NIST Special Publication 1061

Forum Workshop on Establishing the Scientific Foundation for Performance-Based Fire Codes: Proceedings

William Grosshandler
Editor

International FORUM of Fire Research Directors

National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

NIST Special Publication 1061

Forum Workshop on Establishing the Scientific Foundation for Performance-Based Fire Codes: Proceedings

William Grosshandler
Editor
Building and Fire Research Laboratory

December 2006

U.S. Department of Commerce
Carlos M. Gutierrez, Secretary

Technology Administration
Robert C. Cresanti, Under Secretary for Technology

National Institute of Standards and Technology
William Jeffrey, Director

ABSTRACT

The International Forum of Fire Research Directors (FORUM) is a group of the Directors of fire research organizations throughout the world which aim 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. The desirability of having a roadmap to advance the scientific foundation for performance-based fire safety design (PBD) was agreed upon at the 2005 FORUM meeting in Magdeburg, Germany. Representatives from the FORUM membership 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. It was recognized that performance-based fire safety design already exists and is practiced in many parts of the world today, and that our current tools and level of understanding are adequate to support certain classes of performance-based fire safety design; however, other significant PBD applications were identified that exceed the capabilities of these tools. A vision for the next generation of performance-based design tools was developed that included a wide-range of enhanced capabilities that are documented in this report. Methods for the attainment of this vision were identified that included the establishment of

- a hierarchy of meaningful benchmark fire experiments and simulations;
- tractable combustion models that capture the essence of solid fuels, and with simple multi-step reaction mechanisms for prediction of CO and soot;
- data sets and experimental facilities for unraveling the relationships within and interactions among fire dynamics, structural dynamics, and human behavior;
- efficient interfaces among fire models, structural models, human behavior models, and risk models; and
- data and means to track uncertainty in risk and hazard analysis, and to incorporate rare, high consequence events.

Five areas were identified at the top of the list of research priorities:

- 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; and
- the prediction of the response of a structure to full building burn-out.

In general, the commitment by the FORUM members to support research in a given area was consistent with its priority. A summary of the activities and justification for the vision and research priorities are contained in this report.

ACKNOWLEDGEMENTS

The success of any workshop is dependent upon the hard work of the individual speakers and facilitators, and the efforts of participants motivated toward a common goal. These proceedings are an assimilation of the contributions from the workshop participants, with some of the text coming directly from the presentations of the invited participants from the organizations listed below; additional input from FORUM Members during the review process is acknowledged:

Building Research Association of New Zealand (Greg Baker, Colleen Wade)
Building Research Institute (Ichiro Hagiwara)
CSIRO Manufacturing and Infrastructure (Vince Dowling)
FM Global (Robert Bill, Paul Croce, Lou Gritzo, Franco Tamanini)
Hughes Associates, Inc. (Craig Beyler)
Institut der Feuerwehr (Reinhard Grabski)
ITC-CNR (Giovanni Gallina)
Korea Institute of Construction Technology (Hyun-Joon Shin)
National Institute of Standards and Technology (Jason Averill, Richard Bukowski, Richard Gann, John Gross, Anthony Hamins, Kevin McGrattan, William Pitts)
National Research Council of Canada (Noureddine Bénichou, Guylène Proulx, J. Russell Thomas)
National Research Institute of Fire and Disaster (Yoshiteru Murosaki)
Sandia National Laboratories (Sheldon Tieszen)
Society of Fire Protection Engineering (Morgan Hurley)
Southwest Research Institute (Marc Janssens)
State Key Laboratory of Fire Science (W-C. Fan)
Tianjin Fire Research Institute (Zhaopeng Ni)
U.S. Nuclear Regulatory Commission (J.S. Hyslop)
VTT Technical Research Center of Finland (Jukka Hietaniemi)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS AND ABBREVIATIONS

AD	approved document
AHJ	authority having jurisdiction
ALARP	as low as reasonably practicable
ASET	available safe escape time
BEAP	building emergency action plan
BS	British standard
BSL	Japanese Building Standard Law
CCTV	closed-circuit television
CDF	core damage frequency
CFD	computational fluid dynamics
CIB	International Council for Innovation and Research in Building and Construction
CPD	European Construction Products Directive
CSEARE-Risk	risk assessment computer model
DD	draft document
DTR	draft technical report
EN	European national standard
EPRI	Electric Power Research Institute
FDIS	final draft interim standard
FHA	fire hazard analysis
FIERAsystem	risk assessment computer model
FiRECAM	risk assessment computer model
FORUM	International Forum of Fire Research Directors
FPE	fire protection engineering
FRA	fire risk analysis
FSES	fire safety evaluation system
FSL	Japanese Fire Service Law
GSA	U.S. General Services Administration
h_c	enthalpy of combustion
ICAL	intermediate-scale oxygen-depletion calorimeter
ICC	International Code Council
IMO	International Maritime Organization
IRCC	Interjurisdictional Regulatory Collaboration Committee
ISO	International Organization of Standards
LERF	large early release frequency
MLIT	Japanese Ministry of Land, Infrastructure and Transport
NDP	nationally determined parameters
NFPA	National Fire Protection Association
NIST	National Institute of Standards and Technology
NPP	nuclear power plant
NRC	U.S. Nuclear Regulatory Commission
NRC-C	National Research Council Canada
NSF	U.S. National Science Foundation
PBD	performance-based design
PRA	performance-based risk analysis
RANS	Reynolds-averaged Navier-Stokes
RC	reserve capacity
RSET	required safe escape time
SBI	single-burning item

SC	subcommittee
SFPE	Society of Fire Protection Engineering
TC	technical committee
U.S.	United States
VTT	Technical Research Center of Finland
V&V	verification and validation
WG	working group
WPI	Worcester Polytechnic Institute
y_s	fraction of fuel converted to smoke

CFD software
ALOFT
C-SAFE
CAFÉ
CFX
COCOSYS
FDS
Fire
Fluent
FUEGO
Jasmine
Kameleon
KOBRA
MEFE
PHOENICS
RMFIRE
SmartFire
SOFIE
Solvent
Splash
Star-CD
UNDSAFE
VULCAN

Zone model software
ARGOS
ASET
ASET-B
BRANZFIRE
BRI-2
CALTECH
CCFM.VENTS
CFAST
CFIRE-X
CiFi
COMPBRN-III
COMF2
DACFIR-3
DETACT
DSLAYV
FASTlite
FFM
FIGARO-II
FIRAC
FireMD
FIREWIND
FIRIN
FIRM
FIRST
FMD
G-Jet
HarvardMarkVI
HEMFAST
HYSLAV
IMFE
JET
LAVENT
MAGIC
MRFC
NAT
NBS
NRCC1
NRCC2
OSU
OZone
PALDET
POGAR
RADISM
RFIRES
R-VENT
SFIRE-4
SICOM
SMKFLW
SmokePro
SP
PRINK
WPI-2
WPIFIRE
ZMFE

Finite element software
Abaqus
ANSYS
Nastran
LS-Dyna
SAFIR

Evacuation software
ALLSAFE
ASERI
BGRAF
buildingEXODUS
CRISP
ECM
EESCAPE
EGRESS
EVACNET4
EvacSim
EXIT 89
EXITT
FPETool
Gridflow
Legion
Myriad
PathFinder
PedGo
PEDROUTE
SGEM
Simulex
STEPS
TIMTEX
WAYOUT

PREFACE

What is the problem?

Fires continue to kill more people per capita in the U.S. (by as much as a factor of two) than in many other developed nations.[i] In 2005 there were 3675 deaths and 17 925 injuries attributed to unwanted fires.[ii] The direct property loss due to fire was $10.7 B in 2005[ii] and the total burden of fire on the U.S. economy is estimated to be around $200 B/year.[iii] Elsewhere in the world the statistics are equally grim, with the number of deaths approaching 2 per 100 000 persons in Japan and several European countries, and the direct losses exceeding 0.2 % of GDP in the U.S. and much of Europe.[ii]

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 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 as practiced today 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.

What is the role of the FORUM?

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. The focus of the FORUM is identifying

---

[i] The Geneva Assoc. Newsletter, "World Fire Statistics," No. 22, October 2006, Information Bulletin of the World Fire Statistics Centre, http://www.genevaassociation.org/FIRE%20N°22.pdf.
[ii] Karter, M.J., "Fire Loss in the United States During 2005: Full Report," Nat'l Fire Protection Assoc., Sept. 2006.
[iii] Hall, J.R., "The Total Cost of Fire in the United States," Nat'l Fire Protection Assoc., June 2003.

strategic partnerships to advance fire safety engineering through scientifically-based knowledge of fire; validated computational tools; sound and reliable supporting data; and recognized professional status for the discipline of fire safety engineering with appropriate training and education. The research of FORUM members supports advances in all aspects of fire safety engineering with the intent of influencing national and international standard setting authorities and improving society's ability to reduce and manage the risks of fire and the costs of fire safety.

Research needed to close gaps in data and knowledge for supporting performance-based codes has been and is being conducted at FORUM member institutions, and over the past fifteen years this research has enabled innovative materials, products, and building designs to be introduced into the market while having a measurable impact on improving fire safety standards and codes. The wide range of expertise contained within the 20 member laboratories from Asia, Europe and North America, if properly harnessed, can be used to hurdle the increasingly complex physical, sociological, and economic barriers that stand in the way of more flexible, broadly used and defensible performance-based design of structures.

The proceedings of the workshop included in this special publication describe an effort by FORUM members to guide investments in research that will moves us more quickly and cost-effectively to the next level of performance-based design, a level that that will support tractable methods for dealing with human behavior in emergency situations, more fault-resistant fire detection systems, alternative fire suppression systems, environmentally benign fire resistant materials and products, more effective fire fighting technologies and fire fighter training, a supply of trained engineers and architects more closely matched to their demand, and better trained building code officials.

FORUM WORKSHOP ON ESTABLISHING THE SCIENTIFIC FOUNDATION FOR PERFORMANCE-BASED FIRE CODES

I. BACKGROUND ON PERFORMANCE-BASED CODES

The desirability of having a roadmap to more effectively develop the scientific foundation for performance-based fire safety design was agreed upon at the 2005 FORUM (International Forum of Fire Research Directors) meeting in Magdeburg, Germany. Numerous workshops had been held around the world on aspects of this topic over the past 20 years, and the needs/desires of various stakeholders had been documented in proceedings. While many of the FORUM members and the wider fire research community had participated in some of these workshops, no documents existed that were aimed specifically at those responsible for investing research dollars in an effective manner (i.e., FORUM members) toward a long-range goal.

There is no lack of interesting or challenging technical problems to tackle in fire research, and there is no unique path towards the goal of science-based fire safety design. The FORUM as an organization is uniquely positioned to establish a 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. Representatives from the FORUM membership and other invited technical experts gathered at the National Institute of Standards and Technology (NIST) in Gaithersburg, Maryland, on April 5 to 7, 2006, to develop a common, international vision of the future, to agree upon research milestones to keep us focused, and to develop an understanding of which laboratories are poised to invest in which aspects of the vision. The agenda for the workshop, a list of attendees, and the names and organizations represented in the FORUM are included in the appendix. A summary of the activities and a list of recommendations and priorities are contained in this report.

<u>Previous U.S. Workshops (W. Grosshandler)</u>

The U.S. General Services Administration (GSA) held an international conference[1] in 1971 on fire safety in high-rise buildings. In that conference the attendees recognized the importance of applying a total systems design and management approach to foster innovation and relieve unwarranted constraints on the design of the structure and operation of the building. The benefit of using functional goals and desired attributes to guide design and evaluate alternative fire safety approaches was emphasized. While the phrase "performance-based design" (or PBD) was not coined at that conference, much of what was discussed revolved around the concept of PBD. A striking difference between the atmosphere of 1971 and the reality of our post 9/11 era is apparent in a portion of the stated premise for a fire-safety system in a high-rise building in 1971: "the height of the building makes total evacuation impractical and creates a situation where fire must be fought and controlled internally." While the latter part of the premise remains valid, a recommendation coming from the NIST investigation into the collapse of the World Trade Center Towers,[2] if adopted into building codes, would make full-building evacuation a design consideration.

In 1991, after the GSA conference, 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:

> that "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."

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.

Our success in providing functional engineering tools and demonstrating their validity to both the designer and the authority having jurisdiction is tied to our ability to measure the effectiveness of alternative fire-safety designs. This requirement was part of the motivation for a workshop[4] held at NIST in 2000 to identify measurement needs for fire safety in general. Accurate measurement of heat flux to the surface of a burning sample was rated the most critical need, followed by measurements of gas velocity and temperatures in a room fire, heat release rate from full-scale burning objects, and smoke characteristics.

At a second workshop in 2000, the Society of Fire Protection Engineering (SFPE) focused on the needs of the fire protection engineering profession to develop a research agenda.[5] Participants included FPE consultants, industrial facility owners, materials and equipment suppliers, insurance companies, government laboratories and facility operators, code bodies, academics, and the fire service. The objective of the workshop was to identify research needed 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. Areas in most urgent need of attention included:

- Fire phenomena research to
  - predict heat release rates during fire growth and fully developed fires;
  - predict suppression system effectiveness;
  - predict response of fire detectors to different fire signatures;
  - predict smoke movement from low energy (smoldering) fires;
  - investigate impact of fire and fire protection on the environment.

- Human behavior research to
  - better understand how people will react in fire and the actions that they will take;
  - better understand how people are affected by exposure to fire and fire effects;
  - develop design methods based upon human behavior in a fire situation.

- Risk management research to
  - determine what level of risk is acceptable to society, and how acceptable risk varies among communities;
  - develop risk management framework to describe fire/building/people interaction and impact of system operation success or failure.
- Data collection research to
  - establish reporting methods such that reliability, installation, maintenance, near miss, ageing and failure data on products and systems are available to the design community, with known confidence and limitations;
  - support post fire analysis;
  - better monitor and manage systems and components that affect building performance.

The workshop participants agreed that successful development and implementation of the research program required collaborations and partnerships (including with organizations not traditionally involved in fire research); and identification of a champion to coalesce diverse interests, advocate the agenda, break down inter-organizational barriers, and oversee and monitor completion of agenda topics.

Of most direct relevance to the current FORUM workshop was the United Engineering Conference[6] held in January of 2001. The objective of the conference was to assess 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. The main participants were academics, FORUM members, fire protection engineering firms, materials and equipment suppliers, government agencies, and code bodies.

Areas to focus research to meet the conference objectives included:

- Fire phenomena and modeling
    - flame spread and fire growth;
    - thermal and smoke detection;
    - water suppression;
    - damage to structures;
    - ventilation effects in buildings;
    - stochastic models.

- Human factors research
    - overarching human behavior model to guide application of human behavior concepts and identify process for considering human behavior;
    - cue response sequencing model that is occupancy and conveyance (bell, voice, smoke, etc.) dependent;
    - human behavior scenario classification;
    - toxic generation, transport, tenability, and human response;

- Risk assessment research
    - improve data archiving and accessibility
    - define acceptability of risk methods by public decision-makers
    - set acceptable metrics for risk acceptance
    - compare risk metrics to prescriptive requirements and better define acceptance thresholds

Key roadblocks to implementation were cited as:

- privatization and commercialization of national laboratories resulting in
    - replacement of underpinning scientific research with income-producing consultancy and standardized fire testing,
    - erosion of urgently needed fundamental research in support of performance-based regulation, and
    - proliferation of dubious fire testing in support of certification;

- 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 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.[7] Two high level recommendations resulted from the study: (i) that NSF should reestablish a program in basic fire research and interdisciplinary fire studies, and (ii) 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[8] 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.[9]

The last workshop worthy of special mention is the one organized by SFPE, with NIST sponsorship, to develop a national R&D roadmap for structural fire safety design and retrofit of structures,[10] held in Baltimore in October, 2003. The participants included representatives from professional associations, engineering and design firms, academics, testing laboratories, materials and equipment suppliers, government, and code officials. Recommended areas to focus research were laboratory and real performance data, and methodologies and tools for implementation in codes and standards, including the following specific tasks:

- Obtain/develop research-quality real and experimental data on structural fire performance.
    - Build and utilize structural-fire experimental facilities to apply complex structural loads to large-scale components at elevated temperature.
    - Develop reliable database on multi-axial stress and rate effects (creep) of structural materials at elevated temperatures.
    - Develop an experimental database of the behavior of structural connections, members under complex loading, subassemblies and structural systems at elevated temperatures.
    - Collect actual fire performance data.
    - Investigate fire performance of structural connections to develop and validate engineering methods to predict this performance.
    - Develop benchmark problems for verification of analytical tools.

- Codify/standardize performance goals, criteria and methodologies for structural fire design and analysis.
    - Quantify level of protection provided by current prescriptive code requirements.
    - Define failure/limit states for structural response in fire.
    - Develop guidelines for enforcement and engineering communities on evaluation and remediation of structural fire performance of existing buildings.
    - Specify performance goals in the building code for prescriptive and performance-based options.
    - Develop performance metrics for multi-hazard building robustness.
    - Develop a risk-based methodology for design fires and the data to support it; place it into a standard.
    - Develop standard methods for determining material properties at elevated temperatures.
    - Specify professional responsibilities for structural fire protection of buildings.

Concerns were raised regarding the implementation of some of the recommendations; namely,

- Structural fire safety is only part of the overall provision of fire safety.

- How does one identify the relevant fire scenarios to be analyzed?

- There are practical limits to advancing risk-informed decision making; e.g.,
    - accuracy of failure probabilities
    - identifying stakeholders and their interests
    - communication of risk and performance metrics

- benefit-cost tradeoffs
- quality and assurance in design, construction and operations
- comprehensive assessment of performance and consequences

- Code officials need guidance (now) as to standards by which engineering solutions can be evaluated; e.g.,
  - there is a general lack of design practices, educational opportunities and designers educated and experienced in the field of structural design.
  - there is no code of practice specifically for retrofitting for structural fire performance analogous to the code of practice that has been developed for seismic retrofit.

The output of the above workshops provided a fertile ground upon which the FORUM participants were able to nurture the recommendations that remained valid, and to plant new ideas for overcoming implementation obstacles previously identified.

Current Status of Performance-based Codes and ISO TC92

Performance-based building and fire codes and regulations exist around the world today. Their use in North America was reviewed by Richard Bukowski; Morgan Hurley focused on the goals outlined in the current U.S. model codes; Ichiro Hagiwara discussed the Japanese system; and Jukka Hietaniemi and Nigel Smithies provided status reports on the European and United Kingdom situations, respectively. Björn 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.

North America (R. Bukowski and M. Hurley)
According to Bukowski, the motivations for performance-based regulations are the flexibility in design and construction they permit (including the ability to deal with unique structures not well addressed by prescriptive regulations), their cost effectiveness, and a general reduction in regulatory burden. (Note the distinction that regulations are laws that are adopted and enforced with the legal system of the country, while codes are documents upon which the language of regulations can be modeled.) Recently developed concepts of limit-state design for structures and improved fire modeling software have permitted the objective assessment of performance against structural stability and fire/life safety objectives of the regulations.

Although performance-based codes now exist in North America (e.g., 2001 ICC Performance Code for Buildings and Facilities,[11] 2003 NFPA 5000 -- Performance Option,[12] and 2005 National Construction Code of Canada -- Objective-based[13]), these typically contain equivalency clauses which lack specificity since the objectives of the prescriptive codes are unclear. The fire safety concept tree and fire safety evaluation system (FSES) were developed previously to help guide the equivalency assessment. Within NFPA 5000, performance regulation is included in the prescriptive code as an alternate path, with the prescriptive requirements set as the minimum. The performance path requires eight design fire scenarios, three structural load scenarios, and two safety-during-use scenarios. There are a number of engineering guidelines to help in developing and evaluating these scenarios, including the SFPE Engineering Guide to Performance-based Fire Protection[14] and the International Fire Engineering Guidelines.[15]

The Canadian objective-based code involves a top down analysis that reveals regulatory requirements that are not associated with any code objectives, and a bottom up analysis that establishes explicit linkages to the design objectives. Within Central and South America, there is some interest in performance-based regulation, although significant enforcement issues exist with current regulations. It is likely that the new code developed for Spain will have an influence on the direction taken by Latin America.

The Interjurisdictional Regulatory Collaboration Committee (IRCC), an association of chief building regulatory officials in countries with performance-based regulatory systems, was formed in 1996 to exchange information on issues and regulatory methods of mutual interest, and to provide guidance to those interested in adopting such regulatory methods. Closely associated with the IRCC is CIB TG11/37, which is organized to stimulate research in support of performance-based regulation, as exemplified by papers presented at the CIB World Congress in 2001.[16,17,18,19]

Hurley described the goals for PBD as outlined in the ICC and NFPA performance codes and as currently developed in the U.S. The guidelines for obtaining these goals are either explicitly stated or implicitly derived within the codes. Table 1, taken from the ICC Performance Code,[11] shows how performance requirements are adjusted with the expected magnitude of an adverse event.

Mild impact implies no structural damage, non-structural building systems and emergency systems remain fully operational (emergency and normal), injuries to building or facility occupants are minimal in numbers and minor in nature, there is a very low likelihood of single or multiple life loss, damage to building or facility contents is minimal in extent and minor in cost, and minimal hazardous materials are released to the environment. By contrast, a severe impact means substantial structural damage is sustained, but significant components continue to carry gravity loads. Repair may not be possible. Non-

Table 1. Required performance versus magnitude (Table 303.3 in ICC Performance Code[11])

INCREASING LEVEL OF PERFORMANCE

→→→→→→→→ → →→→→→→→→

PERFORMANCE GROUPS

MAGNITUDE OF DESIGN EVENT

INCREASING MAGNITUDE OF EVENT ↑↑↑↑↑↑↑↑↑↑↑↑↑↑

Very Large (Very Rare)	Severe	Severe	High	Moderate
Large (Rare)	Severe	High	Moderate	Mild
Medium (Less Frequent)	High	Moderate	Mild	Mild
Small (Frequent)	Moderate	Mild	Mild	Mild

structural building systems and emergency systems may be completely nonfunctional. Injuries to building or facility occupants may be high in number and significant in nature. Damage to building or facility contents may be total, and significant hazardous materials may be released to the environment.

The goals as specified in NFPA 5000[12] are aimed at safety (from fire, from structural failure, during building use, and from hazardous materials), building usability, health, and public welfare (including energy efficiency, cultural heritage, mission continuity, and environmental protection). Safety from fire implies that occupants not intimate with the initial fire are protected, that people and property in adjacent spaces and buildings are protected, and that accesses is provided for fire fighters and they can expect a "reasonable" level of safety during fire fighting operations. Under the goal that addresses public welfare, cultural heritage is defined as the preservation of the original quality or character of historic buildings, and mission continuity means that buildings that perform a public welfare role shall be designed to continue to perform that role after a fire.

Japan (I. Hagiwara)
The Building Standard Law (BSL) and the Fire Service Law (FSL) that govern building fire safety performance in Japan were summarized by Hagiwara. The BSL deals with fire resistance, compartmentation, materials, smoke control, and egress. The FSL focuses on active fire protection, including alarm and automatic suppression systems, emergency guidance systems, water sources, and facilities for fire fighting operations. In addition to conventional prescriptive methods, the BSL allows two alternate design approaches: the verification methods specified in the notification of the Ministry of Land, Infrastructure and Transport (MLIT), and advanced simulation models that are evaluated by a committee of experts. The objectives of the fire safety performance design are the following:

- prevention of building collapse
- safe evacuation
- reduction in fire occurrences
- assurance of fire fighting
- prevention of urban fire spread

A flow chart indicating how the different objectives are interrelated is shown in Figure 1.

Prevention of building collapse requires the building to be fire resistive, which, on a prescriptive basis, is defined by the BSL as one constructed of fire resistant elements. On a performance basis, a fire resistive building is defined as one that resists expected indoor fires corresponding to the construction and service equipment of the building, and one that resists ordinary fires occurring in the neighborhood, throughout the duration of the respective fires. For the indoor fire, the fire resistance time must be greater than the duration of the expected fire, while for external exposure, the fire resistance of the exterior walls must withstand a standard fire for either 30 minutes or 60 minutes.

Evacuation safety, using the prescriptive approach, is accomplished through specified fire separations, corridors and egress paths, smoke control and emergency lighting, and use of specific interior finish materials. The performance-based approach requires analysis of egress and verification methods. Escape from both the fire floor and the building are considered. A satisfactory floor evacuation performance means that evacuation from the fire floor is completed prior to the smoke layer descending below a level that is detrimental for evacuation of any room on that floor. For safe building evacuation, this definition is extended to include all rooms, corridors and stairways leading to the ground.

Performance-based design in Japan has led to greater transparency in the fire and building codes, and a system in which the design objectives are easier to explain and to be understood by the designer, user, and

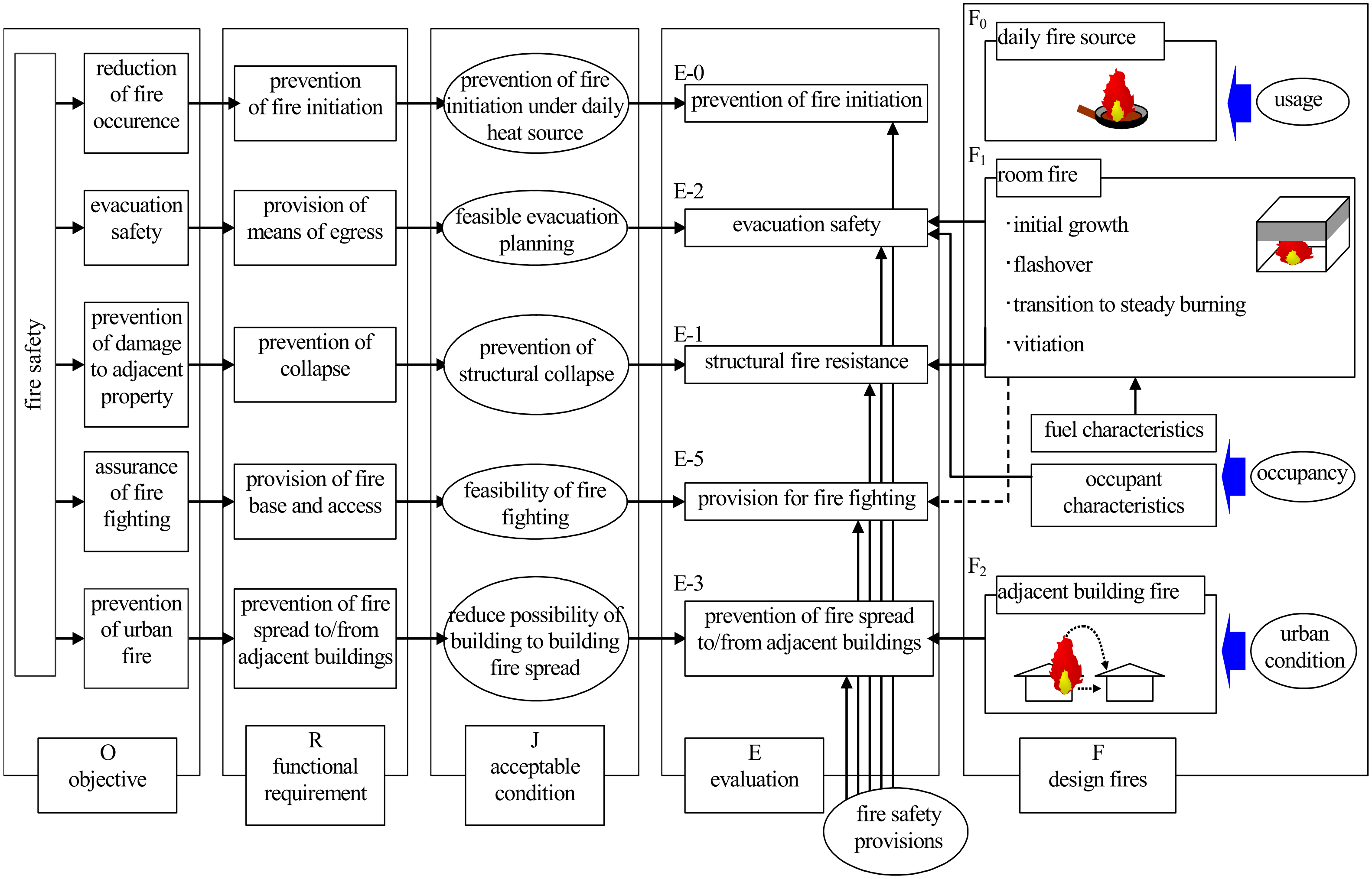

Figure 1. Japanese framework for fire safety evaluation (Hagiwara)

other stakeholders. The Japanese system has encouraged the use of performance design using verification methods by fire safety engineers and also architects. Their experience is that alternatives to prescriptive designs are easily allowed. On the down side, the application of PBD has been motivated primarily as a cost-savings approach rather than leading to improved fire safety. The verification methods, most often based upon two zone layer models, allow designers to go through a rote calculation procedure that does not require the designer to actually imagine what a reasonable worst case fire might be. New and advanced simulation models are not likely to be developed for an evaluation because of the difficulty in verifying their accuracy and validating their applicability.

Europe (J. Hietaniemi and N. Smithies)
As explained by Hietaniemi, one of the most important drivers of European unification is the wish to lower and ultimately eliminate barriers to trade. With respect to fire safety, attempts to achieve this goal are through test method harmonization and harmonization of structural design norms via the Eurocodes. However, regulations are not unified as the safety levels are determined in National fire regulations.

The Construction Products Directive (CPD) is the European "law" concerning construction products that is aimed at test method harmonization. Directives from the European Commission are binding on the Member States, which incorporate the directives in their respective National Building Codes. The core of the CPD is the essential requirements for the works (given in annex I of the CPD). These are:

- Mechanical resistance and stability
- Safety in case of fire
- Hygiene, health and the environment
- Safety in use
- Protection against noise
- Energy economy and heat retention

The essential requirement for the limitation of fire risks states that "the construction works must be designed and built in such a way, that in the event of an outbreak of fire the load bearing resistance of the construction can be assumed for a specified period of time, the generation and spread of fire and smoke within the works are limited, the spread of fire to neighboring construction works is limited, the occupants can leave the works or can be rescued by other means, and the safety of rescue teams is taken into consideration."

While the CPD has been seen as a way towards abolishment of the barriers to trade related to fire requirements, the Directive leads to product conformity attestation only; i.e., it does not provide the link between the performance-based approach used in product specifications and a performance-based approach for works. Justifying the need for fire safety simply on the basis of the general objectives of fire protection, i.e., to safeguard life including rescue personnel (taking into account the individual and societal aspect), to protect property (with neighboring property often given the first priority), and, where required, the environment and other relevant values appears to Hietaniemi to be a more appropriate bases for the performance-based approach and use of fire safety engineering.

The Eurocodes provide the structural design norms that include also design for fire conditions. (Refer to Figure 2 for a block diagram of this structure.) The Commission considers the use of the EN Eurocodes as fulfilling the conformity requirement. The guidelines relevant to fire are contained in Eurocode 1: Actions on Structures - Part 1-2: General Actions –Actions on structures exposed to fire (EN 1991-1-2).[20] By acknowledging the use of fire safety engineering in the evaluation of the thermal actions, Eurocodes in

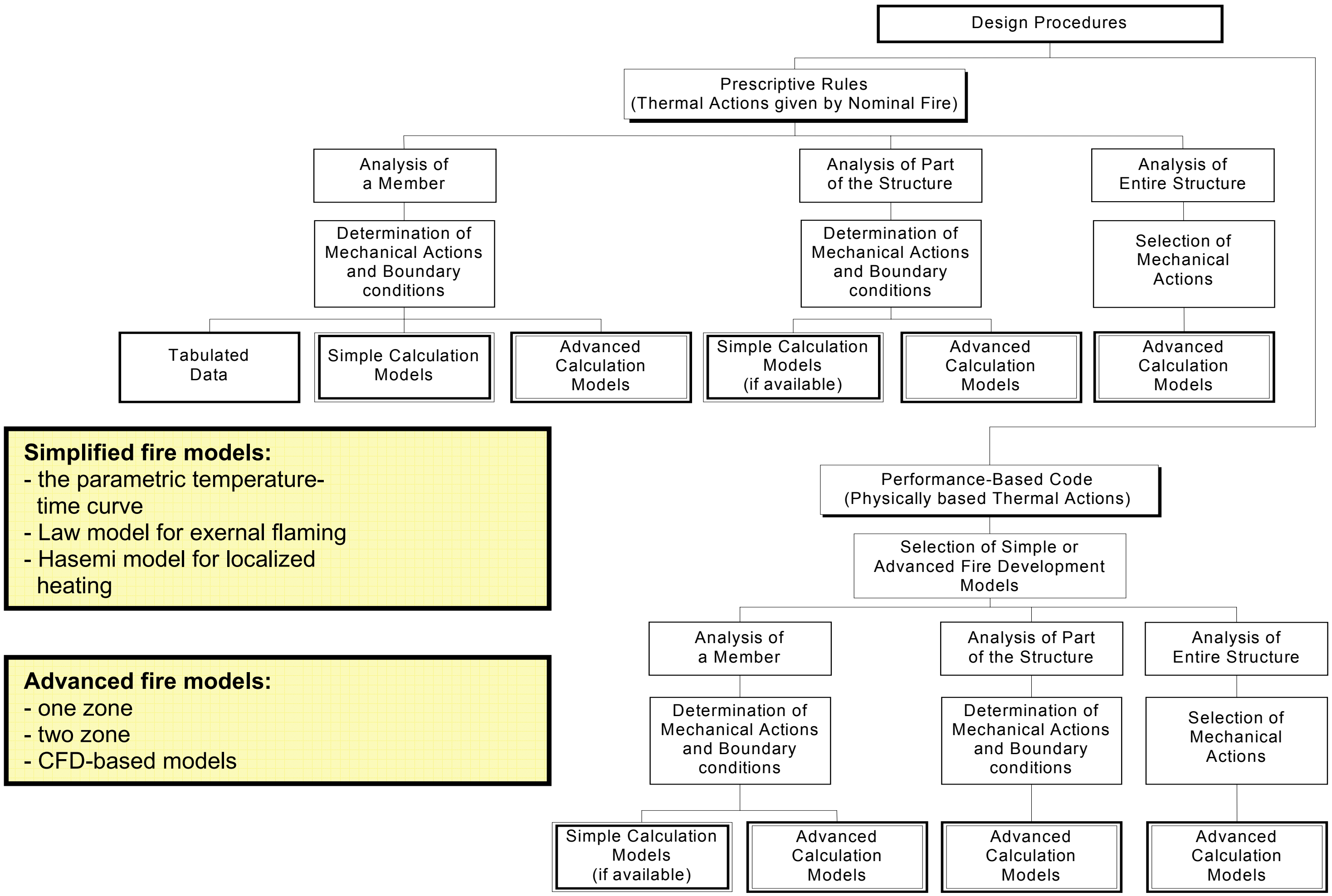

Figure 2. Design procedures acknowledged by EN 1991-1-2 (Hietaniemi)

principle pave the way for performance-based fire design. There are, however, some potential drawbacks with this thought process: there may be a tendency to think that with the Eurocodes things have reached a completed stage, e.g., "the parametric curve is better than CFD...": so why develop CDF models?; and there are NDP's (Nationally Determined Parameters) in the Eurocodes and adjusting these values may escalate to tuning the whole design procedures resulting in re-creation of National norms.

Within Europe, there are some countries in which the fire regulations are basically performance-based. Yet, there is always also the deemed-to-satisfy approach, e.g., as guidelines. The more common situation is that fire regulations allow use of fire safety engineering as an option to compute the load-bearing capability of structures, evacuation times, and smoke spread to assure safety in case of fire. For example, in one building project there may be some aspects designed strictly in accordance with the regulatory prescriptions, and with some specific fire safety goals met through fire safety engineering methods. Those countries that can be classified as performance-based are the United Kingdom, Sweden, and Norway. Those countries allowing fire safety engineering alternatives are Belgium, France, Italy, Luxembourg, Netherlands, Germany, Denmark, Ireland, Greece, Portugal, Spain, Austria, Finland, and Switzerland. Western Russia is a question mark, although Finnish firms are trying to get their products and PBD into the Russian market.

As fire engineering design is a non deterministic process, probabilistic and risk-based approaches will most likely increase. Acceptance criteria should evolve toward risk-based criteria, in which public policy makers and regulators establish quantifiable minimum tolerable risk levels. An example of what this might look like is shown in Figure 3. What we need to construct such a figure are data, especially on large-scale, high risk events, as well as a more integrated approach covering the whole building design.

Smithies reviewed performance-based fire safety in England and Wales. The primary goal for building regulations is life safety; i.e., the building shall be acceptably safe at all material times in case of fire and other adverse events. The regulators are responsible for approving documents and deeming that the performance-based equivalent levels of safety are met. Regulations are underpinned by codes and standards. In performing a fire safety analysis, the assumptions are that the fire is accidental in nature and starts within a compartment (not in a corridor or stairway), that there is a single seat of ignition with no accelerant present, that the passive and active safety systems are intact and operational (within reliability limits), and that the building is well managed and occupants behave.

BS 7974, the Code of Practice, Application of Fire Safety Engineering Principles,[21] is supported by PBD, and is now being revised. Approved Document (AD) B (domestic and non-domestic parts) is under review, looking for performance-based equivalents dealing with life safety, property loss, continuity of operation, and environmental impact. Use of lifts in fires and emergencies, sprinklers in warehouses, requirements for schools, and domestic fire detection are all being examined. Regulatory Reform Order 2005, which applies to all non-domestic premises, will be coming into force in October, 2006. It requires one to carry out a fire risk assessment of the premises and to record significant findings if more than five people are employed at that premises. Actions are required to reduce fire risk to ALARP (as low as reasonably practicable) accounting for the possibility of deliberately set fires. Eleven guides are written to support the order, covering: offices and shops, premises providing sleeping accommodation, residential care, small and medium places of assembly, large places of assembly, factories and warehouses, theatres and cinemas, educational premises, healthcare premises, transport premises and facilities, and open air events.

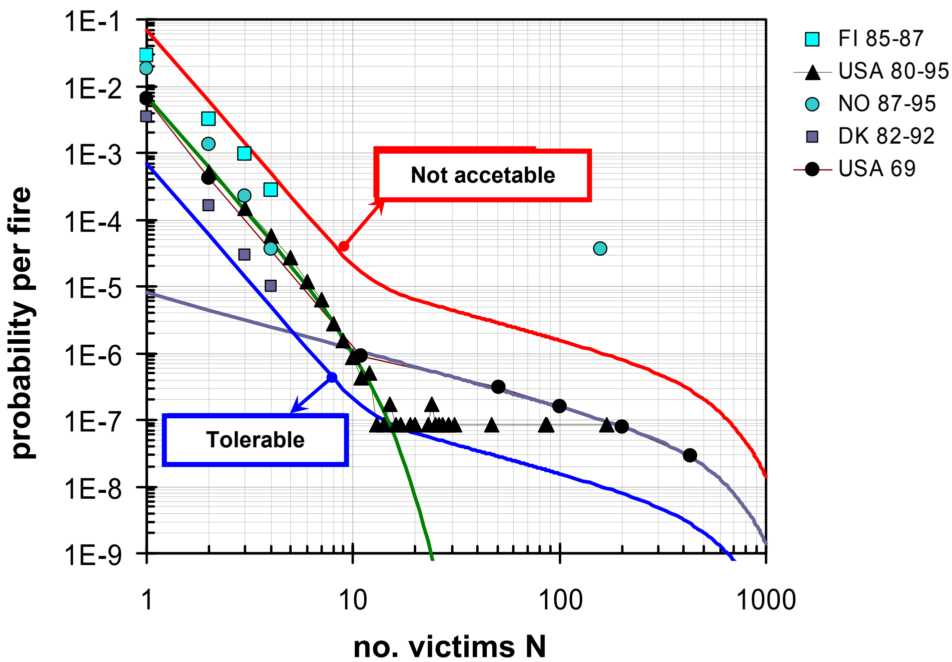

Figure 3. Quantification of risk levels (Hietaniemi)

<u>ISO TC 92 Fire Safety (B. Sundström)</u>
The Technical Committee on Fire Safety (TC92), currently chaired by Björn Sundström of SP, conducts its business through four subcommittees:

- SC1, Fire Initiation and Growth, Koichi Yoshida of NMRI, chair
- SC2, Fire Containment, Deggary Priest of Intertek, chair
- SC3, Fire Threat to People and the Environment, Richard Gann of NIST, chair
- SC4, Fire Safety Engineering, Joel Kruppa of CTICM, chair

The overall objective of the committee is to develop standards and other documents to satisfy market needs, be timely, cost effective, and cover the following topics:

- Fire safety engineering, design and evaluation methods used to verify that appropriate fire safety objectives are achieved. (An example of a fire safety objective is specified risk reduction to people, property and the environment.)
- The performance under fire conditions of materials, products, elements of structure, structures and systems and their contents, where appropriate in end-use conditions.
- The application of fire safety management.
- Characterisation of occupant performance and behavior when subjected to fire conditions and fire-like emergency situations.

ISO TC 92 closely coordinates its actions with other ISO and IEC technical committees (TC 21, TC 38, TC 59, TC 61/SC4, TC 77, TC 85, and TC 162) and has liaisons that associate with the European

Commission, CIB, IMO and other international organizations. The advantages of ISO standardization, and of TC 92 in particular, are that the standards they develop are global in nature and widely used, they have high scientific integrity, and they provide test methods and support fire safety engineering. Table 2 lists the standard test methods in the draft technical report, ISO DTR 17252. On the negative side, market interests can compromise the scientific level of the standard, the tests methods are largely product driven, the fire calculation models imbedded in the standards need more development, and it is unclear if some of the data required by the referenced models can even be measured.

Comment [U1]: CD is a committee Document – it's a complete version, and sufficient for circulation for comment. It has no real standing. However, I believe Bjorn's statement is incorrect – this is not a CD. It is currently being circulated as a New Work Item (to be come a Technical Report) and specifically does not ask for approval to circulate as a CD. The document is not really citable, but, for convenience could be referred to as DTR 17252 (draft technical report).

Table 2. Summary of test methods in ISO DTR 17252

Number	Title
EN ISO 1182	Non-Combustibility
EN ISO 1716	Calorific potential
ISO 5657	Ignitability for a radiant heat source
ISO 5658-2	Spread of flame
ISO 5658-4	Spread of flame
ISO 5659	Smoke Box
ISO 5660	Cone Calorimeter
EN ISO 9239-1	Flooring test
ISO 9705	Room Corner Test
EN ISO 11925-2	Small flame test
ISO FDIS 13784-1	Small room fire test for sandwich panels
ISO FDIS 13784-2	Small room fire test for sandwich panels
ISO FDIS 13785-1	Intermediate scale test for facades
ISO FDIS 13785-2	Large scale test for facades

Selecting the Design Goals

Establishing the goals for a project is the first and most influential single step in a performance-based design. To demonstrate this process Morgan Hurley described how SFPE uses case studies to encourage the application of performance design methods and identify problems that arise with their use. Technical limits to meaningful implementation of performance-based fire codes was the subject of the talk given by Marc Janssens of SwRI. Paul Croce of FM Global put forth an argument that the goal of life safety was insufficient to form the basis of design.

SFPE Case Studies (M. Hurley)

Over the years the Society of Fire Protection Engineering has coordinated a number of case studies that challenge participating teams to apply fire protection engineering methods to a common performance objective for a building design. In one case, a common set of design specifications for a fictitious transportation center was given to the teams from different countries. While a comparison to the prescriptive design was not required (as in previous competitions), some of the teams provided the alternative design as well.

The building to be designed was described as follows:

- Transportation center, providing bus/rail services and shops, and located on the border of a country. (Includes passport control and customs inspection stations, and a secure area for passengers who have cleared passport control to await their train. Secure area would prevent mingling of passengers with those who have not cleared screening.)
- The dining terrace (+5 m level) and the balcony where the shops are located on the 0 m level shall be open to the waiting room below.
- With the exception of the shops, no visual obstructions (doors, walls, etc.) shall be provided between the waiting room and the rail platform.
- The interior of the train terminal must convey a feeling of openness and be covered with long span construction with a maximum amount of glass to allow maximum natural lighting.
- The shops shall be provided with display windows and shall be easily accessible to travelers.
- The bus terminal shall provide for ease of access to busses and include both bus storage and repair facilities. Fueling of busses shall take place outside of the facility.
- Exposed open web steel joists are to be used in the bus terminal.
- Long-span arched exposed steel trusses are to be used in the rail station.

The fire safety goals were for the occupants to be safeguarded from injury due to fire until they reach a safe place, for the fire fighters to be safeguarded while performing rescue operations or attacking the fire, for collapse of all or part of the structure in the event of a fire to be avoided, and for business interruption to be minimized in the event of a fire.

The teams described their design approach, how their performance criteria were selected, and how this led to the fire heat release rates and scenarios evaluated. They were specifically asked how passengers in the secure area were to be protected in the event of a fire such that security was not compromised. The teams addressed human behavior and egress, fire safety measures, systems test and maintenance requirements, and fire safety management including material control and change of occupancy concerns. Safety factors, uncertainties and reliability issues surrounding the design methods, models, and engineering judgment were discussed. Three of the five teams applied the NIST Fire Dynamic Simulator (FDS)[22] to analyze the fire scenarios, and the others used recognized correlations. The design teams all focused their computational efforts on tasks that are felt to be modeled reasonably well with existing technology: smoke movement and filling, fire induced temperatures, and people movement.

The full reports of these case studies are available (for purchase) from SFPE.[23]

<u>Technical Limits to Meaningful Implementation of Performance-based Fire Codes (M. Janssens)</u>
Janssens reviewed the steps in the performance-based design process spelled out by SFPE:

1. define project design scope
2. identify goals and objectives
3. express objectives as performance criteria
4. identify fire scenarios
5. select design fire scenarios
6. develop trial designs
7. evaluate trial designs
8. select final design

Implementation of PBD is project-specific, and some stakeholders (e.g., insurance providers) may be left out. As well, technically qualified stakeholder representatives, such as the fire service, may not be available for a specific project or in a particular location.

Moving from the identified goals through the stakeholder objectives to design objectives in step 2 requires increased levels of specificity. The most difficult step is number 3, developing the performance criteria from the design objectives, because that process requires selecting hard numbers.

When it comes to identifying and selecting the design scenarios in steps 4 and 5, there are no objective criteria and no mandate for extreme events to be considered. The selection of the trial designs, step 7, is biased toward proven methods, the experience of the designer, and the capability to evaluate the design.

Evaluation of the trial designs has its own serious hurdles, including input data that are unavailable and no standard method established to even measure the data; uncertainty in test data that are available (namely, fire response characteristics of materials and people, and full-scale fire test data for model validation); and finally limitations of the numerical models themselves due to phenomena that are not captured, approximations to the physics that is included, and limited computational power.

Janssens gave examples of some of these limitations in reference to the PBD conducted by Schirmer Engineering.[24] This was part of a case study on the design of a twenty-story hotel proposed by SFPE. When it came to eliminating a sprinkler system as part of the study, nearly every engineer had a problem with this since their bias was that sprinklers save lives. A fire in a guest room without sprinkler protection could grow very quickly and become lethal for occupants who are intoxicated or impaired. The fire could also be a bigger challenge for the fire department. Even if guests managed to escape from the fire room, the absence of door closers would increase the likelihood of rapid fire spread to adjacent rooms.

Another difficult design decision was associated with the open balconies and stairways. Flames emerging from open doors could hit the unprotected ceiling of the open balcony, possibly resulting in premature failure. Hot gases and flames could enter the open balcony above the fire floor and expose the structure and fleeing guests. Since the stairways were not pressurized, a fire close to a stairway could result in exposure to smoke of guests who decided to use it. The open design also might make it difficult to use the stairways under inclement weather.

Other issues were brought out from the exercise.

- If one of the two ballroom exits were blocked by the fire, the entire occupancy had to evacuate through the single remaining exit potentially against the flow of fire fighters.
- The smoke control system would increase the rate of air supplied to the fire and therefore the rate of fire growth.
- What happens to the extracted smoke? If it is not properly released in the atmosphere, the smoke could affect guests who are evacuating from their room through the open balconies.
- What would be the liability for an authority having jurisdiction (AHJ) who signs off on this performance-based design?
- The fact that the fire department might need more than five minutes due to traffic, bad weather, reduced staffing, etc. was not considered.
- How would the building perform in other emergency situations (terrorist attack, hurricane, etc.)?
- Would the Class I standpipes be supplied by a dedicated pump or by the fire department?

<u>Competing PBD Goals (P. Croce)</u>

Before discussing issues surrounding the selection of design goal, Croce commented on the goals of fire research in general. In his words the goal of fire research 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.

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 are not yet consistent and reliable, and confusion and uncertainty exists among regulators.

One can list 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.

II. THE SCIENTIFIC FOUNDATIONAL BUILDING BLOCKS

The acceptance of performance-based codes and regulations occurs only where the authorities having jurisdiction and other stakeholders achieve a threshold level of confidence in PBD methods. This confidence relies on the state of understanding by the designer of material behavior, fire dynamics, building dynamics, human dynamics, and analytical and computational tools, and the designers success in conveying that level of understanding. At the workshop, experts in each of these disciplines reviewed our current state of understanding.

Material Behavior (R. Gann)

For discussion purposes, Gann 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 participants were asked to answer each question either "yes, now," "yes, partly," or "no." The average response of the 14 or so respondents is summarized in the table below, with a value of +1 reflecting a solid yes and a -1 a solid no.

While the numbers, themselves, in each box have no meaning, if one divides the range between -1 and +1 into three bins, islands appear that suggest a general consensus on our state of knowledge. 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 questions addressed to finished products. The averages are displayed in a similar manner in Table 4, with one additional column to assess the opinion of the group on the readiness of our standard measurement methods and models for designing fire safety on a performance basis.

It is not surprising to see scores much more toward the negative in Table 4 because of the greater complexity of finished products vis a vis homogeneous materials. Also, while there has been a lot of "study" of finished products, it has generally been build-and-burn testing. (Note that to be of much use,

Table 3. Summary of workshop poll on the state of understanding the fire behavior of well-behaved, homogeneous materials

Phenomena	Physics/Chem. Understood	Standard Meas. Method	Validated Model
Ignition, smoldering	**-.08**	**+.36**	**-.5**
Transition to flaming	**-.54**	**-1.0**	**-1.0**
Ignition, flaming	**+.36**	**+.77**	**+.15**
Flame spread	**+.13**	**+.29**	**-.07**
Mass burning rate	**+.64**	**+1.0**	**-.08**
CO	**-.07**	**0.0**	**-.77**
Other toxic gases	**-.62**	**-.33**	**-.85**
Smoke	**-.25**	**+.13**	**-.93**

-1 insufficiently understood 0 sufficiently understood +1

Table 4. Summary of workshop poll on the state of understanding the fire behavior of finished products

Phenomena	Physics/Chem. Understood	Standard Meas. Method	Validated Model	Good Enough for P-B Design
Ignition, smoldering	**-.62**	**-.33**	**-1.0**	**-.71**
Transition to flaming	**-1.0**	**-.90**	**-1.0**	**-.71**
Ignition, flaming	**-.25**	**+.11**	**-1.0**	**+.43**
Flame spread	**-.58**	**-.30**	**-1.0**	**-.71**
Mass burning rate	**-.38**	**+.25**	**-1.0**	**+.23**
CO	**-.93**	**-.22**	**-1.0**	**-.83**
Other toxic gases	**-1.0**	**-.36**	**-1.0**	**-.64**
Smoke	**-1.0**	**-.07**	**-1.0**	**-.71**

the binning in Table 4 had to be adjusted so that green represents responses equal to or greater than +.23 and red represents responses less than or equal to -.58.) 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. (Note that the numbers in the last column are based upon assigning a +1 to "yes" answer and a -1 to a "no" answer.)

Fire Dynamics (W. Pitts)

If one agrees with the premise that the move from prescriptive to performance-based design requires an improved understanding of fire behavior and improved modeling capability, then the question is what research into the dynamics of fire is required to attain that increased understanding and capability? Pitts described a research program being conducted at NIST in response to this question.

The Reduced Risk of Fire Spread Program is aimed at the long term goal of fire loss reduction, and is not restricted to support performance-based design. The objective of the program is to develop effective strategies for cost-effectively reducing the fire losses in the U.S. (both human and financial) based on strategies for limiting fire growth and spread in and to residences. Two areas, reduction of the risk of flashover in residences and reduction in the probability of building ignition during urban/wildland interface fires, have been identified as targets providing opportunities for significant short-term reductions in fire losses.

Eliminating the possibility of flashover has many obvious advantages:

- It could reduce U.S. fire deaths by 80 % and injuries by 50 %.
- It could reduce direct U.S. property losses by 80 %.
- Improved understanding of flashover will allow more effective testing and cut time-to-market for new products.
- It could impact standard test methods (e.g., ISO 9705 and SBI) with trade implications.

The rate of heat release, and hence the likelihood of flashover, can be controlled through passive means (e.g., control of wall lining materials and contents) and active means (early detection followed by manual intervention, or early detection followed by automatic suppression). To these ends, the Reduced Risk of Fire Spread Program is focused on enabling the development of fire safe materials, fault-free detection test methods and standards, fire suppression test method development, and a new generation of models for fire growth and spread on room contents. The fire growth and spread models will be physics-based and deal with fuel pyrolysis, radiation and convection; however they will need to rely on small-scale test results as input as opposed to fundamental first principles models. To be useful these models will need to handle complicated geometries, complicated fuel behavior (e.g., charring, shape change, melting), and they will have to allow interactions between the burning objects, the fire and the enclosure. The development of the fundamental understanding of fire spread and growth on objects is impeded by the lack of heat flux measurements, which inhibits the development of the engineering models. There is a need for an experimental diagnostic capable of determining the heat flux into burning and non-burning material located adjacent to a spreading fire.

The major conclusion from a previous workshop on fire growth and spread was that the development of an effective model for fire spread and growth on real objects is feasible and necessary.[25] This remains a long-range goal of the NIST research.

Reduction in the probability of building ignition during urban/wildland interface fires is the second area targeted to reduce fire losses. Frequency and severity of large fires that destroy large numbers of buildings during a single event are increasing. The factors responsible for this increase include increased construction in wildland areas, widespread build up of wildland fuel due to the effective suppression of small fires, and a persistent drought in parts of the U.S. In the presence of high winds, these conditions can be very dangerous. (In October, 2003 a series of fires destroyed over 3 300 dwellings in Southern California at an estimated total insured loss exceeding $2 B.) Understanding of these fires is limited because, historically, the subject has fallen between traditional studies of building fires and forest fires. The NIST work is extending FDS to handle wildland fire spread, it is determining heat release rates of wildland fuels, it is characterizing brands and their role as an ignition source, and it is examining the effects of burning structures on fire spread rates of fires in wildland fuels (which requires estimates of the heat release rates of the burning structures). A major need is to understand details of brand formation and transport, and the process of the ignition of structures by these brands in high intensity wind-drive fires.

Building Dynamics (U. Wickstrom)

Wickstrom led the discussion on building dynamics. The focus of his presentation was on heat transfer to structures, how to best measure it, and the mechanical response of the structure to the fire. Comments were made on the role of computational fluid dynamics, the need to specify the design fire, ad hoc fire experiments, and their relation to standard fire resistance tests. The concept of adiabatic surface temperature (as measured with a plate thermometer) was put forth as a useful link between gas phase temperatures obtained by CFD calculations, ad hoc experiments, or furnace tests, and temperature calculations in fire exposed structures, e.g. by finite element analysis. Figure 4 demonstrates the

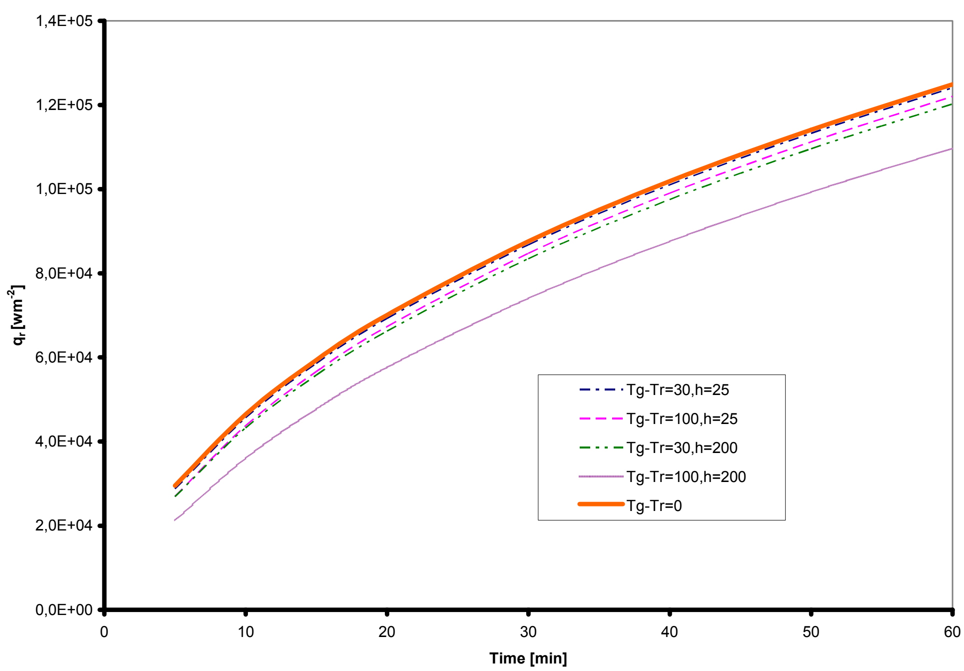

Figure 4. Radiation incident on a surface as function of time in standard furnace test controlled with plate thermometers for different furnace gas and black body radiation temperatures, and convective heat transfer coefficient.

relationship between the incident radiation to a specimen and the exposure time in the standard furnace test controlled with plate thermometers. The red curve represents the incident radiation calculated based on the plate thermometer temperatures which is the true value when the furnace gas and black body radiation temperatures are equal. The dotted lines show the true reduced radiant heat flux for furnaces where the gas temperature is lower than the black body radiation temperature. Note that the incident radiation is very well predicted based on plate thermometer readings (the red line) for differences of the furnace gas and black body radiation temperature and convective heat transfer conditions representative for real fire resistance furnaces, i.e., 30 °C and 25 W/m^2K, respectively. The prediction is probably better then could be obtained with any direct measuring instrument available in fire safety engineering. These curves do also indicate that the furnace testing is harmonized when the furnaces are controlled with plate thermometers and that the incident radiation then is almost the same in furnaces with various thermal characteristics.

Human Dynamics (J.R. Thomas and Guylène Proulx)

Proulx began her presentation by reviewing the research priorities identified in the January, 2001, workshop in San Diego.[6] 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.

Since the San Diego workshop there have been two Symposia on Human Behaviour in Fire,[26,27] publications of the SFPE Human Behavior in Fire engineering guide[28] and a second edition of the SFPE Handbook,[29] and the release of an ISO TC92 document on behavior and movement.[30] During that same period we have experienced multiple disasters in which human behavior and movement have been directly linked to the casualty toll; namely, the collapse of the World Trade Center towers in 2001, The Station nightclub fire in 2003, the Cook County Administration Building fire in 2003, the Buenos Aires nightclub fire in 2004, and the London bombings in 2005.

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). (The elements which make up these calculations are shown in Figure 5.) 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.

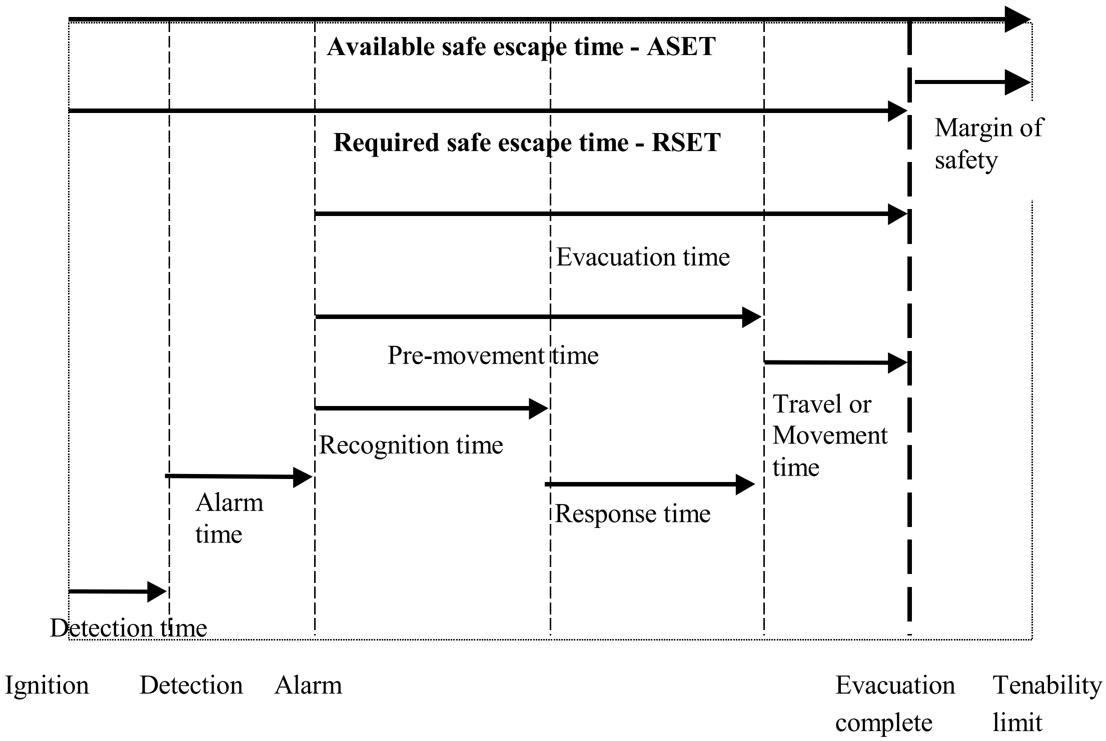

Figure 5. Elements of Required safe escape time (RSET) compared to Available Safe Escape Time (ASET)[30]

Some may need to get dressed and gather belongings. Others may wait for instructions, or devote time to way-finding.

There are different ways to estimate pre-movement time. These include time distributions based upon the literature or best judgment, assuming that it is double the movement time,[31] using DD 240,[32] or simply setting the pre-movement time to zero due to lack of reliable data.

Evacuation time is the sum of the pre-movement and the movement times. There are multiple approaches for estimating movement time, ranging from hand calculations described in the SFPE Handbook to computer evacuation models. Over 35 evacuation models have been identified, some including human behavior and others not including human behavior but with various levels of sophistication for movement. 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[33] suggests that the analysis be done for eight different locations/extents of the fire.

Building characteristics that influence the evacuation process include:

- Occupancy and activities
- Building layout, geometry
- Evacuation route, configuration, distances, stairs (number and arrangement)
- Way-finding
- Evacuation plan or Building Emergency Action Plan (BEAP)
- Staff and operation
- Contents and hazards
- Fire safety features and equipments (detectors, sprinklers, fire doors, refuge areas)
- Fire alarm (directional sounders), voice communication (recorded/ live), CCTV
- Signage (directional, names of location), lighting, photo-luminescent markings
- Fire department (availability, speed of response)

The following list applies to the characteristics of the occupants that are needed for a thorough analysis:

- Past experience (familiarity with the building, knowledge of emergency procedure)
- Activity performed in building
- Alertness, presence of alcohol
- Commitment
- Focal point
- Culture, social affiliation
- Role and responsibility
- Alone or with others
- Occupant number and density, distribution in building
- Age, gender
- Capabilities (physical, sensory, cognitive)

Behavioral scenarios were to be discussed at the ISO TC92 WG 11 meeting following shortly after the close of the FORUM workshop. Other ongoing related activities include research into the waking effectiveness of smoke alarms, highrise 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.

<u>Analytical/Computational Tools (A. Hamins)</u>

Hamins moderated the session on the role of analytical and computational tools. 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 6. 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.

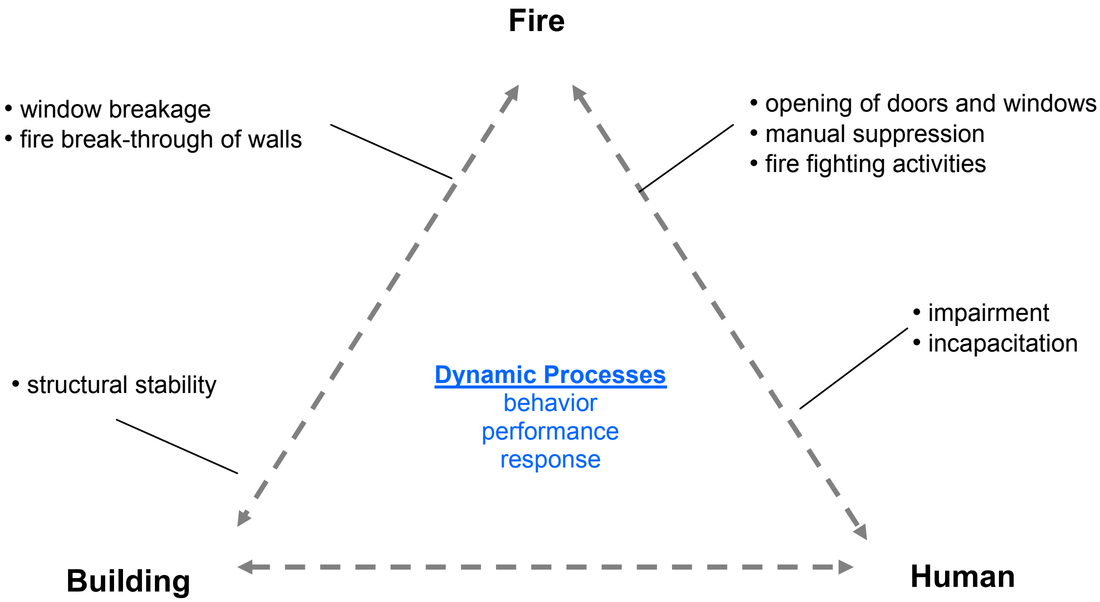

Figure 6. Simplistic View of interaction of dynamic processes

Models of Dynamic Processes (K. McGrattan, J. Gross, J. Averill)

Fire Dynamics -- McGrattan spoke of CFD and zone models, indicating that both types had an important role to play in PBD. Referencing the review conducted by Olenick and Carpenter,[34] he listed four commercial, general purpose codes (CFX, Fluent, PHOENICS, and Star-CD); five fire-specific engineering codes (FDS, Jasmine, Kameleon, SmartFire, and SOFIE); and eight research or special purpose codes (ALOFT, Fire, KOBRA, MEFE, RMFIRE, Solvent, Splash, and UNDSAFE). Not included in the list by Olenick and Carpenter were VULCAN, FUEGO, C-SAFE, and CAFÉ.

An even larger number of zone models were listed for reference, but were not characterized: ARGOS, ASET, ASET-B, BRANZFIRE, BRI-2, CALTECH, CCFM.VENTS, CFAST, CFIRE-X, CiFi, COMPBRN-III, COMF2, DACFIR-3, DETACT, DSLAYV, FASTlite, FFM, FIGARO-II, FIRAC, FireMD, FIREWIND, FIRIN, FIRM, FIRST, FMD, G-Jet, HarvardMarkVI, HEMFAST, HYSLAV, IMFE, JET, LAVENT, MAGIC, MRFC, NAT, NBS, NRCC1, NRCC2, OSU, OZone, PALDET, POGAR, RADISM, RFIRES, R-VENT, SFIRE-4, SICOM, SMKFLW, SmokePro, SP, PRINK, WPI-2, WPIFIRE, ZMFE.

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

- Continued development of Zone Models, except obvious global 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 do 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

Satisfactory validation is critical to obtaining acceptance of computational tools by the AHJ. Since 2000, the U.S. Nuclear Regulatory Commission (NRC) has participated in an international effort to evaluate fire models for nuclear power plant applications. NIST has participated, evaluating FDS and CFAST, along with modelers and experimentalists from the Fire Research Station, UK (JASMINE); GRS, Germany (COCOSYS, CFX); iBMB, Germany (validation experiments); Électricité de France (Magic); IRSN, France (Flamme-S, Isis); and VTT, Finland (validation experiments).

Current research is moving the capability of computational tools forward. At NIST, McGrattan and Floyd are developing an FDS algorithm for multi-step combustion, which is being complemented by an experimental program at NIST in reduced-scale and ISO 9705 rooms. An improved solid phase and charring model is being developed by Hostikka, et al. at VTT, McGrattan and Baum at NIST are implementing improved parallel processing in FDS, and Forney at NIST is improving visualization with Smokeview software. FDS is being adapted to outdoor fires by Mell, Maranghides, Manzello and Rehm at NIST. McGrattan continues to be the sole support of the international user community in applications of FDS. Experimental validation of FDS and other computational tools is being conducted at multiple locations in the U.S., including Sandia, NRC, NIST and SFPE.

Building Dynamics -- Gross 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 7 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) as a result of conforming to the building regulations in force in that jurisdiction (the red line). The light blue band represents the accumulated uncertainty in the estimation of reserve capacity as the fire progresses. 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). (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 7. Commercially available general purpose codes include Abaqus, ANSYS, Nastran, and LS-Dyna. SAFIR is a code specifically developed for fire/structure calculations, and is used more for research than for design.

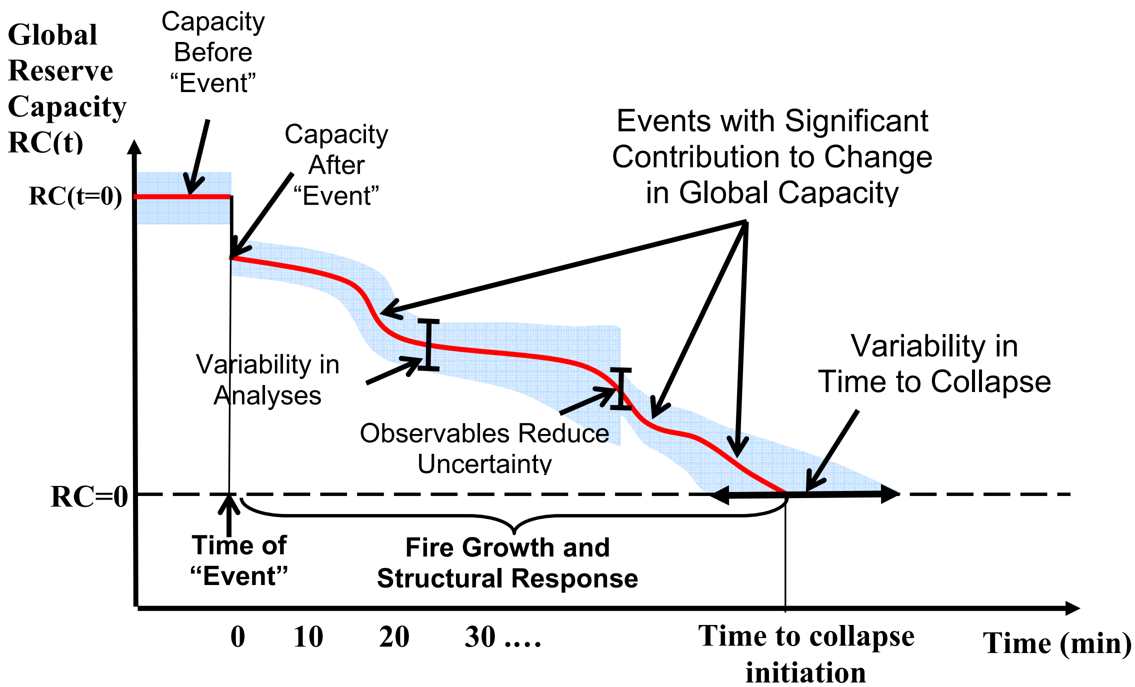

Figure 7. Variability in Sequential Analyses Due to Imperfect Information

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 8 illustrates the interdependencies of a complete structural analysis. The large box on the left of the figure encompasses the physical description of the structure, material data, boundary conditions, and initial conditions based upon the scenario under study. These all feed into the computer codes used for the fire dynamics, the thermal analysis and the resulting structural response. The extent to which the fire, structural temperature, and the deformation and loss of strength of the structure are coupled is dependent upon the scenario.

Gross 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

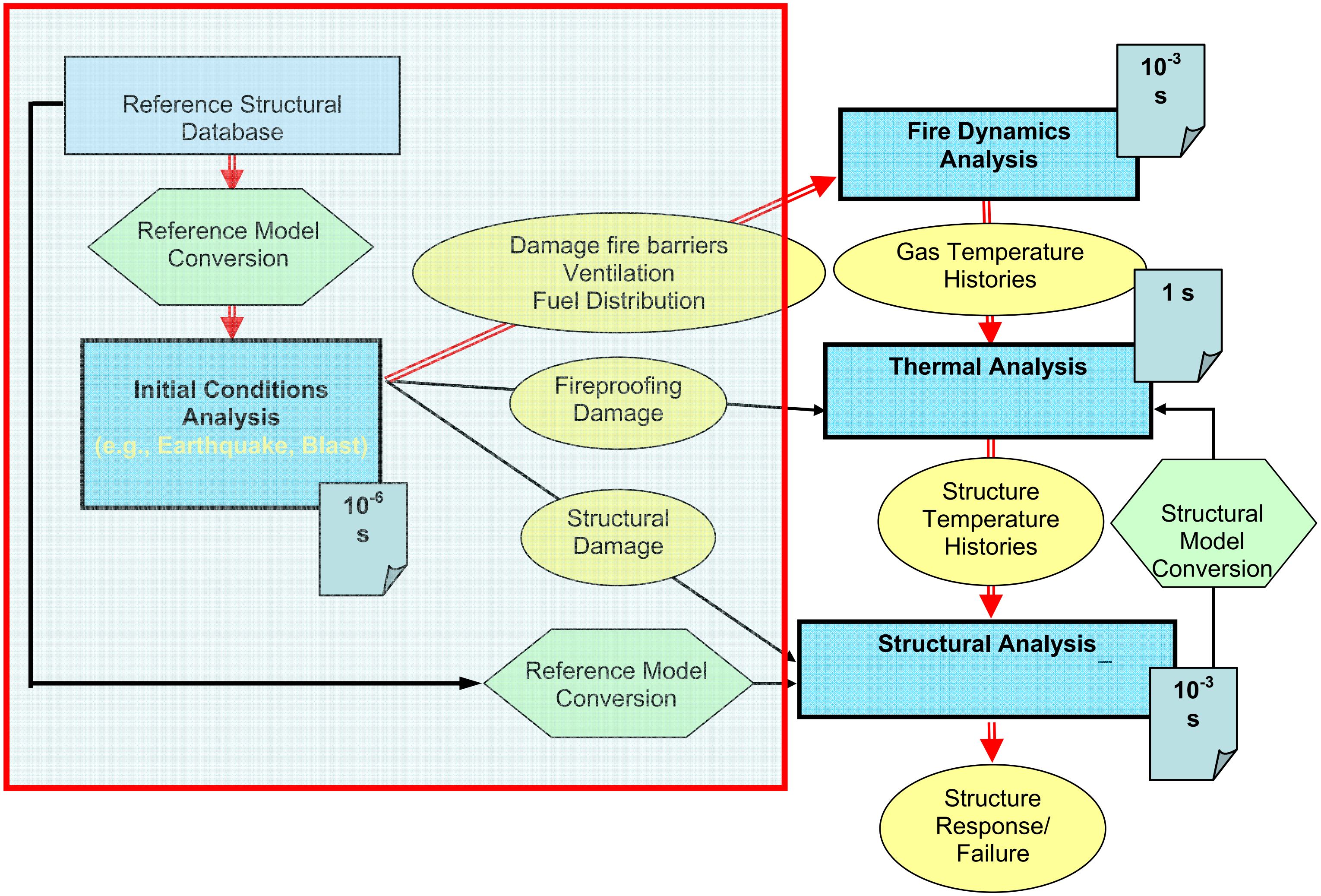

Figure 8. Analysis interdependencies

- 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)

Human Dynamics -- Averill 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. Figure 9, based upon Gwynne et al.,[35] is a diagram of the key components of a building evacuation model: building characteristics, occupant characteristics, building procedures, and the environment. 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.[36] Those that are publicly available, most often for a fee, include FPETool (free from NIST), EVACNET4, TIMTEX, STEPS, WAYOUT, PedGo, PEDROUTE, ASERI, buildingEXODUS, EXITT, Legion, Simulex and Gridflow. Proprietary models available in a consultancy arrangement include PathFinder, EESCAPE, Myriad, ALLSAFE, CRISP, and EGRESS. Additional models that remain unpublished include EXIT 89, EvacSim, SGEM, BGRAF, and ECM.

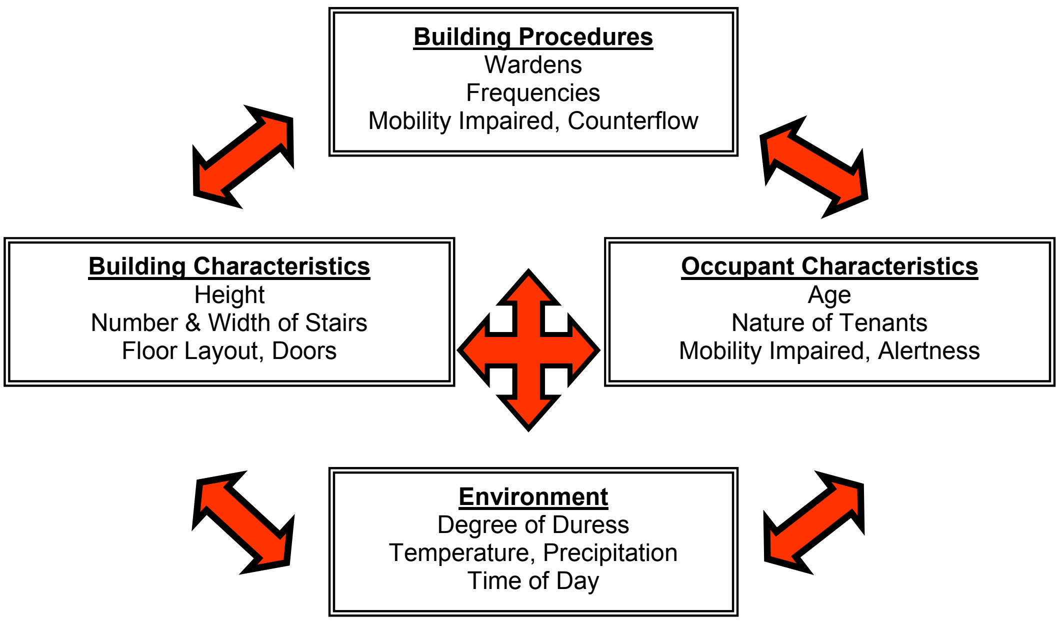

Figure 9. Elements of a building evacuation model[35]

Very few data exist for actual emergency evacuations. Data from evacuation drills and observing other situations involving the movement of large numbers of people recently have been compiled by Lord et al.[37]

Averill ended his presentation emphasizing three points: occupants do not always escape buildings in emergencies, there are multiple approaches to select from for modeling building evacuation, and there is an acute shortage of the data needed to develop, validate and apply models.

Risk (J.S. Hyslop, R. Bukowski, and N. Bénichou)

Performance-based Risk Analysis of Nuclear Power Plants -- Hyslop explained that the U.S. Nuclear Regulatory Commission (NRC) sets regulations to ensure the public safety of commercial nuclear power plants (NPPs) in the U.S. The NRC has recently established a voluntary risk-informed, performance basis fire protection rule, 10CFR50.48(c), which endorses, with exceptions, National Fire Protection Association (NFPA) Standard 805, "Performance-Based Standard for Fire Protection for Light Water Reactor Electric Generating Plants." This rule establishes requirements for a permanent change to the NPP licensing basis and requires a fire risk analysis for any change. The figures of merit for this risk analysis are core damage frequency (CDF) and large early release frequency (LERF). Acceptance criteria are contained in U.S. NRC Regulatory Guide 1.174; the criteria for CDF are characterized in Figure 10.

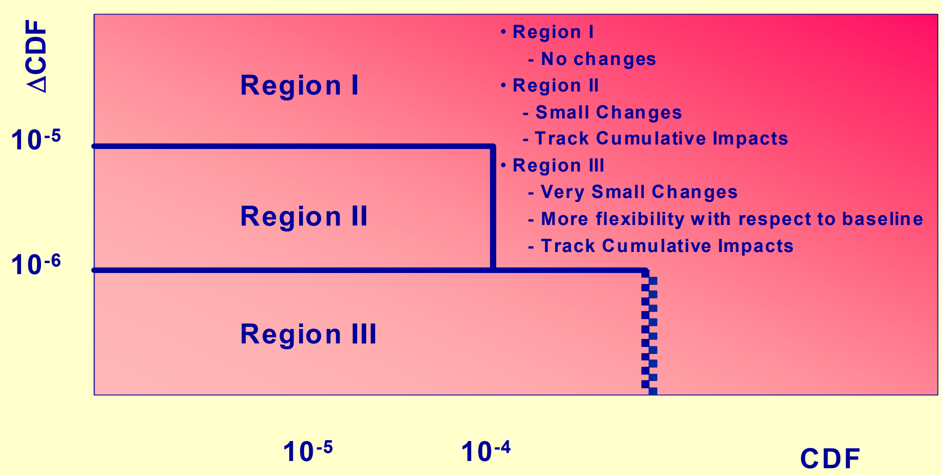

Figure 10. Acceptance Guidelines for Core Damage Frequency

The ordinate of the graph, the ΔCDF, represents the change in CDF from the change to the plant licensing basis. The abscissa of the graph, the CDF, represents the total baseline CDF from all contributors (i.e. internal events, external events, full power operations, low power and shutdown operations) prior to the plant change. No plant change is allowed if the evaluation produces values of CDF and ΔCDF which lie in Region I. Plant changes are allowed in Regions II and III; however as can be seen, Region II has more constraints on the total CDF than Region III (see Regulatory Guide 1.174 for more discussion).

A fire performance risk analysis (PRA) consists of identifying fire event data and ignition frequency, modeling the fire to predict fire damage to structures, systems, and components, incorporating the reliability of fire protection systems and features, and analyzing the response of the plant which includes systems, circuits, and human reliability. To date, fire damage assessment has primarily focused on the susceptibility of electrical cables to fire effects. Electrical cables can often be located in the vicinity of other cables, leading to failure of multiple components from a single fire; and are exposed to fires in several areas since they can often transverse through a large portion of the NPP.

The methods for conducting the PRA are described in NUREG/CR-6850 (EPRI 1011989) and are shown schematically in Figure 11. These methods are based upon a fire events database for nuclear power plants

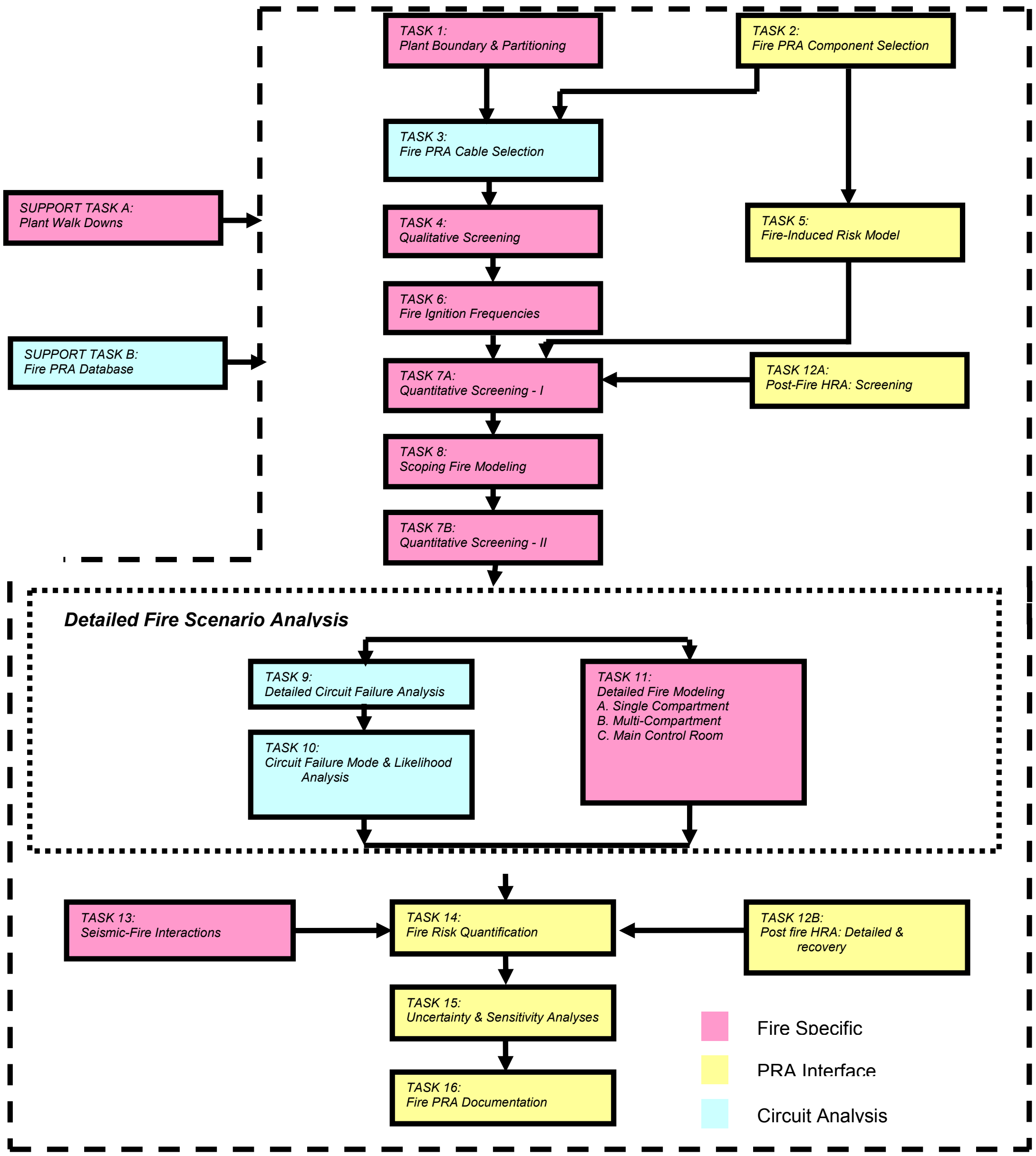

Figure 11. Fire PRA process flow chart

containing data from 1968 to 2000, which serves as the basis for fire ignition frequency and fire brigade reliability. Probabilities of spurious operations as a result of fire-induced failure of cables are based upon tests performed by the U.S industry, with more data soon to be collected by the U.S. NRC. The response of the plant is based upon the different designs of NPPs, the response of systems designed to provide core cooling under postulated fire-induced events, and the recovery of those failed systems by operators as directed by procedure. Future work is planned by NRC to further evaluate manual actions in NPPs.

The American Nuclear Society is developing a Fire PRA Standard which is performance based and directed specifically to NPPs. The Standard identifies those objectives to be attained for fire PRA, and therefore is important to identifying quality for fire PRA.

Furthermore, research studies supported by NRC are being conducted to verify and validate five fire models - from simple models based upon empirical equations, to zone models, to computational fluid dynamics. The fire models in this verification and validation are FIVE-Rev 1 developed by EPRI, the Fire Dynamics Tools developed by the NRC (NUREG-1805), the zone fire model MAGIC developed by Electricite De France, the zone fire model CFAST developed by NIST, and the computational fluid dynamics Fire Dynamics Simulator (FDS) also developed by NIST. This project is documented in draft NUREG-1824 (EPRI 1011999).

Fire Hazard and Risk Assessment in Regulations for General Applications -- Bukowski provided an overview of fire hazard and fire risk assessment in regulations for general applications unrelated to nuclear power plants. For these purposes, a "scenario" is defined as a detailed description of the building, fire and occupants which fully define the outcome. A fire hazard analysis (FHA) addresses individual design scenarios. The fire risk analysis (FRA) sums all scenarios for all combinations of distributed variables weighted by their likelihood.

Generic and specific data, along with key assumptions, are needed for the FHA. 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.

A number of questions must be answered and additional data provided to conduct the FRA, including:

- *design fire model:* 6 fires, frequency of each?
- *fire growth model:* h_c, y_s, fuel load, ventilation?
- *smoke movement model:* openings (hidden)?
- *fire detection model:* reliability?
- *fire brigade model:* response and effectiveness?
- *smoke hazard, evacuation duration, and egress models:* distribution of occupant characteristics?
- *boundary element model:* material properties, failure modes, arbitrary exposures?
- *life loss model:* toxicology of humans?

Early risk models used a brute force approach to cover all bases; current risk models trade physics for speed. The question remains: 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?

Fire Hazard and Risk Assessment in the Built Environment -- Bénichou 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 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 help/support changes to the prescriptive regulations.

NRC-C has been developing FiRECAM (Fire Risk Evaluation and Cost Assessment Model) to evaluate the risk posed by fire in an apartment or office building. A companion model (FIERAsystem, or Fire Evaluation and Risk Assessment system) has been developed for light industrial buildings. FiRECAM calculates two overall decision-making parameters: expected risk to life as measured by the expected number of deaths, and fire cost expectation as measured by the expected direct costs and fire losses. Risk is calculated from the sums of the probabilities times the consequences, where the probability of each fire scenario is based upon statistics or experience, and the consequences of each fire scenario is based on the time dependent calculation.

The fire is characterized by a number of parameters: types of fire (smoldering, non-flashover, or flashover), door condition (open or closed), location (all floors), and season (winter, spring/fall or summer). A fire scenario is a combination of the fire characteristic parameters (e.g., a flashover fire with door open, on 2nd floor, in winter), and the scenario probability equals the product of the probability of the parameters.

FIERAsystem evaluates compliance with established fire safety objectives. The model assesses life hazard and fire costs in buildings, including the number of deaths and property damage and downtime. The risk calculation takes into account the reliability of active fire protection systems and produces an estimate of risk to life using hazard analysis of a set of scenarios, along with the expected cost. The eight main sub-models compute: fire development, smoke development, detections and suppression effectiveness, failure of boundaries, fire department response and effectiveness, occupant response and evacuation, radiation to adjacent buildings, and economic impact and downtime. The life hazard sub-model, which predicts the probability of death, considers the hazards due to thermal radiation from the hot layer smoke, and due to exposure to CO, CO_2 and high temperature at a location 1.5 m above the floor, all based upon predictions from the fire model. The overall probability of death at any time is assumed to be the sum of the probabilities from the individual hazards.

Bénichou presented two case studies to demonstrate the use of these models: a three story commercial building analyzed with FIERAsystem, and a study using FiRECAM to assess the reduction of risk to life as a consequence of upgrades to a sprinkler system, additional stairwells, and/or smoke control for a building. These studies highlighted the challenges that exist for implementing reliable risk analyses, namely:

- Reliability of fire statistics data
- Data on reliability and efficiency of active fire protection systems
- Data on human behavior
- Data on probability of scenarios
- Agreement on the definition of design fires
- Agreement on the definition of tenable conditions
- Validation of probabilistic models
- Validation of the overall systems
- How to deal with expert judgement?

<u>Integration of Models (C. Beyler)</u>
In the ideal situation, one would be able to fully integrate models for fire dynamics, building dynamics, and human dynamics into 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 can be difficult.

What is required for successful model integration? Four things: 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 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 (as has been done using CSEARE-Risk, for example). 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 summary, 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.

III. RESEARCH PRIORITIES

A general discussion followed the day and a half of presentations summarized above to help clarify issues and to ferret out key themes. In brainstorming fashion, the participants identified barriers to implementation of PBD and suggested areas for research that might be conducted by FORUM members or others to help overcome these barriers. The list (included as Appendix A) was organized by a subcommittee and presented to the workshop as a whole the following day. The FORUM members were given the option of modifying the list after returning to their institutions, and several members did. These additions have been incorporated explicitly or absorbed into closely related needs.

Observations

There are a number of observations that can be made as a result of the workshop:

- Constructing a solid scientific foundation for performance-based fire safety design is a worthy goal for the FORUM to espouse because PBD can be used to support designs outside of the applicability of prescriptive codes in a balanced, cost-effective and safe manner.
- Performance-based fire safety design already exists and is practiced in many parts of the world today.
- The implementation of PBD varies widely internationally, and is tied to the individual country's regulatory system.
- Current tools and level of understanding are adequate to support certain classes of performance-based fire safety design.
- There are many PBD applications that exceed the capabilities of these tools.
- In some countries, PBD is used primarily to reduce costs or to allow exceptions to prescriptive guidelines without the scientific basis for assuring fire safety.
- PBD as practiced today in some countries is a boutique approach, and will remain in that status until a more solid scientific foundation is established.
- The research needs identified in the current workshop are closely reminiscent of the needs identified in previous workshops over the past 15 years.

Vision

Recall the goal from the 1991 WPI conference:[3]

> "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."

One could argue that this goal has been met, if not by 2000 then by 2006. How do we move beyond this goal? With 15 years of research behind us, what can we conceive of today that may be *obtainable* in the *next* generation of PBD tools and performance-based codes? Consider the following desirable enhancements to our fire protection engineering arsenal:

- The ability to predict the reduction in ignition or fire spread provided by:
  - a change in materials and products;
  - enhanced fire detection/alarm systems;
  - alternative suppression systems.
- The ability to determine the impact on the safety of building occupants of design changes in:
  - smoke control systems;

  - partitions;
  - corridors, doorways, stairs;
  - elevators;
  - areas of refuge;
  - novel egress approaches for occupants with impaired mobility, sight, hearing, or mental state.
- The ability to determine the safety/effectiveness of first responders provided by new designs for:
  - fire sensing and alarm;
  - delivering information on the building, occupants, fire spread, and firefighting resources;
  - elevators and stairs;
  - fire suppression techniques;
  - security and multi-hazard situations.
- The ability to determine the structural response of a building to fires of varying magnitude, including those initiated by criminal acts and leading to full building burn-out.
- The ability to determine the impact of fire on neighboring buildings, infrastructure, and business interruption.
- The ability to determine the level of safety provided by standard fire test methods and legacy prescriptive codes.
- The ability to estimate the uncertainty in all of the above deterministic predictions and incorporate them into reliable probabilistic calculations of hazard and risk.

Key Obstacles

The above enhancements are likely to be obtained in an incremental fashion, with some successes achieved in a matter of years and others taking decades. Numerous technical obstacles that must be overcome to attain them are mentioned in the complete list of research needs included in Appendix A. The overarching obstacles to success are summarized here:

1. An incomplete hierarchy of rigorous benchmark fire experiments and simulations;
2. Lack of tractable, generalizable combustion models that capture the essence of solid fuels, including simple multi-step reaction mechanisms for prediction of CO and soot;
3. Insufficient data and experimental facilities for unraveling all of the significant relationships within, and interactions among, fire dynamics, structural dynamics, and human behavior;
4. Incompatible interfacing among fire models, structural models, human behavior models, and risk models;
5. Limited data and means to track uncertainty in risk and hazard analysis, and inability to incorporate rare, high consequence events;
6. Limited computational speed, memory size, and data file exchange rate;
7. Lack of vision on the part of most of those who would be involved in the key efforts (and those who would pay for the research);
8. Lack of FORUM unity on the types of cases toward which the research should be directed, and an inability to focus resources on PBD-driven research given the pressures of here-and-now problems.

The last two obstacles are policy related; obstacle 6 will be overcome independent of FORUM actions with the natural progression of next-generation computers. By turning the first five obstacles in the list into positive statements, we can establish overarching goals and their relationship to each other as shown schematically in Figure 12. These overarching goals are further explained in the following paragraphs.

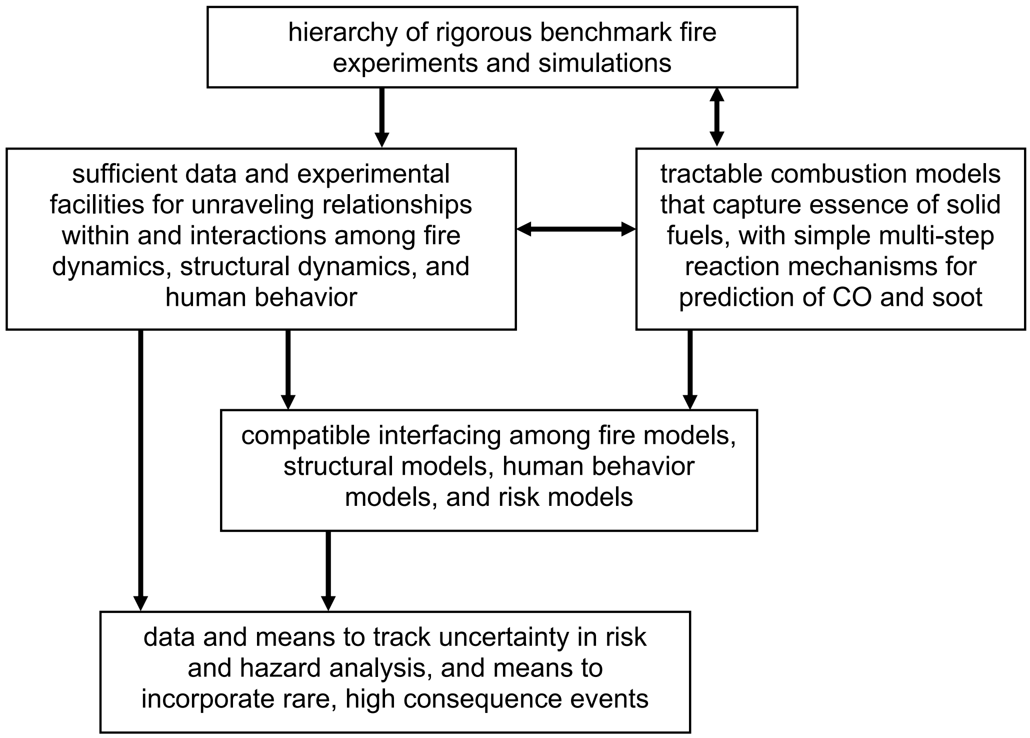

Figure 12. Overarching goals and their inter-relationships

<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, such as fire suppression and the phenomena and conditions suggested by the red boxes in Tables 3 and 4 of this report. 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 performance-based design. 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.

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, etc.

Data and experimental facilities for unraveling relationships within structural models

Research in structural analysis as it bears on performance-based fire safety design 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 thermal-mechanical 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.

Data and experiments for unraveling relationships within human behavior models

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.

Data and experimental facilities for determining interactions among fire dynamics, structural dynamics, and human behavior

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.

Solid fuel combustion models

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.

Compatible interfacing among fire, structural, human behavior, and risk models
Performance-based design 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.

Uncertainty in risk and hazard analysis, and incorporation of rare, high consequence events
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. New risk assessment algorithms are required which interface more directly with evolving fire, structural, and human behavioral models, and 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

Research Priorities and Commitments

At the October 2006, meeting of the FORUM in Wellington, New Zealand, the 14 members in attendance prioritized the different performance-based design-driven research areas and identified enhancements to fire safety science that each laboratory was committed to pursue. Prioritization was done by grouping the enhancements listed on pages 34 and 35 of this report and assigning a low, medium, or high priority rating to each. A laboratory's commitment to conduct appropriate research in these areas was gauged by the fraction of one's budget that the laboratory was willing to invest. Table 5 shows the collective results of this exercise.

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.**

In general, the commitment to support research in a given area was consistent with its priority. (Note that a low priority or low commitment in Table 5 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 5. Combined Priority Rankings of Areas for Enhancement of PBD Capabilities and Levels of Commitment to Support Research by FORUM Members

Enhanced Capability	Priority	Commitment
prediction of reduction in fire growth and products of combustion provided by enhanced fire detection/alarm systems and alternative suppression systems	Highest	High
estimation of uncertainty in deterministic predictions and incorporation of uncertainties into reliable probabilistic calculations of hazard and risk	High	High
determination of the impact on safety of building occupants of design changes in smoke control systems, compartmentation, and egress systems	High	High
prediction of reduction in ignition, fire growth and products of combustion provided by changes in materials and products (including geometry and configuration)	High	Highest
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	Moderate
determination of the potential and impact of fires for damaged or degraded structures	Moderate	Low
determination of the impact of fire on neighboring buildings and physical infrastructure	Moderate	Low
determination of the impact of fire on business interruption	Low	Low
determination of the level of safety provided by standard fire test methods and legacy prescriptive codes	Low	Moderate
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	Moderate

FORUM members are individually responsible for setting their own priorities and timelines, and are strongly encouraged to consider the research agenda put forth in this document and the priorities set in Table 5 when doing so. Collaborative projects to shore up and expand the scientific foundation for performance-based codes and building design proposed at the 2006 meeting of the FORUM in New Zealand included: establishing the variability associated with room fire testing (based upon the ISO 9705 corner test) with different room contents and arrangements; examining the response of structural members, assemblies and systems (including connections) to real fire environments; and determining the failure modes and weak links in fire resistance of partitions. FORUM members are committed to documenting progress on these collaborative efforts as well as the results of their individual research programs in support of this research agenda.

IV. REFERENCES

[1] "International Conference on Firesafety in High-Rise Buildings," Harold Nelson, Editor, General Services Administration, April 12-16, 1971, Airlie House, Warrenton, VA.

[2] *Final Report on the Collapse of the World Trade Center Towers*, NIST NCSTAR 1, National Institute of Standards and Technology, Gaithersburg, MD, September 2005.

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

[4] "Measurement Needs for Fire Safety: Proceedings of an International Workshop," NISTIR 6527, National Institute of Standards and Technology, Gaithersburg, MD, June 2000.

[5] Hurley, M., "A Research Agenda for Fire Protection Engineering," NIST GCR 00-791, National Institute of Standards and Technology, Gaithersburg, MD, June 2000.

[6] Cox, G. (editor), "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.

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

[8] "Fire Resistance Determination and Performance Prediction Research Needs Workshop: Proceedings," NISTIR 6890, National Institute of Standards and Technology, September 2002.

[9] "Fire Protection of Structural Steel in High-rise Buildings," NIST GCR 04-872, National Institute of Standards and Technology, Gaithersburg, MD, July 2004.

[10] 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, National Institute of Standards and Technology, Gaithersburg, MD, April 2004.

[11] *ICC Performance Code for Buildings and Facilities (2001 ed.)*, International Codes Council, Falls Church, VA.

[12] *Building Construction and Safety Code (NFPA 5000 2003 edition*) Chapter 5 Performance-based Option, National Fire Protection Assn, Quincy, MA 02269.

[13] National Building Code of Canada 2005 Vols. 1 & 2, National Research Council of Canada, Ottawa, Canada.

[14] SFPE Engineering Guide to Performance-based Fire Protection, The Society of Fire Protection Engineering, Bethesda, MD, 2000.

[15] International Fire Engineering Guidelines, 2005 edition, jointly published by International Codes Council (US) Falls Church, VA, National Research Council (Canada), Ottawa, Ontario, Department of Building and Housing, Wellington NZ and Australian Buildings Code Board, Canberra, AU, 2005.

[16] Bukowski, R. W., "Standards Linkages to a Performance-Based Regulatory Framework." in *Performance in Product and Practice. CIB (International Council for Innovation and Research in Building and Construction) World Building Congress*. Paper 262. Proceedings. April 2-6, 2001, Wellington, New Zealand, 1-9 pp, 2001

[17] Acceptable Solutions Performance in Product and Practice. CIB (International Council for Innovation and Research in Building and Construction) World Building Congress. Proceedings. April 2-6, 2001, Wellington, New Zealand, 2001

[18] Meacham, B., "Identifying and Regulating Multiple Levels of Performance," in Performance in Product and Practice. CIB (International Council for Innovation and Research in Building and Construction) World Building Congress. Proceedings. April 2-6, 2001, Wellington, New Zealand, 2001.

[19] Qualitative versus Quantitative Aspects of Performance-based Regulation (Beller, D. *et al*) Performance in Product and Practice. CIB (International Council for Innovation and Research in Building and Construction) World Building Congress. Proceedings. April 2-6, 2001, Wellington, New Zealand, 2001

[20] Eurocode 1: Actions on Structures Part 1-2: General Actions –Actions on structures exposed to fire (EN 1991-1-2)

[21] BS 7974, the Code of practice Application of Fire Safety Engineering Principles.

[22] McGrattan, K., and Forney, G., *Fire Dynamics Simulator (Version 4): User's Guide*, NIST SP 1019, National Institute of Standards and Technology, Gaithersburg, MD, March 2006.

[23] http://www.sfpe.org/Publications.aspx

[24] Schirmer Engineering, SFPE Case Study, 2002

[25] Peacock, R. D. and Pitts, W. M., *Extended Abstracts and Presentations from the Workshop on Fire Growth and Spread on Objects, March 4-6*, 2002, NIST SP 998 (2003).

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

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

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

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

[30] 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.

[31]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.

[32] Fire Safety Engineering in Buildings, 1997, DD240, Part 1: Guide to the Application of Fire Safety Engineering Principles, British Standard Institute, London, UK.

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

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

[35] Gwynne, S., Galea, E.R., Owen, M., Lawrence, P.J., and Filippidis, L., "A Review of the Methodologies Used in Evacuation Modeling," *Fire and Materials 23* (6) , 383-389, Nov.-Dec., 1999.

[36] Kuligowski, E. D.; Peacock, R. D., "Review of Building Evacuation Models," NIST TN 1471; NIST Technical Note 1471; July 2005.

[37] Lord, J.; Meacham, B.; Moore, A.; Fahy, R.; Proulx, G. “Guide for Evaluating the Predictive Capabilities of Computer Egress Models.” NIST GCR 06-886; 107 p. December 2005.