other important items of data are: (1) ignition characteristics of secondary fuel items and (2) the heat transfer parameters for ceiling and wall materials. In each case, 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. (See subsection "Accounting for Uncertainty" later in this chapter.)

Performing an Evacuation Calculation

The prediction of the time needed by the building occupants to evacuate to a safe area is performed next, and compared to the time available from the previous steps.

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, there is time required for detection and notification *before* the evacuation process can begin. Next, unless the information is compelling (again, they see the actual fire), it takes time for people to decide to take action. 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. Excellent discussion of this topic is found in Pauls'[17] and Bryan's[18] chapters in the *The SFPE Handbook of Fire Protection Engineering.*

Models: The process of emergency evacuation of people follows the general concepts of traffic flow. There are a number of models that perform such calculations that 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. This is appropriate in most public occupancies where people do not know each other. In residential occupancies, family members will interact strongly; and in office occupancies, people who work together on a daily basis would be expected to interact similarly. The literature reports incidents of providing assistance to disabled persons, again especially in office settings.[19] If such behavior is expected, it should be included, as it can result in significant delays in evacuating a building.

Another situation where models (e.g., Fahy's EXIT89[20]) are preferred to hand calculations is with large populations where congestion in stairways and doorways can cause the flow to back up. However, this can be accounted for in hand calculations, as well. Crowded conditions, as well as smoke density, can result in reduced walking speeds.[21] (See Figure 11-7F.) Care should be exercised in using models relative to how they select the path (usually the *shortest* path) over which the person travels. Some models are *optimization* calculations that give the best possible performance. These are inappropriate for a code equivalency determination, unless a suitable safety factor was used.

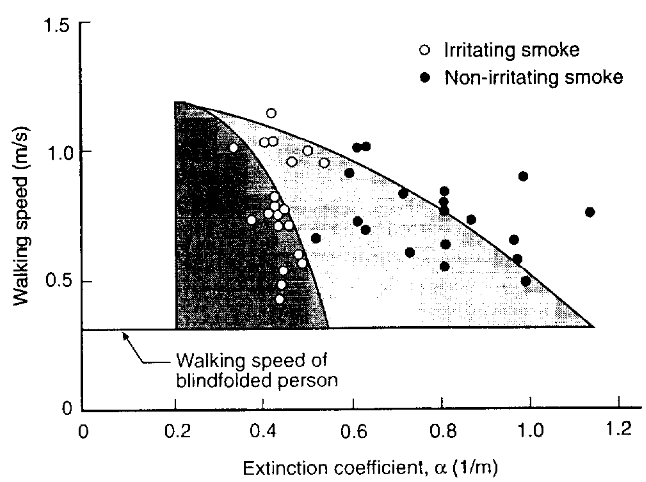

FIG. 11-7F. A person's walking speed decreases in dense smoke until he or she moves as if blindfolded.

Hand calculations: Evacuation calculations are sometimes simple enough to be done by hand. The most thorough presentation on this subject (and the one most often used in alternate design analysis) is that of Nelson and MacLennen.[22] Their procedure explicitly includes all of the factors discussed previously, along with suggestions on how to account for each. They also deal with congestion, movement through doors and on stairs, and other related considerations.

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 involves the application of combustion toxicology models. The HAZARD I software package contains the only toxicological computer model, called TENAB,[23] which is based on research at NIST on lethality to rats[24] and by Purser[25] on incapacitation of monkeys. These methods can also be applied in hand calculations, utilizing the material by Purser[25] and the equations found in reference 22. TENAB accounts for the variation 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 actually decreases. Details such as these ensure that the results are reasonable. It is important that these details be observed in hand calculations, as well.

Assessing the impact of exposure to sensitive equipment is more difficult, since little data exists 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 known to be 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, and 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 accountability refers to dealing with the uncertainty that is 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 design 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. In present practice for the evacuation calculation, a safety factor of 2 is generally recommended to account for unknown variability in a given population.

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., vary the data to the limits and see whether the conclusions change) should be performed. This is also a good time to justify the appropriateness of the model or calculation method.

Final Review

If a model or calculation produces a result that seems counterintuitive, there is probably something wrong. Cases have been seen where the model clearly produced a wrong answer (e.g., the temperature predicted approached the surface temperature of the sun), and those where 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 uncertainties addressed sufficiently to provide a comfort level similar to that obtained when the plan review shows that all code requirements have been met?

CONCLUSION

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 11, Chapter 9, of this handbook.) 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.

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