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Fire Safety Engineering in the Pursuit of Performance-based Codes: Collected Papers

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Preface

The Building and Fire Research Laboratory (BFRL) at the National Institute of Standards and Technology (NIST) has been engaged in the development of advanced, scientifically-based tools for fire safety engineering for several decades, dating at least to their support of the first computer fire models[1] from Emmons at Harvard University in the 1980's. In 1989 the thoughts of many turned to the development of performance-based fire and building codes enabled by the availability of engineering tools like HAZARD I[2] which operated on the personal computers becoming common in engineering offices. Several publications followed on the use of fire hazard and fire risk assessment to quantify the performance of materials and products in the context of their end use[3,4,5,6].

BFRL's effort to facilitate a transition to performance-based codes began in earnest with the publication of an overview paper by Bukowski and Babrauskas in 1994 [paper 1]. Based in part on a review of international efforts in this arena presented at *Interflam '93* and a philosophical work co-authored with Takeyoshi Tanaka of Japan's Building Research Institute, this overview paper suggested guidelines for the development of performance-based codes which could achieve international consensus.

In 1995 the International Council for Building Research Studies and Documentation, Working Commission 14: Fire (CIB W14) approved a work plan developed by the newly-appointed convener Matti Kokkala of VTT in Finland. This plan included a Sub-Group 1 chaired by Bukowski of NIST on **Engineering Evaluation of Building Fire Safety**. The objectives of this activity included the identification of appropriate techniques for assessing the ability of buildings to achieve a specified level of fire safety performance and to provide guidance on appropriate performance criteria.

Under this charge, efforts to establish performance-based codes in a number of countries were reviewed in detail. This revealed that, while prototype codes were beginning to be used in Japan, New Zealand, and England/Wales, all lacked important details which would be needed to provide a complete performance system -- a fact attributed to the monumental scope of such a transition from prescriptive code systems which had been evolving for centuries. Recognizing that these shortcomings must be identified and addressed before an international consensus on these methods could be achieved, NIST undertook the task of developing a series of papers which discussed the issues which needed to be addressed. The compilation presented herein is the set of papers written for this purpose.

To foster a better understanding of the performance approach and its similarity to the use of "equivalencies" under prescriptive codes, guidance was developed for regulatory officials as to what constitutes an appropriate engineering analysis and associated reporting [paper 2]. To generate interest among the architectural community a short article was prepared for one of their most popular journals [paper 3].

An updated review of international activities was presented at a meeting of the FORUM for International Cooperation on Fire Research comprising the leaders of the world's fire research organizations [paper 4].

All of the proposed methodologies embrace fire risk assessment as a goal, but default to fire hazard assessment given the lack of data needed for the former to be accomplished. Codes and standards organizations in the U.S. and elsewhere are struggling to understand their future relationships as performance codes become the norm. Thus two papers were written which deal with these topics [papers 5 and 6]. All of the proposed methodologies further lack detailed goals and objectives, rather including general statements which are open to broad interpretation. This led to [paper 7]. Once these critical issues were open for discussion, the implications for the development of a performance-based system in the U.S. were explored [paper 8]. Finally, some suggestions on the use of a combination of fire hazard and fire risk-based methods for the evaluation of building fire safety performance were formulated as a result of many of the preceeding papers [paper 9].

It is hoped that the total impact of these works is to stimulate a dialogue among the parties developing performance code systems around the world and to allow solutions to these issues to be found. Only then can we hope to reach a consensus on the detailed workings of a performance code structure which might be standardized internationally. Thus, these collected papers should represent a proper starting point for deliberations of CIB W14 Sub-group 1.

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Contents

Developing Rational, Performance-based Fire Safety Requirements in Model Building Codes†

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Abstract

The technical and philosophical basis for performance-based assessment of building fire performance is reviewed. A strategy for the evolution of a performance code is described. Current efforts toward the development of performance codes in the US and Japan are reviewed. Recommendations for critical steps necessary to advance the development and acceptance of performance codes are presented. The table of contents of the Japanese risk methodology for assessing "Article 38 equivalencies" is included in an appendix.

Key Words: building codes, fire models, fire risk, international standards org., performance evaluation

Section 1

The Basis for Assessing Fire Safety Performance of Buildings

A. Fire safety objectives or tasks

The general goal of fire safety is, of course, ``to provide fire safety." This does not by itself provide a basis of a useful operational methodology. Instead, we need to subdivide this goal into more specific objectives or tasks. The subdivision can be done in an **infinite number of ways**. It must only be ensured that the totality of these objectives adds up to ensuring the totality of fire safety in buildings. Not all the conceivable ways in which this goal can be subdivided, however, are equally practical or usable. Thus, we will first consider some proposals and alternatives in this area, then verge towards recommendations.

ISO objectives

ISO set up in 1990 a new subcommittee, ISO/TC 92/SC 4 on "Fire Safety Engineering." The scope of this subcommittee goes beyond buildings, but its original work program [1] is specifically focused towards fire safety in buildings. In this activity-which has not yet formally produced recommendations-the totality of building fire safety was divided into 5 elements, each assigned a different Working Group:

1. Application of fire safety performance concepts to design objectives.
2. Fire development and smoke movement.
3. Fire spread beyond the compartment of origin.
4. Detection, activation and suppression.
5. Evacuation and rescue.

The scope of WG1 is, essentially, coordination of the whole system, with the remaining 4 working groups being the `four-way split' of the fire safety system. This division was done ad hoc, without specific debate outside of this particular subcommittee.

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† *Fire and Materials*, **18**, 173-191, (1994)

Is this ultimately the best way to subdivide the fire protection problem? Probably not. We can consider some logical analysis at this point.

It is clear that an objective of the fire safety system must be to limit the spread of fire and smoke. Instead of a two-way split (WG 2 and 3, above), the following stages, in fact, must be considered:

- spread of fire in the room of fire origin
- spread out of the room of fire origin
- successive propagation throughout the building on fire
- spread from the building on fire to adjoining buildings.

We may recall that such a system was originally proposed by H.E. Nelson when he was in charge of fire safety activities for the General Services administration in the early 1970s.

Even these four elements do not suffice to pin down the basic calculational elements. For instance, during spread within the room of fire origin, typically two types of computations will need to be made: ignitions of discrete objects, and flame spread along extended surfaces. The spread of fire out the room of fire origin can probably be handled by a simple calculation determining whether or not flashover does occur in that room. For the successive propagation component, however, three entirely different calculational methods will need to be used: (a) direct flame propagation through openings such as open doors; (b) fire propagation due to failure of fire endurance, i.e., due to walls or doors burning through, beams falling down, etc.; and (c) the flow of smoke along all paths that smoke can flow in that building.

It is clear that such details should be deferred until the next layer down. Instead, the global objective here is **limit the spread of fire and smoke**.

The suggested ISO scheme merges evacuation and rescue activities. This seems natural since both involve `movement of persons.' It may not be the best way of looking at the problem, however. In most actual fires it is clear that two entirely different phases of activity occur: (a) the self-evacuation of occupants during the initial period after the alarm is raised. (b) The rescue activities commenced when the fire fighters have arrived on the scene. Here we immediately note that even though rescue activities are the most important task for the firefighters once they have arrived, it is not their only task. Firefighting needs also to begin. We also note the obvious fact that, generally speaking, occupants move **down and out**, while firefighters move **in and up**. Thus, it will be more fruitful to consider the needs of these separate groups of individuals separately.

By such considerations, we can come to the conclusion that there are 3 basic societal objectives to be achieved in providing fire safety in buildings:

I. Limit the spread of fire and smoke
II. Provide for successful evacuation of occupants
III. Provide for effective fire fighting and rescue operations.

We may also note that the above are only the **societal** objectives. In addition to those, there can well be **organizational** objectives. In the simplest terms, these basically say: ``a fire should not lead to a bankruptcy." Thus, organizations need to plan how to minimize fire impact to their operations and to speed the resumption of full operations after a fire. Such issues–while paramount to any sensible organization–are not a reasonable concern of a regulatory body.

Prof. Beck's scheme

Another tri-partite scheme has been proposed by Prof. V. Beck, who headed the Australian group studying performance code concepts. He suggests [2] the following objectives:

I. Life safety for occupants of the building of fire origin
II. Life safety for occupants of adjoining buildings
III. Life safety for fire brigade personnel.

This does not appear to be the optimum scheme. Certainly there is no denying that life safety of occupants of adjoining buildings must be ensured; but, the same holds true for motorists driving by the fire scene, police officers assisting at the fireground, utility workers called in to disconnect services, *ad infinitum*. It would clearly be best to group all such concerns under `effective fire fighting and rescue operations." Furthermore, Prof. Beck, while providing some explicatory matter to this issue, nonetheless excludes from consideration **control of the fire itself**. There would seem to be general, worldwide agreement that one cannot just tacitly subsume this under the rubric of providing life safety. All societies express explicit concern with managing the size and spread of fires.

United Kingdom: Performance Code Concepts

In principle, the UK went to a performance-based model building code by adopting the Housing and Building Control Act of 1984 [3]. This system replaced the existing prescriptive requirements with broad functional statements. The basic regulation was then supplemented by a series of `Approved Documents.' These documents spell out **a** way by which the intent of the regulation can be deemed to be satisfied. It was understood that these Approved Documents would then, in the long term, comprise fire safety engineering guidelines and minimums. This was seen as requiring a long time and significant funding to accomplish. Thus, the first edition of the Approved Documents consisted, essentially, of a re-publishing of the old prescriptive code. Complying with the old code, therefore, was deemed to comply with the new regulation also. Other designs could be offered up, however, if they met with the approval of the local building authority. For an architect to achieve this approval, however, might be difficult, since no newer guidelines were issued to the authorities to tell them how to evaluate such designs. It can readily be seen that, under such circumstances, it might not be easy to convince the local building authority that a design based on entirely different calculational procedures than contained in the old code/new Approved Document is acceptable.

The first step towards putting some flesh on these performance bones was a study [4] commissioned by the Department of Environment from H.L. Malhotra, who was then recently retired from the Fire Research Station. Malhotra considered that the building fire safety objectives are three:

1. Life safety
2. Prevention of conflagration
3. Property protection.

This particular tripartite split is notably very general. `Life safety' is so general as to be nearly akin to `public welfare.' Prevention of conflagrations is certainly important and essential, yet there are some quite unrelated issues put together there, to wit, building construction, lot sizes and zoning, and fire fighting operations. Finally, some people disagree that property protection, apart from conflagration control, is a governmental function (see discussion of New Zealand's performance code later). It may not necessarily be wise to call it out in this manner, since once life safety and the prevention of conflagrations is assured, the government's role would appear to be finished.

To develop further details in his plan, Malhotra then examines several building codes from different parts of the world and proposes a model scheme for occupancy classifications. By and large, this scheme is very similar to ones used by UBC and other traditional codes. There are classifications for residential, educational, business, factory, etc. occupancies. By contrast, here we shall take an opportunity to point out that **traditional concepts of primary regulation according to occupancy type are not founded on sound engineering principles**. Correct fire safety engineering concepts would demand that such `top-level' classifications be based on (1) degrees of hazard; (2) degrees of risk; or (3) similarity of fire environments. The traditional occupancy classifications are simply based on **uninformed judgment**, i.e., judgment not supported by physics, statistics, or even case-trend analysis.

We consider it one of the most essential objectives of a rational, performance-based building code shall be to either present scientific bases for a `top-level' buildings categorization scheme or else to abandon the concept entirely.

Taking a further look at Malhotra's scheme, major engineering modules (using our terminology) are provided for:

The design of means of escape.
Fire development within the initial space of fire origin.
Fire propagation from room to room.
Fire propagation to another building from the one on fire.
Detection, firefighting, and extinguishment.
Fire safety management (e.g., staffing, training, maintenance of equipment).

These more detailed building blocks are developed in some detail in Malhotra's study. While conceptual planning of the principles of fire protection have progressed some ways since his study was issued, we find that the detailed engineering concepts and voluminous references which he examines in connection with each of these engineering modules represents a valuable starting point for future work.

Draft UK Code of Practice

In 1991 the British Standards Institution (BSI) commissioned the Warrington Fire Research Centre to start drafting documents for a Code of Practice for the application of fire engineering principles to fire safety of buildings. This work has not yet been finished and a report has not been issued. However, the principal investigator in this research project is also the convener of WG1 in the work being taken by ISO and has described some of the features of this work. The Warrington approach discusses both stochastic and deterministic design approaches but details of guidance to be given in this area are not yet made clear. What has been presented is the outline of the main engineering modules, which are grouped into 7 `design sub-systems':

DSS1 Building and occupant characterization
    Effective fire load
    Design fires
    Number of people
    Distribution of people
    Occupancy efficiency
    Occupancy characterisation
    Environmental effects.

DSS2 Initiation and development of fire in room of origin and beyond, but within compartment
    Rate of heat release (as a function of time)
    Smoke mass (")
    CO mass (")
    Flame size (")

DSS3 Spread of smoke and toxic gases within and beyond room of origin
    Temperature profiles (as a function of time and for various locations)
    Smoke profiles (")
    CO profiles (")

DSS4 Fire spread beyond compartment of origin
- Time to ignition in adjacent fire compartment

DSS5 Detection and activation
- Activation times of alarm
- Activation times of control systems
- Activation times of barriers
- Activation times of suppression
- Fire brigade notification time

DSS6 Fire brigade communication and response
- Arrival time
- Attack time
- Fire control time
- Fire out time

DSS7 Escape and evacuation
- Occupant escape profile
- Occupant evacuation profile.

These basic concepts, in the presentations given so far, are fleshed out in terms of exceedingly large flow charts and diagrams where all the relationships between the elements are worked out as events on a flow chart.

We have some concerns that a new, performance-based building code should not be inordinately complex. Furthermore, it should be possible to *read* the building code. That is, it should be possible to see the basic concepts which need to be complied with, along with how proof is presented of such compliance. Without a doubt, in modern building design practice there will arise numerous issues which bring into play some very subtle interactions of requirements. Fundamentally, however, it should be possible to (a) know what primary safety features are expected; and (b) examine the plans, calculations and specifications to verify their presence. To put it in other terms, it should be possible to review the major safety features of a building design without running a large computer program or hiring a systems analyst. We cannot, of course, pre-judge the Warrington proposal prior to it being fully completed and documented. We see, however, that the issue of great complexity and inadequate clarity will need to be carefully considered in examining this approach when it is completed.

New Zealand: Performance Code Concepts

New Zealand adopted a new Building Act in 1991 [5] mandating a performance-type of building code. The act itself is concerned mainly with legal aspects of implementation. The building regulation objectives themselves were set down in parallel [6] in the following year. The objectives pertinent to fire safety are (condensed and paraphrased):

Outbreak of fire: combustion appliances to be installed in such a way as to reduce the likelihood of fire.

Means of escape: (1) escape routes shall be adequate to allow people to reach a safe place without being overcome by effects of fire. (2) Fire service personnel to have suitable routes so as to have adequate time for rescue operations.

Spread of fire: (1) occupants not to be endangered while escaping. (2) Fire fighters not to be endangered while fighting fire. (3) Adjacent buildings or ownership units not to be threatened by the fire. (4) The environment to be protected against adverse effects from fire.

Structural stability during fire: adequate fire endurance shall be present to (1) allow safe evacuation of occupants. (2) Allow fire fighters to rescue people and fight the fire. (3) Adjacent buildings or ownership units should not be damaged.

The New Zealand code then provides for a series of Approved Documents which are intended to function similarly as the ones in UK.

We can point to several unique features in the NZ formulation. Combustion appliances are being given a very prominent role here. This is different from, say, the US building codes, where mechanical equipment is normally treated in a Mechanical Code and also in numerous NFPA codes and standards, but very little being said on this topic in the building code. Another is the position that property protection is a matter between the building owner and his/her insurance company. Other than limiting damage to third parties (similar to the Japanese philosophy), the NZ code contains no provisions for protecting property. Insurance companies are imposing *additional* requirements on building owners to protect their interests (and are objecting to the additional work that this requires).

We also note here the rather recent concern about the environment vis-a-vis fires. This issue, of course, has received significant publicity in Europe. Clearly it is in the society's best interest to carefully protect the environment. The concerns over fires or, especially, fire-fighting damaging the environment we believe, however, have been vastly overstated in European publicity. Even from absolutely gigantic fires (e.g., major forest fires, Kuwait oil field fires) the environmental effects are localized and temporary. We especially emphasize that these do not entail **buildings** burning. The issue with chemical plant protection is, on the other hand, a very specialized case. Again, in many cases the facility does not comprise a **building**. In all cases, however, the issue is of **chemical safety and chemical hazard**. Hazards from stored dangerous chemicals do not need to come into play by means of fire. Careless operations, sabotage, airplane crashes, and many other types of accidents can cause hazardous chemical incidents; fire is just one of many such possible causes. Such facilities need total protection planning, in which fire will play but a subsidiary role. In all other cases of buildings other than hazardous chemicals facilities, the protection of the environment from fire appears to be a moot point: the hazards associated directly with the burning building are vastly more important than residual pollution to the environment.

B. Other requirements of a performance building code

The previous discussion focused on **technical completeness** of the code. This is clearly the most essential issue and one where a great deal of effort is to be expended. It behooves us, however, to consider other requirements of such a code. S. Grubits has suggested [7] that the code must:

Set out the process to be adopted.
Provide the factors to be considered in design.
Specify the performance levels to be attained.
Adopt explicit safety margins.
Specify what relevant data sources are acceptable.

These issues cannot be solved in the preliminary planning stage. However, some discussion of the performance levels, safety margins, and data sources is appropriate.

The *performance levels* are usually derived from a direct comparison against existing prescriptive codes. To this day, the most fleshed-out example of such procedures has probably been the series of Fire Safety Evaluation Systems (FSES) developed by Nelson and coworkers. These covered such diverse areas as multifamily housing [8], health care facilities [9], board & care homes [10], park service accommodations [11], correctional facilities [12], NASA buildings [13], and coal mines [14]. It is of some relevance to point out that there was not *a* FSES; instead, the systems had to be tailored to different occupancies, each of which have their own, different requirements laid down under present prescriptive regulations.

Such historical precedent based correlation has only a limited utility in future planning. The main problem is lack of consistency in existing regulations. Certainly nobody has ever hegemonized current codes to provide known levels of safety for various applications. In other words, consistent advice can scarcely be taken from inconsistent documents.

As a *policy matter*, however, there is general agreement among those interested in developing performance codes that initially, the new system should neither raise nor lower overall fire safety levels. To minimize needless controversy, any needed overall raising or decreasing of safety levels should be worked as separate work items, quite apart from providing an engineering foundation for a performance-based code.

As far as general requirements go, we point out here that international bodies have already made *model* provision. ISO have two standards on this topic: ISO 6241 [15] and ISO 7162 [16]. These are known in the architectural community but do not seem to have significant applicability towards guidance in the present case. Of more utility is a report issued by CIB, Publication 64 [17]. This document provides some quite useful general guidance in how to structure a performance based code so as to be effective.

C. Risk- versus hazard-based fire safety assessment

In determining the basic orientation of a performance-based building code, the decision must be made as to whether it be risk- or hazard-based. First, the terms as to be used here need to be explained. A risk-based building code would be one where every possible fire event or scenario would be identified, its probability of occurrence determined, and then the engineering consequences of each of these scenarios computed. The presentation of the analysis would then, roughly speaking, multiply out the probabilities times the losses associated with each scenario. Specialists in this area generally run into problems when they discover that not all the losses can be measured on the same scale; assigning a dollar value to human life always becomes an controversial task.

A purely hazard-based approach would define a `canonical' fire, then compute the course of and losses from this fire. The results would then be judged against prescribed criteria for performance.

Some contemplation of the implications of both approaches lead one to consider that neither approach, in its pure form, is viable. The problems with the risk approach are two-fold: (1) is exceedingly difficult to enumerate **all** the scenarios that can occur. For instance, clearly the case of an airliner flying into a high-rise building can–and has–occurred. It is doubtful that all risk analyses have properly taken this eventuality into account. Terrorist bombs, wartime bombs, inadvertent explosions and endless other unusual events would need to be computed. Note that we cannot dismiss them necessarily out of hand at the start by declaring the probabilities to be very low because we neither know the probabilities nor the consequences. In the pure risk approach we would be entitled to omit a scenario when the {probability} x {consequence} product is tiny, not just the probability alone. (2) A relatively-pure exercise in risk-based design becomes dominated by statistical and probabilistic computations. There is a strong case to be made, however, that if the entire goal is not to be lost sight of in arcane manipulations, the engineer rather than the mathematician should remain to be the crucial design person in charge.

Conversely, it can also be seen that a pure hazard-based design, if this means using one and only one scenario for the whole process, somehow defeats the purpose of a performance-based code. Such a design process would fail to introduce adequate performance elements and, instead, continue to rest largely on historical dogma. Clearly something in between is needed.

From the recent NFPRF risk study [18] it is also clear that adequate information to do a fully `pure' risk-based design will rarely be available. What should be available, however, is adequate means to design against important scenarios. This, then, leads one to conclude that, for the foreseeable future, a deterministic hazard-based design should be used, but one with components of risk. Those components should take the form of **multiple evaluation scenarios**. Some thought on this will also lead one to conclude that the **same** scenario should not necessarily be invoked for the design of the entire building. Instead, each different element or sub-system should be challenged against as many scenarios as are appropriately diversely challenging to that particular sub-system.

D. A Strategy for Evolving to a Performance-based Code

In 1991 Bukowski and Tanaka published a paper [19] in which they set out a plan by which a performance-based code might be developed. A key criterion is that the code needs to change smoothly -- materials and constructions which are prohibited as unsafe cannot suddenly be allowed and vice versa. This is crucial to the credibility of the system and to assure that code officials do not "lose face" through an abrupt change in regulation.

The way to achieve this criterion is to provide for continuity with the current regulations. That is, the performance level targeted in the new code should be that which is *implied* by the current code. This is logical since the current regulations represent the level of safety that the society has determined to be desirable even though it is not explicit. The methodology(s) that are deemed to be acceptable for demonstrating compliance with the performance code then become an equivalency system for the existing code; allowing it to be validated in the minds of the regulators and regulated and establishing credibility for the new code.

Establishing the Fire Safety Goals

The underlying goals for the public safety from fires are universal; only the means chosen to achieve them vary. These goals can be rather simply stated in the following short list [20]:

Goals for a Performance Fire Code

- Prevent the fire or retard its growth and spread.
    - Control fire properties of combustible items.
    - Provide adequate compartmentation.
    - Provide for suppression of the fire.
- Protect building occupants from the fire effects.
    - Provide timely notification of the emergency.
    - Protect escape routes.
    - Provide areas of refuge where necessary.
- Minimize the impact of fire.
    - Provide separation by tenant, occupancy, or maximum area.
    - Maintain the structural integrity of building.
    - Provide for continued operation of shared properties.
- Support fire service operations.
    - Provide for identification of fire location.
    - Provide reliable communication with areas of refuge.
    - Provide for fire department access, control, communication, and water supply.

Note the similarity to the various lists of fire safety goals previously presented in this paper. This list is more detailed because any **generic** list of goals must be inclusive; with the ability for any nation or society to decide that one or more of them will not be adopted within their country for whatever reason. For example, New Zealand decided that protection of one's own property is between the property owner and their insurance company -- and not a societal goal (however protection of a third party's property **is** something that needs to be dealt with).

The universal nature of these goals should make agreement to them on an international scale the easiest part of this process. Following such agreement, we can proceed to the establishment of the evaluation procedures and the infrastructure necessary to support their use. It is these steps which will be the focus of the remainder of this section.

Choosing the Simulation Model(s)

Because the criterion is the actual performance of the design against the established goals, any ***valid*** model or predictive procedure which provides the required level of detail can be used. This would allow the individual regulatory authority to use the model in which they had the most confidence. Fire hazard assessment systems such as HAZARD I [21] or risk assessment systems such as the one developed at the National Research Council of Canada [22] can serve as a prototype for others, or individual modules of HAZARD I can be replaced with similar models if preferred.

Thus, the developmental work required in this area is to expand the scope of HAZARD I from residential occupancies into the broader range of regulated occupancies for which the performance code will be used. This involves the addition of physical phenomena such as the impact of mechanical ventilation in larger buildings and alternate evacuation models which place more emphasis on route selection and congestion at stairwells and less emphasis of the behavior of family groups. But again, the modular structure of these procedures allows portions developed by various groups to be utilized by those without expertise in those specific areas.

The real issue then becomes the development of three key elements which establish the details of the calculation. These elements encompass the specific problems of the building and its occupants with respect to their safety from the effects of fire and as such control the ability of the design to meet those needs. These elements also embody most of the areas in which cultural or regional factors will influence the fire safety needs for the building. Thus, there should be a standard procedure by which these are established, but an allowance for them to vary when the need arises.

These three key elements are:

- standard fire conditions (design fire),
- standard safety criteria, and
- standard safety factors.

The Standard Fire Conditions

This element refers to the range of fire conditions (or scenarios) which could occur in the building under evaluation. In structural engineering this corresponds to the design load, and in fire resistance it is equivalent to the Standard Time-Temperature Curve. However, here it is not a single value or curve, but rather includes a range of possible fires, variations in building configuration (position of doors or operation of building systems), and an assumed number, location, and condition of occupants.

The traditional means of deriving such information has been from historical incidents; in the form of the personal experience of code officials or participants in code committees. For our purposes we can do the same, although the mechanism needs to be more formalized.

In 1987, a project to develop a fire risk assessment method was initiated with funding from the National Fire Protection Research Foundation. This effort faced a similar need to derive fire scenarios for specified occupancies from (U.S.) national fire incident databases, and developed a detailed procedure for doing so. This procedure described in the project reports [23], can be employed in conjunction with any national or regional fire incident database containing the same or equivalent data elements.

Establishing a Peak Rate of Heat Release

The risk assessment method referenced above incorporates a detailed method for quantifying the full range of fire sizes expected to originate in a given space of a specified occupancy. Such detailed scenario descriptions are necessary to evaluate the contribution to risk of individual products. For the purpose of building regulation however, codes generally envision the maximum threat and design the protection systems to that threat.

Thus, for establishing the peak energy release rate for the design fire for a given occupancy, the performance code should use the threat level considered in the current (specification) codes for that occupancy. This would be obtained by describing a building which just complies with the current code and modeling successively increasing fire sizes until the required building systems no longer provide the desired occupant protection. This value of peak energy release rate represents the current code requirement for which the performance code should provide equivalence.

While this method can be used to establish the peak value, it does not address the growth phase or burnout behavior of the design fire. The former is crucial in properly estimating the fire's effects on occupants near to the fire origin and the response of fire initiated devices, and the latter will affect structural integrity and occupant safety in areas of refuge.

The risk method uses a fire and smoke transport model, FAST [24], to compute heat build up from ignition through flashover based on an assumed exponentially-growing fire, and fuel burn out in the room of fire origin using estimates of total fire load.

Fuel Load per Square Meter

Because a flashover fire will involve all components of the room's fuel load, this quantity will need to be estimated, possibly from field surveys or if necessary from expert judgment. It will normally be expressed as two terms -- the fuel load per square meter (normally expressed as an equivalent weight of wood) and the effective heat of combustion (the value assumed in deriving the equivalency). When multiplied by the room area the fuel load per square meter converts to the entire fuel load of the room.

Quantifying the Rate of Fire Growth

The fire growth (heat release) rate for any item can be represented by an exponential curve. Many such experimental curves can be shown to be approximately proportional to time squared, where the curve is defined by the time required for the heat release rate to reach a particular value.

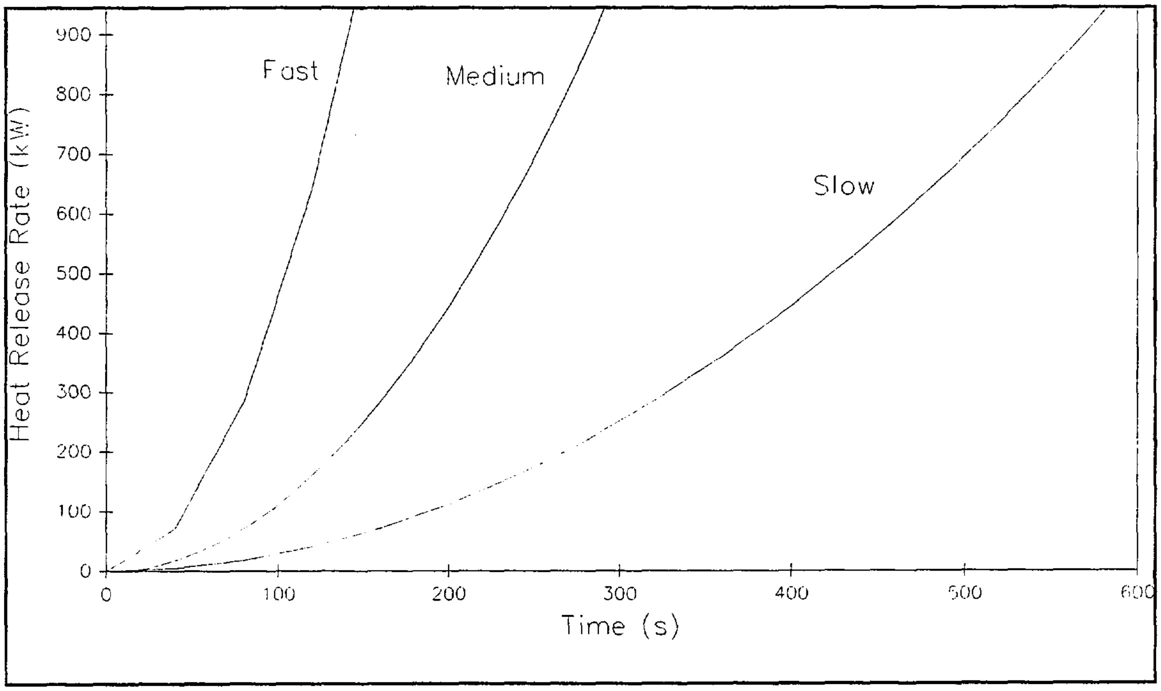

Figure 1 - T-square fire growth curves

Three growth rate curves would be employed -- slow, which grows to 1055 kW in 600 s; medium, which grows to 1055 kW in 300 s; and fast, which grows to 1055 kW in 150 s (see Figure 1). Typical contents items expected to be found in the building occupancy of interest can be assigned to one of these curves based on typical form and type of *material first ignited* data found in the national database. In detector and sprinkler design systems that require similar assignments of general burning items to classes, the NFPA Technical Committees on Detection Devices and on Automatic Sprinklers are using these same curves. Some such assignments are tabulated in Appendix C of the Standard on Automatic Fire Detectors (NFPA 72E) [25].

In the absence of manual or automatic intervention (suppression), it was arbitrarily assumed that the rate of heat release declines from its peak value according to a linear curve that requires the same time to decline to zero as was required to reach the peak rate from zero.

Establishing the Standard Fire Condition

The procedures described above can be utilized to develop a standard (design) fire for each principal occupancy class or building (construction) type considered in the current code. This will result in an associated design fire for each building (and major space within that building) which for the first time, establishes a quantitative benchmark for the threat against which the building is expected to perform.

The design fire for one building becomes the quantified exposure threat to its neighboring buildings. By expressing required performance in such terms, the code becomes unambiguous, and directly comparable to required performance levels for similar buildings anywhere which uses the same performance code system.

Standard Safety Criteria

The establishment of standard safety criteria is the second element in the performance code development. Extensive work conducted over the past decade has resulted in a body of knowledge about the susceptibility of people to the fire environment. These data and a resulting model for human tolerance are presented in the *Technical Reference Guide for HAZARD I* [26]. Since there is no evidence that there are significant differences in human tolerance among persons in different countries, these values should represent a universal set of criteria.

Another crucial addition to our capability to produce realistic predictions of the outcome of building fires involves the addition of human behavior to the modeling of evacuation. The egress model included in the HAZARD I package contains such behavioral rules which allow the occupants to respond (i.e., investigation, rescue, way finding, impedance by smoke, etc.) to the individual situation. Thus, the *psychological* impacts of alarm/notification systems, path markings, and other features which affect the efficiency with which that process proceeds can now be explicitly included. Such models also provide the means to deal directly with specific handicaps to senses or locomotion rather than applying all handicaps to a single class.

What would remain to be determined is the susceptibility of the building and its components to the fire environment. For example, failure of partitions needs to be predicted both for its influence on the distribution of products throughout the building, and its role in structural failure. This will require some translation of data from current fire resistance tests (e.g., ASTM E-119) and the response of these assemblies to different temperature histories. Since calculated fire resistance has been a topic of research in a number of countries and has been adopted to a limited extent in a few, this should not be an impossible task.

Standard Safety Factors

Safety factors are a universal, engineering approach to account for uncertainties in calculations, and would serve the same purpose here. Standard safety factors would be needed to account for our inability to incorporate details, assumptions made for practicality, and for conservatism, until experience is gained with a new system. These safety factors can also serve to account for the levels of uncertainty present in both the model and the data input to it. Thus, the use of simple models of higher uncertainty or of estimates of burning rates would result in a higher safety factor where using a field model or actual burning rate data would be compensated by a lower safety factor. Such an approach would also serve as a metric for the validity of models and data in terms the engineering and regulatory communities can easily relate.

Strategy for Developing the Performance Code

The process by which we work toward the performance code should be evolutionary rather than revolutionary. Thus a development strategy has been established by which we can move in that direction.

This strategy involves the initial reorganization of existing code requirements relative to a set of performance goals such as those listed earlier. For example, requirements which impact limiting the spread of fire or protecting escape routes would be identified with these goals. This will result in the cataloging of the current requirements for each goal. These may be prescriptive specifications, descriptions which rely on the judgement of the regulatory authority, or might currently represent a performance type rule.

This type of organization is not new, but would be quite similar to the Fire Safety Evaluation Systems developed by BFRL and now incorporated into the Life Safety Code from the National Fire Protection Association (NFPA) in the US [27]. These code equivalency systems assign point values to various protection features and weight them according to their contribution to safety in each of several categories such as evacuation of occupants. This weighting is a quantification of the relative benefit provided by the feature to that safety category. Similarly, the performance code would need to relate the influence of the feature to its impact. In this way, a partial sprinkler system installed only in the corridors would assure safe exit access, but would not receive full credit for maintaining the building's structural integrity.

A prototype tabulation for such a performance code supporting the list of goals presented earlier is shown below. In each case, a judgement has been made as to whether each requirement could currently be assessed in terms of a Performance Standard (PS), Specification Standard (SS), Deemed to Satisfy (DS), or would require Expert Judgement (EJ). The Performance Standard would be one where only the safety goals (*what* is the desired outcome or condition) were specified. The Specification Standard would state *how* something was to be done, although it too should be clear on the goal and should be based on defensible, technical arguments. For example, modern stair design is based on extensive research with people walking stairs, results in specifications for tread dimensions which allow safe and efficient movement; and the layout of sprinklers is determined by the design of their spray patterns.

The category "Deemed to Satisfy" would be used for specifications in the current codes which are not based on hard data. For example, the "heights and areas" tables in the codes limit building height and maximum area of a fire compartment based on construction and occupancy. They are arbitrary specifications which have been handed down from code committees and represent their best judgements for safety. Therefore a three story, wood frame building would be "deemed to satisfy" the code. As research data becomes available, some items in this category will transfer into the Specification Standard or Performance Standard categories. The Expert Judgement category refers to all of those qualitative decisions which have traditionally been left up to the local authority. Such decisions usually involve a determination as to whether to accept one thing in combination with a number of other factors, or other special cases. The code must continue to allow for the approval authority's discretion.

Once this process is completed, we can begin to develop the design fires, safety criteria, and safety factors necessary to replace each specification related goal to a performance base. In some cases, the existing specifications may be judged to be sufficient (for example, the detailed specifications on stair design - height of rise and length of run - are well established and need not be made more subjective.)

Current Status of Performance Code Elements

Requirements	P S	S S	D S	E J
1. Fundamental Requirements for Fire Safety of Individual Buildings				
1.1 Prevention of fire			X	
1.2 Exclusion of hazardous areas			X	
1.3 Assurance of safe evacuation				
1.3.1 Restrictions on the use of certain materials			X	
1.3.2 Evacuation planning				
1.3.2.1 Plans prepared in advance				X
1.3.2.2 Plans include all potential occupants				X
1.3.2.3 Plans consider all important building uses				X
1.3.2.4 Plans are practicable				X
1.3.3 Assurance of safe refuge				
1.3.3.1 Adequate refuge(s) provided	X			
1.3.3.2 Safe refuge(s) provided	X			
1.3.3.3 Location of refuge(s)				X
1.3.3.4 Alternate refuge(s)				X
1.3.4 Assurance of safe paths of egress				
1.3.4.1 Assurance of at least one exit			X	
1.3.4.2 Exits are clear and continuous			X	

1.3.4.3 Exits are protected	X			
1.3.4.4 Exits are properly designed		X		
1.3.4.5 Special protection for unique circumstances			X	
1.4 Prevention of damage to third parties				
1.4.1 Prevention of fire spread to other tenant's space	X			
1.4.1.1 Prevention of spread to other buildings	X			
1.4.1.2 Prevention of collapse onto other buildings		X		
1.4.1.3 Reuse of buildings of multiple ownership		X		
1.5 Assurance of firefighting activities				
1.5.1 Design to facilitate fire service operations			X	
1.5.2 Bases of operation			X	
1.5.2.1 Sufficient bases provided			X	
1.5.2.2 Bases are safe	X			
1.5.3 Access to bases			X	
1.5.4 Arrangement of bases			X	
1.5.4.1 Cover search and rescue range			X	
1.5.4.2 Cover suppression range			X	
1.5.5 Limitation of fire size			X	
2. Prevention of urban fires				
2.1 Buildings in designated urban fire districts			X	
2.2 Buildings in designated quasi-urban fire districts			X	

National and Cultural Variations

Most modern codes focus on life safety, with property protection secondary. (A possible exception may be the Russians who seem to place primary emphasis on avoiding an interruption in use of the building.) Thus we feel that most nations could agree in principle to a list of goals like those presented in this paper. Certain code sections, such as the provisions relating to urban fires from the Japanese code, could be made optional as a function of local need.

Cultural differences are a bit more difficult to address. While occupant behavior is a major part of the evacuation model in HAZARD I (EXITT), these behaviors are displayed generally only with family groups. They are not important in the present context since most residences in the U.S. are not regulated occupancies. In other circumstances or for other cultural differences like the inherent trust the Japanese place in people following instructions, some allowances can be incorporated into the code provisions.

Further, there is significant work going on in the world in advanced behavioral (evacuation) models. For example, the successor to the EXITT and TENAB modules of HAZARD is SURVIVAL; which modularizes the behavioral rule set so that it can be easily modified for different occupant groups. Behavioral models such as EXODUS [28] and VEGAS [29] are being developed in the UK and similar projects are ongoing in other countries.

Section 2

U.S. Efforts towards a Performance Code

A. Current Status

Unlike most countries, development of codes in the US is distributed among many players, both private and public. Model code organizations (private) develop the basic code requirements which are then adapted and adopted by legislative bodies at the state and local levels. Several competing model code organizations exist and, while similar, there are sufficient differences that a unified national model is not extant. Coupled with modifications adopted at the local level (the California amendments to the Uniform Building Code occupy more pages than the original code) and the fact that many jurisdictions fall significantly behind in adopting revisions (the model codes are modified on a cycle ranging from six months to three years but a specific locale may be enforcing a decade old edition) often leads to confusion.

One common feature in the US codes is the provision of "equivalency clauses" which allow for the acceptance of alternative approaches which meet the intent of the prescriptive requirements. Intended to allow flexibility and foster innovation, these have long been used as the basis for "variances" to the code -- a now common practice in most areas. In all cases, since the legal responsibility for code enforcement resides at the local level, the final determination of equivalency is made by the Authority Having Jurisdiction (AHJ), usually the local code official. Formerly, the substantiation for such variances was in the form of logical arguments, data from tests, or example (it was accepted elsewhere and has worked). More recently, engineering models and calculations are being submitted to the AHJ as the evidence of compliance -- a practice that brings fear to many who are uncertain of the validity of the calculations and data which feed them.

A more formal equivalency determination system was introduced into the Health Care occupancy chapter of NFPA's Life Safety Code in the 1980's and has since been expanded into several more occupancy types. Generally referred to as Fire Safety Evaluation Systems (FSES's) these provide relative scores for specific building features; positive for features which enhance safety and negative for those which detract from safety. The FSES is then calibrated against the prescriptive requirements of the code to ascertain the minimum score needed in several categories. Depending on the occupancy these include fire control or containment, egress or people movement, extinguishment, refuge, and general fire safety.

B. Are these Performance Codes?

Some argue that they are, because the code sets a performance level and the equivalency provisions allow for alternative methods of meeting the intent without strict compliance with the code; so the codes allow for performance based acceptance. The problem with this argument is that the level of performance is only ***implied***; it is not quantitative such that it represents a target against which the alternative method can be measured.

The FSES's are only semi-quantitative because their parameter values are on a relative scale. You cannot compare a parameter value from one FSES with one from another, much less to the estimated value of a feature in a different context. Thus, these too cannot be considered a performance code.

Some portions of the building codes **are** performance based. For example, structural design aspects are performance based because the procedures for determining loads are specified, including wind and snow loads by geographical region. Earthquake loads are covered in a similar fashion with special provisions in the code for earthquake prone zones. Based on these loads and accepted safety factors, calculations referenced in the codes are used to produce the design; and which need only be verified by the code official to receive the needed permits.

C. Recent Progress

With positive experience, code officials are becoming more comfortable with calculations for egress and fire growth in granting variances; at least for cases where the differences from the code are small. It has been recognized that performance codes are a worthy goal in that they promise to allow safety to be maintained while improving design flexibility and reducing cost. Successes in the application of calculations to fire reconstruction for litigation has given some methods a legal credibility which should carry over to the regulatory arena.

It has further been recognized that the move toward performance codes will require some fundamental changes in the way that fire safety regulation is done.

Test Methods

The entire philosophy of material and product testing is undergoing change. Historically, test methods were developed which produced pass/fail results or categorized materials into a few classes which could be required in certain areas of a building. All buildings of a given occupancy use were treated the same, generally only subdivided into high rise (normally over 6 stories) and low rise. For example, interior finish for exit access corridors in high rise health care is must be class A, but class B is allowed in buildings up to six stories -- these requirements are applied no matter what other compensating features are provided. The test method which is used to classify finish materials (ASTM E84) uses a single testing configuration and fire exposure for any material, regardless of where or how it is used -- in recent years many codes have begun to relax such requirements in fully sprinklered buildings.

A growing number of fire safety professionals now subscribe to the view that we need to test a material's *reaction to fire* in quantitative terms and then evaluate its performance in the specific *context of use* in the application. There is no sense in requiring a material with high fire performance in an area with limited ignition sources, low fuel load, and rapid egress capabilities. Since these measurement methods deal with generic fire performance of materials the results are generally applicable. An indicator of the changes in attitude in the US is the fact that Underwriters Laboratories is exploring ways in which they will interface with these new methods. Their vision is that they will become a source of third-party certified data rather than simply certifying that a product meets their standard.

This new thinking has resulted in the evolution of a generation of standard tests which are replacing the old test methods. The Cone Calorimeter (ASTM E1354) and the LIFT (ASTM E1321) are two such apparatus gaining worldwide acceptance -- which also leads to questions of acceptance of data from foreign laboratories or with unfamiliar certifications. On the positive side these trends are opening world markets for US goods which have previously been closed.

Prediction Tools

As mentioned above, prediction tools are slowly gaining acceptance among the regulatory community. Successes in fire reconstruction for litigation, successful application to design problems and code change proposals, and the growing body of verification experiments all influence this acceptance. Comfort is growing among regulators largely with the simpler methods when applied to simpler problems where the results are considered reasonable in their expert judgement. Discomfort still exists for the more difficult applications where the correctness of the solution is not obvious. Here, the regulators are demanding some metric for the uncertainty in the calculation. This needs to be a measure which has meaning to the code official -- he or she has difficulty in understanding whether uncertainties of 30% in temperature and a factor of three in gas concentration are significant in the degree of safety provided.

One answer to this which has been proposed by NIST is to relate the predictive uncertainty -- including both the calculational uncertainty and the uncertainty in the input data as it propagates through the calculation -- to a design safety factor which will insure that an undesirable result will not occur. Safety factors are something with which the code official has dealt for years in the other areas of the code which are performance based. As this concept has been discussed in both national and international circles, it has been well received and some researchers have begun work to develop it.

The prediction tools themselves do not seem to be questioned other than for their uncertainty. Of particular concern is the fact that the regulators do not question the appropriateness of certain techniques -- simple, single-zone models are often used in very large spaces with no discussion of the weakness of the zone assumptions in such spaces. Rather the code officials seem to be depending on the ethics and professionalism of the submitter in the same way as they would for design calculations.

D. Next Steps

Credibility (and the comfort it brings) of the prediction tools as an equivalency method is still developing among regulators. What is really needed to advance the process is for specific models or calculation methods to be reviewed and sanctioned by an independent body for such uses. An ASTM committee is developing guides for fire hazard and fire risk analyses, but these will not address this need. The model codes or related organizations need to establish guidelines of use and to "sanction" specific models, within limits, for use in determining equivalency.

The fire protection profession also needs to address this issue through the development of manuals of practice which lay out the proper procedures (e.g., data sources, appropriateness of a model relative to its assumptions, the role of sensitivity analysis, accuracy and uncertainty estimates, etc.) which constitute competency.

There is an effort to address these issues beginning at Worcester Polytechnic's Center for Firesafety Studies under the leadership of Prof. Dave Lucht. The goal is to have such a system in place by the end of the decade.

Section 3
Japanese efforts towards a performance-based code

A. Current Status

The Japanese are a long way ahead of the US in this area. Beginning a decade ago, they developed a detailed methodology which can be used to establish equivalency to the Building Standard Law of Japan. This method was published in 1988 and has been growing in use since. The number of "Article 38 Appraisals" has increased to hundreds per year, although still limited to special projects with unique requirements which could not be easily achieved under the prescriptive law.

Their ability to accomplish this is due, in part, to the fact that they have a single, national code promulgated by the Ministry of Construction (MOC) but enforced locally. It allows equivalency like the US codes, but the determination of such rests with the MOC. Thus, when the Building Research Institute (part of MOC) published the calculational method it represented a "sanctioned method" for establishing equivalency. Further, there is a mechanism established whereby the local authority can solicit the advice of MOC on the appropriateness of a calculation, further adding to the comfort of the Authority Having Jurisdiction (AHJ).

Published in four volumes, the method represents a Manual of Practice for evaluating the fire safety of a building. Volume one discusses the goals and objectives of achieving safety and presents several case studies as examples. Volume two covers fire prevention and containment. Calculation methods for predicting fire and smoke spread within a building are included along with typical data needed to perform the calculations for most buildings. An example calculation for an atrium is included. In volume three, egress calculations and tenability calculations are covered. Necessary data including occupant characteristics and loadings by occupancy type are given along with several example calculations. The fourth volume is a manual of fire resistant design containing design standards, calculation methods, data, and examples. For common assemblies charts and simplified calculations are presented. The complete tables of contents of the four volumes have been translated and included in Appendix I of this report.

While the Japanese do not currently have a performance code, they do have a performance based method which is officially sanctioned as providing equivalent designs. They have a manual of practice which provides details of the calculation methods and all necessary data, along with numerous examples. And they have established a system by which local authorities can receive assistance in evaluating the appropriateness of the calculation in any case where they feel uncertain or uncomfortable in making that decision.

B. New Directions

With this in place, the Japanese are now studying how to evolve to a performance based building regulation system to replace the current prescriptive law. They are also very involved in attempting to harmonize their requirements and methods with those of other countries in order to allow them to better access foreign markets and to comply with the GATT agreement.

Harmonization

The Japanese are working through ISO/TC92 to harmonize their testing methods with ISO standards. They are developing a method for accepting foreign test data for use in their own calculational methods This will likely involve mutual agreements between testing labs which will also insure that data from Japanese labs will be accepted elsewhere. They are also examining their current laboratory registration rules which have been cited as impediments to trade in the past.

Performance Based Design

The current assessment methods are practically limited to typical buildings by assumptions in the calculations and limitations in the data. These will be expanded and refined to allow their use in any building. They are developing a new materials testing and certification system which will include calculated fire growth, reaction to fire, and toxicity assessment, all to be harmonized with ISO/TC92/SC1 and SC3. Fire resistance determinations will use a single test and will employ the ISO834 time-temperature curve, with methods of calculating fire endurance of components and related measurement methods to provide the required data.

Section 4

Conclusions, recommendations, and future directions

The advantages of performance-based codes are seen to be largely in their cost effectiveness: either money can be saved while maintaining the same level of safety, or safety levels can be raised while maintaining unchanged the expenditures.

It is quite clear why prescriptive codes are not cost effective:

1. Mandated over-design of certain features, this being defeated by proportionately `weaker links in the chain' as regards other requirements.
2. Exclusion of certain products from usage because they are not specifically enumerated. It is entirely likely that designs can be found where the excluded products are the best suited and most economical.
3. No built-in process available which would allow checking for the weakest link versus the over-specified ones. In other words, the question itself as to whether a certain provision is wasteful is never on the agenda.

By exactly the same reasoning it can be seen that performance-based codes, if properly set up and utilized can be free of all of these shortcomings. It is appropriate, however, to not adopt an over-rosy view and to consider the hurdles which will need to be faced before performance-based codes are a reality. Summarized below are a few of the more salient issues that will need to be worked in developing a suitable performance-based approach, along with cautions where appropriate.

Identification of all of the needed objectives. In this review it is noted that the set of objectives defined for the fire safety of buildings can be formulated in a variety of ways, including many correct ways. Some formulations, however, will be more clear and more useful in deriving guidance than others. Reaching an agreement on this point is not seen as a difficult task, but it is one which will need a reasonable consensus.

Assembling of existing engineering tools. The first step in an actual engineering implementation is to assemble all of the tools needed for each computational module. Many will be seen to be at hand, but others will evidently be lacking. Three sources published so far have been identified where a serious attempt has been made to catalogue the available methods: (1) the Malhotra report for BRE. (2) The Australian Building Regulations Review. (3) The Japanese Art. 38 report. The Malhotra report mainly assembles references to tried-and-true technology. The Australian report develops a great deal of detail of the proposed methodology, but the engineering methods themselves are only sketchily surveyed. This report seems to be more useful in the human factors and safety management areas than in the fire physics area. The Japanese report appears to be extremely detailed. It focuses heavily on both physics and evacuation of people, although not upon some `softer' human factors issues. More detailed statements cannot be made at this time due to lack of a translation.

Augmenting engineering tools where needed. From an engineer's point of view, this will be the major task required to successfully implement the performance-based code concept. It is clear that at the beginning there will be many and major gaps in calculational procedures. Thus, it is suggested that gap filling shall have to be staged. That is, initially, some quite drastic assumptions will be made and some very simple stopgap methods will be provided. This will enable the system to get off the ground. Later, the gaps will be filled with better engineering methods and refined techniques.

Approved documents. A problem with Approved Documents is not what is said but what is not said. In general, a suitable design procedure can be outlined for a given requirement. Something of this kind will need to be present in any scheme, to be used for routine work -- the "Deemed to Satisfy" concept discussed by Bukowski and Tanaka. The challenge instead, lies in determining what is **equivalent**. In the UK and NZ schemes (and, apparently, in Japan), this is left to the local building authority, who in turn need explicit advice themselves. In Japan there is a mechanism to provide expert advice to the local authority. Both the technical competence and the experience of building authorities varies tremendously among the various jurisdictions of any one country. Yet, such a scheme relies upon a tacit assumption that the officials are all equally competent in judging complex engineering assumptions **and judging them to the same standard**. Inconsistent enforcement will doom any performance code system to failure.

Codes of practice. More recently in the UK the development of a Code of Practice appears to have replaced Approved Documents. From the information available, there are concerns that the specific Code of Practice being evolved may be too complex. This should not be taken as a criticism of the British work; instead, it should be taken as an indicator of the difficulty of the task. From what can be seen today, it is apparent that a Code of Practice is perhaps the best way that detailed professional instructions can be given. Yet, it is a daunting task -- not only must **an** engineering method be provided for every aspect of fire safety, but a `meta-methodology' must be evolved which can vet any and all methods. This is indeed a daunting task.

Quality of data. The issue of validity of methodology should be answered by a Code of Practice. Methodologies, however, are not of value if adequate data are not available. Thus, Grubits' emphasis on assuring the quality of data is crucial. This has manifold implications, ranging from approval/disapproval of standard test types, to accreditation of laboratories, to establishing the confidence intervals possible with various tests, and to the qualification of testing laboratories who produce the data. We also note that the latest project of the Japanese includes tasks addressing the quality and acceptance of data on an international level.

Quality of practitioners. This issue is already of serious concern to the community in the context of using fire modeling in litigation. Equally well-known, generally-regarded-as-competent professionals can readily be found who will use well-regarded fire models and come up with antipodal conclusions in a particular case. In the case of prescriptive design methods, it is generally clear when a practitioner would be guilty of improper design or of malpractice. Incorrect constants, wrong measurements, omitted calculations, etc., all can be tracked in a fairly linear way. With a performance-based code, such checking can rapidly degenerate into a clash of opinions not resolvable by objective means. This issue will need to be successfully solved in order to inspire requisite confidence in the process.

Consistent enforcement. In most countries now, building codes work on a fairly uniform basis, either for the entire nation, province-by-province, or by some other major geographic area. As pointed out above, leaving the judgment of approving or disapproving engineering methods to the local building authority could drastically change this picture. Building standards could effectively become vastly different town to town or county to county. This, of course, would not be desirable. Thus, a mechanism will need to be found which, while not abrogating the role of local building authorities, nonetheless works to stabilize the system and discourage arbitrary local variations.

Sanctioned methods. A potential solution to limit local variations involves the Evaluation Services function associated with the US building codes. Currently, they evaluate submitted **products** and issue recommendations. The recommendations are not *ipso facto* binding upon building officials, but almost invariably such guidance is taken as given by the Evaluation Service. A similar scheme could be seen for **engineering methods**. An Evaluation Service could evaluate the engineering method proposed and either publish its approval or disapprove. Local building authorities could then rely on such determinations without having or needing the advanced educational background to make such determinations themselves.

Appendix I

Table of contents to the Japanese report giving design methods for conforming to Art. 38

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Predicting the Fire Performance of Buildings: Establishing Appropriate Calculation Methods for Regulatory Applications[†]

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Abstract

A recently organized effort in CIB W14 on Engineering Evaluation of Building Fire Safety is examining the various quantitative methods being promulgated to underpin performance-based codes or for determining equivalency with the implied performance of existing prescriptive codes. These methods share many common features and all recognize the range of fire models and calculational methods that the fire safety engineering profession have begun to embrace as their technical foundation.

The broad range of assumptions inherent in the available methods as well as the data required to utilize them raises some interesting legal, moral, and ethical questions about their appropriateness in applications where legal considerations are involved. Many fire-related computations have no exact solutions, so any calculation represents an approximation. Thus, one can ask, where law defines a minimum level of performance, how far must the fire safety engineer go to minimize uncertainty in a calculation intended to verify compliance? The variability of fire means that there are no inherently "correct" answers against which to define accuracy; and fire experiments involve measurement uncertainties as well as approximations used to reduce the data which often have similar form to the calculations we wish to verify.

These methods all focus on managing fire risk, and their successful application depends on assessing the acceptable level of risk implied by the current codes. From a legal standpoint it cannot be asserted that society accepts current levels of losses because there is no public outcry. Thus, how can acceptable levels of risk be determined when regulatory authorities and legislators are uncomfortable with the notion that there is no zero risk so some fatalities are inevitable?

This paper explores these questions from the perspective of the fire scientist, the practicing engineer, and the regulatory official. The fire scientist needs to be explicit about the impact of assumptions on the applicability of the results to regulatory uses. The engineer needs to utilize methods and assumptions which are justified by the application and to assess the sensitivity and uncertainty implications. The regulatory official must insist on appropriate and properly documented methods. Models and calculations incorporated into codes of practice, handbooks, or the codes themselves must be reviewed, validated, documented, and approved for use in specific manners and by qualified persons. Levels of risk acceptable to society in specific occupancies must be established. Until these issues are resolved, the transition to performance-based codes cannot be made with confidence.

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Introduction

The use of fire models and other predictive methods are becoming common means of supporting the design and arrangement of fire protection features to code officials. Typically, this is done under existing provisions in the codes for "equivalency" to the prescriptive requirements therein. This practice is most prevalent with respect to unique buildings or large projects where variation from normal practice is more common. The result is that the code official, faced with the application of a new engineering method in a high profile project, can experience a high degree of discomfort without some independent verification that the analysis has been done properly.

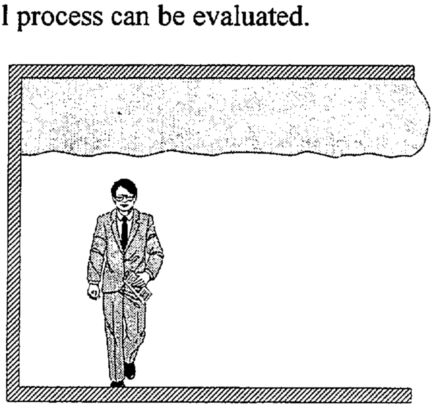
It is for these reasons that this paper was written -- to provide some guidelines for the code official to use in making an initial determination of whether an alternative design analysis is credible. The comments herein are based on the author's own experience in assessing alternate design analyses for several high profile projects and considerable experience in the development and application of fire models.

Key Factors in an Analysis

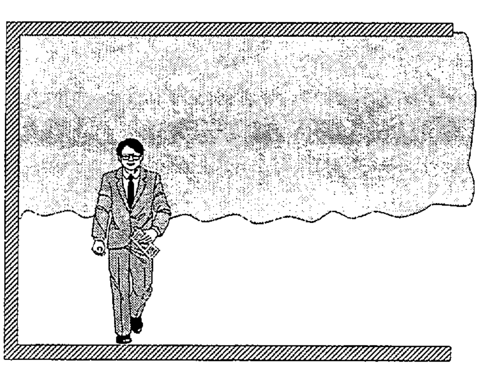
In performing a calculation to assess equivalency to code provisions for safe evacuation of building occupants several steps are required to assure a valid result. These include:

1. Establish the acceptance criteria.
2. Select appropriate fire models/methods.
3. Select design fire(s).
4. Perform an evacuation calculation.
5. Account for uncertainty.
6. Reality check.

In the following sections each of these steps will be discussed in detail so that the objective of each as well as the overall process can be evaluated.



The conservative assumption is that the person is safe until the smoke layer reaches head height.



Actually, people can continue to move through smoke as long as it is cool enough and light enough to see through. Such limits on temperature and smoke density have been incorporated into some egress models and provide valid results.

Establish the Acceptance Criteria

The primary purpose of fire safety code requirements is to allow for safe egress by all building occupants. Thus, the vast majority of alternative design calculations involve egress analysis. This is typically in two parts -- an estimate of the fire development/smoke filling time which establishes the time available for safe egress; and an estimate of the evacuation time needed by the maximum population expected in the exposed area. If time available is greater than the time needed, the occupants are safe and the building complies with the intent of the code.

For the first part of the calculation, the conservative assumption is normally used -- that once the smoke layer fills down to head height (usually 1.5 meters or 5 feet from the floor) escape is no longer possible. In fact, the models can predict the increase in smoke density within the layer (either upper or lower) so that a specified limit either of smoke level or visibility distance can be used. Other than for slowly developing fires, which are not normally used as design fires, or situations where little buoyant layering is expected, there will not be much difference with the conservative assumption.

There are also some situations where egress is not the objective or at least not the only one. In some industrial occupancies (nuclear power or chemical processing plants) the public safety consequences of a fire lead to code requirements intended to prevent exposure of critical systems or processes. In occupancies where persons have limited mobility (health care, correctional, and some board and care) the codes may envision "protection in place." In both of these instances only the filling time calculation is necessary and it may be desirable to make some estimate of the susceptibility of the critical equipment or people to damage. Again, models that do this are available.

Select Appropriate Models/Methods

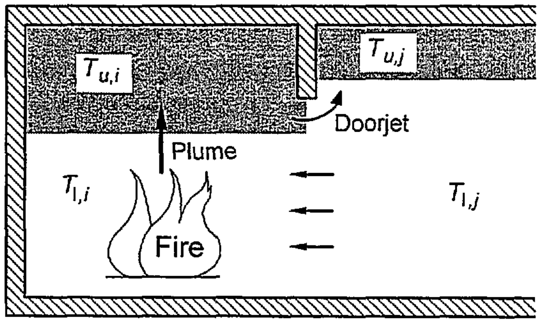
Fire Models

A recent survey [1] documented 62 models and calculation methods that could be applied to these uses. Thus the need is to determine which ones are appropriate to a given situation and which 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 assessed.

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 [2] and the MQH Upper Layer Temperature correlation [3] are generally held to provide useful engineering estimates.

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 should be used. Single room models are appropriate where the conditions of interest are limited to a single, freely connected space. Where the area of interest involves more than one space, and especially where they are on more than one 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 [4]). 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.



Zone models assume that fire gases collect in layers that are internally uniform.

The model should include the limitation of burning by available oxygen. This is straightforward to implement (based on the oxygen consumption principal) 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, CCFM [5]). 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 losses 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.

Another problem can occur in tall spaces like 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 [6], this constraint is implemented through an initial limitation on the height to which the plume rises based on its buoyancy.

Documentation

Only models which 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 which 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 is not 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

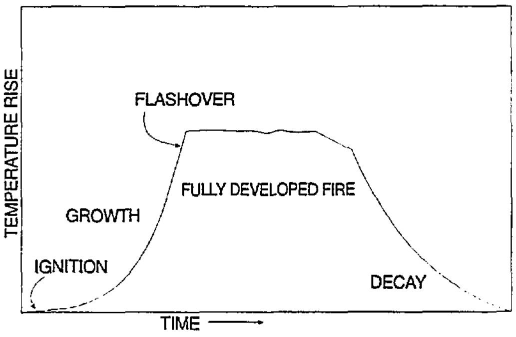
Even if the model is correct the results can be seriously in error if the data input to the model does not represent the condition being analyzed. Proper specification of the fire is the most critical, and will be addressed in detail in the following section on selecting the design fire(s).

Next in importance is specifying sources of air supply to the fire -- open doors or windows, but also cracks behind trim or around closed doors are important. 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.

Other important items of data include ignition characteristics of secondary fuel items and the heat transfer parameters for ceiling and wall materials. In each case, the alternative design analysis should include a listing of all data values used, their source (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 section, Account for Uncertainty).

Select Design Fire(s)

Along with selecting an appropriate model, 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 -- 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.



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. Thus this is the most important to an egress analysis which makes up the majority of alternate design analyses.

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 [7]. He suggested fires of the form:

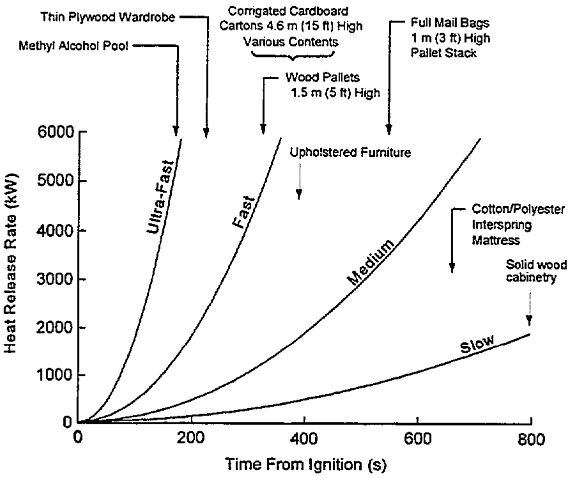
$$Q = \alpha t^n$$

where: Q is the rate of heat release (kW)
α is the fire intensity coefficient (kW/s^2)
t is time (s)
n is 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 was an excellent representation [8]. A set of specific T-squared fires labeled slow, medium, and fast, with fire intensity coefficients (α) such that the fires reached 1055 kW (1000 BTU/s) in 600, 300, and 150 seconds, respectively were proposed for design of fire detection systems [9]. Later, these specific growth curves and a fourth called "Ultra-fast" [10] which reaches 1055 kW in 75 seconds, gained favor in general fire protection applications.

This specific set of fire growth curves have been incorporated into several design methods such as for the design of fire detection systems in the *National Fire Alarm Code* [11]. 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 [12]. 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 appropriate since the growth rate is related to the form, arrangement, and type of material and not simply its quantity. Consider 10 kg (22 pounds) of wood; arranged in a solid cube, sticks arranged in a crib, and as a layer of sawdust. These three arrangements would have significantly different growth rates while representing identical fuel loads.

This set of T-squared growth curves are shown on the next page. The slow curve is appropriate for fires involving thick, solid objects (solid wood table, bedroom dresser, or cabinet). The medium growth curve is typical of solid fuels of lower density (upholstered furniture and mattresses). Fast fires are thin, combustible items (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.

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 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 the steady burning region can be specified at any level that results in a flame out the door and the heat released inside the room will be controlled to the appropriate level by the model's calculation of available oxygen. For the much smaller number of fuel controlled scenarios values of heat release rate per unit area at a given radiant exposure (from the Cone calorimeter, ASTM E-1354) can be found in handbooks and used with an estimate of the total fuel area.

Decay

The burning rate declines as the fuel is exhausted. This decline is often specified 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 point at which decay begins is when 20% of the original fuel is left. While these are assumptions, they are technically reasonable.

Of course if a sprinkler system is present this decay will proceed as the fire is extinguished by the water. A simple assumption is that the fire immediately goes out; but this is not conservative. It is better to use a recent NIST study which documents a (conservative) linear diminution in burning rate under the application of water from a sprinkler [13]. 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.

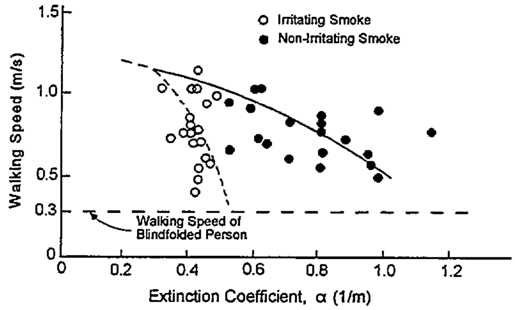
Evacuation calculations

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 people 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. An excellent discussion of this topic is found in Pauls' [14] and Bryan's [15] chapters in the SFPE Handbook.

Models

The process of emergency evacuation of people follows the general concepts of traffic flow. There are a number of models which perform such calculations and which 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 [16]. If such behavior is expected it should be included as it can result in significant delays in evacuating a building.

Another situation where models 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 [17]. 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 which give the best possible performance. These are inappropriate for a code equivalency determination.



A person's walking speed decreases in dense smoke until they move as slowly as if blindfolded.

Hand calculations

Luckily, evacuation calculations are generally 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 in [18]. 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.

Account for Uncertainty

This refers to dealing with the uncertainty which is inherent in any prediction. In the calculations this uncertainty derives from the models and from 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 be safe.

In the prediction of fire development/filling time the intent is to select design fires which 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 analysis 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 (vary the data to the limits and see whether the conclusions change) should be performed. This is also a good section in which to justify the appropriateness of the model or calculation method in the manner discussed previously.

Reality Check

The last step in any calculated analysis is the reality check. If a model or calculation produces a result which defies logic there is probably something wrong. Cases have been seen where the model clearly produced a wrong answer (the temperature predicted approached the surface temperature of the sun) and those where it initially looked wrong but was not (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 if 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 plans review shows that all code requirements have been met?

Obtaining Help

For the large, high profile project, the public outcry likely to occur if something goes wrong presents a risk which may demand a higher level of confidence. The code official may feel compelled to obtain an independent opinion about the appropriateness of the analysis. This is reasonable to expect.

Qualified engineering firms exist in nearly any area of the country, although they will need to be paid. The model codes make provision for the submitter to pay for "special studies" needed; and this could include such reviews. Several universities have fire science or fire protection engineering programs where faculty can serve as experts. Finally, NIST experts are available answer questions from code officials about the models or data which have been developed here.

In Japan, a formal system was put into place for this purpose. For major projects where alternate design analyses have been performed, the local code official can call on an expert panel drawn from government and university experts for consultation. These experts advise the code official who ultimately makes the final decision. A similar system could be organized through organizations such as NIBS, NCSBCS, or CABO if there is a demand for such from the code enforcement community.

Certification of Methods

Considering the complexity of the methods and the criteria presented in this paper against which these methods should be judged, most code officials will not be comfortable with making decisions about the appropriateness of a model's physics or some complex assumptions. But for projects where obtaining outside advice is not practical this is exactly what would be required. For these cases the answer may lie in another approach familiar to the regulatory community -- third party certification.

Criteria such as those presented in this paper might be used to initiate a draft standard for models and calculations appropriate to alternate design analysis. Following review and a consensus process some organization might then certify or sanction specific models or methods for such, when used under specified conditions. This might be accomplished through the model code process since these codes already contain "sanctioned methods" for doing structural calculations. Such a process has been undertaken in New Zealand where a software package has been sanctioned and directly produces a certified report suitable for submittal directly to the code official.

Concluding Remarks

Alternate design calculations provide a way to achieve design flexibility and code equivalence based on performance. The advantages of such a system are widely recognized and research is underway all around the globe to formalize the process through national and international standards. Use in this country is growing as well.

By applying the information presented in this paper we hope that the level of comfort of the code official faced with assessing these calculations will be high and code officials will be able to deal better with the alternate design process.

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Fire Codes for Global Practice[†]

Fire codes applicable anywhere in the world, based on performance, are now closer to reality. A progress report *by Richard W. Bukowski.* The author is a Senior Research Engineer at NIST's Building and Fire Research Laboratory in Gaithersburg, Maryland

Abstract

Architecture in a world economy, with multinational clients and a global range of building materials and systems, demands fire codes based on performance. The International Council for Building Research is now working on methods to verify compliance under performance-based fire codes. Performance codes will have several advantages: code objectives clearly stated and understood by all parties, and analytical methods, data, and assumptions formalized in a single code of practice.

Introduction

Imagine that a multinational corporation wants you to design for it a signature building that will be reproduced in a dozen countries. Your job will be to develop a single design that complies with the individual fire-code requirements in each nation and satisfies all local authorities. After you obtain copies of the relevant codes and have them translated into English, you will likely discover that you have to use unfamiliar, locally produced products and materials in the design since only these have been certified to meet the local requirements. Many of the code allowances available in the U.S., when fire sprinklers, alarms, and smoke control systems are used, are unavailable under these prescriptive codes, especially in Asia.

Sound like a challenge? By the end of the decade this might be a task requiring only a single design analysis package that will be acceptable nearly anywhere in the world. The International Council for Building Research (CIB), Working Commission 14 (chaired by the author) is developing a common method of fire safety engineering analysis to underpin performance-based fire codes. There is a parallel effort under CIB Task Group 11 to coordinate the development of performance-based building codes. This is part of a worldwide interest in moving away from prescriptive codes driven by a desire to make the regulatory process more flexible and more cost effective. Programs to develop performance codes are under way in Eastern and Western Europe, North America, and across the Pacific Rim.

The Building and Fire Research Laboratory (BFRL) at the National Institute of Standards and Technology (NIST) is recognized as a leader in predictive fire models and their application to fire hazard and fire risk assessment. The evolution of these analytical tools over the past decade has allowed the transition to performance-based codes. Quantitative determinations can now be made as to whether a given design meets explicit performance objectives.

Code Equivalency

Alternative approaches to fire safety around the world were examined under the "equivalency clauses" in the codes. Under these clauses, the architect must convince the local authority that the difference from the prescriptive requirement still meets the intent of the code. In recent years it has become common to use analytical methods to justify variances from code requirements. Most code officials with whom we have spoken are willing to accept such analyses when they are

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[†] *Progressive Architecture* 117-119, June 1995

sufficiently documented. In some high-profile projects the regulators have sought second opinions from independent parties to increase their confidence.

Performance Objectives

Performance-based codes have several advantages over these ad hoc methods. First, the code objectives are clearly stated and understood by all parties. Second, the analytical methods, data, and assumptions are formalized in a "code of practice," avoiding disagreements over procedures. Third, the former, prescriptive requirements are retained as "deemed to satisfy" provisions, providing continuity and a simpler method for the majority of projects where a performance analysis may not be warranted.

The greatest appeal of performance codes is the provision of explicit objectives independent of the methods used to achieve them. These objectives are universally based on the concepts of protection of life and property, with some variations for cultural and societal differences. For example, in their new performance code New Zealand decided that the code should not require that owners protect their property from a fire. Insurance carriers now set such requirements as a condition of coverage.

Under a performance code the designer is free to use any means to assure that the occupants of a building can be safely evacuated. Codes of practice are being developed that provide guidance on characterizing fires, occupant loading and characteristics, and other parameters as a function of occupancy type. For example, in a mercantile occupancy in Australia several types of fires, numbers of customers (including the mix of disabled) and allowances for staff training and fire department response are all specified. These are used as design criteria in the same way design loads are.

Fire scenarios likely to occur in the given region are based on actual experience, and so vary from country to country. The frequency of these scenarios is accounted for in the analysis, producing a result that represents the risk of life loss by fire. For instance, the weight given to an arson scenario in an office building in Japan's fire code is lower than it is in England, reflecting Japan's lower rate of arson.

The ultimate criteria for acceptability of any design reflect the degree to which society accepts fire risk; either implicitly in the risk presented by building designs considered acceptable under the prescriptive code, or explicitly under performance codes. Thus, individual countries will establish their own criteria and a common evaluation method will be used to establish compliance. Several years ago an architect fought a protracted battle with code officials in London over the use of a textile roofing system proposed for a covered shopping area. The material had a coating proported to have high toxicity when exposed to fire. Under the new UK performance code and engineering code of practice this arrangement could easily be shown to be acceptable.

Resistance to Change

There are those who are uncomfortable with changing a system they feel is working well. Regulators are overwhelmed by the complexity of performance-based analysis, and lawmakers are reluctant to acknowledge that some losses are inevitable, even in code-compliant buildings. Material and product producers have also grown comfortable with traditional test methods and their ability to produce products that pass. However, in every country where performance codes have been introduced experience has shown these fears to be unfounded. For example, new product test methods require measurement of a product's reaction to fire and its acceptability, dependent on the context of use, as opposed to universal acceptance.

In spite of these concerns the process is clearly moving forward. The widespread desire for regulatory reform is attributed to the perception that in an increasingly competitive world, prescriptive codes limit economic development. The promise of more open international markets is softening the position of manufacturers. U.S. leadership, with regard to both analytical methods and their application to modern building fire safety design, is leading to increased design business in other countries.. Some U.S. fire protection consulting firms cite this view as the reason for significant growth in the demand for engineered designs for high-rise buildings in the Pacific Rim and South America. Because the U.S. is now viewed as a leader in this area, U.S. architects can use this knowledge to better sell their services for work abroad.

Next Steps

While the U.S. is a leader in analytical methods and their application to modern building fire safety design, by most accounts America is lagging behind other countries in the transition to performance codes. The U.S. has a multiplicity of codes instead of a single, national code common in many countries. The three model code organizations, plus the Society of Fire Protection Engineers and the National Fire Protection Association, are studying what their role should be and how they can encourage the transition. Beyond overhauling the codes and standards process, the task of educating architects, engineers, code officials, and builders is daunting. Generally, designing to specific performance levels for energy, acoustical, environmental, fire, and others will result in more dependence on specialty engineering. But performance codes will all demand increased understanding by the architect coordinating these consultants. Expertise in performance codes will also provide the architect with another valuable service for a global array of clients.

Testing laboratories are struggling with the need to move from providing lists of acceptable products to providing the certified performance data needed by these new methods. Professional societies are examining their roles in providing peer review of the evolving methods and the development of the needed codes of practice. We are in a period of rapid technological change and all parties need to work together to assure that the evolution goes smoothly.

BFRL sees its role as developing and verifying the predictive tools as well as providing a national focus in the international standards arena. As part of NIST, we assist industry in technological development and in remaining competitive. We welcome the opportunity to work with the design community through the American Institute of Architects and other organizations.

Final Thoughts

Making the advance to performance-based fire codes in this country is going to take a coordinated effort by all of the institutions and organizations with stakes in the process. Clearly, the model code groups and professional societies are trying to shape their role. Code officials are dealing with increasingly complex, alternate design analyses, and many of them are gaining confidence in the accuracy of such methods. BFRL is continuing to invest in advancing the technology and in integrating our analytical tools with CAD to encourage the use of these tools by the design community. For example, we are working on linking our fire models to architectural CAD software so that proposed designs can be evaluated in the architect's office. By moving to a system where the ultimate performance is clear, the methods to meet that level of performance are left to the expertise of the designer. Without prescriptive codes and greater choice for the architect, it should be possible to produce more cost effective buildings with no sacrifice in fire safety.

With worldwide acceptance of a common evaluation method, it should no longer be necessary to deal with a range of sometimes conflicting local code requirements. This should go a long way toward the elimination of barriers to trade in the design and construction industries.

For More Information

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International Activities for Developing Performance-based Fire Codes[†]

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INTRODUCTION

The purpose of this paper is to review the status of current activities associated with the development of performance-based fire codes in various countries across the globe, as well as the coordinated activities of international standardization and pre-standardization research in this field. Every attempt was made to include the latest developments but some activities in individual countries that do not participate in international conferences or standards activities may have been overlooked.

ISO TC92SC4 and CIB W14

The activities of ISO TC92SC4 and CIB W14 are focused on the development of the field of Fire Safety Engineering (FSE) to underpin and enable the transition to performance-based fire codes by providing the means to evaluate the ability of fire safety designs to meet the performance objectives of the code. The detailed activities of these groups is the subject of another paper in this symposium and will not be treated here.

It should be noted, however, that there is a related group in CIB whose activities should be followed; this is TG11, Performance Building Codes. It is likely that performance building and fire codes will go hand-in-hand in any individual country. Further, the issues being debated in CIB TG11 have direct analogs in the movement toward performance fire codes. In particular, the development of detailed objectives is an issue which has received little attention on the fire side but is a major item on the building side.

AUSTRALIA

The Australians were among the first to begin movement towards performance-based codes; based in large part on the visionary Warren Centre Conference and reports published in 1989. This has led to the formation of the Fire Code Reform Centre Ltd. (FCRC), a non-profit corporation focused on facilitating the reform of the Building Code of Australia (BCA). The format which has been proposed by the Building Regulations Review Task Force (BRRTF) is similar to the draft Code of Practice recently circulated for review in the UK and to the New Zealand approach, but is not intended to replace the current requirements, only to provide a performance-based means of certifying alternative designs.

CANADA

Working closely with Vaughan Beck at the Victoria Institute of Technology in Australia, David Yung and his colleagues at the National Fire Laboratory of the National Research Council of Canada have developed FiRECAM (Fire Risk Evaluation and Cost Assessment Model) as a key element of the performance fire code effort there and in Australia. Extensive work is underway to convert the Canadian National Building Code to a performance form by 2001, in the form of performance objectives as the substantive code document with a set of supporting documents which will include a set of "acceptable solutions" and a methodology for evaluating alternative approaches. A Strategic Planning Task Group has suggested a better description of these codes is "objective-based codes," and this terminology has appeared elsewhere as well.

[†] *Fire Safety Design og Buildings and Fire Safety Engineering,* Proceedings of the Mini-Symposium June 12, 1995, Tsukuba Japan, p 25-27, Building Research Institute, MOC, Japan.

ENGLAND AND WALES

In 1985 the Building Regulations were revised to utilize performance language and to allow alternative designs which could be shown to provide equivalent performance using any reasonable method. In the process, these regulations were reduced from 307 pages to only 23 (although much of the prior prescriptive code requirements were appended as "Approved Documents"). As these new approaches gained acceptance it became clear that the methods used to establish equivalency needed codification, so a Code of Practice was developed by Warrington Fire Research under the leadership of John Barnfield, Geoff Deakin, Gordon Cooke, and a host of other experts in the field. This Code of Practice, currently under public review, is similar to the New Zealand Design Guide, the Japanese Regulations for Comprehensive Designs for Fire Protection, and others, but (at least in the draft as released), attempts to establish acceptable levels of risk of life loss; in the home (1.5×10^{-5} per person per year), and elsewhere (1.5×10^{-6}), as well as limiting the risk of >10 deaths per incident to 5×10^{-7} per building per year and >100 deaths per incident to 5×10^{-8} per building per year.

NEW ZEALAND

The 1992 edition of the New Zealand Building Code introduced a performance-based format while keeping the prescriptive requirements as an "acceptable solution." The performance-based approach with its supporting calculations are required for any occupancy with fire loads exceeding 1500 MJ/m^2. Similar to the situation in England there is a Fire Engineering Design Guide, published by the Centre for Advanced Engineering at the University of Canterbury which serves as the Code of Practice for engineering calculations performed in support of a performance-based design. This linkage to the University has produced a burgeoning graduate degree program to educate the fire protection engineers needed to make the system work -- a fact which seems to be overlooked in some countries developing performance-based codes.

In a controversial move, New Zealand decided that the protection of property at the regulated occupancy is not a matter for the code but is rather between the owner and his insurance company. Thus, the code only includes provisions to protect the property of third parties. This has upset the insurance industry who find that they must develop and enforce their own regulations in addition to those in the code.

SWEDEN

The Swedish codes also have been extensively revised to incorporate performance language throughout. Their latest code, adopted in 1994, includes design criteria within the code document under subsequent headings of the same section. They are developing a guidance document similar in structure to the UK Code of Practice and New Zealand's Design Guide, which will include functional requirements, calculation methods with examples which represent acceptable solutions, uncertainties, and suggestions for solutions which exceed the minimum. Sweden has an advantage in that (like many European countries) fire department officers are all trained as fire protection engineers and have the educational basis for understanding and evaluating engineering calculations.

UNITED STATES

Efforts in the U.S. are more diffuse since the legal responsibility for building and fire codes lies with 50 states and derives from the activities of a number of private code and standards organizations. In the area of fire codes, the principal organization is the National Fire Protection Association (NFPA) and its Life Safety Code (NFPA 101). The NFPA has recognized the need to provide leadership in the evolution of its documents to a performance basis, and has taken several crucial steps. They constituted an in-house task group to develop recommendations to their Board of Directors. This group has written a white paper in which they suggest:

1. Establish a standard format for a performance-based code which can serve to guide the process of conversion of existing documents or the development of new documents by committees. The structure would include sections on (1) fire safety goals, (2) assumptions, (3) fire scenarios, (4) approved calculations and (5) prescriptive requirements ("approved solutions").

2. Establish a support system to provide technical guidance to both staff and technical committees. This would include recruitment of a staff person with expertise in fire safety engineering calculations and their application to code equivalency analysis. Additionally, establish a Performance-based Support Team under NFPA's Standards Council as an advisory body to assist staff and committees.

3. Begin to work with specific committees to develop prototype, performance-based documents which can serve as models to other committees for format, content, and process.

4. Partner with other organizations to begin to address the needs for supporting products and services such as handbooks, seminars, and educational programs, software and data resources, certification of methods and of professional competence in applying them, and training of and support for enforcers.

Other key players in the U.S. are the (professional) Engineering Societies, especially the Society of Fire Protection Engineers (SFPE). In 1988 the first edition of the *SFPE Handbook of Fire Protection Engineering* was published, which has been widely praised as an essential compilation of the state-of-the-art. The second edition of this landmark publication is due to be published by the end of 1995. They are cooperating with the American Society of Civil Engineers (ASCE) to produce a standard containing engineering methods for structural fire safety calculations. The SFPE has organized a series of Engineering Seminars on Performance-based Fire Safety Engineering and on performance-based design, and has recently hired a technical director to provide a focal point for these and other activities, and to provide improved technical support to its membership.

On the building code side, the three U.S. model building code organizations are actively pursuing the goal of resolving differences among their codes and achieving a single, national model code by the turn of the century. This will greatly facilitate the ability of the U.S. to achieve a performance-based building code in the form being studied in the rest of the world. But this is not to say that the transition will have to wait until then. The U.S. codes have long contained "equivalency clauses" which allow enforcers to accept alternate methods which provide equivalent performance. These clauses are increasingly being invoked where the equivalency is being established through the identical calculations which are being included in the Codes of Practice cited previously. Code officials are gaining experience with and comfort in these methods as more projects are completed under their use.

OTHER COUNTRIES

It is known that a number of other countries have some type of program under way to develop performance-based fire and/or building codes. These include Poland, Romania, Peoples Republic of China, Finland, Norway, Italy, Germany, France, Spain, South Africa, and probably many more. Central and South America is exhibiting increased interest in codes and standards in general and in performance-based approaches in particular. The NFPA has recently entered into an agreement with a Mexican organization to begin to translate NFPA standards into Spanish for use in that country. An organization in Venezuela requested permission from NIST to produce a Spanish language version of FPEtool to support engineering calculations there. With the recent decision of the (U.S.) National Science Foundation to utilize performance-based methods in the design of a new South Polar Research Station, the trend has touched every continent on the globe.

RISK AND PERFORMANCE STANDARDS[†]

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Abstract

Performance codes are replacing prescriptive codes in much of the world. As the form of the codes change, the form of standards which support those codes needs to evolve in concert. Thus, performance standards need to be explicit about the purpose(s) served by the standardized systems and to provide quantitative means to assess the degree to which they serve that purpose. Most of the engineering methods evolving to support performance based codes assess risk to life of building occupants relative to the risk to occupants in buildings which comply with the prescriptive code. Such *relative* risk assessment is cumbersome and unreliable, and should be replaced by absolute risk limits to enjoy all of the efficiencies of performance codes. Financial risk is easy to understand but is inappropriate to codes that exist to protect life. Risk to life is difficult to understand and communicate to the public. These risk analysis methods utilize scenarios as a bridge to experience and the means to quantify likelihoods. In the absence of incident data some systematic methods of identifying scenarios is needed. This paper deals with each of these issues in an attempt to stimulate research needed to find the answers.

1. BACKGROUND

The worldwide migration to performance-based fire and building codes has placed new demands on the engineering profession. One of the most challenging is for meaningful ways of assessing the degree to which specific designs meet the requirements which society places on its constructed facilities.

With regard to fire safety, it can be argued that society expects the risk of death or injury from fire to be held to some acceptable level that varies with occupancy. For example in residential occupancies, people are generally willing to accept higher risks in their own homes as compared to hotels. The general risk literature suggests that society expects the risk of multiple deaths or injuries per incident to be decreased, roughly in inverse proportion to the numbers (i.e., the risk of 10 deaths in an incident should be 1/10 that of a single fatality). What is not clear is how to communicate risk implications to policy makers and the public, and how to arrive at risk targets that society considers acceptable.

The fact that every draft performance evaluation system is risk based makes it clear that risk is the metric of choice for the performance-based safety regulations of the future. This fact raises certain issues which need to be addressed early so that this beneficial process is not unnecessarily delayed. Some such issues include:

1. The regulatory system is made up of codes and standards -- the former dictate *what* is required and the latter *how* to implement something that is required or provided voluntarily. When adopted, both have the force of law, but codes establish the fundamental requirements and standards expand on the details. In the debate over

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[†] Fire Risk & Hazard Assessment Symposium June 26-28, 1996, San Francisco, CA, National Fire Protection Research Foundation, Boston, MA 02269, 1996.

performance-based codes and standards, they are lumped together. How should standards change (if at all) to support the evolving performance-based codes?

2. Insurance has long used financial loss as the metric for risk decisions, as this can be compared against rates charged, and the customer can choose to lower the risk and reduce the premium. However, fire codes are concerned with life loss, raising the specter of the "value of a human life" problem. Use of the risk of death directly is no better since this is a difficult concept to understand, and people are willing to accept much higher risk of the death of strangers as compared to themselves or their family. Thus, what is the most appropriate unit for fire risk?
3. There are (at least) two ways of performing a fire risk analysis. One is to identify a small number of scenarios that are representative of a class of scenarios and do detailed (and time consuming) predictions with a complex set of models. The other is to identify a range of values for a number of independent variables which define the scenarios and do a Monte Carlo simulation of a large number of variations using simple (and very fast) calculations. Which provides a more reliable picture of the risk?
4. Risk analysis requires the likelihood and consequences of events, some of which may not be known in advance. Fire safety engineering analysis can address the consequences, given the event. This leaves us to determine the scenarios of concern and their likelihoods. Fire incident data can yield both, but these are uncommon in the world, and those that exist are not always reliable or don't provide all the needed data. Can scenarios and their likelihoods be generated by models of initiating events?

2. PERFORMANCE CODES

Much of the discussion to date has focused on performance-based codes. From those codes in place or under development around the world there is a clear consensus on their general characteristics[1]. These include first, a set of clear, quantitative objectives and second, a means to establish whether those objectives have been met. A performance code will usually also include "deemed to satisfy" provisions which codify approaches which experience has shown to provide acceptable solutions, such as the dimensions of egress stairs. These performance codes further include "Approved Documents" which are intended to catalog acceptable solutions for use in cases where a performance analysis is not needed. The first such approved document is generally the old prescriptive code.

In this way, the role of the code is to make clear the objectives which society desire for its constructed facilities. Examples from the fire regulations in the New Zealand Building Regulations of 1992[2] (which are typical of those being developed in other countries) include:

"Clause C2 - MEANS OF ESCAPE

OBJECTIVE

C.2.1 The objective of this provision is to:

(a) Safeguard people from injury or illness from a fire while escaping to a safe place, and

(b) Facilitate fire rescue operations."

Nearly everyone would agree that this is the fundamental intent of fire regulations -- to allow for safe egress. With prescriptive codes it was implied that buildings which provided all of the features and arrangements required would be "safe," and in a performance code this is an explicit objective. It can be argued, however, that this is still not sufficiently clear. For example, does society intend that *everyone* be able to exit without injury? Does this include those with physical limitations, infants, persons intimate with the ignition, and under all conditions and at all times of the day or night? Are even minor injuries which do not result in lasting deficits prohibited? Is society willing to accept the cost implications of fully protecting everyone all of the time? We certainly need to do a better job of understanding what society expects and at what cost.

3.0 PERFORMANCE STANDARDS

As the world transitions to performance codes, standards will still be needed to provide the detail of how to meet the intent of the code. However, since the form of the code has changed, the form of the standard should be re-thought so as to best complement the performance oriented nature of the system. Specifically, what form should a standard take relative to that generally agreed for a performance code?

Since the code is built around explicit objectives, the standard needs to clearly state its intent regarding the purpose of the system or feature covered. For example, alarm systems are intended to provide early detection of an unwanted fire, notification to the occupants of the need to evacuate or relocate, and notification of the fire service of the need for their assistance and, in large buildings, direct them to where they need to go. Further, an alarm system should **not** respond to conditions not associated with an unwanted fire and should **not** direct the fire service to areas other than where the fire is to be extinguished. Finally, alarm systems should be reliable and able to meet their stated objectives (or some subset thereof) during any single fault condition from a specified set.

Thus, the form of a performance standard is first, to explicitly state its purposes and second, to provide a means to establish quantitatively what constitutes meeting those purposes. In addition, any quantitative measure of the ability of the system to fulfil its purpose needs to include the reliability of systems. This refers to the likelihood that such protective systems will perform as intended when called upon to do so. Like the code, the performance standard will have "deemed to satisfy" provisions which describe arrangements which are known to meet the intent. Current prescriptive standards are likely to comprise early "Approved Documents" for standards as well.

3.1 Purposes of Standards

Fire safety standards cover a myriad of topics, but can be considered to fall into several, broad categories. Standards on fire protection systems and components such as fire alarm, sprinkler systems, fire pumps, emergency power systems, etc., are all intended to assure the reliable operation of critical equipment in the event of a fire. They detail the proper installation, maintenance, and use of the equipment or systems covered which are deemed necessary to assure reliable operation. Here, the purpose statement would include the function provided by the system, such as notification of occupants and emergency services for an alarm system, extinguishment of the fire for a sprinkler system, provision of sufficient pressure and flow for a fire pump or voltage, current, and frequency for an emergency power system.

Another category of fire standards covers the safe installation and operation of equipment and systems needed to prevent fires from starting or to limit their size or impact. Examples would include standards on ovens and furnaces, chimneys and fireplaces, power plants (nuclear or fossil fueled), and various standards on the safe storage and handling of combustible or hazardous materials. In this case, the statement of purpose needs to include quantitative performance measures such as the maximum heat release rate which would be allowed from the maximum quantity of material which can be stored in a given fire area, or the maximum temperature which is allowed on a surface under the most severe conditions of operation.

A third category of fire standards relate to test or measurement methods or standard guides on methods for the collection of information or to define a process such as the investigation of fires or the conduct of fire hazard or fire risk assessments. These standards attempt to provide reliable and consistent information on which decisions can be made with confidence.

3.2 Quantitative Measures of Performance

The first category of standards might talk of detection of fires before they constitute a threat to occupants and while there is sufficient time for safe egress, or of sprinkler activation and fire extinguishment before tenability limits are exceeded in the room of fire origin. In these cases, the quantitative measures of performance are the fire size at detection or activation and the "worst case" exposure to occupants before extinguishment. In addition, an estimate of the system reliability in terms of the likelihood that the system will perform its function when called upon if the provisions of the standard are followed, must be included.

For those standards intended to prevent fires or limit their impact or size, the measure of performance is the assumed rate of ignitions or the limiting conditions that can be assumed if the standard is followed. Where standards are intended to provide uniform procedures for making measurements or testing performance, techniques of assessing repeatability and reproducibility exist and should be used as both the measure for performance and reliability.

4. ASSESSING RISK

Once the Performance Codes and Performance Standards are in this format, the use of risk assessment as the method to determine compliance becomes possible. The Codes will express for any occupancy, the consequences of fire which society is willing to accept as its objectives, and the types of analysis or "acceptable solutions" which demonstrate compliance.

From these, an engineering analysis will identify what approaches can satisfy the list of acceptable consequences. Each approach requires that certain functions are performed, and these are associated with Standards that explain how the equipment, systems, or procedures are to be implemented and maintained in order to assure the function, and an associated reliability by which the function must be discounted.

This method identifies the complementary aspects of systems such that if one fails to provide its function, another will provide it, perhaps at a reduced level (in the absence of common failure modes). This allows redundancy without unnecessary duplication, allowing cost optimization without sacrificing safety.

However, what has been described so far (avoidance of specified consequences) is not risk, but rather hazard assessment. Design fires may be specified in the codes by occupancy along with the ability of the engineer to suggest alternatives for specific applications, based on an analysis of the fuels and ignition sources present. If probability distributions for these as well as some other parameters such as occupant loadings and characteristics (e.g., age, sex, physical and mental capabilities) are provided, a risk assessment can then be performed.

4.1 Relative Risk

In all but one of the engineering methods proposed in support of 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 (BRRTF) which said,[3]

> "... 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 which need to be considered. For example, Brannigan argues,[4]

> "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 four 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. Fire, 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 which 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 1980's, 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 code compliant building.

Third, they assume that the engineering methods accurately reflect the expected risk to life in different buildings. It may not be possible to predict accurately loss rates in the future due to the fact that stochastic elements are based on past materials and lifestyles which may change (e.g., smoking materials are among the most commonly cited ignition sources in fatal fires, and the rate of smoking is rapidly declining in many countries).

Fourth, they assume that both the buildings and society's views of risk are static. Fire disasters often point out flaws in the code which are subsequently corrected. If such a flaw were uncovered, the performance method would allow buildings to continue to be built with that aspect of risk uncorrected as long as that hazard goes unrecognized by the prescriptive code. Most societies would not accept such a practice.

4.2 Absolute Risk

The draft Code of Practice from the British Standards Institution (BSI)[5] is the only method which 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}). 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 is needed.

As discovered by the nuclear power industry, the problem is that risk to life is too abstract to be understood by the public. Risk acceptance is highly variable, depending on to whom the risk applies (individual vs. society), the perceived value of the 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). Perhaps if the risk were expressed in a way which had meaning to the public it would be easier to obtain policy decisions on what is acceptable.

5. EXPRESSING RISK

5.1 Risk to life

Expressing risk to life in a way which can be understood by the public is a problem which 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. While the public impression is that these are rare events, they really have no good feel for how rare.

5.2 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 thus 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, 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.

6. 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 analysis) 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 which 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[6,7]. Since then, other risk assessment methods have been developed which 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. A more recent risk model[8] 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.

7. SCENARIO GENERATORS

Most of the research effort in the development of risk assessment methods has been in the estimation of the consequences of events. But the quantification of risk is equally dependant on the ability to describe detailed scenarios and their likelihood of occurrence. In a few countries fire incident data are collected that can be used for this purpose, but often we find that not all the needed information is collected[6]. The most recent national fire incident data system was initiated in Australia to provide such data for risk assessment in support of their new performance codes.

But these are the exception. Most countries do not collect incident data in any comprehensive way. Instead, risk methods use scenario descriptions and frequency estimates obtained from experts such as the fire service or insurance interests. This approach suffers from numerous shortcomings not the least of which are data skewed by the perception of the expert and lack of representativeness in sampling.

In 1989 NIST sponsored some work at UCLA on the feasibility of modeling initiating events for the purpose of making improved scenario descriptions and ignition frequencies, based on techniques developed for use in nuclear power plants[9]. While the techniques show some promise, limited resources has resulted in a halt to this line of research.

8. 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 support codes in the building regulatory process and the format of performance standards needs to change in a way which 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 which comply with the prescriptive code. One, developed for England and Wales, has established explicit risk targets equal to current loss experience. However, arguments have been raised which may mean that either approach might not withstand legal challenges. Further, no regulatory bodies other than in Japan have accepted either approach in practice. Hazard based approaches that measure performance in a prescribed set of scenarios avoid these problems, but these generally do not consider the most rare events which 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.

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Section 11/Chapter 7 - Fire Hazard Assessment†

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Historically, most fire safety regulation has been on the basis of fire hazard assessment; where such assessments were based on the judgement of "experts." Today formal, scientifically-based fire hazard assessments (often referred to as FHA's) are common and increasingly are being required as a means to avert certain outcomes, regardless of their likliehood. This chapter will discuss the differences between hazard and risk assessment, the process of performing a fire hazard assessment, and resources available to assist in this process.

Hazard vs. Risk

The goal of a fire hazard assessment is to determine the most likely 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 which will have an effect on the outcome of interest. This outcome determination can be made by expert judgement, 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 judgement. While probabilistic methods are widely used in risk assessment, they find little overt 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 which have been weighted for their likliehood of occurrence. The total risk is then the sum of all of the ways that the result can be obtained. 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.

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 a 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 which can be tolerated by these items before unacceptable damage occurs.

Performing a FHA

Performing a fire hazard assessment is a fairly straightforward, engineering analysis. The steps include:

- Selecting a target outcome,
- determining the scenario(s) of concern that could result in that outcome,
- selecting an appropriate method (s) for prediction,
- evaluating the results, and
- examining the uncertainty.

SELECTING A TARGET OUTCOME

The target outcome most often specified is to avoid fatalities of occupants of a building. Another might be to assure that firefighters are provided with protected areas from which to fight fires in high rise buildings. The U.S. Department of Energy requires that FHA's be performed for all DOE facilities [1]. Their objectives for such FHA's as stated in DOE 5480.7A include:

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†NFPA Fire Protection Handbook, 18th ed., J. Linville, ed., NFPA Boston, MA 1996.

- minimize 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), and
- property damage does not exceed acceptable levels ($150M per incident).

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

- Limit the probability of fatalities or major injuries to only those occupants intimate with the fire ignition.
- Limit the probability of minor injuries to only those in the dwelling unit of origin.
- No occupant outside of the dwelling unit of origin should be exposed to the products of combustion in a manner that causes any injury.
- 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).
- Limit the probability of reaching hazardous levels of smoke and toxic gases to 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.
- Limit the incident to one manageable by the Boston Fire Department without major commitment of resources or excessive danger to firefighters 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 as providing safe and comfortable accommodations. Any combination of these outcomes may be selected as appropriate for FHA's 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 which 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. 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 a major contributor to fire disasters -- 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 the DOE required FHA's, one part of the analysis is to assume that both automatic systems fail and the fire department does not respond. This is used to determine a worst case loss and establish the real value of these systems. If nothing else, such assumptions can help to identify the factors which mean the difference between an incidental fire and a major disaster, so that appropriate backups can be arranged.

SELECTING AN APPROPRIATE METHOD(S) FOR PREDICTION

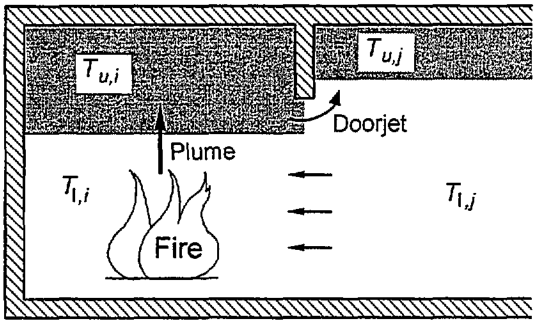
Fire Models

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 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 assessed.

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 McCaffery/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.



Zone models assume that fire gases collect in layers that are internally uniform.

The model should include the limitation of burning by available oxygen. This is straightforward to implement (based on the oxygen consumption principal) 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.

Another problem can occur in tall spaces like 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 which 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 which 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

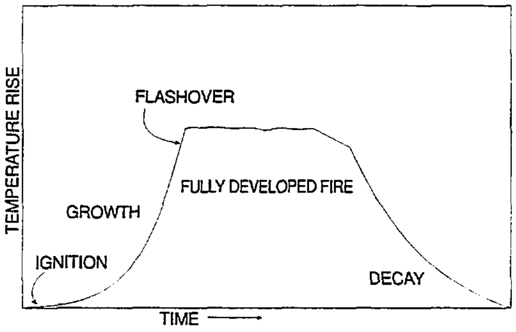
Even if the model is correct the results can be seriously in error if the data input to the model does not represent the condition being analyzed. Proper specification of the fire is the most critical, and will be addressed in detail in the following section on selecting the design fire(s).

Next in importance is specifying sources of air supply to the fire -- open doors or windows, but also cracks behind trim or around closed doors are important. 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.

Other important items of data include ignition characteristics of secondary fuel items and 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 (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 section, Account for Uncertainty).

Selecting Design Fire(s)

Along with selecting an appropriate model, 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 -- 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.



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.

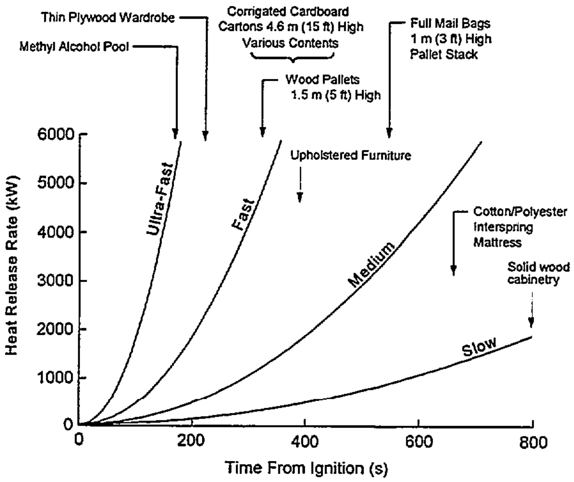
In 1972, Heskestad first proposed that for these early times, the assumption that fires grow according to a power law relation works well and is supported by experimental data [9]. He suggested fires of the form:

$$\dot{Q} = \alpha t^n$$

where: $\dot{Q}$ is the rate of heat release (kW)
α is the fire intensity coefficient (kW/s^n)
t is time (s)
n is 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 1055 kW (1000 BTU/s) in 600, 300, and 150 seconds, respectively were proposed for design of fire detection systems [11]. Later, these specific growth curves and a fourth called "Ultra-fast" [12] which reaches 1055 kW in 75 seconds, gained favor in general fire protection applications.

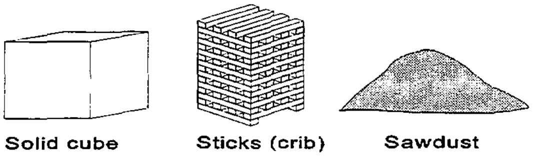
This set of T-squared growth curves are shown in the adjacent figure. The slow curve is appropriate for fires involving thick, solid objects (solid wood table, bedroom dresser, or cabinet). The medium growth curve is typical of solid fuels of lower density (upholstered furniture and mattresses). Fast fires are thin, combustible items (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 have been incorporated into several design methods such as for the design of fire detection systems in the *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 pounds) of wood; arranged in a solid cube, sticks arranged in a crib, and as a layer of sawdust. These three arrangements would have significantly different growth rates while representing identical fuel loads.

Fire Growth depends on fuel form and arrangement



10 kg (22 lbs) of wood represent identical fuel loads but produce vastly different rates of heat release in a room.

Steady burning

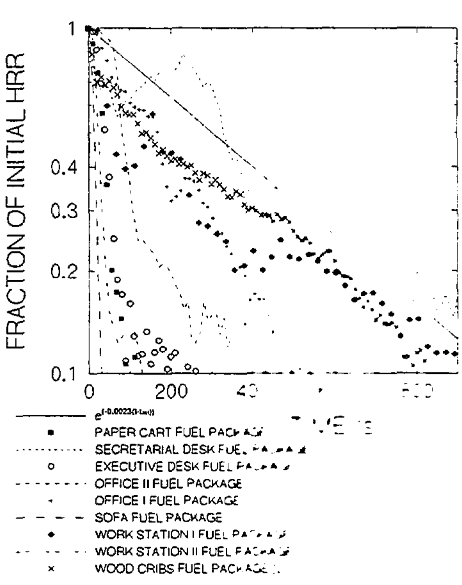
Once all of the surface area of the fuel is burning the heat release rate goes into a steady burning phase. This may be at a sub-flashover or a post-flashover level -- the former will be fuel controlled and the latter ventilation controlled. It should be obvious from the model output (for oxygen concentration 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 the heat release rate can be specified at a level that results in a flame out the door and 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 effect 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 Cone calorimeter, ASTM E-1354) 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 is to specify 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 point at which decay begins is when 20% of the original fuel is left. While these are assumptions, they are technically reasonable.

Of course if a sprinkler system is present this decay will proceed as the fire is extinguished by the water. A simple assumption is that the fire immediately goes out; but this is not conservative. A recent NIST study documents an (conservative) exponential diminution in burning rate under the application of water from a sprinkler [15]. 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..



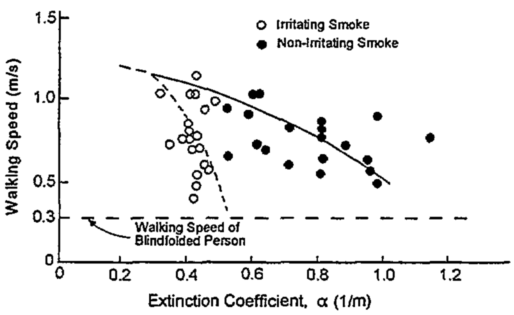
Evacuation calculations

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 people 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. An excellent discussion of this topic is found in Pauls' [16] and Bryan's [17] chapters in the SFPE Handbook.

Models

The process of emergency evacuation of people follows the general concepts of traffic flow. There are a number of models which perform such calculations and which 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 [18]. 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., EXIT89 [19])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 [20]. 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 which give the best possible performance. These are inappropriate for a code equivalency determination unless a suitable safety factor was used.



A person's walking speed decreases in dense smoke until they move as slowly as if blindfolded.

Hand calculations

Evacuation calculations are generally 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 in [21]. 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.

Assessing 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 [22], which is based on research at NIST on lethality to rats [23] and by Purser [24] on incapacitation of monkeys. These methods can also be applied in hand calculations utilizing the material by Purser and the equations found in reference 21. 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 assure 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., pvc's) 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 which models this process and the associated diminution of HCl concentration.

Accounting for Uncertainty

This refers to dealing with the uncertainty which is inherent in any prediction. In the calculations this uncertainty derives 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 which 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 (vary the data to the limits and see whether the conclusions change) should be performed. This is also a good section in which to justify the appropriateness of the model or calculation method in the manner discussed previously.

Final Review

If a model or calculation produces a result which seems strange there is probably something wrong. Cases have been seen where the model clearly produced a wrong answer (the temperature predicted approached the surface temperature of the sun) and those where it initially looked wrong but was not (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 plans review shows that all code requirements have been met?

Conclusions

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. The tools and techniques described in this chapter hopefully 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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SETTING PERFORMANCE CODE OBJECTIVES[†]
HOW DO WE DECIDE WHAT PERFORMANCE THE CODES INTEND?

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ABSTRACT

There is a worldwide movement toward the replacement of prescriptive codes with those based on performance against a set of clear and quantifiable objectives. This has sparked an important discussion of just what are appropriate objectives for society to demand of its built environment. Building codes have evolved well beyond their traditional roles of assuring the public health and welfare by incorporating requirements addressing social issues such as conservation and protection of heritage. In the fire codes, debate is raging over whether people should be required to protect their own property from fire, and whether society can afford to protect all of the occupants and the fire service throughout any incident. Thus far, the discussion has been limited to identifying objectives, and has not yet turned to performance levels; a step that must be taken before performance codes can be implemented. Performance levels cannot simply be derived from current codes. Defining code objectives and performance levels in the U.S. presents a special challenge since these public policy issues must be debated by several model code groups, fifty state legislatures, and countless local bodies. NIST's role in the process is to provide the technical basis for the evaluation of performance against objectives, but not in setting the objectives nor their levels. However, since the code objectives in part determine the need for specific performance evaluation methods, NIST has an interest in facilitating the reaching of consensus on these difficult issues related to its role in the application of technology to maintaining U.S. competitiveness in world markets.

1. BACKGROUND

Much of the world is engaged in a process to replace prescriptive building and fire codes with ones based on performance. That is, instead of *prescribing* the precise number and arrangement of protective measures which are required, the *performance* of the overall system against a specified set of objectives is presented. Canada has proposed to refer to these as objective-based codes because, in fact it is the objectives that are stated and not the performance per se.

There is a general consensus on the form of performance codes[1]. These include first, a set of clear, quantitative objectives and second, a means to establish whether those objectives have been met. A performance code will usually also include "deemed to satisfy" provisions which codify approaches which experience has shown to provide acceptable solutions, such as the dimensions of egress stairs. These performance codes further include "Approved Documents" which are intended to catalog acceptable solutions for use in cases where a performance analysis is not needed. The first such approved document is generally the old prescriptive code.

The purpose of this paper is to raise some important issues regarding this process and to begin a discussion of some important questions. These include:

1. What are appropriate objectives for building and fire codes, and at what level of detail must they be specified?

2. Who makes these policy decisions for the public and how do they become mandated and enforced? and,

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[†] InterFlam '96, Seventh International Fire Science and Engineering Conference, March 26-28, Cambridge, England, 555-561 pp, Interscience Communications, London, 1996.

3. How do we begin the process of determining the objectives appropriate for U.S. codes?

2.BUILDING CODES

As many others have pointed out, the Code of Hammurabi (attributed to King Hammurabi of Babylonia who reigned from 1955 B.C. to 1913 B.C.) is credited as the first building code and was a performance code which included requirements such as:

> *In the case of the collapse of a defective building, the architect is to be put to death if the owner is killed by accident; and the architect's son if the son of the owner loses his life.*

The objective is clear as is the penalty for failure, but the means to assess compliance is to wait for the failure -- clearly unacceptable in modern society. Further, it is unclear what is the intent with regard to the deaths of occupants other than the owner.

Modern building codes have evolved well beyond their traditional areas of public health and welfare. Frequently building codes are vehicles for the implementation of environmental policy by incorporating requirements for energy and water conservation. Some address noise pollution with requirements for the acoustic transmission properties of partitions. Others address the preservation of historical structures and still others include quality of life issues such as prohibiting the mixture of certain building uses (i.e., zoning requirements). The latest in this growing list involve electromagnetic fields from electrical equipment and "sick building syndrome."

A number of groups, individually or through international committees such as the International Commission on Building Standards and Research (CIB) TG11 are seeking to develop appropriate objectives for building codes which are compatible with the transition to performance codes. This debate is focused on identifying the needs of society from the perspective of the designers, builders, owners, and users of buildings as a key to setting the code's objectives. The process has demonstrated that there are significant cultural differences among countries which impact such decisions, so no clear answers have yet surfaced.

3. STRUCTURAL CODES

The structural portions of building codes underwent a transition to a performance format about a decade ago. The objective of a structural code is unquestionable -- the building must continue to stand under any foreseeable circumstance. The process followed by the structural engineering profession is of general interest in the move to performance codes. A technique of structural calculations was developed in which the profession had confidence. These calculations were then used to "back out" the design loads implied by the prescriptive code, and inconsistencies identified by this process were resolved. Finally, safety factors were specified both by inflating these loads and derating material strengths to arrive at a solution which is always on the high side of the uncertainty band.

Of more interest to the topic of this paper is the debate over how to set appropriate wind, snow, and seismic loads for given zones, as these are statistically distributed. Do you design to the 10 year, 50 year, or 100 year event? The decision was made for the codes to design to the 50 year level, understanding the likelihood that this level will be exceeded (2% per year, 64% over the 50 years) and using a safety factor of 1.3. This represents a policy decision made by the engineers and confirmed by the legislators who adopted the code into law. Current discussions center on whether the entire building needs to resist the 50 year wind or if roofs and windows can be designed for less if the structure survives.

4. FIRE CODES

4.1 GENERAL OBJECTIVES

Several fire code groups are debating the list of objectives which should be included. A general discussion of the history of fire code objectives is included in reference 1. This paper and another by Bukowski & Tanaka[2] lead to the general objectives of:

- Prevent the fire or retard its growth and spread,
- Protect building occupants from the fire effects,
- Minimize the impact of fire, and
- Support fire service operations.

However, even objectives such as these, which most recognize as the fundamental goals of traditional fire codes are being debated in the process of developing performance codes. Some of these debates have become quite heated. For example, in New Zealand it was decided that protection of the property of the person who has the fire is a matter between that person and their insurance company, and is not something to be regulated in the code[3]. This decision was not supported by the insurance industry as it meant that they had to establish their own regulation and enforcement. It has further been suggested that the impact of fire losses on the economy (e.g., loss of jobs, inconvenience to society) makes protection of such property an issue for the codes.

Even more controversial is the questioning of code requirements for the safety and integrity of a building after the evacuation of all occupants. It has been suggested that the code should only require the building to remain safe until the occupants are out, since society demands fire safety for the "public" which does not include firefighters . This debate in Canada has not been well received by the fire service there. Most countries have taken the position that protection of firefighters and support of their suppression operations are explicitly included in the list of objectives contained in the code.

4.2 DETAILED OBJECTIVES

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), the goal that there should be no fatalities among building occupants is reasonable. However, the goal of eliminating all risk to life from fire is not. Further, setting a goal with respect to life loss says nothing of the acceptability of injury. In the World Trade Center bombing incident, litigation has been filed seeking compensation for the emotional trauma of being exposed to smoke during the evacuation, even though no physical injury was sustained!

This raises many questions of who makes the public policy decisions for society, how the policy is established, and what society is willing to accept in terms of both losses and cost. While the general objectives as discussed in the previous section may be sufficient for policy makers, engineers and enforcers need much more detailed objectives in order to properly judge the ability of specific designs to meet those goals across the spectrum of possible fire scenarios. If there is one thing which we should have learned from the history of fire losses is that the greatest losses have occurred in the cases where multiple things have gone wrong.

In Boston, the Office of the Fire Marshal[4] established a set of objectives for fire hazard assessments for multi-family residential occupancies performed in support of requests for waivers of the prescriptive requirements of the code. These would certainly be suitable as objectives of a performance based code, and provide an additional level of detail necessary for engineering analysis. They are:

- Limit the probability of fatalities or major injuries to only those occupants intimate with the fire ignition.
- Limit the probability of minor injuries to only those in the dwelling unit of origin.
- No occupant outside of the dwelling unit of origin should be exposed to the products of combustion in a manner that causes any injury.
- 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).
- Limit the probability of reaching hazardous levels of smoke and toxic gases to 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.

- Limit the incident to one manageable by the Boston Fire Department without major commitment of resources or excessive danger to firefighters during all phases of Fire Department operation, i.e., search and rescue, evacuation, and extinguishment.

While attorneys would argue that these statements are still not sufficiently precise for regulation, they begin to give the engineer and architect the guidance needed to arrive at a specific design. Note as well that these objectives incorporate the expectations of the fire service with regard to the conditions which they will face when they respond.

5. PUBLIC POLICY

5.1 WHO MAKES THE DECISIONS?

Whether building or fire code, who makes the technical decisions for the public? Many countries operate under national codes promulgated by the government (e.g., Japan, England and Wales) and some produce a national model code with local concurrence (e.g., Australia, Canada). In the U.S., the several model code organizations are private and the regulatory authority rests wholly within the States. Yet in each case, the technical issues regarding appropriate levels of safety required are debated and set by the codes committees with the eventual concurrence of the public authority. In each case, a process exists by which local modifications can be made to the model code, but these are generally done to address a local issue or to make a requirement of the model code more stringent. Seldom are local modifications made which relax requirements below the minimums established in the model code.

This means that the debate over which objectives are appropriate would begin in the model codes process. The codes committees could debate the issues and produce a "sense of the committee" which could be taken to the oversight committee[††] which serves as the gatekeeper to each of the model codes. From there, the list could be debated by the state Fire Marshals through the National Association of State Fire Marshals (NASFM) and Fire Marshals Association of North America (FMANA) and organizations like National Conference of States for Building Codes and Standards (NCSBCS) as a means to determine its acceptability to regulators.

5.2 HOW DOES THE POLICY BECOME MANDATED?

The current system is that the codes and standards are set by the model codes groups and they are adopted into law by the state and local jurisdictions. This would not change. The legislators who adopt the codes and standards have powers delegated to them by the Constitution, and are elected to office to act for the public good. However, these officials are accountable to the public and will need a means to explain the impact of these new regulations. In the past, they merely said that, "The experts say compliance with this new code will result in safe buildings." Now they may have to explain why "a few fatalities" are acceptable.

5.3 HOW IS THE SYSTEM ENFORCED?

Documentation of compliance with prescriptive requirements can be as simple as a list of building features. Under a performance code the engineering analysis which demonstrates compliance must become part of the building's records. Modifications to the building must be shown not to compromise the ability to meet the code's objectives, and assumptions made in the engineering analysis must be preserved.

In fact, the engineering analysis in effect becomes the code to which the building is built. If in the future there is a fire, the analysis would be examined to determine if the building was "code compliant" at the time of the fire. Variations with assumptions in the analysis would be code violations in the same way that variations with the prescriptive code are.

[††] For the National Fire Protection Association this is the Standards Council. For the Model Codes organizations they are referred to as the Code Committees.

A complication is the fact that a city's review and acceptance of an engineering analysis which may assume a certain level of service from the fire department and subsequent issuance of a permit on that basis, does not imply a contract with the building owner to provide these services in perpetuity. Governments are allowed the legal right to "change the rules" as they see fit; tax codes, social security and welfare benefits, and building codes can all be changed unilaterally and retroactively[5]. Designers and building owners who counted on the fire service to provide a certain level of service may be required to provide additional protection later, to compensate for a reduction in fire department services. This may mean that, for example, an engineering analysis should discount fire department intervention to remain conservative in the long run.

6. ESTABLISHING CLEAR OBJECTIVES

In light of the degree of international work in this area, it is timely to begin the process of establishing objectives for U.S. performance codes. This will require that the existing, national codes committees be polled to document their positions. From there, the consensus process can be used to establish a set of National goals.

The set of questions presented at the end of this paper is a starting point for this discussion. These questions have been formulated in a check-off format to facilitate the compilation of the responses across many responding groups. It is crucial that all affected groups be given an opportunity to have their opinions heard at this early stage. Traditionally, the fire service has not participated in this process except for those with regulatory responsibilities (the Fire Marshals). The fire service in Australia recently complained that they were not given such an opportunity to insure that their needs were met as that country moves toward a performance code. In the United Kingdom, Graham Butler (Assistant Chief Officer, Tyne and Wear Metropolitan Fire Brigade) observed,

> *"When the fire service arrives at a burning building they assume certain factors and performance which have an impact on their safety during suppression operations. If the fire service does not make these assumptions explicit so that they can be incorporated into performance codes, we have no assurances that these will continue to be in evidence in future buildings."*

It is further hoped that this same process can be extended to other nations undergoing such change, through the work being performed on Fire Safety Engineering in CIB W14 and the International Standards Organization (ISO) committee TC92/SC4. By doing so, we can assure that the transition to performance codes will facilitate open international trade in building design and construction by eliminating arbitrary, prescriptive requirements and replacing them with sound performance requirements supported by a common analytical methodology.

7. NIST'S ROLE

The role of the National Institute of Standards and Technology (NIST) in the promulgation of codes and standards has always been one of technical support. Historically, this support has come largely through the development of test methods and staff participation in the consensus process. More recently, NIST has been at the center of the development of fire safety engineering principles and practices which underpin the new performance methods. NIST has also tried to provide a U.S. focus in international performance code development.

In this capacity, NIST has an interest in facilitating the debate on the public policy issues presented in this paper so that the research and development on the supporting engineering methods can address the needs of the codes process into the future. As the developer of key parts of the engineering methods used, NIST provides assistance in the education of designers, engineers, and regulators in the proper application of these techniques. Thus NIST is working with fire safety educators and professional societies in developing educational resources.

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Given that the general objectives of a performance-based fire code fall into the categories:

1. Provide life safety, and
2. Limit loss of property,

please answer the following questions.

1. Should the objectives include anything else (such as prevention of fire ignitions)? If yes, please list them.

2. **Provide life safety:** (check all that apply)

☐ Provide life safety means to design the building to save persons *intimate with the ignition* (e.g., clothing fires, furniture fires where the person is lying on the item ignited).
☐ Provide life safety means to design the building to save persons who are *incapable of self-preservation*, requiring rescue or at least assistance by others, or "protected-in-place."
☐ Provide life safety means to design the building to save persons within the room of fire origin but not otherwise intimate with the ignition or incapable of self-preservation.
☐ Provide life safety means to design the building to save persons outside the room of fire origin who are *incapable of self-preservation*, requiring rescue or at least assistance by others, or "protected-in-place."
☐ Provide life safety means to design the building to protect the fire service or other emergency personnel who must enter the building to affect rescues of occupants.
☐ Provide life safety means to design the building to protect the fire service or other emergency personnel who enter the building to fight the fire and preserve property, after all occupants have evacuated.
☐ Provide life safety means that any of these persons described above will not be killed but some may suffer major (permanently disabling) injuries.
☐ Provide life safety means that any of these persons described above will not be killed but may suffer minor injuries.
☐ Provide life safety means that any building occupant has a right to a protected means of egress which will prevent ANY exposure to heat, smoke or fire gases during their evacuation.
☐ Provide life safety means that any building occupant has a right to a protected means of egress in which they might be exposed to small quantities of heat, smoke or fire gases during their evacuation as long as these exposures do not cause injury.
☐ Provide life safety means that any building occupant who is *incapable of self-preservation* has a right to a *area of refuge* in which to await rescue without ANY exposure to heat, smoke or fire gases.
☐ Since there is generally no public outcry, society is willing to accept the current level of fire deaths, injuries, and property losses as long as the majority of life loss remains in the home.
☐ The risk of a fire which can result in 10 fatalities should be about 1/10 of the risk of a single fatality incident.

Do any of the above responses change as a function of occupancy? For example, should the codes allow a higher risk in the home, lower in a hotel, and lowest in a health care facility? Should educational properties be safer than mercantile? (if yes, please explain)

2. **Limit loss of Property:** (check all that apply)

☐ The codes should be concerned only with direct losses associated with fires.
☐ The codes should be concerned with indirect losses such as the effects of loss of jobs or lost tax revenue on the economy.
☐ The codes should be concerned with the environmental impacts (such as toxic fire products released into the air or runoff of contaminated firefighting water) of fires.
☐ The codes should not be concerned with preserving property belonging to the person having the fire, since this should be between that person and his/her insurance company.
☐ Limitation of property loss applies only to the building in which the fire occurs.
☐ The decision NOT to protect property should be allowed if the cost of protection exceeds its value.

Do any of the above responses change as a function of occupancy? (if yes, please explain)

A Hypothetical Model for a Performance-based Codes System for the United States[†]

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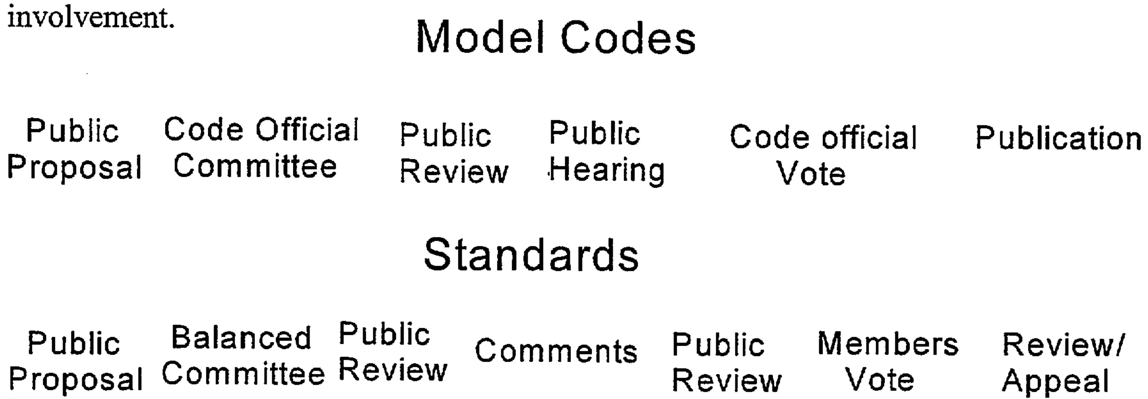
The transition to performance-based codes is well underway in many countries of the world, and several have adopted such. Interest in performance-based codes in the U.S. is high, but the diffuse nature of the codes system here presents some special challenges which will need to be addressed. This paper attempts to highlight these challenges and suggest one possible approach to meeting them.

THE CURRENT U.S. SYSTEM

Building regulation in the U.S. is the responsibility of the States, some of which delegate this responsibility to local (county, city) jurisdictions. Most codes are based on model regulations developed by private sector organizations through a public hearing process in which code changes can be proposed and challenged by anyone but the right to vote to adopt, modify, or reject proposals is limited to code enforcing officials. Responsibility for final publication of the model regulations rests with a "Code Committee" which serves as the gatekeeper to the system and a point of appeal of the process. Further changes are made as these model regulations are adapted and adopted into law by local legislatures. Proponents of this process hold that while anyone can propose changes, keeping the responsibility for acceptance with enforcing officials assures that the model regulation best serves those charged with applying it to assure public safety.

Most standards are also developed by private sector organizations, but using a consensus process whereby committees of volunteers draft and maintain the standards. Proposals, which can be made by anyone are processed by the committee and can be challenged and appealed through a defined procedure. These committees must meet "balance" criteria under which participants are categorized (manufacturer, enforcer, user, special expert, insurance, etc.) and no category can hold more than a third of the votes. The standards process often also involves a committee to provide final review and appeal. Proponents of this system suggest that the resulting standards benefit from the diversity of involvement.



[†] International Conference on Performance-based Codes and Fire Safety Design Methods, Sept. 24-26, 1996, Ottawa, Ontario, Canada, SFPE, Boston, MA, 1996 (in press)

Responsibility for code enforcement also resides at the local level. Local officials review plans and issue building permits, inspect work in progress, and conduct final inspections before issuing a certificate of occupancy. Decisions as to what meets or does not meet the code, including equivalencies, are made by local officials. Assistance can be requested from higher authorities and interpretations can be obtained from codes and standards developers, but these are advisory only. Ultimate responsibility rests with the code enforcement official.

The codes prescribe requirements for health, safety, environmental, and conservation aspects of buildings as a function of general use categories. Restrictions on land use are the responsibility of a different organization called a zoning commission, and are not a part of the building code as is the case in some countries. Preservation of buildings of historical significance is yet another independent function, usually assigned to local commissions separate from the building regulatory process.

As the codes are written, there are standards cited within them which prescribe how to install and maintain systems which meet or exceed the minimum requirements of the voluntary regulations. These standards may be included or referenced.

Standards referenced in the codes prescribe how to install and maintain systems required or utilized voluntarily above minimum requirements set in the codes or describe test methods for regulated materials or products. All codes and standards in use in the U.S. incorporate an "equivalency clause" which provides for the approval of alternate methods of achieving the "intent of the code." These clauses are frequently cited as evidence that the current system is performance-based or at least allows performance evaluation. The problem is that the "intent of the code" is often unclear or at least subject to interpretation. Such interpretations may change over time, and the original, implicit assumptions may become lost. Thus, one major advantage of performance-based codes would be the clarification of the objectives (intent) of the code as well as agreement on acceptable methods of demonstrating that the objectives are met.

A MODEL FOR A PERFORMANCE-BASED SYSTEM

The defining characteristic of a performance-based system is the replacement of prescriptive requirements with performance objectives and the means to assess whether these objectives will likely be met. Thus, the transition to a performance-based code system will require that society agrees on its objectives for the built environment and on the methods by which performance is to be assessed. In the current system recommendations are made by the codes and standards community which are then adapted and adopted into law by state and local legislatures. It is reasonable to expect that these lines of responsibility will remain in any new system.

Setting Objectives

Prescriptive codes have implicit objectives which underlie the intent of the code's provisions. Thus the current codes and standards development process makes the public policy decisions as to what level of performance society expects of its built environment. Under this model, the existing codes and standards committees would develop quantitative objective statements for their documents through their existing open procedures.

Many countries going through this transition have taken the position that the level of performance desired by society is that embodied in the prescriptive code because, "Since there is no public outcry that they are too high, society is clearly willing to accept the current level of fire losses." Brannigan[1] has argued that such statements cannot be made for a number of reasons.

Paraphrasing Brannigan's points: First, such statements assume that the public is satisfied with an expected risk to life rather than a safety level. Fire, 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 which 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 1980's, 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 code compliant building.

Third, it is assumed that the engineering methods accurately reflect the expected risk to life in different buildings. It may not be possible to predict accurately loss rates in the future due to the fact that stochastic elements are based on past materials and lifestyles which may change (e.g., Smoking materials are among the most commonly cited ignition sources in fatal fires. The rate of smoking is rapidly declining in many countries so the risk of cigarette ignition should be declining).

Fourth, by requiring that performance is measured against buildings built to the prescriptive code without specifying performance levels, it is assumed that both the buildings and society's views of risk are static. Fire disasters often point out flaws in the code(s) which are subsequently corrected. If such a flaw were uncovered, the performance method would allow buildings to continue to be built with that aspect of risk uncorrected as long as that hazard goes unrecognized by the prescriptive code. Most societies would not accept such a practice.

Another approach has been to use selected engineering methods to evaluate buildings which just comply with the prescriptive code to quantify the implied level of performance. This approach is only a variation on the above, and suffers from the same problems.

A better approach is to ask the code committees and regulators to quantify their intent when they wrote the prescriptive code. Since they have been delegated the responsibility to set levels for society, this is appropriate and the result will be the levels they actually intended.

As an example, the Fire Marshal[2] in Boston established a set of objectives for fire hazard assessments for multi-family residential occupancies performed in support of requests for waivers of the prescriptive requirements of the code. They are:

- Limit fatalities or major injuries to only those occupants intimate with the fire ignition.
- Limit minor injuries to only those in the dwelling unit of origin.
- No occupant outside of the dwelling unit of origin should be exposed to the products of combustion in a manner that causes any injury.
- Limit 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).

- Limit reaching of hazardous levels of smoke and toxic gases to 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.
- Limit the incident to one manageable by the Boston Fire Department without major commitment of resources or excessive danger to firefighters during all phases of Fire Department operation, i.e., search and rescue, evacuation, and extinguishment.

These would certainly be suitable as objectives of a performance-based code, and provide an additional level of detail necessary for engineering analysis. But this raises a question of whether the regulations should be based on overall fire risk or on fire hazards for a defined set of scenarios. This question will be addressed later in this paper.

Evaluating Performance

The evaluation of performance traditionally falls to the engineering professions so the responsibility for the evaluation methods logically rests with the engineering societies. The structural engineers went through this process over the past decade as they moved to a performance method. The Civil and Fire Protection Engineering societies are engaged in an effort to publish methods for assessing the structural fire resistance of steel, wood, concrete, and masonry assemblies. The Society of Fire Protection Engineers (SFPE) has pilot programs in fire model verification and to develop a "Code of Practice" for the profession similar to those developed for England and Wales[3], and in New Zealand[4].

A key aspect of performance evaluation is the framework of the engineering analysis to be employed. While the concept of overall risk management is growing in popularity in the business and insurance fields, the actual conduct of fire risk assessment may be technologically premature and may pose potential problems for regulators.

Deemed to Satisfy Provisions

All performance-based codes contain deemed to satisfy provisions. These recognize the fact that many aspects of fire safety design are well understood and do not need to be evaluated. Examples would include the physical dimensions of evacuation stairs (the so-called 7-11 stair) or that the provision of fire sprinklers would satisfy a performance objective of preventing flashover.
The inclusion of deemed to satisfy provisions are not intended to preclude the application of engineering analysis to justify alternate approaches -- only that experience has shown that certain approaches perform in a specific way. Such provisions will generally require compliance with specified standards to assure that the functions are performed reliably.

Approved Documents

Appended to the performance code are a series of Approved Documents, the first of which is generally the prescriptive code, recognizing that the complying with the prescriptive code is one way of meeting society's performance objectives. Other Approved Documents would include the collection of performance-based standards referenced in the code on the installation, operation, and maintenance of fire protection systems; safe operation of equipment or facilities; or methods of test or measurement of fire performance.

The Approved Documents might also include any Codes of Practice which are deemed appropriate for assessing the performance of designs against the objectives of the codes. Such referencing of methods within the code itself would give regulatory officials additional confidence that these methods provide acceptable results when properly used. In this context the term *sanctioned for use* within specific bounds would be preferable to being *approved* or *validated.*

RISK V.S. HAZARD ASSESSMENT

Risk assesses the *likliehood* of suffering a specific loss over all possible fire scenarios, thus requiring that many probabilities and statistical distributions be utilized in an analysis. Hazard analysis is a subset of risk which presumes certain scenarios (design fires) and assesses only the consequences of these fires. Adoption of either approach by local legislatures and enforcement by local officials requires that the basis for regulation be understandable by non-technical people. Further, legislators are hard pressed to accept the concept that risk can never be eliminated so risk goals involve an "acceptable level of life loss." The international community seems to agree that risk assessment is the preferred basis for establishing compliance with performance-based code objectives. However, a major problem with risk assessment remains the selection of an appropriate metric and the explanation of its meaning to non-technical people.

Risk of Life Loss

Expressing risk to life in a way which can be understood by the public is a problem which has been faced 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. Risk is normally compared to events or activities such as the risk of being struck by lightning or the risk of death while skydiving. While the public impression is that these are rare events, they really have no good feel for how rare. This leads to the consideration of other metrics for risk.

Risk of Financial Loss

The measure 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 thus the perfect metric for risk but for one problem. The primary focus of fire codes is life safety, requiring that risk to life 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.

Hazard Analysis

Such problems have led many to the conclusion that hazard analysis against a set of design fires derived for specific occupancies represents a more practical approach. Here, design fires established for specific occupancies will need to meet specific criteria including:

- They represent the range of challenges expected in the occupancy as identified by incident data and the expert judgement of code officials.
- They represent the range of occupant loadings and characteristics expected in the occupancy.

In order to be compatible with other provisions of an hazard analysis factors need to be addressed in a similar manner such as,

- Independent variables such as door positions, ventilation, transient fuels, weather, etc. can be distributed and accounted for.
- Reliability of fire protection features can be realistically accounted for in identifying the need for redundancy.

In a practical sense, basing regulation on hazard analysis for a specific set of design fires allows legislators to require that there be no losses expected under the design conditions; a much more palatable situation to explain to your constituents.

IMPLEMENTING THE MODEL SYSTEM

By overlaying the preceding considerations onto the existing U.S. building regulatory system a process for moving the U.S. toward a performance-based system emerges. This new system would still be implemented and enforced at the state and local level and be based on model codes and standards developed by the existing organizations under their current process. In these ways the change would be evolutionary rather than revolutionary. It further needs to be made clear that the prescriptive code is still available as an Approved Document and will continue to be used.

Setting Objectives

The process would start by developing a set of explicit objectives for codes, and function statements for standards. Standards, especially those for fire protection systems, should include reliability statements to quantify the likelihood that the specified function will be performed. These would be developed by the existing committees responsible for occupancy requirements in the current codes or for the standards they reference. Since performance evaluation would be hazard based, the objectives would be established for a specified set of fire scenarios which would also be established by these groups. These scenarios would thus represent design criteria in the same way that snow loads or wind loads are specified in current codes. The National Fire Protection Association's Life Safety Code Correlating Committee has recently assigned each of that Code's occupancy committees to develop an initial list of objectives within their area of responsibility.

Developing design scenarios will be more difficult as it needs to incorporate both data on the historical incidence of fire in a given occupancy and the judgement of experts as to what other conditions might prevail. All uncontrolled variables (weather, occupant loadings and characteristics, door positions, fuel load and distribution, etc.) should be specified as distributions so that the sensitivity to such variations can be determined. In these decisions in particular it is crucial to have the full involvement of the fire service both for the benefit of their experience and to assure that their needs will be met.

Evaluating Performance

In parallel with the establishment of performance objectives the engineering societies would continue the process of documenting appropriate engineering evaluation methods already begun. The results of these efforts would be incorporated into a Code of Practice and supporting standards of ASTM and NFPA. This Code of Practice would cover not only engineering methods sanctioned for use within specified bounds, but also should include a means to derive safety factors to account for the uncertainty of both methods and data used in them. Such a methodology is being developed under the umbrella of CIB W14[5].

This process presents an unique opportunity to harmonize international requirements and promote trade in the building design and construction field. Many countries are developing performance codes and there is general agreement on the form and content of the engineering evaluation methods. Efforts are underway under ISO TC92SC4, and CIB TG11 and W14 to develop common methods and this joint conference is seminal to the advancement of these activities.

Deemed to Satisfy Provisions

Coordination between the codes, standards, and engineering communities is crucial to the success of the entire process. One key area where consensus is needed is in the specification of design features which are deemed to satisfy objectives or functions identified in the code. Some proposals may be highly controversial and what may work in some countries may be unworkable in others. But agreement is not critical to harmonization since the performance approach is always available where countries are unwilling to concede that specific provisions meet related performance criteria.

SHIFTING PARADIGMS

This transition to performance-based codes and standards will result in many changes in the traditional roles of most organizations involved in the process as they change to provide the infrastructure needed for the new system to function. This is where most of the resistance to this change is rooted -- since many groups see nothing wrong with how they currently function. The point is not that they are now wrong, but that the advantages of a performance basis require a different approach to the process. The downside is that, if they fail to take up the new roles these will be addressed by others as the performance system comes into general use.

Model Codes

The existing model code bodies would continue to develop and promulgate the code, but now containing explicit objectives, "deemed to satisfy" provisions extracted from the prescriptive code, and Approved Documents, the first of which consist of the prescriptive code itself. The prescriptive code would then represent one acceptable solution, which would be expected to be used in most (about 90%) of cases. The performance objectives would represent public policy on the minimum acceptable level of performance permitted, by occupancy. Performance objectives may (and would be expected to) vary by occupancy or even within a single occupancy category. For example, within residential occupancies, hotels would continue to require higher performance than rooming houses which in turn require higher performance than for single-family.

The resulting model codes would continue to be adapted and adopted by local jurisdictions who may decide to modify objectives based on local conditions. Enforcement would continue at the local level, but increased technical assistance would need to be made available through the existing Evaluation Services system as needed by local officials. The fees for these services would be borne by the applicant as they are now. Alternatively, a system of peer review of engineering analyses by competing engineering firms might be established, modeled after the system used in New Zealand. Once again, the costs of the review are paid by the applicant.

Performance Standards

The role of standards would also not change significantly, but their format would evolve to support performance codes[6]. The central objectives enumerated in codes would identify functions (e.g., alerting occupants, extinguishing fires, providing reliable power to critical systems) which need to be performed for the objective to be met. Standards would identify functions that the systems covered would perform and how those systems need to be installed and maintained in order to be capable of providing those functions. Reliability estimates for systems in compliance with the standard would be included so that the need for redundancy could be assessed.

Professional Societies

Professional societies are the guardians of the profession. They develop codes of practice and provide the peer review upon which other professions depend for confidence in the applicability of the work submitted to them. In the same way that doctors provide second opinions, engineers may be called upon to review work of their peers in an unbiased and professional manner. The professional society facilitates this process and would act as an appeals board. As with the medical profession, it should become sufficiently commonplace that it would not be treated as adversarial. Professional societies further would serve a role in the continuing education of their members and in the education of those who interact directly with their members. This is particularly important as evolving calculational procedures play a more important role in the process.

Testing Agencies

Since the prescriptive codes will still be used, there will still be a need for lists of products which meet minimum performance criteria. However, performance analysis will result in a demand for certified data from an independent source for many products and materials. While examples of performance measurement methods exist, additional methods will be needed and these agencies could fill this role as well.

Code Enforcement

The enforcement community will become more familiar with fire safety engineering methods with experience. They would call upon their own consultants for technical review until such time as the workload demands an in-house expertise. As the fire service adds fire protection engineering expertise, this might be shared with the potential of improved cooperation between these agencies. Likewise, the fire service would become more involved in the development of performance objectives as a means to assure that their needs are met for safe operations in performance qualified buildings.

The application of performance techniques to a building's approval will mean that the supporting fire safety analysis will become, in effect, the "code" for that building. Variations from the design or assumptions in that analysis would represent code violations, so the analysis would need to be kept on file for the life of the building. This represents another opportunity for the fire service in their pre-planning activities or as a resource in fighting a fire or providing other emergency services in these buildings. The analysis should provide insight into what is likely to occur in a fire which would be of value in developing successful tactics.

CONCLUSION

Performance codes and standards represent a new way to design, qualify, build, and maintain buildings. The infrastructure is in place to allow an evolution to these new methods. The details of the functions of various organizations will change or expand to address the needs embodied in the performance-based methods. The common thread is that continuing education is crucial.

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Fire Risk or Fire Hazard as the Basis for Building Fire Safety Performance Evaluation†

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Background

Nearly every developed country has committed to the goal of a performance-based code by early in the next century. Most have expressed interest in the use of fire risk assessment as the means to judge performance against the code's explicit objectives. The fact that risk can never be eliminated may lead to the public perception that officials feel a few deaths are somehow acceptable. 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.

Since a rigorous risk assessment is computationally intense and requires a vast amount of historical data that is frequently not collected, most analyses conducted in support of performance evaluation are hazard assessments. These measure performance in a specified set of conditions which 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. The purpose of this paper is to identify research issues to be addressed by international programs such as the CIB W14 Task Group on Engineering Evaluation of Building Fire Performance.

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 which will have an effect on the outcome. The trend today is to use computer models wherever possible, supplemented where necessary by expert judgement 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 which have been weighted for their likelihood of occurrence. The value of risk over hazard is its ability to identify scenarios which contribute significantly to the risk but which 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 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

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† Fire Safety Conference on Performance Based Concepts, Oct. 15-17, 1996, Zurich, Switzerland, Institute of Safety and Security, Zurich, Switzerland (in press)

example, in a museum or historical structure, the purpose of a 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 which can be tolerated by these items before unacceptable damage occurs.

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[1], FASTLite[2], CFAST[3], and HAZARD I[4], all from NIST, FIRECALC[5] from Australia, or ARGOS[6] from Denmark are the most frequently cited. The Japanese prefer BRI2[7] and the French use MAGIC[8] as these are locally produced and use the local language for the software and manuals. Several nations have or are developing engineering Codes of Practice, e.g., Japan[9], UK[10], Australia[11], and New Zealand[12]; and the SFPE Handbook of Fire Protection Engineering[13] is a universal reference work for the underlying science, although Japan has its own version of a comprehensive engineering handbook.

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[14] in the U.S., FiRECAM[15] in Canada, and CRISP2[16] in the U.K.

Data Needs for Risk

While the 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 which underlie the desire for risk based regulation.

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

The *design fire model* considers six design fires; smouldering, flaming non-flashover, 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 data bases 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 which are available for common homogeneous fuels but rarely for end use products. Fuel loads (energy content per floor area in wood equivalent) has been surveyed for a few occupancies but smoke and gas yields can vary substantially across fuels (e.g., soot yield fractions vary by 2 orders of magnitude from wood to plastics). Since the smouldering and non-flashover 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 U.S. and U.K.

The *occupant warning and response model* depends on the fire detection model to initiate 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 are 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 2-3) 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 which is 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 is 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 is well documented, but for incapacitation is 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 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 add to the uncertainty of the results.

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. So far, 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 is collected. The observation that most major incidents have contributing factors of variations with codes or practices, or systems that failed, each of which complicate 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. In the World Trade Center bombing incident, litigation has been filed seeking compensation for the emotional trauma of being exposed to smoke during the evacuation, even though no physical injury was sustained.

Providing for the public safety is a governmental function. Thus, legislators have the responsibility for establishing objectives for the built environment which 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.

4.1 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 (BRRTF) which said,[17]

> "... 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 which need to be considered. For example, Brannigan argues,[18]

> "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 four 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. Fire, 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 which 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 1980's, 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 predict accurately loss rates in the future due to the fact that stochastic elements are based on past materials and lifestyles which may change (e.g., declining smoking rates should reduce rates of cigarette ignitions).

4.2 Absolute Risk

The draft Code of Practice from the British Standards Institution (BSI)[19] is the only method which 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 U.K. 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 which 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 which can be understood by the public is a problem which 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, 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[15].

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 analysis) 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 which 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[20,21]. Since then, other risk assessment methods have been developed which 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. A more recent risk model[22] 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 losses in these design scenarios. It is further possible to allow for additional 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 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 which 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 which 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 which 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 well as to avoid unacceptable losses. This approach is being introduced within the U.S. 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 and standardized within a few years.

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This is a collection of papers on the application of modern fire safety engineering concepts to the evaluation of building performance in the context of performance-based codes. BFRL's effort to facilitate a transition to performance-based codes began in earnest with the publication of an overview paper by Bukowski and Babrauskas in 1994 [paper 1]. To foster a better understanding of the performance approach and its similarity to the use of "equivalencies" under prescriptive codes, guidance was developed for regulatory officials as to what constitutes an appropriate engineering analysis and associated reporting [paper 2]. To generate interest among the architectural community a short article was prepared for one of their most popular journals [paper 3].

An updated review of international activities was presented at a meeting of the FORUM for International Cooperation on Fire Research comprising the leaders of the world's fire research organizations [paper 4].

All of the proposed methodologies embrace fire risk assessment as a goal, but default to fire hazard assessment given the lack of data needed for the former to be accomplished. Codes and standards organizations in the U.S. and elsewhere are struggling to understand their future relationships as performance codes become the norm. Thus two papers were written which deal with these topics [papers 5 and 6]. All of the proposed methodologies further lack detailed goals and objectives, rather including general statements which are open to broad interpretation. This led to [paper 7]. Once these critical issues were open for discussion, the implications for the development of a performance-based system in the U.S. were explored [paper 8]. Finally, some suggestions on the use of a combination of fire hazard and fire risk-based methods for the evaluation of building fire safety performance were formulated as a result of many of the preceeding papers [paper 9].

KEY WORDS (MAXIMUM OF 9; 28 CHARACTERS AND SPACES EACH; SEPARATE WITH SEMICOLONS; ALPHABETIC ORDER; CAPITALIZE ONLY PROPER NAMES)

fire codes; life safety; performance codes; risk assessment; scenarios

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