A RESEARCH AGENDA FOR THE NEXT GENERATION OF PERFORMANCE-BASED DESIGN TOOLS

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ABSTRACT

Performance-based design (PBD) is practiced in many parts of the world today, and our current tools and level of understanding are adequate to support certain classes of fire safety designs; however, other significant applications exist that exceed the capabilities of these tools. Representatives from the FORUM* and invited technical experts attended a workshop to develop a vision for the next generation of performance-based design tools. Five areas were identified at the top of the list of research priorities to support this vision:

- improvement of our ability to predict the impact of active fire protection systems on fire growth and fate of combustion products;
- estimation of uncertainty and the means to incorporate it into hazard and risk analyses;
- the relationship between aspects of the building design and the safety of building occupants;
- the impact of material and geometry changes on fire growth and the fate of combustion products;
- the prediction of the response of a structure to full building burn-out.

A summary of the workshop that led to these research priorities are contained in this paper.†

BACKGROUND

Fire codes and standards are developed and regulations implemented in most countries with the objective of protecting societies and reducing their losses from fire. For the majority of traditional buildings with low hazard occupancies, modern prescriptive building and fire codes, when enforced, achieve this objective. Nontraditional buildings include many of societies most important and iconic structures, such as opera houses, museums, sports stadiums, transportation centers, super-high-rise structures, and government buildings. Prescriptive codes cannot anticipate all of the requirements that these nontraditional structures impose; prescriptive codes do not adapt rapidly to changing materials and methods of construction, nor to radical architectural designs; and prescriptive codes based upon historical loss experiences are not designed to deal with very low probability, very high impact events or ill-defined threats such as from terrorism.

Regulating the design, construction, and operation of buildings on the basis of performance is viewed as a means to overcome many of the shortcomings of prescriptive codes for nontraditional structures, as well as for more traditional buildings on unusual sites, or for an existing building undergoing

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* The International Forum of Fire Research Directors (FORUM) was formed in 1991 with a goal to reduce the burden of fire (including the loss of life and property, and effects of fire on the environment and heritage) through international cooperation on fire research.

† This paper is an assimilation of the contributions from workshop participants, with some of the text coming directly from the following contributors to reference 1: N. Smithies (BRE); I. Hagiwara (BRI); P. Croce (FM Global); C. Beyler (Hughes Associates, Inc.); J. Averill, R. Bukowski, R. Gann, J. Gross, A. Hamins, K. McGrattan, and W. Pitts (NIST); N. Bénichou, G. Proulx, and J. R. Thomas (NRC-C); M. Hurley (SFPE); B. Sundstrom (SP); M. Janssens (SwRI); J. Hyslop (U.S. NRC); and J. Hietaniemi (VTT).

renovation or a change of occupancy. Performance-based codes provide much greater flexibility and promote innovation in building design, materials, products and fire protection systems; however, the success of a performance-based code hinges on the establishment of critical solution-enabling tools, a profession properly educated to implement these innovations, and code officials capable of evaluating the safety of the performance-based design (PBD).

Performance-based fire safety design already exists and is practiced in many parts of the world today, and current tools and our level of understanding are adequate to support certain classes of PBD; however, there are many PBD applications that exceed the capabilities of these tools. Due to this limitation, PBD in some countries remains a boutique approach to fire safety design, and will remain in that status until a more solid scientific foundation is established. In other countries where PBD is applied more broadly, the risk exists for it to be used primarily to reduce costs or to allow exceptions to prescriptive guidelines without the scientific basis for assuring fire safety.

Research is needed to close gaps in data and knowledge for supporting the next generation of performance-based codes. Members of the FORUM and other invited technical experts gathered at the National Institute of Standards and Technology (NIST) in Gaithersburg on April 5-7, 2006, to develop a common, international vision for how a scientific foundation might be structured, which parts of the foundation are likely to be robust and where gaps are likely to exist into the foreseeable future. The prioritization of performance-based-design-driven research areas took place at the annual meeting of the FORUM in Wellington, New Zealand in October, 2006; the process used and justification for these priorities are more fully documented in the Proceedings of the workshop.[1]

Previous Workshops

Numerous workshops have been held in the United States that relate to performance-based design. The General Services Administration (GSA) held an international conference[2] in 1971 on fire safety in high-rise buildings. While the phrase "performance-based design" was not coined at that conference, much of what was discussed revolved around the concept of PBD. In 1991, Worcester Polytechnic Institute (WPI) convened a meeting[3] to develop strategies for shaping the future for fire-safety design. The following common national goal was agreed upon by the attendees: "by the year 2000 the first generation of an entirely new concept in performance-based building codes be made available to engineers, architects and authorities having jurisdiction...in a credible and useful form."[3] Five strategic thrusts were identified to help the nation achieve this goal: form centers of excellence, develop new code concepts, provide functional engineering tools acceptable to multiple stakeholders, document the validity of these engineering tools, and strengthen programs that educate the design professional and inform the public and political leaders.

The Society of Fire Protection Engineering (SFPE), in 2000, focused on the needs of the fire protection engineering profession to develop a research agenda[4] to gain innovation that could be implemented to reduce direct and indirect fire related costs, improve life safety, improve international competitiveness and facilitate regulatory reform.

The United Engineering Conference[5] held in January of 2001 had the objective of assessing the level of our understanding, at that time, of fire science and engineering in support of regulation, and to identify if and where research efforts and educational activities were required. Areas to focus research to meet the conference objectives included fire phenomena and modeling, human factors research, and risk assessment research. Key roadblocks to implementation were cited as privatization and commercialization of national laboratories, a need for development of new fire test methods that supply data on product performance that is translatable to "real world" scenarios; and a lack of adequately qualified graduates to satisfy the demand from designers, building code authorities and industry.

The National Science Foundation (NSF) followed up the United Engineering Conference by sponsoring a National Research Council study to determine the research path necessary to make the nation safe from fire.[6] Two high level recommendations resulted from the study: (1) that NSF should reestablish a program in basic fire research and interdisciplinary fire studies, and (2) that a coordinated national attack should be launched to increase fire research and improve fire safety practices.

Following the events of 9/11, a marked change occurred in the concerns of the government, building and fire code development organizations, the fire protection and construction professions, and the general public. The spotlight on fire safety had brightened immensely and been shifted to structural fire resistance. NIST sponsored a workshop[7] in 2002 to identify the general areas of research needed to determine the fire resistance of structures and predict their performance in the field. A second workshop was held focusing on the specific problem of protecting structural steel high-rise buildings from fire.[8]

The SFPE, with NIST sponsorship, held a workshop in Baltimore in October, 2003, to develop a national R&D roadmap for structural fire safety design and retrofit of structures.[9] Recommended areas to focus research were laboratory and real performance data, and methodologies and tools for implementation in codes and standards. Concerns were raised regarding the implementation of some of the recommendations; namely, that structural fire safety is only part of the overall provision of fire safety, that the appropriate means to identify relevant fire scenarios have not been established, that there are practical limits to advancing risk-informed decision making, and that code officials need guidance (now) as to standards by which engineering solutions can be evaluated.

Performance Objectives

The 2006 FORUM workshop participants were briefed on the objectives of performance-based building and fire codes and regulations that exist around the world today. The use of PBD in North America was reviewed by Bukowski; Hurley focused on the goals outlined in the current U.S. model codes; Hagiwara discussed the Japanese system; and Hietaniemi and Smithies provided status reports on the European and United Kingdom situations, respectively. Sundström provided his perspective on the general trends occurring in ISO TC 92 (International Organization of Standards Technical Committee 92 on Fire Safety) as they related to the workshop objectives. Their comments are summarized in the proceedings of the workshop.[1]

According to Croce,[1] performance-based regulations have taken hold with the resulting PBD using a life safety criterion (i.e., ensuring time for safe evacuation) as the primary objective. However, PBDs, in Croce's opinion, are not yet consistent and reliable, and confusion and uncertainty exists among regulators.

Croce listed the following possible fire safety design outcomes:
- life safety
- safety for room-of-origin occupants
- safety for building occupants
- safety for general public
- public security
- protection for building of origin
- protection for neighboring structures
- protection for historical buildings
- protection for firefighters
- protection for first responders
- protection for infrastructure
- facility operability

If life safety were the primary design goal, this would ensure safety for the room-of-origin occupants and safety for the other building occupants; the nine remaining desired outcomes would not necessarily be achieved. Alternatively, with a design goal of ensuring public well-being, the focus for design outcomes would shift to protection for building of origin and protection for infrastructure. Protection for the building of origin would lead to the desired outcomes of life safety, safety for all building occupants, safety for the general public, protection for neighboring structures, protection for historical buildings, and protection for firefighters and first responders. Protection for infrastructure ensures protection for building stock, livelihood supplies, communications, utilities, transportation systems, and electronics and computer systems. Protection for infrastructure also ensures facility operability. In other words, using the broader criteria of ensuring public well-being, life safety is achieved, fire service and other responders are protected, there is less overall damage and disruption, there is better public safety and security, and the economy is maintained with a faster and less costly recovery. This approach can be more expensive up front, but less so over time, and the public well-being is better served.

SCIENTIFIC FOUNDATIONAL BUILDING BLOCKS

The appropriate goal for fire research, in general, as suggested by Croce,[1] is to develop scientifically-based methods, models and tools that are well understood, accurate and easy to use for performance-based design work and for worldwide product and material testing leading to a fire-safe built environment. The impact of fire research can be seen in:

- performance-based regulation for life safety,
- new standardized tests,
- increasing computer model applications,
- more measured data characterizing fire behavior, and
- more fire laboratories around the world.

While these impacts do represent real progress, it can be argued that these should be replaced by the following parallel set of metrics:

- reliable performance-based designs for regulation,
- reliable assessments of products and materials for global end-use applications,
- reliable end-use models for application,
- reliable material property data for end-use models, and
- more relevant fire research for public well-being.

The widespread acceptance of performance-based standards, codes and regulations will occur only where the authorities having jurisdiction (AHJ) and other stakeholders achieve a threshold level of confidence in PBD methods. This confidence relies on the state of a designer's understanding of material behavior, fire dynamics, building dynamics, human dynamics, and analytical/computational tools, and the designer's success in conveying that level of understanding to the stake-holders. Experts at the workshop in each of these key disciplines reviewed our current state of understanding.

Material Behavior

For discussion purposes, Gann[1] divided our level of understanding of material behavior into two major categories: understanding of materials that are homogeneous and well-behaved (e.g., solid PMMA, or a sheet of nylon), and understanding of the fire behavior of finished products that contain multiple materials and irregular geometry (e.g., upholstered furniture or sandwich panels). He then enumerated the different phenomena that influence the overall behavior of materials in a fire: smoldering ignition, transition from smoldering to flaming, flaming ignition, flame spread, mass burning rate, CO formation, other toxic gas formation, and smoke formation.

Gann posed three questions for the workshop participants regarding the class of materials that are well-behaved and homogeneous:

- Are the basic physical and chemical processes that control the different phenomena mentioned above understood?
- Are there standard methods to measure these different phenomena?

- Do models, which have been validated rigorously, exist to predict these measurements?

The workshop participants were asked to answer each question either "yes, now," "yes, partly," or "no." Based upon the response of the group, one can say that as a category, our capability to understand, measure, and model flaming ignition and mass burning rate appear to be solid. At the other extreme, transition to flaming and the production of toxic gases show up as phenomena that are not well understood, measurable through standard methods, or well modeled. Validation models for CO and smoke were also considered lacking.

The same exercise was conducted with the above questions applied to finished products, supplemented with the opinion of the participants as to the readiness of our standard measurement methods and models for designing fire safety on a performance basis. It was not surprising to see the answers shift much more toward the "insufficiently understood" end of things because of the greater complexity of finished products vis a vis homogeneous materials. As with the homogeneous materials, the mass burning rate and flaming ignition were felt to be better understood than the other phenomena, and with a more acceptable standard measurement method. No one considered the models of fire behavior of finished products to be fully validated; however the group did feel that current models and standard measurement methods were "good enough" for performance-based design when applied to flaming ignition and mass burning rate.

Human Dynamics

The state of understanding human dynamics was reviewed by Proulx,[1] who began her presentation by restating the research priorities identified in the January, 2001, workshop in San Diego.[5] There were five recommendations related to human dynamics from that workshop:

- Develop an overarching human behavior model to guide the application of human behavior concepts and to identify processes for considering human behavior.
- Develop a cue-response sequencing model which is occupancy dependent and in which response is a function of information conveyed.
- Identify human behavior "scenarios."
- Understand toxic generation, transport and tenability.
- Find data on occupant characteristics and frequency of behavior, quantify delay in response, and develop methods to reduce evacuation time.

Proulx listed additional guides and symposium proceedings dealing with human behavior in fire which have been published more recently and are included as references [10,11 ,12,,13,14] in this paper.

Buildings designed on a performance basis must consider evacuation and fire safety management plans. Given a particular building design, one must specify the occupant groups to be considered and several fire scenarios for each evacuation analysis. The critical calculation is a comparison of the available safe evacuation time (ASET) to the required safe evacuation time (RSET). In addition it is necessary to estimate the harm done to people by the range of fires that can occur in the building for the design proposed. Estimates of uncertainty are required for each step along the way. Assuming that detection and alarm time are functions of the installed automatic systems and not human behavior, the human element enters the RSET equation during the recognition and response phases, which make up the pre-movement time. How much time is needed for awakening to the alarm, fire cues, or warning from others? Time is required to evaluate and investigate the threat. Fire fighting may be involved before the occupant decides to evacuate. Group dynamics come into play, including the milling process, affiliation with family members, and warning others inside and outside of the building. Some may need to get dressed and gather belongings. Others may wait for instructions, or devote time to way-finding.

Evacuation time is the sum of the pre-movement and the movement times. There are different ways to estimate pre-movement time, including distributions based upon the literature, best judgment, or assuming that pre-movement time is double the movement time.[15] There are also multiple approaches for estimating movement time, ranging from hand calculations described in the SFPE Handbook[12,13] to computer evacuation models. Lack of sufficient verification and validation is a huge issue with the application of these models to PBD. Examples of attributes that are poorly captured in these models include deference behavior, merging behavior of groups, and queues; counter-flow and turning back; route choice and familiarity; interruption and rest periods; movement of occupants with limited mobility; and the impact of fire conditions and smoke on movement.

To improve the credibility of the evacuation calculation it is essential to capture the relevant characteristics of the emergency situation, of the building, and of the building occupants. Relevant emergency characteristics include the location of the fire, the extent of the fire or seriousness of the threat, the time of the event, and identification of systems that are likely to fail. NFPA 101[16] suggests that the analysis be done for eight different locations/extents of the fire.

Research continues into the waking effectiveness of smoke alarms, high-rise building evacuation, evacuation with photo-luminescent materials, tunnel evacuation, and evacuation by elevator. Proulx emphasized a need for the means to convey the information gathered in these and other studies, and a need for theories and models to organize our findings and guide our future efforts.

Analytical/Computational Tools

Hamins[1] moderated a session on the role of analytical and computational tools in fire research. He proposed a conceptual model to more clearly visualize the interactions of fire dynamics with building dynamics and human dynamics. This is shown if Figure 1. A community of specialists (human behavior, fire, building safety, risk, standards), providing a variety of perspectives, is needed to fully anticipate possible roles for these analytical/computational tools. To this end, individual experts spoke on different aspects of the triangle, on ways to deal with risk, and on the difficult process of integrating and extracting useful information from these computational tools.

McGrattan[1] spoke of computational fluid dynamics (CFD) and zone models, indicating that both types had an important role to play in PBD. Referencing the review conducted by Olenick and Carpenter,[17] McGrattan listed four commercial general purpose codes, five fire-specific engineering codes, and eight research or special purpose codes. An even larger number of zone models were listed for reference, but were not characterized.

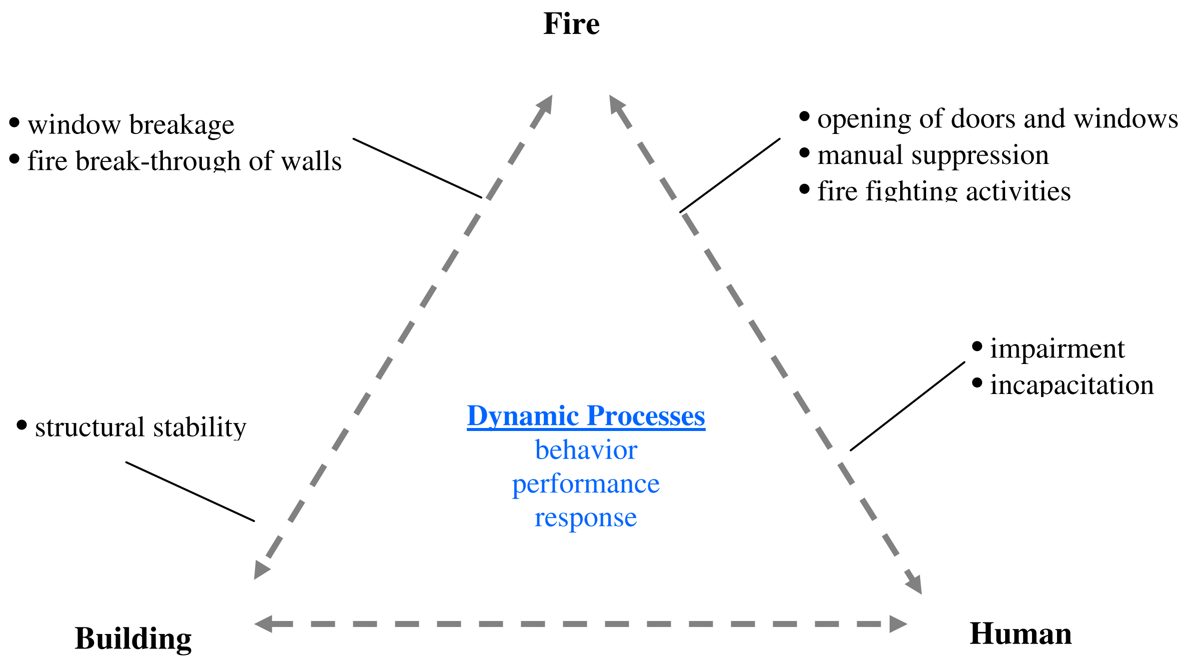

Figure 1. Conceptual view of interaction of dynamic processes

Before stating what the fire research community needs to enhance our capabilities for PBD, McGrattan opined what we do <u>not</u> need:

- Continued development of Zone Models, except obvious <u>global</u> phenomena
- Inclusion in current CFD fire models of
  - turbulent boundary layers
  - detailed flamelets/kinetics
  - high-order turbulence closure schemes
  - continued development of RANS
- Massively parallel computing
- High-order numerical schemes

What we <u>do</u> need for improved PBD of building fire safety include the following:

- Zone and CFD models
  - computer code maintenance, documentation, transparency, usability
- CFD models
  - continued validation beyond specified fires in big boxes
  - tractable characterization of solid/liquid fuels
  - simple interfacing with structural models
  - prediction of major carbon carriers – CO_2, CO, soot, unburned hydrocarbons
  - simple multi-step reaction mechanisms
  - parallel computing on small office clusters

Current research is moving the capability of computational tools forward in several areas including the development by NIST of an FDS algorithm for multi-step combustion, an improved solid phase and charring model being developed by VTT, and implementing improved parallel processing in FDS and visualization with Smokeview software at NIST. Satisfactory validation is critical to obtaining acceptance of computational tools by the AHJ, and experimental validation of FDS and other computational tools is being conducted at multiple locations in the U.S., including Sandia National Laboratories, the Nuclear Regulatory Commission, NIST and SFPE.

Gross[1] discussed the objectives and current tools available for conducting a structural analysis of a building weakened by a fire or other hazard (including an earthquake, high wind loads, or a blast). Figure 2 is a conceptual model of the loss in global reserve capacity in the structure as a consequence of the ongoing hazard event. Initially, at time 0, the structure has an estimated global reserve capacity [RC(t=0)] as a result of conforming to the building regulations in force in that jurisdiction. The sudden drop in RC after time = 0 is associated with an event such as an earthquake or blast that damages or weakens one or more load-bearing structural element (e.g., a column or beam). The dark band around RC represents the accumulated uncertainty in the estimation of reserve capacity as the event progresses. (If the hazard were a conventional fire, the reserve capacity would decrease in a continuous fashion rather than following a discontinuity.) The RC continues to decrease, with abrupt decreases representing a local failure of a structural element or sub-system. Eventually, if the fire is severe enough or the structure is particularly susceptible to the given fire, the reserve capacity goes to zero and global collapse ensues.

Structural analysis computational tools are available to help quantify the ordinate and abscissa in Figure 2. Commercially available general purpose commercial codes can be very powerful, full-featured, and have extensive pre- and post-processing options. They may support parallel processing. Many types of elements and material constitutive relationships are normally included in these tools, and they also allow user-defined elements. Coupled thermal and structural analyses can be handled either sequentially or integrally with one far-reaching caveat: the descritization must be the same for both the thermal and mechanical analyses. Because the length and time scales for thermal and mechanical responses often differ by more than an order-of-magnitude, a common descritization will normally yield more elements and time steps than can be dealt with for a global analysis.

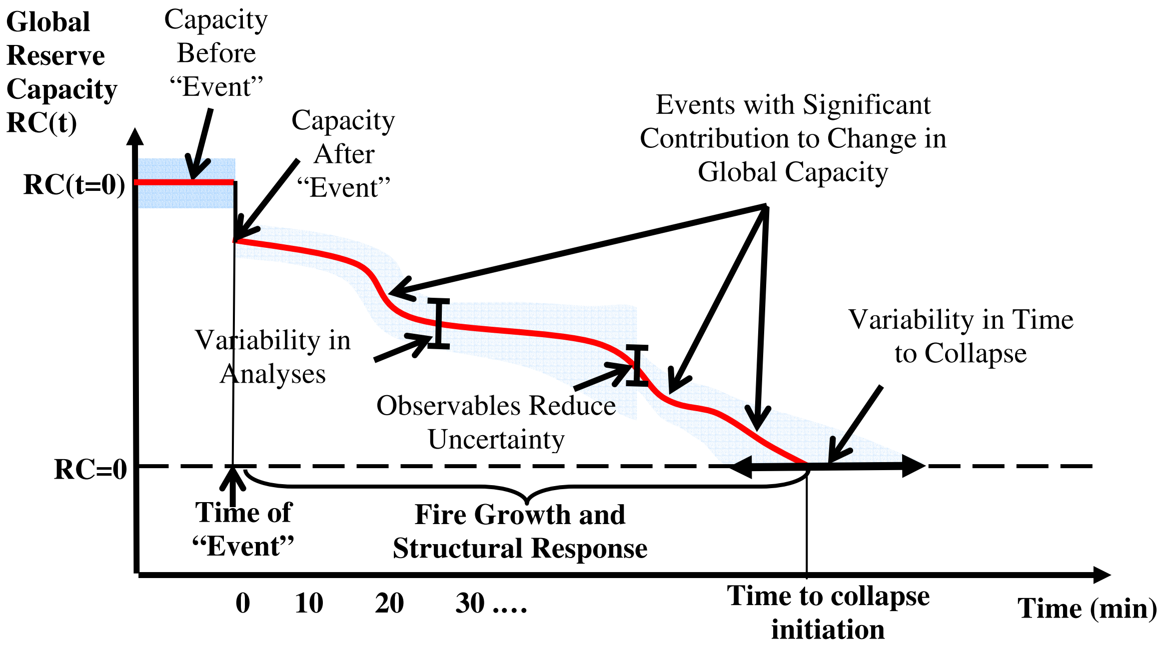

Figure 2. Variability in sequential analyses due to imperfect information

Gross[1] presented the following list of issues associated with structural analysis computations which need research:

- Efficient data transfer and results feedback
- Size of problem – simplifications necessary to make solution tractable
- Stability/convergence/conditioning is challenging for very large structural systems
- Lack of measure of "reserve capacity"
- Uncertainty not formalized
- Improvements to element/material formulations (e.g., concrete, include spalling)

Averill[1] described our ability for modeling building evacuation in a PBD, which boils down to ensuring the inequality ASET > RSET is true for all appropriate scenarios. Three approaches exist for modeling the movement of the occupants within the building, referred to as movement models, partial behavioral models, and behavioral models. Dozens of these models exist, and their attributes have been reviewed by Kuligowski and Peacock;[18] however, there is an acute shortage of the data needed to develop, validate and apply these models.

Bukowski[1] provided an overview of fire hazard and fire risk assessment in regulations for general applications. To conduct a fire hazard analysis, the design fires must be fully specified, including ventilation paths, fire growth and spread, and occupant load characteristics. Of concern in a hazard analysis are system reliability, the effects of distributed variables that may have been missed, and the exclusion of rare but high consequence events. Early risk models used a brute force approach to cover all bases; current risk models trade physics for speed. A key question remains unanswered: Is the estimated fire risk affected more by the distribution of possible conditions, or by the details of the physical and chemical processes present in the fire?

Bénichou[1] reviewed methods for fire hazard and risk assessments in the built environment, and described related research being conducted at the Institute for Research in Construction, National Research Council of Canada (NRC-C). Because performance-based codes are being introduced around the world to take advantage of their flexibility in cost-effective fire safety designs, there is a need for tools and models to evaluate the performance of fire safety designs and to support PBD, to allow assessment of equivalency in fire safety designs, and to support changes to the prescriptive regulations.

Beyler[1] addressed the question of how to integrate the results of the fire, structural, and human dynamics analyses to facilitate a risk-based approach to building fire safety. The most obvious reason for wanting to do this is that the fire, building, and human processes interact in important ways. Less obvious but equally important is that a fully integrated approach forces the analyst to address these interactions. Automation increases the ability to examine the many scenarios that are significant, and a high level analysis naturally moves us further toward risk-based approaches. Effective integration is fraught with technical problems. The component models must be highly reliable, robust, and self diagnostic. The interfaces between the components must be rigorously and thoughtfully designed. Highly disparate time scales are appropriate for the different models. Some models are event-driven, and others are continuous in time; bridging these two types of models can be difficult.

What is required for successful model integration? Four things according to Beyler:[1] all models must be actively supported and maintained; models should be of comparable levels of sophistication and be suited to the modeling objectives; rigorous definitions of model interactions must be defined up front; and verification and validation (V&V) and configuration controls are essential. Integration via a model federation provides modularity and centralized control, and initial condition definition; however, interface protocols must be precisely defined. The extent and sophistication of integration needs to be defined, as well, to assure both completeness and growth potential.

While achieving the above requirement for integration remains a long term goal, an interim strategy is needed in order to begin exploiting the benefits of PBD. Consider alternate deemed-to-satisfy solutions. Define the performance provided via the prescriptive requirements, and evaluate alternate approaches with equivalent performance. This approach provides multiple fire safety strategies from which the design team can select to achieve building performance requirements in the most cost effective way. Why alternate deemed-to-satisfy solutions? Because there is a lower technical risk and the possibility of major social benefit; e.g., these solutions could be applicable to buildings that could not support PBD, or they could result in much lower per building cost. This approach also provides a rational development path for PBD, which for the foreseeable future, will remain a boutique approach.

In general, model integration has value. However, the integration process requires significant institutional commitment, scientific rigor, discipline, and time. Alternate deemed-to-satisfy solutions provide interim results with significant social value and valuable lessons for developers.

RESEARCH PRIORITIES

One could argue that the common goal set at the 1991 WPI workshop[3] (to make available, in a credible and useful form, the first generation of an entirely new concept in performance-based building codes) has been met. How do we move beyond this goal? With 15 years of research since then, what can we conceive of today that may be *obtainable* in the *next* generation of PBD tools and performance-based codes? Based upon the discussions at the workshop, a list was developed of desirable enhancements to fire protection engineering that could better support PBD. These are shown as the first column in Table 1. Prioritization of these enhancements as they support the needs of PBD was done by the FORUM members present at the 2006 meeting in New Zealand. The priority ranking is indicated in the second column of Table 1.

The highest priority identified was for research

- ***to improve our ability to predict the impact of active fire protection systems on the fire growth and fate of combustion products.***

Four other areas were identified as high and of about equal priority:

- ***to estimate the various contributions to uncertainty and to incorporate them into hazard and risk analyses,***
- ***to determine the relationship between aspects of the building design and the safety of building occupants,***

- ***to determine the impact of material and geometry changes on fire growth and the fate of combustion products, and***
- ***to predict the response of a structure to full building burn-out.***

The commitment by the FORUM members to support research in a given area was consistent, in general, with its priority. Note that a lack a high priority associated the enhanced capability should not be construed as indicating that research in a particular area is unwarranted since the context of the current exercise was limited to advancing performance-based design.

Table 1. Areas for Enhancement of PBD Capabilities and Priorities Set by FORUM Members

Enhanced Capability	Priority
Prediction of reduction in fire growth and products of combustion provided by enhanced fire detection/alarm systems and alternative suppression systems	Highest
Estimation of uncertainty in deterministic predictions and incorporation of uncertainties into reliable probabilistic calculations of hazard and risk	High
Determination of the impact on safety of building occupants of design changes in smoke control systems, compartmentation, and egress systems	High
Prediction of reduction in ignition, fire growth and products of combustion provided by changes in materials and products (including geometry and configuration)	High
Determination of structural response of a building to fires of varying magnitude, including those initiated by intentional acts, and leading to full building burn-out	High
Determination of the potential and impact of fires for damaged or degraded structures	Medium
Determination of the impact of fire on neighboring buildings and physical infrastructure	Medium
Determination of the impact of fire on business interruption	Low
Determination of the level of safety provided by standard fire test methods and legacy prescriptive codes	Low
Determination of the safety/effectiveness of first responders provided by new designs for fire sensing and alarm; delivering information; elevators and stairs; fire suppression techniques; security and multi-hazard situations	Low

Overarching Guidance for PBD-driven Research

<u>Benchmark fire experiments and simulations</u> -- The vast number of fire tests and computer simulations published in the open literature and internal reports should be examined to identify those that have the attributes sufficient to be considered "benchmark." Additional carefully designed experiments are required to allow current fire models to more accurately simulate phenomena and conditions that are insufficiently understood to support PBD. The best scale for the benchmark experiments (intermediate or full-scale levels), the sophistication of the measurements, and the amount of data collected should be carefully thought through so that the results can be used to identify the accuracy and range of conditions over which predictive models are valid.

<u>Data and experimental facilities for unraveling relationships within fire models</u> -- Fire models like FDS and CFAST are used today routinely in PBD. Research is needed to extend their applicability to more challenging situations and to demonstrate their validity and limitations to the fire protection engineering profession and authorities having jurisdiction. New experimental facilities (bench-scale and intermediate scale) and instrumentation may be required in order to establish these relationships and develop reliable sub-grid scale models. A combination of empirical relationship and physics-based sub-models will be required to cover the wide range of building materials, products, geometries, and suppression approaches. The development of combustion models of solid materials for the prediction of CO and soot is particularly challenging, and key to the advancement of fire models.

Charring, deformation, and melting occur when real building materials and products burn, and none of these phenomena are dealt with in other than an *ad hoc* fashion in current fire models. The soot formed as these materials are consumed controls the radiant feedback and thus the heat release rate, and the smoke and CO which escape the flames dictate the tenability of the building away from the flames. To be of any practical use, though, sub-grid models of CO and soot formation must remain tractable when they are imbedded in fire models suitable for PBD.

Through a multi-year international effort, it would be possible to populate a database of fire properties of common building materials and products that are needed as input to computer simulations (as opposed to product classification). Fire properties of interest for relatively homogeneous materials might include density, thermal conductivity, heat capacity, enthalpy of combustion; and heat release rate, mass loss, and major products of combustion as a function of incident heat flux and oxygen based upon bench-scale tests. For generic composite materials and free-standing items, the range of mass loss and heat release rates measured in a furniture calorimeter or ICAL apparatus would be useful, and ultimately the behavior of these products and materials in combination within a standard room could be tabulated. Categories of building materials would include wall- and ceiling-linings, floor coverings, siding, roofing, and timber; products would include, for example, chairs, couches, tables, consumer goods, beds, curtains, wire and cabling.

<u>Data and experimental facilities for unraveling relationships within structural models</u> -- Research in structural analysis as it bears on PBD should be focused on predicting the behavior of structural elements, systems, and frames subjected to uneven and locally intense heating. New test methods for generating property data of building materials (including thermal conductivity, thermal diffusivity, thermal expansion, and time-dependent stress-strain relationships) may be required, and a publicly accessible database of these properties established for temperatures up to 1000 ^{o}C. Models for connection failure and redistribution of loads need to be developed and validated at real scale.

<u>Data and experiments for unraveling relationships within human behavior models</u> Gathering data on human behavior under rigorously controlled conditions is problematic at a minimum, and impossible in most emergency situations. However, there is a critical need to understand how individuals and groups behave in emergency situations, including theoretical models of group behavior and group interactions, the role of fire wardens and the fire service, and the conditions leading to and mitigating crowd-crush. Improved egress analysis models, design methodology, and supporting data should be developed to achieve a target evacuation performance by considering the building and egress system designs and human factors such as occupant size, mobility status, stairwell tenability conditions, visibility, and congestion.

<u>Data and experimental facilities for determining interactions among fire dynamics, structural dynamics, and human behavior</u> -- Innovative approaches are required to establish the coupling between fire and structural dynamics and between fire and human behavior. The first of these interactions will require developing experimental facilities and data on the performance of structural elements, assemblies and frames up to the point of fire-induced failure, where failure includes breaching of partitions, roofs, walls or floors; excessive deflection or broken connections of structural elements; and local collapse. Human behavior is strongly influenced by the fire, but no means exist to gather new quantitative data on the impact of smoke, heat and combustion products on occupant movement and behavior. Non-traditional approaches and international collaborations are essential to increase our understanding in this area. Occupant egress and human behavior are influenced by building geometry; however, the relationship between human behavior and transient events in a building (such as a collapsing floor) close to or remote from occupants is unknown.

<u>Compatible interfacing among fire, structural, human behavior, and risk models, including uncertainty in risk and hazard analysis</u> -- Adequate resources are needed to upgrade the data upon which risk and hazard analyses are conducted, including fuel load surveys, incident reporting, failure and near-failure incidents. PBD requires output from one disciplinary model to be exchanged with other disciplinary models. Because each of these models develops from within a given discipline, and the nature of the

phenomena, the time scales and the length scales are tailored to produce the best solution for that discipline, research is needed to determine and evaluate alternative approaches for interfacing these different models. New risk assessment algorithms are required that account for uncertainty in the input and output of these models. Special techniques are needed for quantifying the hazard associated with a criminal or rare high consequence event, and for incorporating this information into a comprehensive risk analysis.

CONCLUDING REMARK

The goal set at the WPI workshop in 1991 to enable a first generation of new performance-based building codes has been met, but the full potential for PBD to influence building and fire codes, regulations and design procedures remains unexploited. The technical topics described in this paper will guide research investment priorities by the FORUM members to accelerate the anticipated benefits of the next generation of defensible performance-based tools for fire safety design.

REFERENCES

[1] Grosshandler, W. (ed.), "Forum Workshop on Establishing the Scientific Foundation for Performance-Based Fire Codes: Proceedings," NIST SP 1061, NIST, Gaithersburg, MD, Dec. 2006.

[2] Nelson, H. (ed.), "International Conference on Firesafety in High-Rise Buildings," General Services Administration, April 12-16, 1971, Airlie House, Warrenton, VA.

[3] "Strategies for Shaping the Future: A report on the Conference on Firesafety Design in the 21st Century," Worcester Polytechnic Institute, May 1991.

[4] Hurley, M., "A Research Agenda for Fire Protection Engineering," NIST GCR 00-791, NIST, Gaithersburg, MD, June 2000.

[5] Cox, G. (ed.), "The Technical Basis for Performance Based Fire Regulations: A discussion of Capabilities, Needs and Benefits of Fire Safety Engineering," United Engineering Foundation, Inc., Three Park Avenue, 27th Floor, New York, NY, 2001.

[6] "Making the Nation Safe from Fire: A Path Forward in Research," National Research Council of the National Academies, 2003.

[7] Grosshandler, W. (ed.), "Fire Resistance Determination and Performance Prediction Research Needs Workshop: Proceedings," NISTIR 6890, NIST, September 2002.

[8] Goode, M. (ed.),"Fire Protection of Structural Steel in High-rise Buildings," NIST GCR 04-872, NIST, Gaithersburg, MD, July 2004.

[9] Almand, K., Phan, L., McAllister, T., Starnes, M., and Gross, J., "NIST-SFPE Workshop for Development of a National R&D Roadmap for Structural Fire Safety Design and Retrofit of Structures," NISTIR 7133, NIST, Gaithersburg, MD, April 2004.

[10] Conference Proceedings of the 2nd International Symposium on Human Behaviour in Fire, MIT, USA, Interscience Communication Limited, 2001.

[11] Conference Proceedings of the 3rd International Symposium on Human Behaviour in Fire, Belfast, UK, 2004, Interscience Communication Limited.

[12] *SFPE, Engineering Guide on Human Behavior in Fire*, Society of Fire Protection Engineers, Bethesda, MD, June 2003.

[13] *The SFPE Handbook of Fire Protection Engineering, 3rd Edition*, The Society of Fire Protection Engineers, Bethesda, MD, 2002.

[14] ISO, 2005, "Fire Safety Engineering: Evaluation of Behaviour and Movement of People," Document 16738 N19 Rev8, 2005, draft standard developed by committee TC92 /SC4/ WG11.

[15] Pauls, Jake, 1995, "Movement of People", *SFPE Handbook of Fire Protection Engineering, 2nd Edition,* Section 3/Chapter 13, NFPA, SFPE, pp. 3-263-3-285.

[16] Cote, R., and Harrington, G.E., *NFPA 101 Life Safety Code Handbook*, National Fire Protection Association, Inc., Quincy, MA, 2006.

[17] Olenick, S., Carpenter, D., *Journal of Fire Protection Engineering 13*, 87-110, 2003.

[18] Kuligowski, E., and Peacock, R., "Review of Building Evacuation Models," NIST TN 1471, NIST, Gaithersburg, MD, July 2005.