REGULATORY REQUIREMENTS FOR PERFORMANCE BASED CODES USING MATHEMATICAL RISK ASSESSMENT

Vincent Brannigan — Department of Fire Protection Engineering, University of Maryland at College Park, College Park Md. 20742 vb15@umail.umd.edu

Carol Smidts — Risk and Reliability Program, Department of Materials and Nuclear Engineering, University of Maryland at College Park

Anthony Kilpatrick — Fire Risk Assessment Program, Caledonian University, Glasgow Scotland

ABSTRACT

Fire safety is one of the most complex and difficult areas proposed for the use of risk assessment and performance based codes. Mathematical risk assessment involves the use of probabilistic models of real world events. However, fire is a rare and complex event for which significant uncertainties exist. Fire safety regulators are often unsophisticated, and code enforcement is fragmented. Current fire safety regulatory systems assume static buildings with ample safety reserves. From a legal perspective, uncertainty is resolved by political, not technical decision making. All these factors argue for a high level of scrutiny of mathematical risk models used for performance based regulation. Technological regulation involves predicting and anticipating technological failures. Compliance with regulations should be connected to a reduction in the risk of injury and mathematical risk models can be used to predict accidents and develop performance based codes. However, regulation is a process in which parties prove that their designs are in compliance with social norms, and it is unclear what standard of proof for mathematical risk models is appropriate. Minimum regulatory standards must be developed for mathematical risk models used to support performance based codes.

INTRODUCTION

A substantial number of members of the fire protection engineering community have argued that society is, or should be, moving towards a "performance based code" (PBC). [1] Under the PBC the designer and builder claim that a building has a certain "real" level of fire safety and that they can prove that level as a statement of scientific or technological fact. Proposals for performance based codes argue that society should accept that prediction in granting regulatory approval to the building. This regulation based on technological "prediction" is the truly radical proposal in performance based fire safety codes. Because traditional fire safety codes do not scientifically validate the relationship between the code requirements and real world fire risk, performance based codes represent a totally new approach not only to building design, but also to the regulation of fire risk.

RISK BASED REGULATION: Nuclear power plants

Safety regulation using mathematical risk models is essentially a development from the nuclear power industry. The hazards of nuclear power plants were so complex that they forced the development of new techniques in risk assessment. Since the first efforts in the mid 1970s there has been a vast effort to develop both probabilistic safety assessments and the associated risk based regulation. The effort to predict nuclear power plant component failures has not been very successful, despite the substantial allocation of time and money. Confident technological predictions have been made and shown to be fundamentally wrong. Most recently engineers from the Maine Yankee nuclear power plant confidently predicted that only a few hundred cracked tubes would be found on inspection of the steam generator. A steam generator is a large array of pipes not much more complex than a automobile radiator. The variables affecting performance were thought to be

Intl. Interflam '96 Conf., 7th Proc. March 26-28, 1996, Cambridge, England. Franks, C.A., Grayson, S., Eds.
Interscience Communications Ltd., London, england, 1996.

well known, and prediction was expected to be easy. But when the tubes were actually checked in 1995 more than 6000 were found to be cracked. The process of tube cracking is simply more complex than the engineers believed.

The fire safety problem of ThermoLag represents a somewhat different problem for the nuclear industry. Thermolag is a fire barrier material that was used to protect various parts of the control system wiring from fire. Fire was only recognized as a major cause of common mode failures after the wiring fire at the Browns ferry reactor knocked out both the primary and backup control systems. Thermolag was developed to shield the control wires, but at least some of the tests used to support the use of Thermolag were fraudulent, and it is unclear how much fire safety is actually provided by the material. The industry is attempting to use mathematical risk models to show that the fire hazard is so low that the problems with the material can be ignored, but so far the NRC has not accepted that approach. The nuclear regulatory commission is moving steadily towards risk based regulation, but acknowledges that it must move very carefully given the unknown nature of many of the risks. [2]

UNKNOWN RISKS PRODUCE MODEL UNCERTAINTY

The most important problem for risk modeling is whether the underlying problem is well understood or not. [3] Most engineering analysis is focused on solving defined problems, not on defining the problem itself. Engineers are primarily trained to think in terms of solving problems in "defined" systems. Problems which are well defined tend to involve clear cut technical requirements, have well understood physical laws, have small values in any uncertainty term, tend to not involve substantial uncontrolled human variables and are relatively simple. Real world fire safety problems are normally "undefined". There may be no real agreement on the actual requirements, there is often little control of over the range of potential variables and there may be poorly understood physical laws. Fire safety in a building can be more difficult problem than safety in a "defined" systems such as a nuclear power plant. Fire safety engineers must cope with a host of poorly defined problems including Human load and reactions, fire department response, arson, fire loads and weather conditions.

For this article the terms "defined" and "undefined" describe boundaries on a multidimensional space. A well defined problem is at the origin of this space and the more a problem moves towards the undefined, the less certainty we can have in technical solutions to any problem. This is especially true in a system as complex as fire safety. Fire disasters are rare probabilistic events. They are the product of complex causal chains and may present very different probabilistic structures depending on the level of aggregation chosen for the analysis.

Performance based codes are often used in situations where the underlying system is well defined and all critical variables are simple and known or knowable. For example, designing a building to carry a static building load is often used as an analogy to performance based fire safety codes. But gravity is a constant and even wind is well bounded. Loads are well understood and assumptions are easily tested in wind tunnels or by loading the structure. However, there are many differences between the well defined systems and the relatively undefined problem of fire safety.

Even in structural engineering undefined problems can create nasty surprises, as was shown in the recent KOBE earthquake. The society has to decide just how much of the problem is understood by the engineers. "Trust us", the engineers say to the regulators, "we know what we are doing". But the Titanic, the Estonia, the Kansas City Hyatt, Three Mile Island, The Amoco Cadiz, the DC-10, the Challenger, Bhopal, the Tacoma Narrows Bridge, Summerland, and the Hindenburg stand as rebuttals to this claim. All were the products of highly qualified engineers. In each case there was a risk that was either misunderstood, incorrectly evaluated or mismanaged. Often there is overconfidence that conventional engineering design gives sufficient reserve to deal with unknowns.

For example an NFPA task group suggests that "safety factors" can deal with "uncertainty" in the methods and assumptions employed in measuring performance criteria. [4] However, if the underlying mechanism of injury is not known, uncertainty in measuring performance cannot be corrected with a safety factor, in the same way that a confidence interval cannot correct for an inadequate model. [5] The relationship between the regulator and the engineer therefore must be thought of as a very complex interaction when dealing with poorly defined systems. The engineer is trying to solve a problem, the regulator is trying to decide whether the problem solving skills are sufficient for the social requirements. Both are critical to the use of mathematical models in performance based codes.

PERFORMANCE BASED CODES

The fire safety version of risk based regulation is described as a performance based code. The proponents argue that fire safety has advanced to the point where fire safety risk assessments can be used to regulate buildings. The technological basis for performance based codes is concentrated in deterministic fire models used to predict time to flashover, tenability and exit paths. But fire risk assessment is much more than just deterministic fire models. Fire safety involves all the different components of fire risk. Measuring fire risk in a building is arguably much more difficult than calculating the fire safety risk in a nuclear power plant. Nuclear power plants are highly engineered systems, with total control over all parts, employees, contents and processes. All activities are monitored, and deviations from specification are immediately followed up. Transplanting these system components to fire safety will require detailed analysis of the entire fire safety regulatory system and new regulatory structures.[6]

REGULATION AS PREDICTION

All technological regulation inherently involves predictive activity. The regulatory system is routinely engaged in attempting to anticipate future injuries or disasters, and mitigating the effects of such disasters. Probabilistic risk assessment (PRA) has been developed to give a quantitative structure to risk analyses which had previously only been qualitative. The use of PRA is an attempt to formalize and validate a portion of the risk based regulatory approach. However, it is a common mistake to believe that the creation of formal risk assessment methodologies can substitute technical analysis for the political and legal judgmental components of the regulatory process. This is simply not the case. Society does not defer to technical expertise that easily. The "pure" performance based code proposal suggests that fire safety experts will simply decide among themselves which new technologies will be permitted, so long as they satisfy some formula or calculation. But it is the public that decides what risks it will take. PRAs requires careful evaluation to make sure that public policy decisions are not subsumed under the technological analysis. For example, one of the most important public decisions is how to deal with uncertainty in a model. For the purpose of this article the term RISK as a statement of the probability of an occurrence and UNCERTAINTY as a statement of confidence in the risk estimate. How does a regulator use a performance based analysis with a high uncertainty in the risk estimate? As just one example PRAs used in fire safety often have a defined safety level where the conditions become "untenable". In the model, as long as the tenability threshold is not violated the path is considered tenable. But just how good is the threshold assumption? Is it supported by overwhelming technical evidence, or even an informed consensus? The belief that a tenability threshold even exists is the type of public policy decision normally made by a legislature, not a technical consultant. The decision reflects the type of error which the society prefers, i.e. would it prefer to err on the side of precaution or costs savings?

REGULATORY DECISIONS: POLITICAL OR TECHNICAL?

In traditional legislative regulatory activities technological decisions are made as part of the

POLITICAL process, with the acceptance by the political process of the inherent limitations of technological knowledge. The legislature's decision that a given technology will satisfy the social objectives is not expected to be scientifically valid. The technical criteria embodied in the statute are simply the society's best political guess as to how to remedy the problem. **The ability to enact regulatory predictions politically does not mean they are accepted scientifically.** In addition, acceptance of a risk analysis methodology by a regulator in no way "validates" the underlying technological determinations. Gaining the current approval of a regulatory authority should not be confused with having reduced a risk to socially acceptable proportions. Long feedback loops between technical decisions and disasters, fundamental uncertainties in the evaluation of new technology and the inability to completely understand extremely complex systems make regulation a highly inexact process. In carrying out the social decision process the society often gives a regulator the authority to carry out the society's political will. However, even when the regulator has technical training, the regulator is still making fundamentally political decisions. some performance based code proposal attempts to simply define away the legal structure by stating: **The codes permit any solution that meets the performance requirement** Since part of that political decision is to determine how the society will deal with uncertainty, it is simply impossible for the regulator in any complex area to simply set a standard and accept "any technology" which meets the standard. The regulator's role is particularly important if the standard uses a mathematical risk model. Technological and policy issues raise fundamentally different kinds of questions:

> **TECHNICAL** decisions are those which deal with scientific or technological phenomenon that are the subject of well defined scientific or technical decision processes.
>
> **POLICY** decisions are those which involve weighing of competing social, legal, cultural, technical and other judgmental factors in the regulatory process. For the purpose of this paper, political and policy decision making have essentially equivalent meanings.

Traditional regulatory system normally evaluated the technical issues as "facts" and then presented technical conclusions as an input to responsible policy officials. The officials then combined the facts of the matter with the delegation of policy judgement in the statutes to regulate the risk. In traditional regulation, the domain of the technical and the policy decision maker were easily separated. Questions were clearly either technical or policy oriented, and the decision maker could easily sort them out. This regulatory model worked well in environments in which technical disputes were minor and easily understood. But PRAs can contain substantial policy judgments presented as technical statements of fact which reflect the risk analyst's judgement on what are arguably political or policy decisions. Such implicit policy decisions must be decided by political, not technical processes. Such decisions would include:

> 1) **Estimates of probabilities which involve social actions** This would include decisions on a variety of social activities, including the probability of terrorist attacks, and the probability that the regulatory agency will continue to act in the same way in the future.
>
> 2) **Estimates of technological events for which insufficient data exists for definitive technical understanding.** This could include risks such as earthquakes, some human responses to accident conditions and the size and probability of an initial or scenario fire
>
> 3) **Choices among different schools of technical thought** Schools of technical thought can be in direct conflict. Resolving disputes among such schools cannot be done technically, since they do not have a common core of beliefs. For example, there are distinct differences between Bayesian and Non Bayesian analysis of probabilities.
>
> 4) **High uncertainty in any risk term** Engineers are trained to think in terms of machines

and often have a roulette wheel concept of risk. Since mathematical risks are expressed as numbers, they can be manipulated using simple mathematical tools. However, if there is uncertainty in the risk estimate it cannot be reduced by manipulation [7]

Regulatory use of mathematical models

When applying mathematical models in the regulatory environment it is important to remember that most mathematical models were developed for EXPLANATION of accident phenomena, such as discovery of root causes. Regulation tries to use models for PREDICTION of probability of a future accident. However, it is a substantial leap to conclude that because we can analyze failure in existing buildings, that we can therefore predict failure in new buildings. The two activities are simply not the same. [8] Some physical systems are so well defined in terms of cause and effect that we can retrospectively determine the status of the system at some earlier date. Such systems can be defined as DETERMINISTIC. Gravity, for most purposes, is deterministic. This makes explaining the structural stability of a building under gravity relatively easy. The growth of fire in a given room system is generally considered to be deterministic. However, it should be noted that even deterministic systems are not always predictable. The growing understanding of chaotic systems demonstrates limits on our ability to predict even deterministic systems such as the weather.[9]

Most of the models used to describe fire spread are "explanatory", not predictive. When engineers use a model to explain a past fire or to predict a laboratory fire they have eliminated most of the uncertainty which may affect real world fire risk. They can be used to explain how a given fire grows and develops. But that is not the same as predicting where and when a given fire occurs, or how big the initial fire will be. The ability to validate these models as predictive safety models is limited. Even substantial experience with a risky environment may not reduce the uncertainty. The problem is especially acute when analyzing rare events, such as major fires.[10]

Fire risk models are not only mathematical models, they are **probabilistic** models. Engineers with experience working with deterministic models often take the same approach when dealing with probabilistic models. They believe that cause and effect are still real, but occur at statistically calculable rates. For example, some authors suggest that arson rates can just be included in a model.[11] But this understates the complexity of modelling probabilities. Engineers are trained to think in terms of machines and often have a roulette wheel concept of risk. I.e. a risk is a definable probability value with low uncertainty. But risk models in undefined environments often have high uncertainties in the risk estimates. Failure to include these uncertainties may produce artificially narrow estimates of risk, easily manipulated by the analyst. The transition from a deterministic "worst case" model to a probabilistic risk model is probably much more difficult than the movement from prescriptive codes to deterministic fire models. Yet there is a tendency to treat deterministic and probabilistic models as effectively equivalent.[12] This may be a serious mistake. Risk rates are subject to much more dispute than deterministic events, and the social approval of risk based PBCs may be much harder to obtain.

As just one example, the NFPA task group report proposed that a performance based sprinkler system only has to "perform" by meeting its "fire safety goals" when challenged by defined "fire scenarios". There is no claim that the dwelling provides a defined level of life safety in all typical ignitions. The scenarios are not described as "worst cases" nor are they claimed to represent the most common or the most hazardous fires. **This scenario concept conflicts directly with the definition of performance based code as proposed by Richardson.** Under Richardson's proposal the society tells engineers how safe to make the buildings, and the engineer designs the building to that level of safety. Under the NFPA task group proposal, the engineers claim only that the system will function if the system was confronted with one of the specified "fire scenarios". This clearly reduces the engineer's uncertainty, but only by increasing the uncertainty of the regulator. How does the regulator know if the chosen fire scenarios are the appropriate tests for the building? Ultimately the fire scenario is simply the technical distillation of a political choice, i.e. how safe do we want the building to be? The ultimate problem with any scenario based standard is the typical problem found in any fire test environment; designing to the test rather than designing to the problem. If the designer knows the test scenario, it is trivial to make a design that will pass.

In particular, establishing the socially acceptable levels of risk often requires determining the "cause" of fires. Society may be willing to accept certain irreducible risks, but not accept the reducible risks. But accidents are the product of a complex web of events, many of which can be described as a "cause" of the accident. Perception of a specific cause may be a function of the fact that a specific accident actually occurred.[13] Analysts cannot simply assemble the root causes and extrapolate them into a predictive model, especially if they have to meet legal standards of causation. From a scientific point of view causation is a difficult element to prove, but correlation is a very useful substitutes. Many risk models do not clearly identify the standards for used for inferring causality from correlative models. Most probabilistic fire risk models use events which not proven to be causally related. The issue of causation is critical because regulators expect to be able to alter a "causative" event and have a real effect on the ultimate rate of injury. If the data element is merely correlated with the risk, regulators may be led to incorrect conclusions.

IMPACT ON REGULATION: ESTIMATING UNPREDICTABILITY

It may be possible to approximate the unpredictability of the system by defining some of the mathematical factors which impact the predictive power of mathematical risk models. These factors include:

F1: If the system is probabilistic in nature and occurrence of events is rare the model will be poorly predictive. If the occurrence of events is frequent the model may be highly predictive.

F2: If the system is deterministic and linear, its behavior in a domain is predictable from its behavior in neighboring domains. If its behavior is either highly non-linear or chaotic, small changes in basic components' characteristics may have extremely large impacts and the behavior becomes difficult to predict.

F3: If the system behavior depends on a small number of system components which interact loosely together or their interaction is known or knowable system behavior can be predicted from component behavior. If system behavior depends on a large number of subsystem components or interactions between components are unknown prediction will not be possible.

F4: If component characteristics are stable prediction is easier. If components evolve dynamically prediction is more difficult.

F5: If data is unbiased prediction is more reliable. If data is biased prediction becomes more difficult.

F6: If the amount of data available is adequate for the model, prediction will be more accurate. If the data is inadequate the prediction will be unreliable.

Each factor may be considered as varying on a scale. For each factor, at the extremities of this scale, there will be outcomes which are totally predictable or totally unpredictable. More importantly the factors are independent and their effects on the level of unpredictability are additive. Hence P, the level of unpredictability is a monotonically increasing function $P(F1=f1,....F6=f6)$ of parameters

Fi, where f_i stands for the value of factor F_i. Each factor may have a separate impact on P, i.e. the strength of the impact may differ from factor to factor.

To use P in regulation it is necessary to define the "unpredictability level" mathematically. For this purpose, let X be a risk variable which must be assessed. Assume that a probability distribution for X exists and that [X] is the average value predicted for X while $[U_p]$ is the predicted uncertainty on X. Historical review can indicate observed values of X. The observed uncertainty $[U_o]$ can be computed from this historical data. [14] We define $p = [U_o]/[X]$ as the real level of unpredictability of the model or level of unpredictability *a posteriori*. Note that $p^* = [U_p]/[X]$ is the level of unpredictability *a priori* and p may be very different from p*. The whole problem is now to determine p from the factors (F,,....F 6) of the system studied.

Given the assumptions on the six factors, the simplest expression of P that one may consider is:

$$P(F_1 = f_1, \ldots F_6 = f_6) = \Sigma\, w_i(f_i)[f_i - f_{i\,0}]$$

where $w_i(f_i)$ represents the respective strength of each factor and $f_{i\,0}$ is the value of factor F, at the origin. The strength for the different factors are obtained either by historical studies or by expert opinion assessment.

Accepting the principle that technical and policy components of the decision making process need to be strictly separated, the level of unpredictability provides a screening criteria for deciding on the domain (technical or policy) which makes initial decisions on matters relevant to a specific system or part of a system. Indeed a threshold of unpredictability P_{lim} could be defined such that a value of P inferior or equal to P_{lim}, leads to assignment of the decision to the technical domain and P superior to P leads to assignment to the political domain.

CRADLE TO GRAVE REGULATION

One of the major uncertainties in predicting the safety of a structure in the future is the change in the environment, scientific knowledge, social acceptance of risk and other dynamic factors. According to one proposal for performance based codes, after fire safety "goals" are established, the designer is to "evaluate the condition of the occupants, building contents, process equipment or facility in question in regard to fire safety". Since this evaluation is part of the design process the condition of the occupants and the contents would presumably be specified for the entire duration of the occupancy. What happens when the factors change?

When society is faced with the necessity of accepting new technological risks, it usually demands a level and duration of integrated regulation much greater than that traditionally found in building construction. Buildings have traditionally been considered static hazards, so a "fire and forget" type of regulation was normally used. Once a building had been built in compliance with the code, it stayed in compliance unless there was a change in occupancy or use. Fire codes normally required maintenance of the features required in a new building. Occasionally a retrospective code would be passed, requiring upgrades, but there was no concept that changes in technological knowledge or outside circumstances could put a building out of compliance. But this static regulation is an artifact of history, not necessarily the most reasonable approach, especially when performance based codes are presented as actually providing a socially defined level of safety.

Performance based regulation has developed in technologies which are under effective unified "Cradle to grave" regulation, such as aircraft, automobiles and ships. Professional licensing, operating permits, public safety responses, and insurance based compensation systems are all used to help control what risks the society will take and under what conditions. Regulatory approval under these performance codes typically involves regular evaluation and corrective action to keep the object meeting the current performance requirements. If performance codes include such variables as fire load, fire department response, arson rates or characteristics of inhabitants, periodic recalculation will be needed to determine whether risks fall within acceptable limits. More importantly, what happens if the assumptions are incorrect. In such a case, the first task will be to deal with other buildings which used the same design philosophy. In a normal performance code environment other structures built to the same assumptions are pulled out of service until the risk is brought up to acceptable levels.

Introducing sophisticated regulatory approaches will require remedying the low level of education and training of the fire safety regulatory community, particularly in the United States. Fire safety regulation in the United States is a disjointed activity. In many cities there is little or no communication between building and fire safety regulators. Fire safety regulators are often untrained and poorly educated. Few are engineers, much less fire protection engineers trained in risk modelling. Who will provide the regulatory structure capable of protecting the public safety? A new kind of regulatory structure will be needed. The regulator will have to integrate the regulation of construction and use of buildings over their lifetime. The agency will have to monitor the changes in risk. The system will have to require effective insurance coverage and authority will be needed to make changes in the operations of the building.

PERFORMANCE BASED REGULATION IN THE EUROPEAN ENVIRONMENT

Within the European Union a key factor driving interest in performance based evaluation is the need to establish the "equivalence" of building design proposals to the traditional requirements of the national fire code, especially in two particular situations:

First the proposal involves innovative design and construction concepts or is a refurbishment project. Additional fire safety measures are normally provided to compensate where strict compliance with the code is not possible. The implicit aim of this approach is to achieve an equivalent level of safety to that specified. In practice, due to the absence of agreed criteria and as appropriate framework for the assessment of equivalence proposals are accepted or rejected on an ad hoc basis [15]. In Belgium the equivalent safety' of buildings which do not strictly comply is considered by a special panel which includes the fire safety inspectorate representative. The panel's recommendation go to the Mayor of the district (the Authority having jurisdiction). In most other countries, by contrast, interpretations of equivalence are made at the local level by technical or professional staff within building control departments or the fire service. In these cases there is usually a right of appeal to a nationally based committee.

Second, products/components specified are from other countries. This situation is of particular interest within the European Union as the removal of technical barriers to trade has been one of the primary aims of code harmonization. The European Commission's approach to this problem has been based on a test-classification-regulation view of regulatory systems. [16][17] However the impact of this work on the functioning of the regulatory systems in different countries is unclear and it is probable that variations will continue to occur in the determination of equivalence for new and imported products.[18][19]

The UK is often described as having a performance based code although it is more appropriate to say that the regulatory system has some of the key elements of such a code. In Scotland Fire safety is covered under regulations 12 and 13 of the Building Standards (Scotland) Regulations 1990, These set the performance goals for structural fire precautions, means of escape and fire fighting facilities. The performance requirements are set out in the Technical Standards to the Regulations. The Technical Standards are not a statutory document but provide the only means of demonstrating

compliance with the regulations and therefore have statutory effect. Any design proposal is acceptable if it complies with the requirements specified in the Technical Standards. The framework of the Regulations and their associated standards thus might be considered a performance based code. However the Regulations do not provide clear quantitative statement of requirement.
At the Enforcement level problems of non-compliance with specifications have important implications for buildings. Quality control failures are much more significant when dealing with complex systems. Lack of resources even for current tasks is a problem. There are major commercial developments that lack Fire Certificates 5 years after being in operation with a Completion Certificate from Building Control. It is not clear that the apparatus exits for enforcing an effective "cradle to grave" regulatory system.

CONCLUSION

Mathematical risk models have a number of inherent limitations:

1) Predictive uncertainty increases as the system becomes more complex.

2) In complex systems, retrospective analysis may not be able to give us adequate information as to the range of potential disaster paths.

3) Safety factors and other engineering tools for coping with risk have limited value in an environment in which the disaster path is not well understood.

The regulatory use of mathematical risk models depends on satisfying certain criteria:

1) The legal requirements for the risk assessment must be expressly defined.

2) Detailed analysis of the sources of uncertainty in the risk assessment must be presented.

3) There must be a clear distinction between political and technical components in model development

4) The nature and quality of causative analysis must be expressly defined in the risk assessment.

5) The regulatory system must have the capability of correcting errors in the risk analysis process for the life of the structure.

Fire safety regulation is a very complex task, with a difficult combination of poorly defined problems, overburdened regulatory agencies, conflicting social agendas, rare catastrophic events and continuously developing technological hazards. Mathematical risk modelling has the potential to make significant contributions to fire safety, if it is not oversold, misused, or treated as a technical panacea for frustration with complex social decision processes.

ACKNOWLEDGEMENT

This work was supported by the Building and Fire Research Laboratory, NIST. The opinions are those of the authors.

REFERENCES

1. Richardson J.K. Ed **Selected Readings in Performance-Based Fire Safety Engineering** Society of Fire Protection Engineers, Boston MA (1995)

2. Stellfox, David **Jackson to stay the course on thermo-lag; but resolution still way off** Inside N.R.C. 11/27/1995 17:24

3. Cooke R. **Experts in Uncertainty: Opinion and Subjective Probability in Science,** Environmental Ethics and Science Policy Series, Oxford U. Press, New York, 1991

4. NFPA In House Task Group **NFPA's Future in Performance Based Codes and Standards** 1995

5. Brannigan VM, Bier VM, Berg C **Risk, statistical inference, and the law of evidence: the use of epidemiological data in toxic tort cases** *J. Risk Anal* 1992 Sep; 12 (3): 343-51

6. Brannigan V., Meeks C, **Computerized Fire Risk Assessment Models: A Regulatory Effectiveness Analysis** *J. of Fire Sciences* 13: 177-196 1995

7. Friedman R. **An International Survey of Computer Models for Fire and Smoke,** *J. Fire Protection Engr* 4 (3) 1992 81-92

8. Lehner PE, Brannigan VM **Computational Domain Models and Regulatory Decision Making** Proc.: Int. Conf. on Fire Research & Engineering, Lund DP, Angell EA eds. 1995

9. Casti J.L. **Searching for Certainty: What Scientists can Know about the Future** William Morrow & Co. New York 1990

10. Clark FB, Bukowski RW, Stiefel SW, Hall JR, Steele SA 1990 **The National Fire Risk Assessment Research Project** (5 volumes) National Fire Protection Research Foundation

11. Bukowski, RW **Fire codes for global practice** Progressive Architecture June; 1995 76:6

12. Beck VR 1991 **Fire Safety System Design using Risk Assessment Models: Developments in Australia** Proc. of the Third International Symposium on Fire Safety Science 1991 45-59

13. Mosleh A. and Bier V. **On Decomposition and Aggregation Error in Estimation: Some Basic principles and Examples,** *J. of Risk Analysis* Vol 12:2,203-214 1992

14. Shlyakhter AI, **Statistics of Past Errors as a Source of Safety Factors for Current Models** Prc. Advanced Topics in Risk and Reliability Analysis: Model Uncertainty its Characterization and Quantification NUREG/CP 0138 pp.209-224 Mosleh A., Siu N., Smidts C., Lui C, Eds. 1994

15. CIB W14, **Fire Safety in Buildings: Needs and Criteria.** CIB Publication 48, 1977

16. Malhotra, **The EEC Proposals for achieving common standards of structural fire protection** Fire, vol. 90. Part 392. pp25-3; (1988)

17. Malhotra : **Towards European Standards in the Manufacture of Construction Products by 1992 and beyond**- Fire Prevention, Part 215. pp 18-19 (1988)

18. Twilt & Witteveen, **Trends in Fire Safety Design** Heron (1987). Vol, 32, pp 95-114.

19. Blachcre, **Report on a Comparative Study on Reaction-to-Fire Tests in the EC: Seminar on Fires in Buildings,** pp 252-260.(1988)