DEALING WITH UNCERTAINTY TO IMPROVE REGULATION

Kathy A. Notarianni, P.E.
Research Fire Protection Engineer
National Institute of Standards and Technology
Gaithersburg, MD 20899

And

Dr. Paul S. Fischbeck,
Associate Professor,
Department of Engineering and Public Policy
Department of Social and Decision Sciences
Carnegie Mellon University
Pittsburgh, PA 15213-3890

ABSTRACT

It is the thesis of this paper that current efforts in fire-safety design comprise a necessary set of actions to enable the shift from prescriptive codes to performance codes, but not a sufficient set of actions to provide for the sound implementation of a performance-based system. Such a system needs to provide all stakeholders a known level of confidence in the final design and to ensure the life-cycle safety of a building. This paper discusses five related issues: 1) barriers to sound implementation and rapid deployment of performance-based standards, 2) the role for uncertainty in improving performance-based regulations, 3) difficulties with uncertainty analyses associated with performance-based evaluation, 4) a taxonomy of use in identifying uncertainties; and 5) a methodology for dealing with these uncertainties.

CURRENT FOCUS

Current efforts focus on 1) developing objective-based, fire- and building-code language, 2) providing professional and public education, 3) validating engineering methods, and 4) conducting research. These efforts mirror important strategies for change identified by participants of the 1991 conference on fire-safety design in the 21st century.[i] These efforts are necessary and will lead to the development of the structure needed for implementation of a performance-based code system. However, even with these pieces in place, a known level of certainty in the final design cannot be guaranteed or documented.

Current strategies in the area of validation and utility of engineering methods focus on third-party involvement. A recommendation of the 1991 conference was that a highly respected and trusted group of engineers and scientists should be organized to scrutinize new methods closely and document their limitations and legitimate applications. These efforts partially address liability and professional use/misuse. However, simply documenting limitations and applications of the methods is just a subset of what is needed. No matter how carefully the chemistry and physics of a fire model are documented, *results* from the fire model still provide only point values of critical outcome criteria upon which decisions regarding fire protection are to be based. Performance-based calculations involve: 1) predictions of future human behavior, 2) inherent uncertainty in the input parameters, and 3) assumptions about individual and societal risk perceptions and values. This makes it difficult for the stakeholders to agree on the validity and utility of a particular fire-protection design.

Firesafety Design in the 21st Century, Second (2nd) Conference. Pre-Conference Papers. Proceedings. Worcester Polytechnic Institute. June 9-11, 1999, Worcester, MA, 121-133 pp, 1999.

BARRIERS TO SOUND IMPLEMENTATION

Performance-based regulations, which specify the results, not the means of regulatory compliance, have the potential to reduce costs, open global markets, and encourage innovation. Fire-protection design, however, is not an obvious venue for this type of regulation. Performance-based regulations work well when the calculation methods are well established, involve little human element, and the results (i.e., actual performance) can be evaluated and verified. Direct measurement of the fire-safety performance of a building or building system is not usually possible; therefore, the technical predictive ability of scientific tools, such as existing fire models, must be relied upon. The numerous uncertainties inherent in the application of these fire-safety design tools often go unrecognized or ignored. It is, therefore, difficult to provide an explicit statement of the benefits, risks, and costs associated with a design.

In order for modern fire-safety design methods to be integrated into routine day-to-day regulatory and design practice, more than "getting all the pieces in place" has to be done. To facilitate widespread usage of performance-based standards, we, the fire-safety community, must do more than review engineering methods and document their limitations. We must develop and implement methods for the *application of* our engineering tools so that they provide all stakeholders with: 1) a shared understanding of benefits, risks, and costs, 2) a known level of confidence in the final design, and 3) an accurate estimation of the life-cycle safety of the building. And, in order to accelerate this process, research must be conducted with priorities established by justifiable importance and/or value-of-information calculations. This process requires a thorough investigation of the link between engineering and policy.

Analysis of the Design Process

The Society of Fire Protection Engineers (SFPE) Engineering Guide to Performance-Based Fire-Protection Analysis and Design details nine steps in the successful performance-based design process.[ii] These are: 1) define project scope; 2) identify goals; 3) define objectives; 4) develop performance criteria; 5) develop fire scenarios and design fires; 6) develop candidate designs; 7) evaluate candidate designs; 8) select final design; and 9) prepare design documents. Other sources may list one fewer or additional steps, but the general process is the same. The stated intent of the guide is to "provide guidance that can be used by both design engineers and approving authorities as means to determine and document achievement of agreed upon levels of fire safety for a particular project."

A through review and analysis of the performance-based design process for fire-safety engineering outlined in the SFPE guide along with a review of several case studies of performance-based, fire-safety engineering designs for actual buildings was conducted. These designs were presented at an international conference on performance-based design in May 1998.[iii] Our review uncovered seven major barriers to determining and documenting achievement of agreed upon levels of fire safety for a particular project using the currently suggested methodology:

1) Performance criteria are not established or agreed upon.
2) The design-fire selection process is unspecified.
3) Assumptions are made about human behaviors in fire.
4) Predictive fire models have limitations that are not well documented or widely understood.
5) Outputs of fire models are point values that do not directly incorporate uncertainty.
6) The design process often requires engineers to work beyond their areas of expertise.
7) No standardized methods exist to incorporate reliability of systems.

The significance of these barriers are demonstrated in the following section.

The Problem of Switchover

Variations in analysis parameters, assumptions, or model inputs, will cause output criteria to change. "Switchover" occurs when outcome criteria change enough so as to cause a change in the design decision, (e.g., the acceptability of a final design). It is critical to know if different sets of reasonable inputs, scenarios, or parameters cause switchover and lead to different final outcomes. Sensitivity of a design to modest variability and uncertainty must be understood.

For example, there is uncertainty (e.g., legitimate disagreements) in the *selection off performance criteria*. In fact, performance criteria have not been established or agreed upon by the fire-safety community, and current policy allows the stakeholders themselves to select the criteria to be used for each design. Discussions occur around such questions as: Is the set of performance criteria sufficient? What do the numerical values actually represent? Should different criteria be used for a sick, elderly or handicapped person?

At one recent international conference, two engineers presented their performance-based case studies conducted for real clients on actual buildings. They had each followed the current design guidelines; however, they had selected very different performance criteria.[iv,v] Differences existed on three levels: 1) parameters included in the set of performance criteria, 2) numerical values selected as the critical or cut-off values, and 3) the presence or absence of a time element. The two sets of criteria are shown in Table 1 below. Since predictions of fire models are compared to selected performance/life-safety criteria in order to determine if a design is acceptable, variations in criteria can cause the same design to pass or fail. Equity issues arise directly (e.g., the act of selecting the set of performance criteria inherently reflects societal values and goals). We believe that performance-based codes would enjoy more rapid adoption and usage if performance criteria were agreed upon.

Another step in the design process that presents a barrier to determining and documenting the achievement of agreed upon levels of fire safety for a particular project is the *selection of a design fires and associated fire scenarios*. Design fires are defined fire challenges (e.g., a grease fire on the stove, a smoldering cigarette fire on the sofa). The design-fire description may be limited to a specific fire growth rate, heat-release rate, and decay duration, or may be much more complicated. Along with design fires, several fire scenarios, or descriptions of possible fire events that could occur are developed. For each design fire evaluated, the goal is to provide a fire-safety design that would mitigate any unwanted fire scenarios from developing. Fire scenarios typically include: form of ignition; different items first ignited; different rooms of a building; whether doors are open or closed; whether and at what time window breakage occurs; and all potential forms of intervention by occupants, sprinklers and the fire brigade. Given a design fire (e.g., a wood and polyurethane foam-sofa fire), there are many possible fire scenarios. Each one could result in dramatically different conditions in the room. Two examples would be:

1. A cigarette ignites the sofa, smolders for several minutes, and eventually leads to flaming ignition of the sofa. Smoke detectors and residential sprinklers are installed and fully operational. Occupants are awake. Doors to the room are open.

2. A pet knocks over candle that ignites the sofa. Open flaming of the sofa occurs rapidly. Automatic sprinklers are not installed and the battery has been removed from the smoke detector. Occupants are asleep and intoxicated. Doors to the room are closed, but one window is open. Radiant heat from the fire ignites other objects in the room. The fire grows large enough to cause the room to flashover.

	Case Study One	Case Study Two
Temperature	150°C, upper smoke layer 2 min	93°C 1.6m above floor/ 260°C max. ceiling
Radiant Heat Flux	2.5 kW/m^2	-------------*
Carbon Monoxide	0.2%, 5 min	0.15 % volume
Carbon Dioxide	5%	-------------*
Reduction in Oxygen	10%	-------------*
Visibility	0.5/OD/m	-------------*

* These criteria were not considered.

Table 1. Differences in Performance Criteria

Since it is impossible to evaluate building systems performance in response to all fire scenarios that might occur, how can one have confidence that the design fires and resulting fire scenarios chosen adequately represent the range of fires that might occur in the building? Usually a designer will try to select "worst-case" scenarios. However, it is not always intuitive which scenarios present a worst-case situation or how likely (or unlikely) a particular scenario is. Should we be designing for the 1-in-a-million fire? Actual case studies, presented at the 2nd International Conference for Performance-based Design, used only *one* fire scenario to evaluate the design. We believe that agreed upon methods for selecting and/or determining the adequacies of the design-fire set are needed.

During several critical steps in the design process, *assumptions are made about human behaviors in fire*. For example, the egress models used by fire-protection engineers to calculate the time required for safely evacuating a building (or part of a building) make many assumptions about how humans behave. Two of the stated assumptions built into one of the internationally used egress models are 1) 100% of the occupants are readily mobile and 2) occupants begin leaving the building immediately.[vi]

Other behavior assumptions are not explicitly stated but can be inferred from an analysis of model outputs. For example, results from a recently published study of a performance calculation using the egress model in CFAST reveal that simplistic and unrealistic assumptions were made about human behavior during fires (see Table 2).[iv] Note that at the lower occupant level, a decrease in the number of exits by 1/3 increase the egress time by exactly 1/3. This suggests an implicit assumption that an equal number of people egress through each available exit. More typically, actual human behavior will be to exit following the path one normally uses to enter and exit the building. Existing egress calculations and models need to be evaluated so that unrecognized and/or unstated uncertainties resulting from assumptions regarding human behavior can be identified. Once found, the implications of these assumptions need to be explored quantitatively.

Fire models and other calculation methodologies are often inappropriately used to develop and evaluate trial designs for buildings and/or scenarios outside of the models predictive capabilities. This occurs because *limitations of fire models are not well documented or widely understood.* Because many existing fire-model and calculation methodologies were originally developed as research tools, model conditions, defined by Brannigan as "fundamental requirements for the model's validity,"[vii] are often unknown or unstated. Estimates provided by a model are technically credible only when model conditions have not been violated. Even when the model is used within its intended limitations, *fire-model outputs are point values* that do not reflect inherent input uncertainties (e.g., fire growth rates, initial conditions).

Number of Exits Available	Number of Occupants	Time to Clear Floor(s)
6	300	67
4	300	100
6	650	150
4	650	220

Table 2. Egress Calculations

Problems can also occur when *fire-protection engineers are required to work in domains outside their expertise* (e.g., selecting performance criteria or modeling human behavior). "Conservative" assumptions made by well-intentioned engineers may not be as conservative as intended. In an example from a recent conference, a design engineer intending to be "conservative" assumed that tenability would be violated when any one of five criteria exceeded its minimum value. However, toxicity experts could argue that gas interactions could easily cause tenability to be violated even when all of the species are in "acceptable" ranges. At the same conference, the time to react to an alarm for a high-rise apartment resident was "conservatively" set to the travel time needed to go from one remote corner of the unit to the other most remote corner of the same unit. However, this may not be that conservative since the occupant may stop to gather belongings, rescue a pet, call a neighbor, etc.

The last barrier identified is the *uncertainty surrounding both the reliability of a given fire-protection device/system/or characteristic and the lack of a standardized method to incorporate reliability* into performance-based engineering calculations and decisions based-upon these calculations.

These seven barriers to determining and documenting achievement of agreed upon levels of fire safety for a particular project must be addressed fully in order for all stakeholders to have a known level of confidence in the science-based predictions and the resulting final design. All seven barriers involve various types of uncertainty. Thus, there is a well-defined and strong role for uncertainty analysis in performance-based calculations.

THE ROLE OF UNCERTAINTY

Beyond being just another step in the process of getting a building approved, properly determining and documenting a level of confidence in the design will have numerous benefits. It will facilitate cooperation among stakeholders by increasing the overall understanding of risks and costs. Displays of distributions of outcomes are richer and more valuable descriptions of what is likely to occur than point-value answers. Though stakeholders and/or policy decisions must still determine how much "risk" is acceptable, with thorough uncertainty analyses, this decision will be informed and free of the uneasiness that typically surrounds acceptance of a deterministic performance calculation.

The use of fire models in performance-based designs requires the treatment of uncertainty in both the model physics and input values. Currently, none of the widely used fire models address uncertainty and many of the stakeholders who use these models do not have experience interpreting uncertain outputs. Even if all the model uncertainties were accounted for, many other uncertainties inherent in the design process would need to be addressed.

Showing that an innovative design can reduce costs and maintain an appropriate level of public safety requires that uncertainty be treated directly. This will assist engineers and architects during the design process, and code officials during the evaluation phase by increasing confidence in safety performance calculations. Researchers who are prioritizing enhancements to the physics and structure of the fire models and policy makers who are drafting new regulations and standards will also benefit from this design approach.

Although there is a clear role for uncertainty in improving the development and implementation of performance-based fire safety regulations, uncertainty analysis is clearly an uncomfortable topic for many of the stakeholders in the process.

DIFFICULTIES WITH UNCERTAINTY ANALYSES

The importance of making good decisions under conditions of uncertainty is clearly understood outside of fire-safety design. In the recently released National Science Policy Study, "Unlocking Our Future: Toward A National Science Policy,"[viii] it is stated that: "decision makers must recognize that uncertainty is a fundamental aspect of the scientific process." However, discussion of the proper treatment of uncertainty in the performance-based design process is difficult for several reasons:

- *The magnitude of the problem is not clearly understood.* It is widely assumed that a mixture of "conservative assumptions" and "factors of safety" can be used to "cover for" uncertainties. However, factors of safety that are applied at various stages of the analysis are not necessarily linearly related to the critical output parameters, resulting in a reduced (or no) factor of safety in the results.
- *There are many types of uncertainties that go unrecognized or ignored.* These include uncertainties in variables "hard-wired" in the scientific tools, uncertainties in tenability/performance criteria, uncertainties surrounding the selection of design fires, and uncertainties in human behaviors and values.
- *Fear of the effect on implementation of performance regulation.* There is a fear that identification and treatment of uncertainty in its full would destroy or delay implementation of the entire performance process by demonstrating how little can be predicted precisely.
- *No quantitative methodology exists for treating uncertainty in performance-based designs.* A methodology is needed that is both rigorous and user-friendly.
- *Impracticality.* Fear that the mathematical rigor needed to conduct such an analysis would render such an analysis impracticable.

It should be pointed out that these are real and valid concerns due to the combination of poorly defined and unstructured problems, and the lack of a user-friendly methodology. Current common practice for doing "uncertainty" analyses involves completing a series of single-variable sensitivity studies. Application of these techniques to a complete performance-based design containing hundreds of uncertainties of various kinds is an impractical task.

The authors have been studying this problem and the following two sections present one approach for solving these problems. Because many types of uncertainties currently go unrecognized or ignored, an uncertainty taxonomy is presented as an aid in understanding and investigating the types of uncertainties found at each step in the design process. The taxonomy covers a wide range of uncertainties; however, application of the methodology does not require the quantification of all uncertainties in the analysis. Some of the uncertainties are handled by the methodology that follows, while others are best handled through policy decisions. However, most of the uncertainties will typically prove to have negligible impact on the output criteria, and from a decision perspective, do not have to be modeled.

A TAXONOMY OF UNCERTAINTIES

Custer and Meacham were among the first to identify various types of uncertainties encountered in a performance-based design[ix]. The purpose of this taxonomy is to develop a framework for understanding, identifying, and investigating these and other types of uncertainties *as a function of the steps in the performance-based design process*. The five major categories of uncertainties discussed are: 1) scientific uncertainties, 2) uncertainties in human behavior, 3) uncertainties in risk perceptions, attitudes, and values, 4) uncertainties related to life-cycle use and safety of the building, and 5) uncertainties related to providing for equity in the design and acceptance process[1]. In the following section, these categories are discussed in detail, including the definition of significant subcategories for each uncertainty.

Scientific Uncertainties

Scientific uncertainties are due to both lack of knowledge (e.g., in the underlying physics, chemistry, fluid mechanics and/or heat transfer of the fire process) and from necessary approximations required for operational practicality of a model or calculation. Of the many types of uncertainty found in performance-based fire-safety design calculations, scientific uncertainties are typically the most easily recognizable and quantifiable. The many types of scientific uncertainty can be roughly divided into five sub-categories: 1) theory and model uncertainties; 2) data and input uncertainties; 3) calculation limitations; 4) level of detail of the model; and 5) representativeness of the design-fire scenarios.

Theory and model uncertainties arise when physical processes are not modeled adequately due to lack of knowledge of how to include them, processes are modeled based on empirically derived correlations, and/or simplifying assumptions are made. These types of uncertainties are present in most compartment fire models, where each of these factors lead to uncertainties in the results. Most compartment fire models are zone models, which make the simplifying assumption that each room can be divided into two volumes or layers, each of which is assumed to be internally uniform. Current zone models do not contain a pyrolysis model to predict fire growth forcing the model user to account for any interactions between the fire and the pyrolysis rate. Many compartment fire models also use an empirical correlation to determine the amount of mass moved between the layers.

Data and input uncertainties arise from both lack of knowledge of specific input values and variations in input values as a function of many factors such as time, temperature, or region of the country. For example, the rate of heat release of a three cushion upholstered sofa may be uncertain due to lack of available data for sofas with the same dimensions, stuffing, and cover materials. It may be also be uncertain because the test method by which the heat release rate was measured could not specify all combinations of ignition source and strength, and because there

---

[1] Portions of the taxonomy were submitted to the Performance-Based Analysis and Design Task Group of the Society of Fire Protection Engineers and appear in the draft for public comment of "The SFPE Engineering Guide to Performance-Based Fire Protection Analysis and Design," December 1998. Input was received from members of the Uncertainty Subcommittee.

are inaccuracies inherent in the instrumentation used in the test (e.g., the mass loss scale and/or the gas analyzers). Other inputs such as concentrations of toxic gases produced vary with time as the fire develops and are uncertain.

For most fire models and calculation procedures, very different answers can result depending on the *calculation limitations*, control volume selected for modeling, the *level of detail* of the model, and the model-domain parameters specified. Model-domain parameters set the scope of the system being modeled and define the model's level of detail and/or base line properties. Though these parameters or quantities are often ignored during uncertainty analysis, they have the potential for considerable impact.[x] Likewise, in most fire models, very different answers will result based on the control volume selected and the level of detail of the model. This has been shown for fires in high bay spaces. Differences in the outcome criteria such as maximum temperature, and time to activation of fire detectors and sprinklers are found when a large space is modeled with a simple zone fire model vs. a more detailed computational fluid dynamics model.[xi] Differences in the outcome criteria are also found when a large space, which is typically sub-divided by draft curtains,[2] is modeled. If a control volume is drawn around a single draft curtained area, (as opposed to drawing the control volume around multiple draft-curtained areas or around the entire building) higher temperatures and faster activation times of installed fire-protection devices will be predicted. Also, significant to the uncertainty in the outcome parameters are the index variables of the model. Index variables are used to identify a location in the domain of a model or to make calculations specific to a population, geographic region, etc.

Uncertainty arises in both the *number and type of design fire scenarios* that need to be modeled for a given design/building. There may be significant differences between reality and the design fire scenarios, which were used to judge the adequacy of the performance-based design. How do variations in the ignition source, rate of growth, and/or the materials burned effect confidence in the results? Should all statistically significant fire scenarios be modeled? Are worst-case scenarios adequate? How does one assure a worst-case scenario? Worst in terms of which variables, death?

Uncertainties and Variability in Human Behavior

Human behavioral uncertainties concern the way in which people act in a fire and also how these actions should be considered during steps in the design process (e.g., definition of project goals, selection of performance criteria, and development and evaluation of trial designs). Behavioral scientists tell us that human actions can range from somewhat predictable to totally unpredictable. Actions are more predictable when 1) choices are limited, 2) procedures are practiced, 3) the situation is not novel, and 4) little chaos is present[xii] Unfortunately, during a typical fire, few if any of these conditions occur. Uncertainties in human behavior can be divided into five sub-categories: 1) response to a fire alarm; 2) behavior during egress; 3) defining goals and objectives; 4) developing performance criteria; and 5) evaluating fire scenarios.

Human behavior in *response to a fire alarm* must be modeled in terms of time to respond to the alarm and type of response. Does the person immediately begin evacuating the building? Does he/she take the stairs or the elevator? What factors into that choice? Does the person try to fight the fire? Does the person stop to gather personal possessions or call a neighbor? Another area of human behavior relevant to performance-based calculations is *behavior during egress*. Does he/she stay low and crawl if necessary to stay below the smoke layer? Does he/she remain calm or does panic increase the breathing rate and thus the intake rate of smoke and products of

[2] A draft curtain is a barrier that extends a certain vertical distance down from the roof. Draft curtains are installed to sub-divide a large area with the intent of corralling the smoke.

combustion? Human factors also effect the analysis needed for *identifying goals and objectives and developing performance criteria*. Fire-safety goals typically include levels of protection for people, with performance criteria being a further refinement of these objectives. Performance criteria are numerical values to which the expected performance of the trial designs can be compared. What range of occupant characteristics such as age and handicaps should be considered? How do human behaviors such as behavior during egress influence the numerical values chosen for performance criteria?

A fifth area where human behaviors affects the calculations is *developing and evaluating fire scenarios*. When developing and evaluating trial designs, the efficacy of the proposed fire-safety measures mitigating all likely fire scenarios should be determined. This involves varying human behavioral elements. For instance, two very different fire scenarios could develop from the same cooking-initiated design fire: 1) a grease fire from cooking sets off a smoke detector which alerts the occupant who reacts and properly extinguishes the fire while it is still small; or 2) the occupant forgets and leaves a pot simmering on a burner, takes a sleeping aid and goes to bed. The overheated pot ignites and the fire spreads to one or more adjacent items.

Uncertainties and Variability in Risk Perceptions and Values

There is both *variability and uncertainty in the way people perceive and value risk*. Capturing the differences that people have in their perceptions of risk and values related to risk is a necessary step in the design process. Research has shown that though people typically view consequences from voluntary risks less severely than equal consequences resulting from an unknown and/or involuntary risk, there is variability[xiii]. For example, while some people would agree that an increase in risk to fire fighters (people who accept risk as part of their job) is justifiable if a corresponding decrease in risk to the public could be achieved, others would not. Few studies have been conducted that clearly demonstrate how society values risks related to fire safety at the level needed to support performance-based trade-offs. It is important to identify where value judgements enter into a performance-based calculation and to make any assumptions explicit regarding values and the impact of different values on the final design.

Another important factor is the concept of *equivalency*. Equivalency can mean different things to different stakeholders. Is the design equivalent in terms of life safety, property protection, business interruption, injuries, and/or prevention of structural collapse? What assumptions, uncertainties, and/or reliabilities is equivalency dependent upon? For example, is a four-hour rated assembly equivalent to a sprinkler system if they are shown to both provide for time to fully egress the building? Or, does the reduction in reliability of the sprinkler system over the four-hour rated assembly prevent them from being truly equivalent?

Uncertainties Related to the Life-Cycle Use and Safety of the Buildings

Many factors change over the lifetime of a building. The uncertainties surrounding future use, occupancy, and other factors contribute to the difficulty in conducting a structured performance-based design. Even daily fluctuations in these design parameters can affect the safety of a building. For example, a building or area of a building that is normally occupied 24-hours/day may become unoccupied (or occupied by very different people) for extended periods of time due to extraneous factors (e.g., business closing, maintenance, renovation). The characteristics of the different occupants can lead to very different design considerations. Other changes that may affect the life-cycle safety of the building are fire-service characteristics such as location, expected response time, and operating procedures and capabilities.

Uncertainties Related to Providing for Equity and Incorporation of Societal Values

This involves determining what is important to the stakeholders and to what degree protection should be provided. Since in most projects there are many stakeholders such as the building owner, design engineer, architect, code official and the public (users of the building), it is difficult to assign worth in the usefulness or importance of something and apply it both to individual and societal issues. The key here is that decisions that change if a value, attitude, or risk perception varies must be made explicit in the design. Agreement on these key decisions by all stakeholders is critical to the success of a performance-based design.

As we have demonstrated, these categories of uncertainty appear throughout the steps of the design process (e.g., scientific uncertainties play a role in developing performance criteria, selecting fire scenarios and design fires, determining and evaluating trial designs, and choosing final designs). Table 3 shows how these major categories can map onto the specific steps of the performance-based design process described in the SFPE guide. Though we do not include the detail, the sub-categories described above apply to design-process stages. For example, *theory and model* uncertainties and *model level of detail* should be considered at Steps 6-8, assuring that the physics and chemistry of the model and the resolution of the model enable discernment among various trial designs.

	Types of Inherent Uncertainties				
Steps in Design Process	*Equity/ Societal Values*	*Human Behavior*	*Scientific*	*Individual Risk Perception*	*Life-Cycle Safety of Building*
1. Define Project Scope	X				X
2. Identify Goals	X	X			X
3. Define Objectives		X	X		
4. Develop Performance Criteria	X	X	X		X
5. Develop Fire Scenarios and Design Fires	X	X	X		X
6. Develop Trial Designs	X		X	X	
7. Evaluate Trial Designs		X	X		X
8. Select Final Designs	X		X		X
9. Prepare Design Documents					X

Table 3. Types of Inherent Uncertainties as a Function of the Steps in the Performance-Based Design Process[3]

[3] This table is designed to provide an overview of the relationship between the major types of uncertainty and the steps of the design process that they effect. The authors do not propose that it is a complete representation of all possible interactions, but that it captures the major interactions.

A METHODOLOGY FOR DEALING WITH UNCERTAINTY

This section presents a methodology that quantitatively treats variability and uncertainty and discusses how it could be applied to a complex fire-protection engineering design. The method is well documented in the decision-analysis literature. It does not require the quantification of all uncertainties in an analysis. A five-step approach is used to identify those variables with the potential to reverse the final decision. Only uncertainty of these critical variables is then modeled and employed in the analysis. Results are displayed graphically as either discrete or continuous joint probability distributions. The methodology also provides guidance for handling value judgements. We have used this methodology in a cost-benefit study of regulations mandating residential sprinklers[xiv] and are currently applying it in expanded form to a case study of a performance-based design of a residential high-rise building.

A Five-Phase Approach

Performance-based design assessment requires understanding and evaluating very uncertain, large, complex, and highly non-linear problems. Only a structured approach will provide the rigor necessary for successfully completing the assessment. In this section, a general methodology for performing these complex engineering analyses is outlined. It consists of five phases and is shown in Figure 1.[xv] The approach incorporates techniques for quantifying and propagating identified uncertainty throughout the engineering analysis. The basic steps are described below.

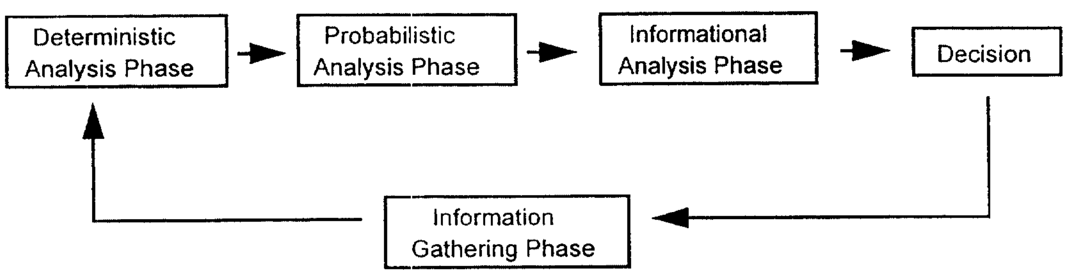

Figure 1. The Decision Analysis Cycle taken from Carl-Axel S. Stael von Holstein[xvi]

In the deterministic phase, the structure of the decision problem is initially captured in a model where variable uncertainty is initially ignored. To identify the crucial variables, i.e., those with uncertainty great enough to reverse the final decision, a systematic sensitivity analysis is used. Based on the results of the sensitivity analysis, variables are either: 1) set at base (most likely) values, 2) eliminated, or 3) earmarked for treatment of uncertainty in the probabilistic phase.

In the probabilistic phase, uncertainty is explicitly modeled. Detailed encoding of the crucial variables is completed and the selection of outcome criteria that reflect value judgments of the decision-makers (or society) and captures their risk preferences is formalized. Given this complete model, the best action is selected, and probabilistic sensitivity analyses are completed. In the third or informational phase, the value of acquiring additional information is assessed. What is the value of reducing uncertainty of the important variables in the problem?

In the decision phase, the choice between acting (i.e., accepting the design) or gathering more information is made. If the value of getting new information is significant (e.g., collecting more statistics, conducting larger surveys, developing/refining engineering models, undertaking additional research), then the design decision is delayed. If new information is valuable, then it is collected and the process cycles. If additional information would not affect the decision or it is too costly to acquire, then the final acceptability of the design is determined and the process ended.

Application to Case Study

This methodology is currently being applied to a performance-based design problem for an actual building to demonstrate the treatment of variability and uncertainty in a relevant and sophisticated engineering calculation. An uncertainty analysis of the case study is under way using Monte-Carlo analyses and the CFAST model. Over 450 input values have been identified and categorized. Of these, just under 200 have potentially significant uncertainty. Software has been developed to generate plausible input sets of these variables for the CFAST model. Correlations between the input variables have been modeled.

Multiple CFAST runs are currently being conducted to determine the relative importance of the input variables. Using regression and rank-order correlation analyses, we will be able to determine which input distributions are causing uncertainty in the important output criteria. This short list of variables can then be used in future design studies. A separate egress model is being developed and evaluated.

Using this approach, we will be able to lower (or remove) the seven barriers to performance-based standards that we introduced at the beginning of this paper and should be able to answer a wide range of questions including: 1) What is the effect of setting differing performance criteria? How many and what types of fires are adequate for a design? How can we best model human behaviors and their associated uncertainties? What are the areas in out current fire models that most need work?

CONCLUSIONS

Beyond being just another step in the process of getting a building approved, properly determining and documenting a level of confidence in the design will have numerous benefits. It will facilitate cooperation among stakeholders by increasing the overall understanding of risks and costs. Distributions of outcomes are a much richer description of what is possible than the typical point-value answers. Though stakeholders and/or policy decisions must still determine how much "risk" to accept, with thorough uncertainty analyses, this decision will be informed and free of the uneasiness that typically surrounds acceptance of a deterministic performance calculation.

REFERENCES

[i] Strategies for Shaping the Future: A Report on the Conference on Firesafety Design in the 21st Century, May 8-10, 1991, Worcester Polytechnic Institute, Worcester, MA.
[ii] The SFPE Engineering Guide to Performance-Based Fire Protection Analysis and Design: Draft for Comments, December, 1998, Society of Fire Protection Engineers, Bethesda, MD.
[iii] Proceedings. Pacific Rim Conference and Second International Conference on Performance-Based Codes and Fire Safety Design Methods, May 3-9, 1998, Maui, Hawaii.
[iv] Sullivan, Paul, Existing Building Performance-Based Firesafety Design, In Proceedings. Pacific Rim Conference and Second International Conference on Performance-Based Codes and Fire Safety Design Methods, May 3-9, 1998, Maui, Hawaii.
[v] Stroup, David S., Using Performance-Based Design Techniques to Evaluate Fire Safety in Two Government Buildings, In Proceedings. Pacific Rim Conference and Second International Conference on Performance-Based Codes and Fire Safety Design Methods, May 3-9, 1998, Maui, Hawaii.
[vi] Portier, Rebecca, W., Peacock, Richard D., and Reneke, Paul A., FASTLite: Engineering Tools for Estimating Fire Growth and Smoke Transport, Special Publication 899, National Institute of Standards and Technology, Gaithersburg, MD.
[vii] Brannigan, Vincent, and Smidths, Carol, Performance Based Fire Safety Regulation Under Intentional Uncertainty, University of Maryland, 1998.
[viii] Unlocking Our Future: Toward A New National Science Policy, A Report to Congress by the House Committee on Science, September 24, 1998.
[ix] Custer, L.P. and Meacham, B.J., Introduction to Performance-Based Fire Safety, Society of Fire Protection Engineers and National Fire Protection Association, Quincy, MA, 1997.
[x] Morgan, Granger M. and Henrion, Max, Uncertainty: A Guide to Dealing With Uncertainty in Quantitative Risk and Policy Analysis, Cambridge University Press, Cambridge, N.Y., 1998.
[xi] Notarianni, Kathy A., Comparison of Computer Fire Models to Fire Experiments in a High-Bay Aircraft Hangar, NISTIR 5304, December, 1993.
[xii] Need a Baruch reference
[xiii] Starr, Chauncey, Social Benefit vs. Technological Risk,
[xiv] Notarianni, Kathy A., and Fischbeck, Paul S., A Methodology for the Quantitative Treatment of Variability and Uncertainty in Performance-Based Engineering Analysis and/or Decision Analysis with a Case Study in Residential Fire Sprinklers, In Proceedings. Pacific Rim Conference and Second International Conference on Performance-Based Codes and Fire Safety Design Methods, May 3-9, 1998, Maui, Hawaii
[xv] Howard, R.A., Decision Analysis: Applied Decision Theory., In D.B. Hertz and J. Melese (Eds.) Proceedings of the Fourth International Conference on Operations Research., New York: Wiley, 1966.
[xvi] Stael Von Holstein, "A Tutorial in Decision Analysis", in Readings on The Principles and Applications of Decision Analysis, edited by Howard, R.A. and Matheson, J.E., Strategic Decisions Group, Stanford University, 1983.