An Overview of Fire Hazard and Fire Risk Assessment in Regulation

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ABSTRACT

Fire hazard and fire risk assessment has gained popularity in assessing the performance of alternative approaches to prescriptive regulations and in justification of proposed changes to regulations and referenced standards. While risk is the preferred methodology, often the probabilities needed are not available and cannot be estimated, resulting in a default to hazard assessment. In other cases society is hazard averse, and hazard assessment is the preferable approach. This paper will provide an overview of fire hazard and fire risk assessment methodologies used in regulatory systems and the tools available for conducting them. Examples of regulatory applications drawn from buildings, transportation, and nuclear safety will be provided.

INTRODUCTION

Nearly every developed country has, or is in the process of implementing, performance-based building regulations as a means to rationalize their regulatory system and to encourage development. Most have expressed interest in the use of fire risk assessment as the means to judge performance against the explicit objectives at the core of such systems. The fact that risk can never be eliminated may lead to the public perception that officials feel a few deaths are somehow acceptable, which is generally unpalatable as a matter of public policy. Risk of financial loss is easier to understand but is difficult to apply to life safety concerns without becoming embroiled in the value of life controversy.

Since a rigorous risk assessment is computationally intense and requires a large amount of historical data that are frequently not collected, most analyses conducted in support of performance evaluation are hazard assessments. These measure performance under a specified set of design conditions that are presumed to represent the principal threats. Since experience has shown that the worst fires are the result of many things going wrong together, it is desirable to account for situations characterized by multiple failures in providing for the safety of the public. Further, since September 11, 2001, regulators are interested in understanding the risk of extreme events that are increasingly influencing security and insurance concerns.

ASSESSING HAZARD AND RISK

The goal of a fire hazard assessment (FHA) is to determine the consequences 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. The trend today is to use computer models wherever possible, supplemented where necessary by expert judgment to determine the outcome. While probabilistic methods are widely used in risk assessment, they find little application in modern hazard assessments.

Hazard assessment can be thought of as a subset of risk assessment. That is, a risk assessment is a series of hazard assessments that have been weighted for their likelihood of occurrence. The value of risk over hazard is its ability to identify scenarios that contribute significantly to the risk but that may not be obvious *a priori*. In the insurance and industrial sectors, risk assessments generally use monetary losses as a measure of risk since these dictate insurance rates or provide the incentive for expenditures on protection. In the nuclear

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power industry, probabilistic risk assessment has been the primary basis for safety regulation worldwide. Here the risk of a release of radioactive material to the environment from anything ranging from a leak of contaminated water to a core meltdown is examined.

Fire hazard assessments 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.

Areas of Application

In the last decade deterministic fire hazard and fire risk assessment has increasingly been used in building regulatory applications, first as substantiation for alternative materials and designs and later for performance-based buildings. These techniques have also been strongly embraced by the historical and cultural preservation communities as a means to raise the level of protection to nearly full compliance with current practice without sacrificing the significant aspects of the building (NFPA 2001).

Another area where fire hazard and fire risk assessment is being applied is in transportation, particularly in the rail and maritime areas. The U.S. Federal Railroad Administration recently adopted new rules for passenger rail that require fire risk assessment of current and proposed rolling stock, and NFPA 130 requires hazard assessment of rail stations and terminals (NFPA 2003).

Beyond code compliance assessment, fire hazard assessment techniques are used in substantiation of proposals for changes to codes and standards. Most often this involves use of the analysis to justify thresholds contained in the requirement. The American Society of Mechanical Engineers (ASME) has a formal hazard assessment procedure used in their code development process. The hazard assessment conducted by the code committee utilizes a template that then becomes a permanent record of the considerations and assumptions of the committee in establishing the requirements of their code.

Available Tools

Fire hazard assessments are routinely performed with one of the several zone models and engineering software packages available in the world. In English-speaking countries,

- FPEtool (Deal 1995), FASTLite (Portier et al. 1996), CFAST (Peacock et al. 1993), and HAZARD I (Bukowski et al. 1989), all from NIST,
- FIRECALC (CSIRO 1991) from Australia, and
- ARGOS (DIFT 1992) from Denmark

are the most frequently cited.

The Japanese prefer BRI2 (Tanaka et al. 1987) and the French use MAGIC (EDF no date), as these are locally produced and use the local language for the software and manuals. Increases in computing power and the potential of parallel processing are leading to more use of field models such as NIST's Fire Dynamics Simulator (McGrattan 2005) for multi-scenario fire hazard analysis. Several nations have or are developing engineering codes of practice, e.g.,

- Japan (MOC 1988),
- UK (Barnfield et al. 1995),
- Australia (ABCB 2001), and
- New Zealand (Buchanan1994).

The SFPE *Handbook of Fire Protection Engineering* (SFPE 2002) is a universal reference work for the underlying science, although Japan has its own version of a comprehensive engineering handbook. Recently, the US, Canada, Australia, and New Zealand collaborated on an international version of the *Fire Safety Engineering Guidelines* (*International Fire Engineering Guidelines* 2005), consisting of a country-specific Part 0 (describing the country's performance-based regulatory system) and a common methodology acceptable for building regulation in any country.

Since all fire hazard assessments involve a small number of scenarios or design fires, no special software arrangements are needed. This is not true for risk assessments, which typically involve hundreds to thousands of scenarios. Here, special software packages, which run the cases and summarize the results, have been developed. These include

- FRAMEworks (Hall et al. 1992) in the US,
- FiRECAM (Beck et al. 1996) in Canada, and
- CRISP2 (Fraser-Mitchell 1994) in the UK.

Data Needs for Risk

While tools exist to do both hazard and risk assessments, the greatest difficulty faced by those applying either is the availability of data. All of these analytical methods need appropriate data, but risk assessments also need statistical distributions for many parameters in order to incorporate the variabilities that underlie the desire for risk-based regulation.

Take, for example, FiRECAM (Beck and Yung 1994), developed by the National Research Council of Canada and Victoria University of Technology in Australia. As with the other risk methods cited above, this product is made up of a series of submodels (names in italics) that provide the needed functionality. The following discussion outlines the complexity of the problem to be analyzed and the types of data and distributions necessary for these risk assessment methods. Many of these data are also needed for hazard methods.

The *design fire model* considers six design fires: smouldering, flaming nonflashover, and flashover fires, each with the door to the room of origin open and closed. While the heat release rate curves are fixed, the statistical incidence of each of these fire types in the target occupancy along with the probability of the door being open in each must be specified. Few countries maintain national fire incident databases from which these data can be obtained. Australia recently initiated a fire incident data system to provide the information.

The *fire growth model* (a single-zone model for rapid processing of large numbers of calculations) then calculates burning rate, temperature, and smoke/gas concentrations. This requires heats of combustion and yield fractions that are available for common homogeneous fuels but rarely for end-use products. Fuel loads (energy content per floor area in wood equivalent) have been surveyed for a few occupancies, but smoke and gas yields can vary substantially across fuels (e.g., soot yield fractions vary by two orders of magnitude from wood to plastics). Since the smoldering and nonflashover fires remain fuel controlled, the values used for these inputs have a significant effect on the results. For the flashover fires, ventilation is the controlling factor. Window breakage and other sources of combustion air play a critical role, especially for the cases with the door closed.

The *smoke movement model* then calculates the distribution of energy and mass and associated tenability times for all spaces. Compartment dimensions and connections as well as heat transfer properties of surfaces must be entered for the target building, but they will be known. The distribution of smoke is dominated by the probabilities of interior doors being open, which will be difficult to assess for many buildings.

The *fire detection model* calculates the probability of detector or sprinkler activation, which depends on the probability that they are present and the probability that they are working. The former is usually available based on code requirements and common practice, but the latter is usually not. Quantification of the operational reliability of fire protection systems is the subject of current studies in the US and UK.

The *occupant warning and response model* depends on the fire detection model to initiate the evacuation of occupants where detectors or sprinklers are present and working. Otherwise the fire growth model predicts a "fire cue time" (presumably for the room of origin only) when the fire would be sufficiently threatening to initiate action. Where occupants are in remote spaces and especially when they are asleep, it is unclear when (or if) evacuation would begin when the only stimulus is cues from the fire.

The *fire brigade action model* evaluates the effectiveness of the fire brigade in both suppression and evacuation assistance. This usually assumes that the fire brigade is successful in suppression if they arrive before flashover, but four of the six design fires do not reach flashover by definition. No differentiation is made for fire brigade staffing, equipment, training, or other variables, although these issues were addressed in the original Australian work. Fire brigade response times are often reported by the brigades, but the time needed after arrival to begin operations (either suppression or rescue) generally is not.

The *smoke hazard model, evacuation duration model,* and *egress model* all deal with the time needed for occupant evacuation and the probability that some or all successfully escape. The ability to react, speed of movement, and sensitivity to smoke and gas are all dependent on the assumed physical characteristics of the occupants. The distribution of age, physical and mental impairments, drug or alcohol use, etc., within the mix of people in a given occupancy is sometimes available but is uncertain. Most evacuation models suggest a large safety factor (at least two to three) to account for these uncertainties.

A *boundary element model* is used to assess the probability that the fire will spread to other spaces by failure of a boundary element or a closed door. If such failures occur, the *fire spread model* calculates the extent of such spread. Deterministic models of the failure of structural assemblies when exposed to an arbitrary fire are in their infancy. All such approaches rely on properties of materials at elevated temperatures that are generally unavailable. The performance of rated assemblies to the standard time-temperature exposure must be extrapolated or statistical data from past incidents must be used. Such statistical data are rare (the author is only aware of such data being collected in the United Kingdom).

The *life loss model* uses toxicology data from animals to estimate the effect on people. Animal data for lethality are well documented but, for incapacitation, are highly uncertain since assessing incapacitation in animals is difficult. In either case the extrapolation from animals to humans is controversial.

When assessing economic losses, the *property loss model* must integrate the replacement costs of contents and structure with the damage expected given the exposure and whether or not the items can be cleaned (along with these costs). The *economic model* and *fire cost expectation model* need the additional inputs of the capital and maintenance costs of all fire protection features. While the capital costs are available in construction cost manuals, maintenance costs are not.

The data needs and availability for CRISP2, FRAMEWORKS, or any risk assessment are the same as for FiRECAM and represent the greatest barrier to the widespread application of these techniques. Data unavailability leads to the use of estimates, which adds to the uncertainty of the results. Of course, there are other approaches to risk, including probabilistic risk analysis (PRA), used extensively in the nuclear power industry; risk index methods common in insurance; event trees; and state transition models that have been utilized in fire risk assessment, but each of these have significant data needs. Detailed discussion of these methods is beyond the scope of this paper.

Data Needs for Hazard

Since hazard assessment is a subset of risk, its need for data is significantly less, but many of the problem areas are common to both. Where hazard assessment is used, the design fire scenarios are more fully specified. Open doors, ventilation paths, fire growth and extent of spread, occupant load and characteristics, and presence of fire protection systems are all generally given. Often, fire detection and suppression systems, as well as fire barriers, are assumed to operate as intended, although the explicit inclusion of reliability is recognized as crucial to obtaining realistic results.

The major problem with the hazard approach is the recognition that the most serious scenarios cannot be identified *a priori,* even where data on past incidents in the occupancy class are collected. The observation is that most major incidents have contributing factors of variations with codes or practices, or systems that failed, each of which complicates the scenario specification. While in most countries the bulk of the fire losses occur in small numbers per incident in residences, societies are equally or more averse to the rare event with high consequences. Thus, some method of reliably identifying such scenarios must be included.

RISK-BASED REGULATION

With the continued evolution of performance codes, and especially as the means for evaluating compliance with the performance objectives have tended toward risk assessment methods, it is becoming apparent that the level of detail at which these objectives are being specified is insufficient. For example, if the analysis is limited to a specific set of design scenarios (i.e., a *hazard* analysis), it is possible to specify the goal that there should be no fatalities among building occupants *in those scenarios*, while in risk-based systems, the goal of eliminating all risk to life from any fire is not practical. Further, setting a goal with respect to life loss says nothing of society's acceptance of significant injury.

Providing for the public safety is a governmental function. Thus, legislators have the responsibility for establishing objectives for the built environment that correspond to what society expects. However, this task is usually delegated to those responsible for enforcing these regulations. In either case, where risk assessment is the method used to regulate, it is important that those making the decisions communicate to the public about the basis for regulation.

Relative Risk

In all but one of the engineering methods proposed in support of national performance codes, the risk assessment is for *relative* risk. This requires that the risk of the subject building be assessed and that the risk for a similar building (same occupancy and general characteristics) but designed in accordance with the prescriptive code also be calculated so the two can be compared. This doubles the computational burden and discourages the calculated solution in all but those few cases where no alternative exists.

Justification of the relative risk approach usually takes a form similar to statements made by Australia's Building Regulatory Review Task Force, which said (BRRTF 1991):

> with a few exceptions the Australian community appears to be reasonably satisfied with the safety levels achieved by our current regulations.

This leads to their conclusion that

> the risk levels achieved by buildings designed to the current regulations can be used for the time being, as convenient benchmarks of the risk levels which must be achieved by any alternative fire safety system arrangements.

But relative risk poses some potential pitfalls that need to be considered. For example, Brannigan argues (Brannigan and Meeks 1995):

> The statement that the public is satisfied with the level of fire safety is debatable, but even if true it does not necessarily support the statement of equivalence (to buildings built to current regulations) for at least three reasons....

Paraphrasing Brannigan's points, first, the equivalence statement assumes that the public is satisfied with an expected risk to life rather than a safety level. Fires, especially disastrous fires, are rare events. When dealing with rare events, the public may believe that the risk to life is actually zero.

Second, the claim that society is "satisfied with the level of safety achieved by our current regulations" assumes that the current regulations are the sole cause of this socially acceptable level of safety. Codes specify minimum requirements that are often exceeded in the recognition of liability or public image (e.g., significant improvements in fire safety were implemented by the lodging industry following the fires of the 1980s, well in advance of changes to the codes). If the performance level is set as equivalent to the minimum code, the result may be an increase in losses when compared to the typical building, presenting an unreasonably negative view of the efficacy of the performance goals and objectives.

Third, they assume that the engineering methods accurately reflect the expected risk to life in different buildings. It may not be possible to accurately predict loss rates in the future due to the fact that stochastic elements are based on past materials and lifestyles that may change (e.g., declining smoking rates should reduce rates of cigarette ignitions).

Absolute Risk

The Code of Practice (BSI 2002) from the British Standards Institution is the only method that has attempted to set acceptable levels of risk. The proposed values are based on current fire losses in the UK. The authors suggest

> that the public broadly tolerates the average risk of death from fire provided that the number of deaths in any one incident is small.

They suggest a value for the risk of death per individual per year at home (1.5×10^{-5}) or elsewhere (1.5×10^{-6}) and for the risk of multiple deaths per building per year (>10 deaths, 5×10^{-7}, and >100 deaths, 5×10^{-8}), which are the current loss rates observed in the UK. Of course, the comments made in the previous section concerning any assumption that society is satisfied with current losses apply here as well. Thus, some better method of making public policy decisions about acceptable levels of risk that do not depend on current experience is needed.

Risk acceptance is highly variable, depending on to whom the risk applies (individual vs. society), the perceived value of the "risky" activity, whether the risk is assumed voluntarily, and whether the people at risk are considered especially deserving of protection (e.g., children, elderly, handicapped, or involuntarily confined). Under these conditions people make decisions to accept risk (engage in "risky" activities) every day, so this can be dealt with if it is put into the proper framework.

EXPRESSING RISK

Risk to Life

Expressing risk to life in a way that can be understood by the public is a problem that has been addressed for years by the nuclear power and air transport industries with limited success. At the most basic level, risk to life is a small number generally expressed in scientific notation, which itself is not understood by most people. The risk is normally compared to events or activities such as the risk of being struck by lightning or the risk of death during skydiving.

Risk of Financial Loss

This leads to the consideration of other metrics for risk. The general unit of value in society is money, and the insurance industry has expressed risk in monetary terms for most of its history. Risk of financial loss is easy to understand and allows direct evaluation of offsetting benefits of investment in reducing risk or in the costs of insurance against the loss.

Financial loss is potentially the perfect metric for risk but for one problem. The primary focus of fire codes is life safety, requiring that risk to life must then include a measure of the value of human life. Numerous (at least partially) objective measures of such value have been proposed: earning potential over the remaining expected life, potential contributions to society, costs of insurance or legal settlements, and costs associated with regulation intended to reduce accidental fatalities, to name just a few. In each case the concept that some people have less "value" to society than others is met with great objection, especially by those whose value is deemed lower. Beck pioneered the concept of the dual criteria of "risk to life" and "expected cost" in addressing these issues in FiRECAM (Beck and Yung 1994).

ESTIMATING RISK

Traditional risk analysis has involved probabilistic techniques for both the likelihood estimates and the consequences of the events. These techniques may use experience (generally the case in most fire analyses) or may involve expert judgement and failure analysis methods where there is little or no experience (such as in the nuclear power industry). Regardless of how it is approached, one of the strengths of risk analysis is its ability to deal with distributions of outcomes based on variations in conditions that affect these outcomes. For example, doors may be open or closed, systems may be out of service, people may be present or not, and so forth. When major fire incidents are examined, it is generally recognized that a number of unfavorable conditions needed to be present for the accident to proceed to the observed condition.

In recent years the evolution of deterministic fire models and other predictive techniques has led to the desire to assess the consequences of events in a more objective manner. An early attempt to develop methods to quantify the fire risk of products met with limited success (Clarke et al. 1990; Bukowski et al. 1990). Since then, other risk assessment methods have been developed that have followed a different philosophy. The early method cited identified a limited number of scenarios, each representing a larger number of scenarios in a class, and used detailed physical models to estimate consequences. Another risk model (Beck and Yung 1994) limits the level of detail included in the physical models to minimize execution time and identifies much larger numbers of scenarios (by establishing distributions for most input variables). It then uses a Monte Carlo technique to determine distributions of outcomes.

This difference raises an interesting question. Is the fire risk affected more by the distribution of possible conditions of the scenarios or by the physical and chemical processes present in the fire itself? Or, more directly, how important is it that the simplified models may predict the wrong consequences because of their simplicity, or that the Monte Carlo approach may miss a dominant case? The former can be addressed by validation studies, and the latter by parametric studies. Some of both have been done, but more work is needed.

HAZARD-BASED REGULATION

Other than the problem of identifying the rare, high-consequence event, hazard-based regulation avoids most of the problems with risk-based regulation. The process is much better defined since the design scenarios are agreed upon in advance. It is possible to require that there be no fatalities in some design scenarios, which is more palatable for legislators and less likely to cause concern among the public who do not understand risk. It is further possible to allow for additional, use-specific scenarios to be specified by the regulator in response to the particular characteristics of the building or its use. The similarities to the accepted practice (limit state design) in structural engineering give the participants comfort that it will work. For these reasons, this approach may be a good intermediate step in the transition to performance codes and standards.

CONCLUDING REMARKS

The world community is clearly moving toward performance codes as replacements for both building and fire codes of a more prescriptive nature. Standards will evolve to better support codes in the building regulatory process, and the format of performance standards needs to change in a way that is consistent with their need to support performance codes. Since the codes specify objectives, it would seem that the standards need to specify the functions to be performed and the reliability with which these functions are provided.

For public safety-related objectives, risk seems to be the method of choice on which to base judgements of acceptable performance. Most fire safety engineering methods currently under development use relative risk based on the hypothesis that society is satisfied with the current fire risk in buildings. Some, such as in New Zealand, Japan, and Australia, do so implicitly by accepting relative risk assessment against buildings that comply with the prescriptive code. One, proposed for England and Wales, has established explicit risk targets equal to current loss experience. Hazard-based approaches that measure performance in a prescribed set of scenarios avoid many of the problems with risk, but these generally do not consider the most rare events that still may incur public outrage. Deterministic models have a seminal role in fire safety engineering analysis to support this process, but the engineering community has yet to sort out the best approaches to estimating risk and communicating the results.

The answer may be to embrace hazard-based regulation but use the risk assessment technology to identify those rare but high consequence scenarios that contribute significantly to the risk exposure in a given occupancy. Once these scenarios have been included, the enhanced set of design challenges should address public safety sufficiently as to avoid unacceptable losses. This approach is being introduced within the US and globally through CIB W14 as a means to arrive at practical and reliable approaches to building fire performance evaluation. International bodies are examining data collection issues raised herein in an effort to modify current practice to better serve the needs of the regulatory community. Through these efforts it is expected that a harmonized method of analysis acceptable in most countries could be agreed upon and standardized within a few years.

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