ELEMENTS OF A FRAMEWORK FOR FIRE SAFETY ENGINEERING*

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ABSTRACT

This paper lays out a framework for fire safety engineering based on scientific tools for fire safety design and decision-making. These tools include computer-based models for fire safety hazard and risk prediction, measurement methods to provide data for such methods, databases and expert systems to provide access to them, and the ultimate integration of these tools with other elements of computer-aided design, construction and conformity assessment. The paper suggests needs, roles and actions required to bring fire safety engineering to the level of sophistication enjoyed in most other areas of engineering practice. The need for international cooperation and public-private collaboration is stressed.

INTRODUCTION

Fire safety engineering (FSE) is a reality of growing importance. In many countries, in numerous circumstances, fire safety engineering calculations are being used today. They are often not yet the mainstream, but they are used - to gain official approval for unconventional designs, to demonstrate the fire safety when challenged, to reconstruct fire incidents, and in various other circumstances. Soon the fire safety engineering approach will be entering "mainstream" applications in various countries; this will happen of its own momentum, without urging or promotion.

However, the benefits to the community will not be as great as they could be if the efforts were systematized, logically constructed and advanced with the maximum participation of groups and professionals able to contribute. This can be done through scientific understanding of fire and the use of practical engineering tools for the quantification of fire risk and hazard and the performance of all fire safety systems. The costs of delay are measured in added lives lost, injuries incurred, and needless burdens on the economies of the world.

In the simplest of terms, FSE provides fire safety decision-makers the quantitative information needed to assure that desired levels of fire safety can be delivered. Such quantification simply has not been possible in the past. We are moving from an era dominated by empiricism into one of scientific measurement and understanding. The implications for practice are enormous.

In this paper, we lay out some of the fundamental considerations which will need to be kept in mind to bring forward top quality fire safety engineering. We begin by looking at fire safety decision-making to define the elements of a framework for fire safety engineering and assess the implications of it. The paper closes with some observations about the kinds of changes needed to accelerate the advance of fire safety engineering and offers a number of suggestions for moving forward.

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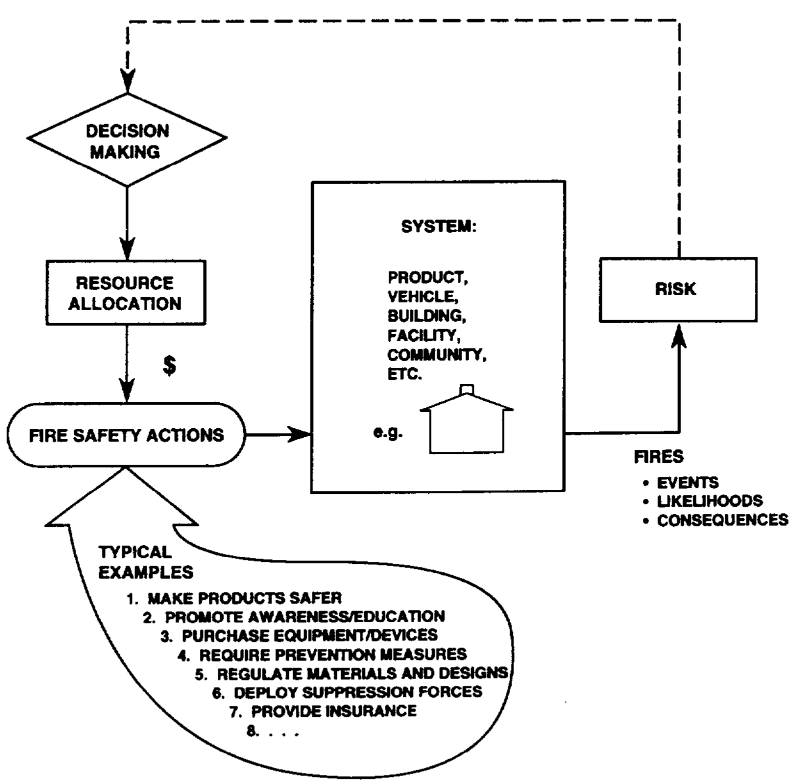
CONTEXT OF FIRE SAFETY ENGINEERING

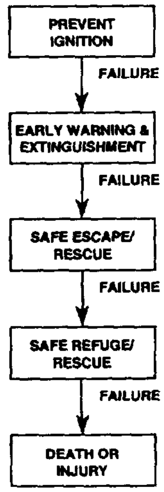
Fire safety engineering is employed in the context of a variety of actions taken for the purposes of making some system, typically one involving people and things, safer from fire as depicted in Figure 1. Resources are applied through a set of actions with the intent of reducing fire losses. The system of attention can be a person, a product, a building, vehicle, facility, etc. Ideally, some measure of system performance enables the decision-maker to compare results with expenditures, so that controllable actions can be adjusted to achieve a desired level of fire safety with available resources. One would expect by increasing investments in appropriately chosen actions, the measured fire losses would decrease until at some point the marginal cost of additional actions is not offset by further reductions in fire loss. More expenditures would result mostly in increasing the total cost or burden of fire safety on the economy.

Figure 1. Fire Safety System



Fire safety is complex. Fire is a random and infrequent event. The likelihood of fire and the potential consequences depend on many factors (some of which we will examine later). These include complex interactions between the systems and their use. Further, most fire losses occur as a result of a sequence of multiple failures or errors. For example, Figure 2, a highly simplified version of a fault tree for fire death, depicts just a few of the types of failure which must occur for a person to succumb to fire. The usual response to a major fire disaster is to institute a number of "fixes" or changes to prevent recurrence of each such failure. But, means are lacking to judge whether these fixes are adequate, excessive, or potentially conflicting with other objectives.

Figure 2. Life Safety from Fire



The complexity of fire and its causes and the difficulties in establishing cause-effect relationships are reasons why many of the decisions taken to manage fire safety are empirical. Scientific knowledge is now becoming available in many areas which previously were guided solely by experience.

Another important concept depicted by Figure 1 is the governing role of fire risk. Risk is defined on three interrelated sets - events, their likelihoods or probabilities of occurrence, and their consequences. There are many possible measures of risk, and different decision-makers have different risk preferences, and thus require different expressions of these data. Management of fire risk is unavoidably empirical unless needed information can be quantified and the relationships between actions taken and outcomes are established. Key fire risk management decisions include questions of the sort: How safe? What level of safety is desired or achieved? What kinds of actions are most effective in a specific situation? What is the best allocation of resources for achieving a desired level of fire safety? etc.

The types of fire safety actions listed on Figure 1 are employed by people with widely differen backgrounds, skills and abilities. Few of them have scientific, engineering or even technica backgrounds.

Traditional fire safety actions do not provide an overall quantitative measure of syster performance in terms of key system parameters. They do not derive from a scientifi understanding of why and how fires occur, nor do they provide explicit understanding of ho controllable factors such as those employed in the various sets of actions listed on Figure 1 ar linked to specific fire scenarios, probabilities or consequences. In other words, building and fir codes typically consist of sets of requirements on or specifications for designs and their use rathe than meaningful models of the systems they address and how they work. What regulations d embody is an expanding knowledge of fires which have occurred and some of the conditio known to have existed at the times at which they occurred. Again, this is an empiric understanding of how inputs may be correlated to outcomes, but with little knowledge of th interconnecting physics, behaviors, chemistry, dependencies, etc. Therefore, little can be said about what levels of fire safety or what combinations of fire safety are most cost-effective for any set of assumptions about the values of the decision-maker.

If one were looking instead at the processes of controlling the risk of an aircraft crash, a bridge collapse, the failure of a business, etc., in this modern day and age, one would expect a more robust basis for decision-making than empiricism. So, it should be for fire safety. This is the role of fire safety engineering.

FRAMEWORK FOR FIRE SAFETY ENGINEERING

a. Definitions

Fire safety engineering (FSE): An engineering approach to fire safety[1]. The art of applying science, i.e., fire science, to solution of problems involving safety from fire. Typically, it is employed at the design stage, though it may also be used in application, use, investigation, etc. The essential functions are to measure, evaluate, and predict performance - of designs, real systems, re-creation simulations, etc. - on the basis of fire science and engineering relationships to make informed decisions regarding fire safety and risk management. FSE may focus on people, products, buildings, facilities, etc., in fully integrated systems.

Framework: a conceptual scheme, structure or system[2].

b. Criteria

Consider the criteria that a fire safety engineering framework should be expected to meet. We suggest the following:

1. *Completeness*. The framework should include all of the essential aspects of the problem or situation.

2. *Quantifiable*. All key aspects of performance, resource use, and technical interdependence should be measurable and expressible in consistent and meaningful units of measure. A well-structured framework should facilitate appropriate quantitation.

3. *Robustness*. It is important that means be available to establish the credibility and efficacy of solutions or actions and to assess their sensitivity to all key parameters. The desired framework should help identify key parameters and their interdependencies.

4. *Comprehensible and practical*. The framework must be easily understood and perceived as useful so that the diverse range of professions involved in fire safety are able to use it to advance their views.

5. *Fairness*. A meaningful framework must make social policy decisions explicit and not bury them concealed as engineering data and thus facilitate objective assessment of the implications of any approach or perspective.

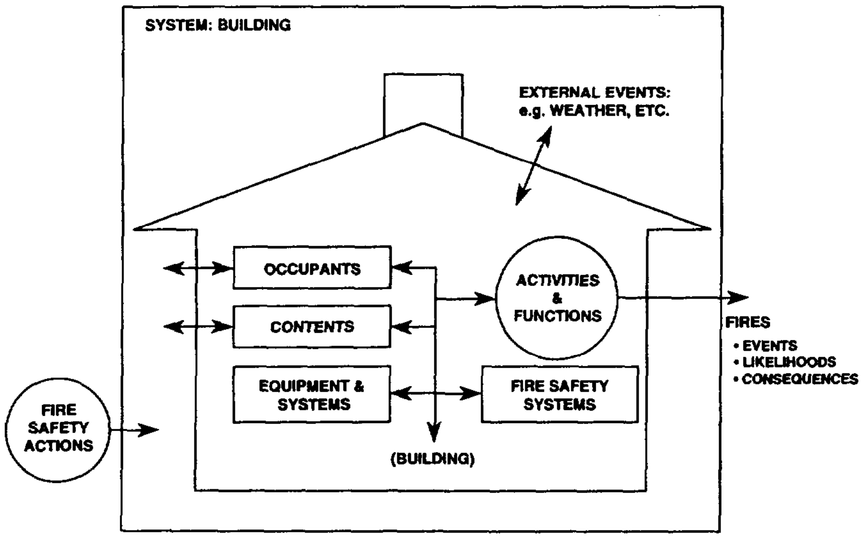
The classic model of a useful framework, of course, is the periodic chart of the elements in chemistry[3]. It meets all of these criteria and has continued to do so for many decades. It is in light of this example, we term this modest offering as simply "elements of" a framework for FSE.

These criteria and the foregoing suggest that a **framework for fire safety engineering be grounded primarily on a scientific and quantitative rather than an empirical basis**; success requires quantitation.

A second requirement for the framework based on the above is that it incorporate, as much as possible, explicit connections between specific fire safety actions and resulting fire outcomes, i.e., the critical interdependencies which are **not** shown on Figure 1.

Doing this requires models of the workings of the subject system under all conditions relevant to the initiation, development and impacts of fire. For example, simulation models incorporating physical science, normal and abnormal operations, human behaviors, fire incident experience, Monte Carlo techniques, etc., can be used for this purpose. Figure 3 suggests some of the essential structure for such simulations involving buildings. Somewhat different models would be required for other systems such as ships or aircraft.

Figure 3. System Simulation Model



The prediction problem suggested by Figure 3 is this: buildings and their interior mechanical equipment and systems are specifiable. There are predictably stable flows of people and things in and out of buildings which in turn are involved in predictably stable sequences of activities, functions and events. Most of the time, these work as intended. Very occasionally, they do not. Even more infrequently, these complex interactions result in meeting the physical conditions necessary for fire to occur, and the additional conditions necessary for unsafe consequences to develop. All of these processes involve random variables so that rarely are all or any of them fully understood in simple deterministic terms.

c. Function

The function of fire safety engineering is to make these processes reliably predictable as the basis for informed decisions on fire safety. The FSE framework should serve as a practical and useful guide for the fire safety community as it shifts emphasis from primarily empirically-based to scientifically-understood fire safety measures. The framework needs to provide a perspective on what FSE is, what it involves and how the pieces fit together.

d. Assumptions

The assumptions underlying the FSE framework include, in particular, . . .

1. People are fallible, i.e., they make mistakes, and sometimes, in fact very infrequently, these mistakes result in conditions necessary for accidental fire to occur.

2. Manufactured products and systems (MPS) are subject to random failure, and sometimes, again very infrequently, these failures result in conditions necessary for accidental fire to occur.

3. The mistake/failure distributions for people/MPS are knowable, but not precisely.

4. The performance of both people and MPS can be improved but not made perfect.

5. The physics of fire are determinable. Once exact physical conditions are specified, fire is a repeatable, predictably deterministic phenomena. However, the conditions which determine the course of a fire and its outcome include random variables, so the outcome of a particular fire may have a random component as well.

e. Framework of Fire Safety Engineering: Classification of FSE Tools

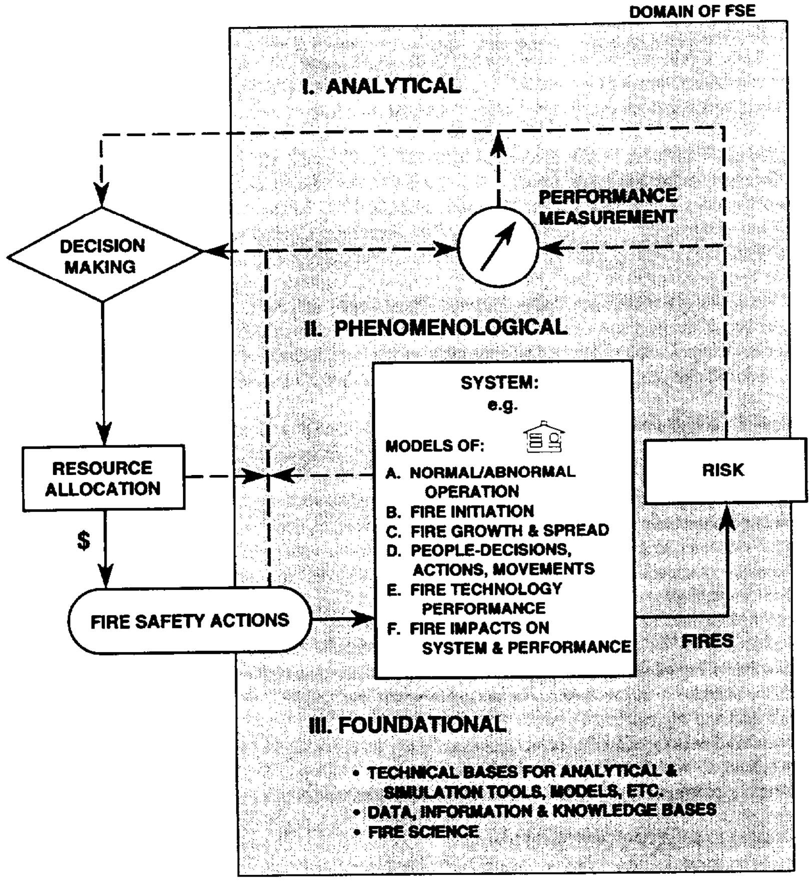
Figure 4 depicts a suggested framework for FSE. The first point to observe is that it involves three levels of measurement and evaluation.

The **first level is primarily analytical** and includes calculational methods for fire risk and cost-benefit evaluation as technical inputs to the decision-makers. The units of measure at this level are likely to be defined broadly in terms of resources required, lost or saved and their impacts. Typically, the decision-maker will draw upon numerous additional inputs, e.g., values and political factors, which are beyond the scope of FSE, in making many fire safety decisions. The tools of benefit-cost analysis are well developed and widely standardized[4]. Central issues at this level are how best to quantify risk, methodologies for characterizing the values and risk preferences of the populations served by the decision-maker, and the means used for risk communication with those people[5].

The **second level is largely phenomenological** and involves tools for predicting fires and their outcomes and for measuring the performance of fire safety technologies or actions. Figure 4 lists a number of types of issues such tools are designed to address in the context of the system being examined. This is the heart of the framework. It begins with representations of the systems context, e.g., Figure 3, in which events occur and simulations of the processes which at times result in conditions likely to lead to fire events. The next stage, produces reasonable predictions of fire events and their probabilities in terms of those controllable or modifiable parameters which various fire safety actions are designed to influence. The remaining stages, are the ones most familiar to those who have fixed their attention for the last decade on fire hazard and risk prediction and the underlying science. Key here are the complex interactions within and between models dealing with fire-system interactions; the decisions, actions, and behaviors/movements of people; the performance of fire protection/fighting technologies; and the physical impacts of fire.

The units of measure for the outputs from this level are fire events/scenarios, their probabilities or likelihoods, and their consequences measured in human or physical terms. This level ranges from modeling the context in which the conditions likely to result in fire exist, to understanding the causes of fire events, to the dynamics of fire spread and growth and the production and movement of combustion products. The tools here are science-based expressions and models, and

Figure 4. Framework for Fire Safety Engineering



simulation and test methods which individually and collectively deal with manageable abstractions of the real phenomenological determinants of fire safety[6]. The central issues here are the availability and adequacy of needed computational tools.

The **third level involves the knowledge, measurement methods, and data** and other information needed to support the tools. The units of measure of the data are the physical, chemical, mechanical and behavioral parameters required as inputs to the various tools, expressions and models. This level includes the measurement methods needed to provide these data, the formats for representation and exchange of such information, and the means used to collect it and to verify or certify its accuracy and limitations. Termed variously as database or knowledge base - this element does not include those traditional tests, indices or ratings for which there is no scientific basis and which have no use in the calculational tools. Issues here include the adequacy and acceptance of scientifically-based measurement methods, and the availability of standards for entering, expressing and using the data.

The adequacy of underlying knowledge, tools, measurement methods and data varies considerably across this framework. Much attention has been devoted to fire dynamics but little to the behavioral determinants of fire events or their probabilities. In some nations, notably the U.S.A., there have been significant efforts to compile fire incident data[7]. To date, these data have been used primarily for identifying critical areas for corrective action rather than developing understanding or causal relationships.

Fire risk methodologies are being developed in Australia, Canada, and the U.S.A.[8,9,10]. In Japan, the Fire Safety Design Method, which is used as an alternative method to prescriptive code requirements, incorporates many state of the art FSE tools[11]. In the U.K., the British Standards Institution has contracted with the Warrington Fire Research Center to draft a code of practice for FSE of buildings as part of its commitment to the activities of ISO TC92/SC4[12]. All of these products fit primarily into the first level of the framework and reach to varying degrees into the second. One glaring limitation of all of them is the absence of predictive models of fire events and their probabilities in terms of the key parameters of the systems which produce them. A high priority need is for physical and behavioral models of these processes. Once developed, they may be tested, at least partially, against the fire incident data that a number of nations now collect.

This framework suggests that fire safety engineering represents a fundamental shift in our fire safety paradigm - from a reactive, largely empirical one to a more proactive scientifically based one. Figure 4 is at best suggestive. Nonetheless, the central point is that fire safety engineering is here, it is advancing at an accelerating rate. What is needed to transform this into a practicable framework, one that fully meets all of the criteria presented earlier, are . . .

1. a more comprehensive and detailed accounting of all relevant system and fire phenomenology;
2. a complete and consistent set of terms and definitions;
3. availability of fire safety engineering tools for each area where they are needed;
4. an accounting of the essential elements of the foundational databases and underpinnings of fire science;
5. well defined measures of system performance;
6. some worked examples of the application of the framework to practical problems, to serve to motivate its use; and
7. translation/adaptation of the framework into terms understandable by all users.

SUGGESTED NEEDS, ROLES, ACTIONS

It appears worthwhile to pursue further development of such a framework. Potential uses for it include the following:

a. Identification and prioritization of research needs,
b. Direction, coordination and collaboration in international fire safety engineering research, development, and application,
c. Guidance in development of performance fire codes, advanced technologies for fire prevention and fire protection,
d. Improved communications within the fire safety community,
e. Design and evaluation of models of technological and institutional change within the fire safety and building communities.

Obviously, considerable effort is needed to extend the framework and advance fire safety engineering and more than just a framework is needed to advance the cause of fire safety engineering. **Necessary conditions for the success of FSE** include the following[13]:

1. A coordinated global research and development effort, and national variants to meet exigencies of unique national needs, in the areas of . . .
    a. fire research and fire modeling;
    b. fire model validation and related large scale tests/experiments; and
    c. fire risk assessment method and data, including Bayesian models to generate probabilities for non-recurrent fire events.
2. Open systems design for fire, fire hazard and fire risk models.
3. Non-exclusive bases for fire safety engineering software, which receives international peer review, Beta testing and trial applications, and ultimately standardization.
4. Standardized data formats and cooperatively networked databases among the nations of the world.
5. Internationally recognized, standardized fire safety engineering training and certification."

Systematic activities are already underway or planned in a number of countries to work some of these issues. Last fall, CSIRO sponsored a Conference on Fire Safety Engineering in cooperation with the FORUM for International Cooperation on Fire Research[14]. (A summary paper on that conference is in preparation by Steven Grubits of the CSIRO Fire Laboratory.)

Similar conferences will be held over the next few years in a number of countries to draw attention to and build support for this rapidly developing area of technology.

The CIB W14 and ISO TC92/SC4 each have activities aimed at development of a framework for fire safety engineering as a guide for international standardization and practice in this field[15,16]. This paper is offered as an input to those processes. A number of other papers presented at this conference, including the provocative keynote by David Woolley, have spoken to some of these issues as well.

The participants of the FORUM meeting in Sydney last fall agreed individually and collectively to support these international standardization activities. Active participation of the fire safety engineering community, the IAFSS, and many others is needed as well.

A recent conference in the United States on "Firesafety Design" addressed a number of issues associated with application of emerging tools of fire safety engineering to building design and fire safety regulation[17]. It identified a number of barriers to innovation of relevance to this discussion of fire safety engineering. High on that list are resistance to change and the momentum of tradition, lack of appropriate educational qualifications among key participants in the fire safety design and regulatory processes, ineffective transfer of new engineering methods to practitioners in validated and useful form, and failure of institutions to embrace innovations.

The challenge for all of us is to translate these "barriers" into opportunities, and into saved lives property and reduced costs.

SUMMARY AND CONCLUSION

Our central message is that fire safety engineering is a reality. FSE is advancing at a accelerating pace. It represents a fundamental shift in our fire safety paradigm - to one that predominantly proactive. FSE will be **the** currency of exchange internationally in the fire safet field. There is no more universally accepted basis or language than that of scientifically-val measurement and evaluation.

It is exciting to be a part of Interflam because this conference has been a leading forum f transfer of technology on the frontiers of this field. It is time now for all of us to focus o attention and, yes, resources on sharpening our perception of what we are about, and to wo together to assure the timely removal of the barriers to progress in fire safety. To that end, we offer these preliminary thoughts about the elements of a framework for fire safety engineering and are willing to work together with all who care to move this cause forward.

REFERENCES

1 Woolley, private communication.

2 "Websters Third New International Dictionary," G. & C. Merriam Company, Publishers, Springfield, MA, 1966.

3 Ibid.

4 "ASTM Standards on Building Economics," Second Edition, American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103, 1992.

5 "Communicating Risk--A Workshop on Risk Communication for Michigan Department of Agriculture," presented by Department of Resource Development, Michigan State University, March 2, 1990.

6 DiNenno, Philip J.; Beyler, Craig L.; Custer, Richard L.P.; Walton, W. Douglas; and Watts, John M. Jr., "SFPE Handbook of Fire Protection Engineering," National Fire Protection Association, Quincy, MA, 1988.

7 "Fire in the United States," Seventh Edition, Federal Emergency Management Agency, U.S. Fire Administration, Emmitsburg, MD 21727, August 1990.

8 Beck, V.R., "Fire Safety System Design Using Risk Assessment Models: Developments in Australia," pp. 45-59 in Fire Safety Science--Proceedings of the Third International Symposium, Elsevier, 1991.

9 Takeda, H., and Yung, D., "Simplified Fire Growth Models for Risk-Cost Assessment in Apartment Buildings," Journal of Fire Protection Engineering, Vol. 4, No. 2, pp. 53-66, 1992.

10 Clarke, Frederic B. III; Bukowski, R.W.; Stiefel, S.W.; Hall, J.R. Jr.; Steele, S.A., "The National Fire Risk Assessment Research Project Final Report," National Fire Protection Research Foundation, Quincy, MA 02269, 1990.

11 Tanaka, T., "The Concept of a Performance Based Design Method for Building Fire Safety," Proceedings of the 11th UJNR Panel on Fire Research and Safety, San Francisco, CA, 1989.

12 "U.K. Code of Practice on the Application of Fire Engineering Principles to Fire Safety of Buildings--Outline and Illustrations," Working Document of ISO/TC92/SC4/WG1/N21, Convenor: Mr. Geoff Deakin, Warrington Fire Research Centre, Holmesfield Road, Warrington, WA1 2DS, U.K., July 1992.

13 Snell, Jack E., "Internationalization of Fire Safety Engineering Research and Strategy," Proceedings of the International Fire Safety Engineering: The Concept and the Tools Conference, held at CSIRO, Sydney, Australia, October 1992.

14 Proceedings of the International Fire Safety Engineering: The Concept and the Tools Conference, held at CSIRO, Sydney, Australia, October 1992.

15 Pedersen, Eric, "CIB W14 Fire Safety Engineering Activities," Proceedings of the International Fire Safety Engineering: The Concept and the Tools Conference, held at CSIRO, Sydney, Australia, October 1992.

16 Becker, Wolfram H.K., "Report on the Work of ISO TC92 SC4--Fire Safety Engineering," Proceedings of the International Fire Safety Engineering: The Concept and the Tools Conference, held at CSIRO, Sydney, Australia, October 1992.

17 "Conference on Firesafety Design in the 21st Century," Proceedings, May 8-10, 1991, Worcester Polytechnic Institute, Worcester, MA 01609-2280.