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

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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 USA 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.

THE BASIS FOR ASSESSING FIRE SAFETY PERFORMANCE OF BUILDINGS

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 five 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, co-ordination of the whole system, with the remaining four working groups being the 'four-way split' of the fire safety system. This division was done *ad hoc*, without specific debate outside this particular subcommittee.

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 of 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: (1) direct flame propagation through openings such as open doors; (2) fire propagation due to failure of fire endurance, i.e. due to walls or doors burning through, beams falling down, etc.; and (3) 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 to *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: (1) the self-evacuation of occupants during the initial period after the alarm is raised; (2) the rescue activities commenced when the firefighters 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 also needs to begin. We also note the obvious fact

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that, generally, 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 three basic societal objectives to be achieved in providing fire safety in buildings:

(1) Limit the spread of fire and smoke
(2) Provide for successful evacuation of occupants
(3) Provide for effective firefighting and rescue operations.

We may also note that the above are only the *societal* objectives. In addition, there can 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 on 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.

Professor Beck's scheme. Another tripartite scheme has been proposed by Professor V. Beck, who headed the Australian group studying performance code concepts. He suggests[2] the following objectives:

(1) Life safety for occupants of the building of fire origin
(2) Life safety for occupants of adjoining buildings
(3) 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 firefighting and rescue operations'. Furthermore, Professor 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 republishing 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, 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 firefighting 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. In general, this scheme is very similar to ones used by UBC and other traditional codes. There are classifications for residential, education, 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 that one of the most essential objectives of a rational, performance-based building code shall be either to present scientific bases for a 'top-level' buildings categorization scheme or to abandon the concept entirely.

Taking a further look at Mallhotra'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 in 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 seven 'design subsystems':

DSS1 Building and occupant characterization
- Effective fire load
- Design fires
- Number of people
- Distribution of people
- Occupancy efficiency
- Occupancy characterization
- 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, to see the basic concepts which need to be complied with, along with how proof is presented of such compliance. Without 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 (1) to know what primary safety features are expected and (2) to 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, prejudge 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) Five 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) Firefighters 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 firefighters 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 similar to those in the UK.

We can point to several unique features in the New Zealand 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 with 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 or her insurance company. Other than limiting damage to third parties (similar to the Japanese philosophy), the New Zealand 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-à-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, firefighting damaging the environment we believe, however, have been greatly overstated in European publicity. Even from gigantic fires (e.g. major forest fires, Kuwait oilfield 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.

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 behoves us, however, to consider other requirements of such a code. 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 and 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 no-one 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 overall raising or decreasing of safety levels required should be separate work items, apart from providing an engineering foundation for a performance-based code.

For general requirements we point out here that international bodies have already made a *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 useful general guidance on how to structure a performance-based code so as to be effective.

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, 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 a 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) It is exceedingly difficult to enumerate *all* the scenarios. 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 know neither the probabilites or the consequences. In the pure risk approach we would be entitled to omit a scenario when the $\{\text{probability}\} \times \{\text{consequence}\}$ product is very small, 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 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 subsystem should be challenged against as many scenarios as are appropriately diversely challenging to that particular subsystem.

A strategy for evolving to a performance-based code

In 1991 Bukowski and Tanaka[19] published a paper 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 society has determined to be desirable even though it is not explicit. The methodology (s) that is deemed to be acceptable for demonstrating compliance with the performance code then becomes 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 public safety from fires are universal; only the means chosen to achieve them vary. These goals can be rather simply stated in the following shortlist:[20]

- 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 the 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 the 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 on 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 encompass the specific problems of the building and its occupants with respect to their safety from the effects of fire and, as such, controlling 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
- 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 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 (US) 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 burnout 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.

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 Fig. 1). Typical contents items expected to be

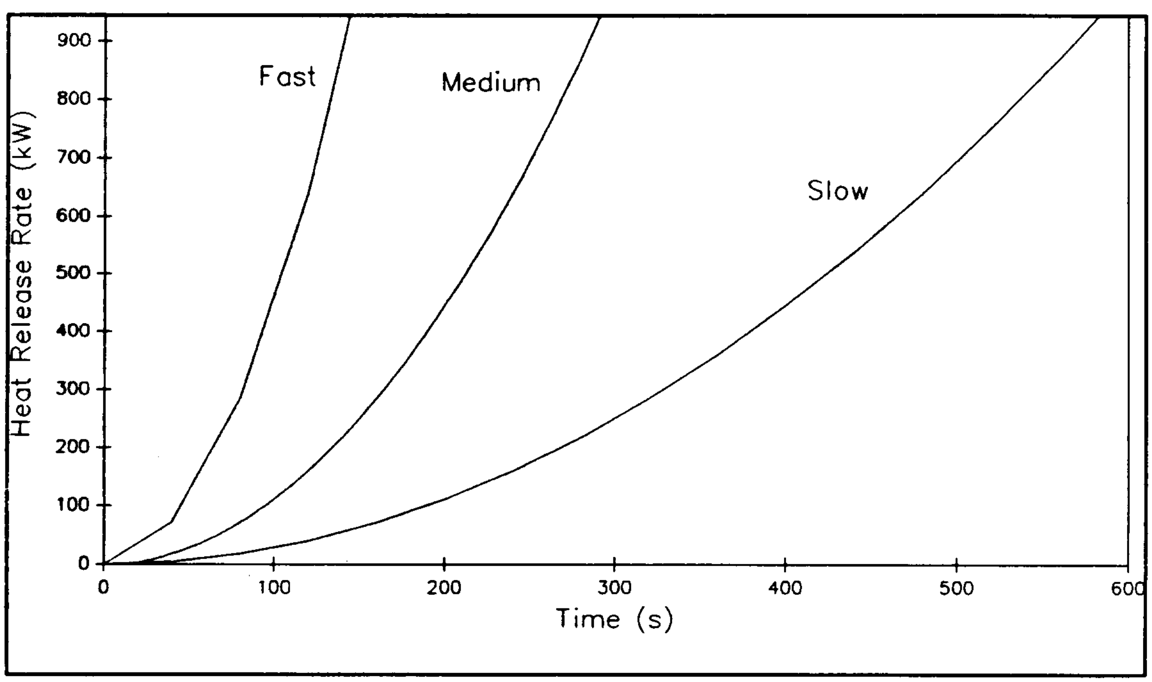

Figure 1. T-square fire-growth curves.

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 for both 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 conservatism, until experience is gained with a new system. Theses 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 results 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 to which engineering and regulatory communities can easily related.

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 USA.[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 given in Table 1. 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

Table 1. Current status of performance code elements

Requirements	PS	SS	DS	EJ
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				X
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 Re-use 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 supression 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	

example, modern stair design, based on extensive research with people walking on 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-storey, wood-frame building would be 'deemed to satisfy' the code. As research data become available, some items in this category will transfer into the Specification Standard or Performance Standard categories. The Expert Judgement category refers to all 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).

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 rather 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 US 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 a significant work going on 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.

US EFFORTS TOWARDS A PERFORMANCE CODE

Current status

Unlike most countries, development of codes in the USA 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 that 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 1980s and has since been expanded into several more occupancy types. Generally referred to as Fire Safety Evaluation Systems (FSESs), 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.

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 way 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 need only be verified by the code official to receive the needed permits.

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 six 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 USA 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-room 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.

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 Professor Dave Lucht. The goal is to have such a system in place by the end of the decade.

JAPANESE EFFORTS TOWARDS A PERFORMANCE-BASED CODE

Current status

The Japanese are a long way ahead of the USA 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 the Appendix to 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. They have also 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.

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 better access to 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.

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 or 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 or in developing a suitable performance-based approach, along with cautions where appropriate:

- *Identification of all 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 methods. 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 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 Article 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 New Zealand 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 greatly 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 is not 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.
- *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 Japanese project 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 practioner 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 solved successfully in order to inspire requisite confidence in the process.
- *Consistent enforcement.* In most countries 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 from 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: TABLE OF CONTENTS OF THE JAPANESE REPORT GIVING DESIGN METHODS FOR CONFORMING TO ARTICLE 38

Volume 1. Regulation for Comprehensive Designs for Fire Prevention

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Volume 2. Designs to Prevent Fire Growth

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Volume 3. Regulations on Designs for Safe Evacuation

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Volume 4. Regulations for a Fire Resistant Designs

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