Making the Nation Safe from Fire

A Path Forward in Research

Committee to Identify Innovative Research Needs to Foster Improved Fire Safety
in the United States

Board on Infrastructure and the Constructed Environment

Division on Engineering and Physical Sciences

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Preface

This study was commissioned by the National Science Foundation (NSF) prior to the attack on the World Trade Center in New York on September 11, 2001. That attack led to the fire-induced collapse of three major commercial buildings and the loss of thousands of lives. The report was being finalized when the nightclub fire in West Warwick, Rhode Island, on February 20, 2003, claimed 99 more lives. Both of these events underscore this nation's continuing vulnerability to major fires. It is this committee's view that an incomplete understanding of the phenomenon of fire, the strategies and technologies to control it, and human behavior in chaotic, life-threatening situations contribute to unnecessary human and economic losses. Of course fire is not a new problem in the United States. In 1871 the City of Chicago burned to the ground, destroying the world market center for grain, livestock, and lumber. Over 17,000 buildings were destroyed and 90,000 people were left homeless. While unprecedented, the World Trade Center collapse is yet another exclamation mark in the history of fire devastation in the United States. It does, however, present a new dimension heretofore not fully considered in the design of buildings and civil infrastructure projects—the potential use of fire as a weapon.

Discussion of national fire research needs by distinguished panelists and committee members is also not new. In 1947 President Harry Truman established the President's Commission on Fire Prevention, which featured a committee on fire research. In 1959 the National Research Council's Committee on Fire Research found a dearth of basic research directed toward a fundamental understanding of the phenomena of ignition, fire growth, and fire spread. In 1973 the National Commission on Fire Prevention and Control recommended that federal funding of fire research be increased by $26 million per year ($113 million in today's dollars). Unfortunately, such support for fire research was not forthcoming. In fact, since 1973, federal funding of university fire research has declined approximately 85 percent in real terms.

While the United States continues to have one of the worst fire loss records in the industrialized world, new engineering tools are emerging that offer great hope for higher levels of safety at less cost. Most particularly, new performance-based codes and fire safety design methods are now becoming available. These new approaches not only stand to offer more cost-effective investment of the fire safety dollar but also will permit more reliable prediction of building fire performance and identification of potential catastrophic failure scenarios. Additionally, they will enable the more widespread use of innovative building systems, devices, and methods.

The committee that prepared this report was charged with assessing the state of fire safety research and describing the potential role of the NSF in improving fire safety in the United States. This report highlights markers along a pathway to the future, discusses the nation's fire research needs and the resources that will be required, and suggests a role for NSF and other key agencies and institutions. The committee urges national leaders in government and industry to aggressively support fire research needs, filling voids in the body of knowledge, sharpening engineering tools, and creating a database that will allow performance-based approaches to maximize their contribution to public safety in the United States.

David A. Lucht, *Chair*
Committee to Identify Innovative Research Needs
to Foster Improved Fire Safety in the United States

Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's (NRC's) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Benigno E. Aguirre, University of Delaware,
Howard Baum, National Institute of Standards and Technology,
Doug Dierdorf, Air Force Research Laboratory,
Brian Meacham, Arup,
Jake Pauls, Consultant,
B. Don Russell, Texas A&M University, and
Richard N. Wright, National Institute of Standards and Technology (retired).

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Frank H. Stillinger, Princeton University. Appointed by the National Research Council, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Contents

Acronyms

ASCE	American Society of Civil Engineers
BRFL	Building and Fire Research Laboratory (NIST)
FEMA	Federal Emergency Management Agency
FPE	fire protection engineering
HPM	high-performance materials
JFSP	Joint Fire Science Program
NBS	National Bureau of Standards (now NIST)
NCFPC	National Commission on Fire Prevention and Control
NEHRP	National Earthquake Hazard Reduction Program
NFIRS	National Fire Incident Reporting System
NIST	National Institute of Standards and Technology
NRC	National Research Council
NSF	National Science Foundation
PBSD	performance-based seismic design
RANN	Research Applied to National Needs
SFPE	Society of Fire Protection Engineers
USFA	United States Fire Administration
USGS	United States Geological Survey

Executive Summary

The world watched in horror as the towers of the World Trade Center collapsed on September 11, 2001, demonstrating yet again the devastating destructive power of uncontrolled fire. On February 20, 2003, a nightclub fire in West Warwick, Rhode Island, left 99 people dead and more than 150 injured. Not since the 70-year period from 1871 to 1941, during which the Great Chicago Fire destroyed the center of the world market for grain, livestock, and lumber and the Triangle Shirtwaist Factory fire and the Cocoanut Grove nightclub fire killed hundreds, has the ability of fire to cause damage and harm figured so prominently in the national consciousness. However, to those involved in fire safety, the recent horrific events only reinforce the knowledge that fire is a dangerous and relentless foe, and one that is not fully understood or controllable despite years of effort and countless billions spent on prevention, mitigation, and response.

In 1968 Congress passed the Fire Research and Safety Act, which mandated creation of a National Commission on Fire Prevention and Control (NCFPC) to study the nation's fire problem. The commission conducted an in-depth study, held hearings throughout the country, and in 1973 submitted its report, *America Burning,* to the President and Congress. The first page of the report stated as follows: "Appallingly, the richest and most technologically advanced nation in the world [the United States] leads all the major industrialized countries in per capita deaths and property loss from fire" (NCFPC, 1973).

In response to the *America Burning* report, Congress passed the Fire Prevention and Control Act of 1974, which created what is now the United States Fire Administration and the National Fire Academy, currently located within the Federal Emergency Management Agency (FEMA). This legislation also established the Fire Research Center at the National Bureau of Standards—now the National Institute of Standards and Technology (NIST)—thereby providing the basis for the existing program at NIST. As a result of concerted efforts to improve fire safety (particularly the advent of an affordable home smoke detector), residential deaths in the United States have declined since then, but this country continues to sustain unnecessarily high levels of fire-related death and destruction. As part of its strategy to improve fire safety, the NCFPC recommended in *America Burning* that federal funding of fire research be increased by $26 million per year ($113 million in today's dollars). That recommendation was not implemented.

In the early 1970s, the National Science Foundation (NSF) supported fire research at a level of approximately $2.2 million every year ($9.6 million in today's dollars) through a program known as Research Applied to National Needs (RANN). The RANN program was terminated in 1977. Subsequently, a fire research grants program at the National Bureau of Standards (now NIST) was funded at about $2 million annually ($8.7 million in today's dollars). However, by 2002, the NIST fire research grants program had declined to only $1.4 million, a decrease of 85 percent from the 1973 level when adjusted for inflation. As a consequence of the limited funding that has been made available, the scope and breadth of university fire research in the United States have declined dramatically over the past 30 years.

As in any technical field, the production of advanced degree scholars with specialized expertise and career paths in fire science and engineering is critical to both conducting the needed research and training the next generation of investigators, teachers, and practitioners. Unfortunately, reduced research funding over the past three decades has caused U.S. production of career-directed young men and women who will make and implement the important fire safety discoveries of the future to all but dry up.

In recognition of the slow pace of advancement in the fire safety field, the paucity of basic research, and the small number of universities offering research and training opportunities, NSF asked the National Research Council (NRC) to help it determine how to align its programs and resources to advance fire safety in the United States. The Committee to Identify Innovative Research Needs to Foster Improved Fire Safety in the United States was appointed to plan and conduct a workshop that would survey and assess the current state of knowledge, research, education and training, technology transfer, and deployment of practices and products in the fire safety field. The committee also set out to help define how NSF could marshal the intellectual, financial, and institutional resources of the United States to develop the knowledge necessary to save lives and reduce injuries and property loss from fire. The workshop was held on April 15 and 16, 2002, and attended by more than 50 national and international experts from various disciplines involved in fire safety.

During the course of the workshop, many themes emerged from the perspectives of the different disciplines represented. However, the committee's overarching conclusion is that there are significant gaps in our knowledge of fire safety science and fire loss mitigation strategies. As a result, the threat posed by fire to people, property, and economic activity is neither well understood nor fully appreciated. The ramifications of these gaps manifest themselves in many ways. For example, the need for a sound and complete knowledge base has never been greater in light of the recent emergence of performance-based codes published by the International Code Council (ICC, 2001) and the National Fire Protection Association (NFPA, 2003) and performance-based design practices such as those released by the Society of Fire Protection Engineers (SFPE, 2000). Performance-based codes and design practices provide a real opportunity to make buildings safer at less cost and further open the doors to innovative building systems, devices, and materials. However, current knowledge gaps force engineers and regulatory officials to apply performance-based practices in a climate of significant uncertainty: For instance, could other buildings suffer catastrophic failures like those that occurred on September 11, 2001, at New York's World Trade Center? In other words, substantial amounts of money continue to be invested in building fire safety features without the benefit of scientifically informed expectations of the resulting safety performance. As a result of the workshop presentations and discussions and its own subsequent deliberations, the committee found significant knowledge gaps in eight topical areas:

- *Fire and explosion fundamentals*. Behavior of fire in buildings where the fire itself has induced changes in compartment geometry and venting; improved prediction from first principles of flame spread and extinction over condensed-phase fuels; explosion phenomena.
- *Materials and retardants*. Coatings, catalysts, additives; smoke and toxicity; melt, flow, and dripping; pyrolysis and flammability; high-temperature performance.
- *Fire protection systems***.** Chemical and physical suppression and extinction phenomena; smart suppression; multiple signature detection.

- *Engineering tools***.** Modeling fire growth, detection, and suppression system performance; hazard analysis and probabilistic risk assessment methodologies; uncertainty analysis; fire scenario definition and quantification.
- *Structural fire performance*. Fuel loads; fire severity and fire-induced changes in geometry and venting; high-temperature properties of materials; performance of structural connections; development and verification of analytical methods.
- *Human behavior***.** Evacuation modeling and data; stair flows and counter flows; group dynamics and decision making; post-9/11 human perceptions and behaviors; effects of toxic products; human factors.
- *Public policy***.** Decision-making methods and validation; quantification of fire severity and frequency; public safety goals; relationship between public policy and technical risk analysis.
- *Data***.** Fuel load, distribution of building contents; explosion losses; thermodynamic, thermophysical, and thermochemical material property data; quantification of model uncertainty; human behavior data for building evacuation models; cost/loss metrics.

Identifying priorities among such a wide range of research needs is a significant challenge and beyond the scope of a single workshop. As noted by the various workshop presenters, almost all areas connected with fire safety will benefit from additional resources and intellectual effort. Because NSF has traditionally served as an incubator for coordinated, interdisciplinary research programs for hazard reduction that involve the university research community, government agencies, and the private sector, the committee identified NSF as the most logical agency to support a new university grants program in fire research, not only to help advance the state of knowledge but also to support the production of young scholars—the human capital so badly needed for the future of U.S. fire safety science and engineering. At the same time, the committee believes that NSF has an opportunity to act as a catalyst for a well-coordinated program of improved fire safety.

The committee's findings and recommendations are presented as a path forward for NSF to expand its role in making the nation safe from fire.

FINDINGS

The High Cost of Fire. Unwanted and preventable fire in the United States continues to exact an unacceptably high cost in terms of human suffering and economic losses. The threat to people, property, and economic activity is neither well understood nor fully appreciated by policy makers and the public at large.

Benefits of Performance-Based Practices. Performance-based building codes, which are now available in the United States for adoption by state and local governments, offer real promise for regulators and public officials to institute regulations that reflect a better understanding of risks and improved safety performance for buildings in their communities. However, performance-based codes depend on the ability of engineers to predict how buildings will perform under fire conditions. There are significant gaps in the data and knowledge base needed to support performance-based codes, engineering tools, predictive models, and risk assessment.

Insufficient Funding. The current funding levels and organizational infrastructure for fire research in the United States are inadequate to address even the most fundamental research needs that were raised at the workshop and subsequently discussed by the committee. The documented costs of unwanted fire, in both human and economic terms, justify substantial investment in fire safety research and the development and deployment of the products of that research. The public at large, businesses, institutions, and government agencies can all benefit from better safety at less cost.

Coordination and Cooperation. Improving fire safety in the United States depends on the combined efforts of a range of disciplines and communities, from fire researchers and academics to the fire services, public officials, codes and standards groups, private industry, government agencies, and professional societies. There is a need for better communication, cooperation, and integration of national fire safety efforts.

Important Role for Universities. University-based fire research has all but evaporated in the United States over the past three decades. In addition to choking off new scientific discovery, this turn of events has all but eliminated the production of young scholars with a career commitment to inquiry and teaching in the fire safety sciences.

Role of the National Science Foundation. The NSF has traditionally served as an incubator for coordinated, interdisciplinary research programs for hazard reduction that involve the university research community, government agencies, and the private sector. As compared with more mission-oriented agencies, an NSF commitment can be particularly beneficial in areas of basic research that will improve our understanding of the nature of fire; its detection, suppression, and control; technology applications (e.g., next-generation residential smoke detectors, material coatings, and intrinsically safe home appliances); human behavior; and interdisciplinary studies to better inform building codes, design, and regulatory/public policy processes.

The National Earthquake Hazards Reduction Program Model. Through NEHRP, the U.S. government has aggressively pursued such an integrated approach for addressing the earthquake hazard. Its approach has resulted in greatly improved building performance and reduced levels of injury and death.

RECOMMENDATIONS

1. **NSF should reestablish and fund a program in basic fire research and interdisciplinary fire studies. Funding of approximately $10 million per year is recommended to initiate this effort. This initial funding level would restore the NSF investment in fire research to its 1973 level (in today's dollars). It should be reconsidered once a robust research infrastructure is in place.**

The level of fire research at U.S. universities has declined greatly since the RANN program was terminated at NSF. Given NSF's charter to support basic research and education, the committee believes that NSF is the appropriate agency for administering a reinvigorated and robust university grants program in fire research. Funding of university principal investigators and graduate students needs to be emphasized, both to accomplish research goals and to invest in the nation's next generation of investigators and teachers—the human capital so necessary for continuous improvement in fire safety. There are many on-going initiatives and programs within NSF (e.g., nanotechnology, sensors, high-performance materials, surface chemistry, human and social factors in hazard mitigation, structural system performance) that could provide a logical nexus (not to speak of existing funding) for reestablishing a comprehensive and interdisciplinary focus on fire safety within NSF.

This report makes no attempt to suggest a national research agenda or to identify fire research priorities for the nation. Such prescription was beyond the scope of this effort. The committee believes that work previously done by others, such as the SFPE Research Agenda 2000, the United States Fire Administration (USFA), and the Joint Fire Science Project (JFSP), along with the discussion of topical areas found in this report, will serve as a valuable resource for evaluating initial research proposals. In the short term, NSF can make use of this report and recent work by others to evaluate research proposals. The committee believes that the recommended funding level of $10 million annually would be an appropriate starting point for supporting multiple investigators in the physical, social, and behavioral sciences and engineering, with an emphasis on fostering interdisciplinary activities. In the longer term, NSF should coordinate its efforts with other agencies to build an integrated and robust research infrastructure for fire safety. Once such an infrastructure is in place, higher funding levels (such as those recommended in *America Burning*—approximately $113 million in today's dollars) should be considered. The committee would note that significant resources are already available through the multiplicity of mission-directed fire safety activities currently under way in federal agencies. Better coordination of existing fire safety planning, research, and implementation and their integration under a renewed initiative by NSF could create significant opportunities to leverage research dollars, increase technology transfer, and speed deployment of new methods and products.

2. A coordinated national attack to increase fire research and improve fire safety practices should be launched. The committee recommends that NSF support exploratory activities to determine if a model such as NEHRP or any other model that combines integration, cooperation, stakeholder involvement, and collaboration in research could hasten the development and deployment of improved fire safety practices through more coordinated, better targeted, and significantly increased levels of fire research in the United States.

Many workshop participants emphasized that, in addition to addressing the paucity of basic research, there also needed to be better coordination, cooperation, and communication among the stakeholders in national fire safety. The United States lacks an adequately funded and well-coordinated national fire research program such as that for earthquake engineering embodied in the NEHRP. Most federally funded fire research is mission-focused and conducted by user agencies, which show little interest in leveraging the research investment, supporting graduate students, or transferring technology. Given the emergence of performance-based design and regulatory practices, the fire safety field is desperately in need of integrated research findings targeted to the priority needs of practice. A number of possible national strategies for achieving this goal were discussed at the workshop. The committee believes that a national attack on the U.S. fire problem requires interdisciplinary communication, cooperation, and coordination supported by adequate funding. The earthquake safety movement, which began in the 1970s and has evolved into the successful NEHRP is an excellent model for the fire safety community to consider. An effort modeled on the NEHRP could engage all federal agencies currently involved with fire safety and, at a minimum, should link a reinvigorated NSF university grants program with the valuable efforts currently under way at other agencies, such as the National Institute of Standards and Technology and the U.S. Fire Administration.

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Introduction

Death rates from unwanted fires in the United States are among the highest in the industrialized world. Despite declines for residential fire death rates over the past 25 years, the U.S. remains a world leader in fire losses (Geneva Association, 2002). The total cost of fire in the U.S. (fire losses plus the costs of fire safety measures) is estimated between $100 and $200 billion per year (Hall, 1999) or between 1 and 2 percent of the gross domestic product. These figures describe a serious national problem, and even though it has been mitigated somewhat by advances in applied research to improve fire safety, basic research into the nature of fire, its causes, characteristics, and effects on people, products, structures, and the environment have the potential to further mitigate the problems. Further improvements in design, construction, and loss reduction strategies that will protect constructed facilities and the people and equipment housed within them are still possible. However, these gains will only be realized if the knowledge base is continually expanded through basic and applied research that has a ready path into practice.

BACKGROUND

In 1968 Congress passed the Fire Research and Safety Act, which mandated creation of the National Commission on Fire Prevention and Control to study the nation's fire problem. The commission conducted an in-depth study and held hearings throughout the country. In 1973 it submitted its report, *America Burning,* to the President and Congress. Page one of the report stated as follows: "Appallingly, the richest and most technologically advanced nation in the world [the United States] leads all the major industrialized countries in per capita deaths and property loss from fire" (NCFPC, 1973).

America Burning offered 90 recommendations for addressing the American fire problem. Among them were creation of the United States Fire Administration (USFA) and the National Fire Academy for the nation's fire services. These agencies were created under the Fire Prevention and Control Act of 1974 and are now functioning within the Federal Emergency Management Agency (FEMA). This same legislation established the Fire Research Center at the National Bureau of Standards—now the National Institute of Standards and Technology (NIST)—thereby consolidating existing programs.

Under the topic "Research for Tomorrow's Fire Problem," *America Burning* also recommended a $26 million increase in federal funds for fire research ($113 million in today's dollars). That recommendation was never acted on.

During the 1960s and early 1970s the NSF Research Applied to National Needs (RANN) program did have a fire research element, under the direction of Ralph Long. RANN funded university professors and graduate students at a host of universities including Harvard, Massachusetts Institute of Technology, Brown, Princeton, the University of California at

Berkeley, and others. The funding was approximately $2.2 million per year in 1973 ($9.6 million in today's dollars). The RANN program was terminated in 1977.

Subsequently, a fire research grants program at NBS was funded at approximately $2 million annually ($8.7 million in today's dollars). Later on, however, funding for the NBS fire program was reduced, so that both the in-house and grants programs declined. NIST currently administers vestiges of the grants program, at a level of approximately $1.4 million (in today's dollars). Adjusted for inflation, this fire research grants program has declined nearly 85 percent. As a result, there is no credible university grants program for fire research supported by the federal government today.

Aside from the extramural fire research grants program at NIST, full-time government employees perform substantial in-house research. It is reported that over the past decades the number of NIST fire research staff declined by more than 50 percent (Lyons, 2002). Moreover, funding for in-house NIST fire research no longer comes primarily from direct congressional appropriation—about half now comes from other agencies. Quintiere has made a strong case for change: "Research funding has been all but eliminated for fundamental studies in fire. These fundamental studies are essential for developing the infrastructure of the discipline and the practice of fire protection engineering" (Quintiere, 2002).

In 2002, the Society of Fire Protection Engineers (SFPE) performed a study of federally funded fire research. It identified a total of $37 million in fire research support among 11 agencies (SFPE, 2002). The preponderance of this support targets shorter-term mission support functions. About 87 percent is used to support federal salaries, contractors, and consultants. About 13 percent ends up supporting university professors and graduate students. It is not known what fraction, if any, is focused on longer-term, higher-risk basic research.

INVOLVEMENT OF THE NATIONAL RESEARCH COUNCIL

NSF, recognizing its potential role in fostering a strong research base to support improved fire safety activities, requested that the National Research Council (NRC) create a committee to plan and convene a 2-day workshop to assess the state of knowledge in fire safety and suggest ways the NSF could align its programs, resources, and collaborations to help advance fire safety in the United States. In response to that request, the NRC assembled an independent panel of experts, the Committee to Identify Innovative Research Needs to Foster Improved Fire Safety in the United States, under the auspices of the Board on Infrastructure and the Constructed Environment. The 16 members of the committee have expertise in fire safety, fire science, fire protection engineering, structural engineering, polymer chemistry, materials performance, building codes and standards, architecture, emergency response, human behavior, and disaster and crisis management. Biographical information about the committee members is provided in Appendix A.

STATEMENT OF TASK

The committee was charged with convening a 2-day workshop to survey and assess the current state of knowledge, research, education and training, technology transfer, and deployment of practices and products in the fire safety field. The objective for the workshop was to define how best to marshal U.S. intellectual, financial, and institutional resources to develop the needed knowledge and break down the barriers to improvements in building design, construction methods, materials, and operations and maintenance that will save lives and reduce injuries and property loss from fire. Although the state of fire research and the research infrastructure were important topics of discussion, the workshop did not seek to develop a research agenda, building instead on recent efforts to identify research needs (e.g., SFPE, 2000). Similarly, the relative merits of performance-based codes and prescriptive approaches were not to be a focus issue, although the question of how best to develop a science base to support performance-based codes was. A critical question for workshop participants was how best to take advantage of NSF-sponsored cutting-edge research in materials and applications that can improve fire safety.

The workshop presentations paid particular attention to the barriers that exist at the intersections of disciplines and institutional sectors as well as to the opportunities that these intersections provide for interdisciplinary research to eliminate barriers. Although these areas often tend to be overlooked by discipline-based activities, the barriers are frequently the primary inhibitors of progress. The outcome of the workshop and the subsequent committee meeting was a clearly articulated statement of research, education, and technology-transfer needs for improved fire safety in the United States, the resources necessary to meet them, and a path forward for NSF and other key U.S. science and technology agencies and institutions.

ORGANIZATION OF THE WORKSHOP

The Workshop to Identify Innovative Research Needs to Foster Improved Fire Safety in the United States was held on April 15 and 16, 2002, in Washington, D.C. In addition to committee members, 36 internationally recognized experts from academia, government, and industry attended the workshop (Appendix C). The participants were chosen for their expertise in fire science, fire protection engineering tools, human behavior, and regulatory processes and represented a broad range of perspectives. The morning of the first day provided a glimpse of the present "fire problem" in the United States. There was also a presentation describing the development of the National Earthquake Hazards Reduction Program (NEHRP), which was offered as a model for improving safety. The remainder of the first day and most of the second day were devoted to invited presentations and moderated discussion focused on seven topics:

- Fire and explosions
- Materials and retardants
- Fire protection systems
- Fire protection engineering tools
- Structural performance
- Human behavior
- Public policy

The invited presenters were requested to submit written papers prior to the workshop to summarize the state of the art in their particular area of expertise. The papers and workshop presentations are included on a CD-ROM that is part of this report.

After the workshop, the committee developed its findings and recommendations for research areas that should be pursued and strategies that could be implemented by NSF and others. The observations, findings, and recommendations for further research, which are presented in this report, are based on discussions facilitated by the workshop and the knowledge and experience of committee members. This report does not purport to be a comprehensive state-of-the-art assessment; rather, it reflects the consensus of the committee on what was learned at the workshop and in subsequent discussion. The report is intended to serve as resource for NSF and others in setting research priorities and evaluating proposals. Although the knowledge and participation of the workshop attendees were invaluable for the preparation of this report, the findings and recommendations represent the judgment of the NRC committee that was appointed for this purpose. The responsibility for the final content of the report rests entirely with the committee and the National Research Council.

From the outset it was recognized that other groups, most recently the Society of Fire Protection Engineers (SFPE, 2000), had already done excellent work on a national fire research agenda. In 1999, with funding from NIST, the SFPE conducted a comprehensive research needs workshop in Washington, D.C. This involved more than 70 fire science, engineering, and business leaders from virtually all sectors, working in a structured 2-day workshop format. The end result was the SFPE Research Agenda Report, dated February 2000. It identified priority research needs in four areas: risk analysis, fire phenomena, human behavior, and data. The SFPE effort defined"fire research" broadly and went well beyond the traditional thermodynamics and fluid dynamics of ignition and combustion phenomena. The findings of the SFPE workshop helped to shape the agenda for the current study.

ORGANIZATION OF THE REPORT

The following chapters provide additional background and contextual material on the evolving practice of fire-related design for buildings and infrastructure. The unique role of universities is discussed, and a few comments are offered on the fire-induced structural collapse of the World Trade Center buildings. A more complete description of NEHRP is also presented.

Chapter 2, organized broadly along the lines of the workshop, covers specific areas of research that are believed to need attention. Every effort has been made to include all of the topics covered in the workshop. Extensive use is made of bulleted lists to give the reader a convenient overview of the spectrum of research needs. Each bullet is an excerpt or paraphrase taken from one of the workshop participants or authors. All papers are found on the CD-ROM, giving the reader the opportunity to refer directly to a paper for the context surrounding excerpts or paraphrases found in the bullet lists. Chapter 3 contains the findings of the committee and its recommendations for a path forward.

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Workshop Synopsis

Many workshop participants pointed out that design, evaluation, and regulation of fire safety for buildings have undergone a sea change since the 1970s. While buildings were traditionally evaluated and regulated with reference to a checklist of specific code requirements, the trend, worldwide, has been toward performance-based approaches, with the United States lagging behind other developed countries in adopting these approaches. While performance-based building codes were implemented in countries such as the United Kingdom, Australia, and New Zealand in the 1980s and 1990s, the first model performance-based building code in the United States was not published until 2001 (ICC, 2001). At the time of the workshop, April 2002, no U.S. state or local jurisdiction was known to have adopted one of the model performance-based building codes.

In practice, performance-based codes rely much more heavily on fire research, basic theoretical understandings, data, and the ability to predict building safety performance under fire conditions. While in the past it was sufficient to establish that a building met the code, in the future there will be more and more pressure on engineers to predict safety performance under fire conditions. As a result of these discussions, the committee concluded that the scientific foundation is incomplete in terms of its ability to support predictive modeling with an acceptable level of uncertainty.

THE ROLE OF THE UNIVERSITY

During the 1960s and early 1970s principal investigators at several U.S. universities received ongoing support for fire research under the NSF/RANN program. While modest in scale, this program not only strengthened the body of knowledge but also expanded the nation's human resource infrastructure by training graduate students who went on to research, teaching, and practice.

Perhaps the most significant example of this was the work of Howard Emmons at Harvard. With ongoing NSF/RANN fire research support, Dr. Emmons was able to sustain a small community of first-rate scholars with a focus on fire fundamentals. Through the years, he and his graduate students were able to unlock new understanding of fires in buildings and produce the first generation of mathematical fire models. Dr. Emmons is now regarded as the father of computer fire modeling. During his career, he guided 51 Ph.D. graduates, a few dozen of whom went on to dedicate their own careers to fire safety.

The production of advanced degree scholars with a specialized expertise and career interest in fire science and engineering is extremely important for the nation. It is these men and women who will make the discoveries of the future. Unfortunately, the production of career-directed young investigators in fire safety has all but dried up in the United States over the past three decades as research funding has severely declined in real terms.

It should also be noted that a robust understanding of the fire performance of a building requires an array of many disciplines—from combustion and materials science to human behavior, architecture, and public policy. In the 1960s and early 1970s most university fire research was performed in departments of chemical, mechanical, or civil engineering. Since then, graduate studies in fire protection engineering have emerged here and worldwide. In the United States, two M.S. degree programs in fire protection engineering were launched, one in 1979 at Worcester Polytechnic Institute (WPI) and one in 1990 at the University of Maryland (UMD). A Ph.D. program in fire protection engineering began at WPI in 1991. Brady Williamson and Pat Pagni at the University of California, Berkeley, have graduated a number of Ph.D. students with excellent research backgrounds in fire safety science, some of whom went on to teach at WPI and UMD. These universities represent a new national resource for the United States, each offering an ongoing scholarly focus on the broad, integrated area of fire science and engineering. However, despite these educational programs, overall support for fire research and education in the United States has declined dramatically.

A sustainable emphasis on fire safety and security can only be maintained through viable educational and research programs that create new knowledge and produce educated research professionals. Universities are highly selective in determining which research and education programs will be fostered and maintained, and without research funding, no research or teaching programs can be viable. Research dollars are the "without which nothing" (including formal fire safety programs) can thrive in university environments.

The workshop participants identified numerous specific training and education needs:

- Formal academic courses in explosion protection are extremely scarce in U.S. universities and colleges (Zalosh).[1]
- New human capital must be produced for utilizing and advancing existing tools, as well as for developing future tools….Academically based fundamental research is critical (Dryer).
- There has been an almost complete demise of basic fire research activity at universities (Dryer).
- Currently there is very limited graduate training in fire chemistry as it requires the interaction of chemists and civil engineers. Cross-disciplinary knowledge and training are needed (Pearce).
- We need an interdisciplinary and holistic approach to materials processing and structural design for fire durability (Riffle).
- Young people at the assistant professor or associate professor level (in the area of chemistry and materials science aspects of fire science) are practically nonexistent in the United States. The United Kingdom, France, Italy, China, Japan, and Russia appear to be training more young people in this area than is the United States (Weil).
- Students must be taught performance-based structural fire performance analysis (Iding).

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[1] Throughout this report, the callouts without dates refer to committee members who expressed the opinion or provided the information in the course of workshop discussions or to participants who did the same in the papers they had prepared for the workshop. The background papers are contained on the CD-ROM that accompanies this report.

- Concepts in risk characterization, uncertainty, variability, and decision-making processes and tools should be a component of education and training for those at all levels of the regulatory, design, and enforcement communities (Meacham).
- Colleges, universities, and professional organizations could more effectively collaborate to offer practical courses and seminars to decision makers in the art of transferring fire safety technology through public policy (Kime).

A WORD ABOUT THE WORLD TRADE CENTER DISASTER

The FEMA/ASCE report on the September 11, 2001, World Trade Center collapse was released in April 2002 (FEMA, 2002). The report made clear that Towers One and Two withstood the physical impact of the aircraft and that the collapse of both towers was fire induced.

Although it is generally understood that the thermal impact of the burning jet fuel, which resulted in the almost simultaneous ignition of the building contents, was a worst-case catastrophic event for the structures, the FEMA/ASCE report does raise questions about our basic understanding of several areas of building fire performance, including fire loadings, fireproofing, structural connections, emergency communications, and human behavior. These areas were spotlighted and discussed during the workshop.

In August 2002, Congress appropriated $16 million to FEMA, which in turn is funding NIST to continue the investigation of the World Trade Center collapse. Although this investment to increase our understanding of that event is laudable, the investigation should not be regarded as a surrogate for the huge amount of sustained fundamental fire research needed in the United States. In fact the need for such an investigation is symptomatic of the inadequate body of knowledge that exists regarding the fire performance of structures.

THE NATIONAL EARTHQUAKE HAZARD REDUCTION PROGRAM AS A MODEL

Earthquake engineering may be an instructive analogy for enhancing fire safety through interdisciplinary research, application, and technology transfer. Earthquake research has had considerable success in changing regulatory attitudes and construction paradigms and moving improved designs, techniques, and materials into practice. This success has been facilitated to a large degree by a network of academic and government research institutions integrated with the educational, design, and regulatory communities. These partnerships can trace their history to action at the federal level in response to unacceptable losses from devastating earthquakes in the 1960s and 1970s. The NSF, the principal government agency charged with support of basic research, has teamed with other federal agencies to support basic earthquake research in the physical, natural, and social sciences, the code and standard development process, engineering applications, and technology transfer. This effort has been successful partly because it addresses the issues from an interdisciplinary perspective and permits all stakeholders to participate in the process.

The National Earthquake Hazards Reduction Program (NEHRP) was an important outcome of the national movement to improve earthquake safety. It was created in 1977, when Congress passed the Earthquake Hazards Reduction Act (P.L. 95-124). This act was significantly amended in 1990 with the National Earthquake Hazards Reduction Program Act (P.L. 101-614), which refined the description of the agencies' responsibilities and the program's goals and objectives. FEMA is the lead agency for this program, but NSF, NIST and the U.S. Geological Survey (USGS) also participate. Each of the agencies is tasked with certain functions that contribute to our understanding of earthquakes and that enhance safety in the face of them:

- In addition to coordinating the program, FEMA manages the federal government's response to earthquakes, funds state and local preparedness activities, and supports the development of improved seismic design and construction.
- USGS conducts and supports earth science research into the origins of earthquakes, predicts and characterizes hazards, and disseminates earth science information.
- NSF funds earthquake engineering research, basic earth science research, and earthquake-related social science research.
- NIST conducts and supports studies related to improving the provisions in building codes and standards that deal with the effects of seismic events.

The total appropriations for the program over the last 3 years has been just slightly more than $100 million per year split unevenly between the four agencies. Similar to NSF's RANN program and its successor (the program at NIST), the funding for NEHRP has also declined significantly in constant dollars since the late 1970s. However, NSF is still providing approximately $30 million per year for earthquake research (NRC, 2002).

Regardless of the decline in real dollars, the NEHRP program has been lauded over the last 25 years for its significant contribution to improving the ability to anticipate and mitigate earthquake damage. An NSF/FEMA-supported project has resulted in the development and periodic update of nationally applicable earthquake design provisions for new buildings. These provisions, which are being incorporated into national building codes and ASCE standards, form the basis for the *International Building Code* (ICC, 2001). NEHRP has also been directly supporting the drive toward performance-based seismic design (PBSD) through FEMA's sponsorship of an effort by the Applied Technology Council (ATC, 2002). FEMA's Existing Building Program has culminated in the publication of FEMA standard 273 for performance-based rehabilitation of buildings. In other NEHRP activities, social scientists supported by NSF have created new tools for understanding the public policy, economic, and societal factors, such as community decision making, that guide state and local adoption of measures to reduce future earthquake losses. To better focus NEHRP resources and create an infrastructure for coordination, NSF decided to reorganize and expand the National Center for Earthquake Engineering Research into three distinct university-based earthquake engineering research centers, indicating a national commitment to multidisciplinary research and outreach. Additionally, NSF and the USGS fund the Southern California Earthquake Center as a science and technology center, and NSF has established the Network for Earthquake Engineering Simulation (Arnold, 1998).

NEHRP demonstrates that a consensus to invest in risk reduction can be achieved by active collaboration among scientists, engineers, government officials, and business leaders and by their interaction with an informed public. The program also demonstrates that leadership and political effectiveness are key elements in developing a successful program.

Although earthquakes and fires both pose serious threats to the American public and the national economy, they are fundamentally different hazards. Serious earthquakes are relatively rare, but a single large earthquake can be catastrophic. Fire events, while far more frequent, are much less likely to cause catastrophic damage to the infrastructure of an entire community. For example, earthquakes have caused, on average, fewer than 10 deaths per year in the United States over the past 25 years (USGS, 2002), but just two events, the Northridge earthquake in 1994, which killed 60 persons and caused over $20 billion in damages and the 1989 Loma Prieta earthquake, which killed 63 and caused over $6 billion in damages, account for 85 percent of the deaths and a quarter of the damage in that time frame (Cutter, 2001). Fires, on the other hand, caused, on average, 5,400 deaths annually during the same period (NFPA, 2002) and are estimated to cause about $10 billion annually in direct property loss (Hall, 1999). In addition, the events of September 11, 2001, demonstrated that fire can pose a potentially catastrophic threat, even to large, robust commercial structures.

AREAS WITH KNOWLEDGE GAPS

As indicated above, the overall goal of the workshop was to identify areas where there are gaps in our knowledge of fire and to explore the potential role of NSF in supporting the research that would fill in those gaps. Continued enquiry into the nature of fire, and its causes, characteristics, and effects on people, products, structures, and the environment can result in even further gains toward the ultimate goal of saving people and property. Improvements in design, construction, and loss reduction strategies for buildings and facilities can be realized if new knowledge, developed through research, has a ready path into practice and the marketplace.

The eight areas where participants found knowledge gaps are discussed next. Identifying priorities among them is a significant challenge and beyond the scope of a single workshop. As noted by the various workshop presenters, almost all areas connected with fire safety will benefit from additional resources and intellectual effort.

Fire and Explosions

Our fundamental understanding of fire has progressed enough in the past 40 years to allow development of the range of engineering methods used today. However, this understanding is still incomplete. Fire and explosion behavior can be predicted only with a thorough grasp of the complex physical interactions that take place. As mentioned earlier, the support of basic fire research at universities has dwindled from what it was in the 1960s and 1970s (NSF/RANN) to what remains in the NIST Building and Fire Research Laboratory (BFRL) extramural grants program. Consequently, the performance codes being introduced in the United States lack the necessary science and technology foundation. Fire tests and standards are developing without a science base to support them or to understand and account for uncertainties. The United States simply cannot afford to have an empirical basis for its fire safety infrastructure but needs instead a science base to build new, more predictive fire models and tools for performance-based design.

The following exemplify the kinds of knowledge that are needed to understand fire and explosions:

- The properties of turbulent flow phenomena in general and turbulent combustion in particular are still poorly understood and likely to remain so for decades to come (Baum).
- The most urgent problems peculiar to fire research occur at the interface between the gas- and condensed-phase materials (Baum)
- The geometry and construction materials of a building need to be defined while at the same time recognizing that the underlying geometry of the building can be altered by the fire and that this affects how the fire behaves and therefore the impact on the structure (Baum).
- There is need for explosion research in (1) flame speeds in highly nonuniform gas-air mixtures, (2) deflagration-to-detonation transitions in congested and turbulent environments, (3) dust cloud formation that can lead to dangerous secondary dust explosions, (4) blast wave propagation in buildings, and (5) blast wave generation of secondary fragments and the development of blast resistant/compliant windows (Zalosh).
- The present level of fundamental knowledge is insufficient for predicting gas-phase extinction (Dryer) and worse for predicting the extinction of flames from solid materials (T'ien).

Materials and Retardants

Advances in flame-retardant polymers and their composites, together with improved predictive capabilities, could reduce the fuel loads due to contents and structural components, reduce the toxicity of combustion products, and allow for longer egress times during fires. Increasing the fire retardancy of structural polymeric composites will also overcome a potential barrier to the more widespread use of these composites, which could also reduce construction time and labor costs.

Important insights mentioned during the workshop include these:

- [Research is needed in] (1) protective, flame retardant, and intumescent coatings, (2) smart polymers and additives, and (3) flame retardant systems operating by catalytic mechanisms (Weil/Pearce).
- Our poor understanding of smoke and toxicity is a critical barrier to the further incorporation of polymers and their composites in building contents and structural applications (Weil/Pearce).
- The literature contains only a few systematic studies of polymer melt, melt flow, and dripping to determine their quantitative effects on fire growth (Kashiwagi).
- Significant improvements are needed in understanding the high-temperature and flammability properties of materials (Mowrer).
- More knowledge about the effects of temperature and heat flux on the mechanical properties of polymeric materials is needed for simulating the structural response of buildings in a fire (Riffle/Lesko).
- There are no fiber-reinforced polymeric materials suitable for all critical fire applications in buildings (Riffle/Lesko).

Fire Protection Systems

Fire detection is the first step to taking mitigating actions, which include evacuating or relocating people, notifying responders, or initiating other strategies such as smoke control and fire suppression. Commercial efforts have focused on developing detection devices that are less prone to unwanted (nonfire) actuation without sacrificing speed of operation or that are more stable without sacrificing sensitivity. Using innovative sensor technologies and signal analysis, fires can be detected with greater speed, accuracy, and clarity. However, developing improved detection devices does not improve fire defenses, protect responding fire fighters, or provide more cost-effective, performance-oriented design. Successful application of new sensor technologies depends on the integrated development of better engineering tools to model the fire stimuli and detection device response to those stimuli. This type of research is well-suited to interdisciplinary teams that include practitioners of the social and decision sciences as well as engineers and physical scientists. In a systems context, there is an underlying need for the sensors to sense what they need to and nothing more and for the actuators to know when and what to actuate and to do so quickly. This is not a problem for engineers alone to solve.

Fire suppression research in recent years has largely focused on replacements for halogenated hydrocarbons (halons). The development of new fire suppression strategies, agents, and methods will require a better understanding of the chemical and physical phenomena of fire suppression and flame extinction. Without breakthroughs in research on fire suppression phenomenology, costly trial-and-error approaches to system development and design will continue.

Some key insights contributed by workshop participants include the following:

- The development of new fire suppression strategies, agents, and methods will require a better understanding of the chemical and physical phenomena of fire suppression and extinction (Dungan).
- Continued research is needed in the area of multisignature detection, particularly detectors for gas and smoke combinations, which hold greater promise for improved performance than detectors for smoke alone (Gottuk).
- Low-cost sensors for gases, particularly CO and CO_2, that are stable and have a functional life of 10 years or more [must be developed in order] to produce marketable multisignature detectors (Gottuk).
- Owing to the large numbers of deaths and injuries in residential fires, there should be more research on improving detection for residential applications (Gottuk).
- Reducing the frequency of nuisance alarms should be a key objective for new fire detection technologies (Gottuk).
- It would be advantageous to have a detection method that could be used for monitoring hazardous chemicals and conditions in addition to providing fast, reliable fire detection (Rose-Pehrsson).
- One can imagine future advances in fire suppression through smart suppression based on scenario-specific engineering analysis (Hamins).
- Research is needed on the complicated multiphase processes by which a condensed-phase agent extinguishes a fire (Hamins).

- A better understanding is needed of the chemical mechanisms associated with halon replacements to provide a scientific basis for improved design of suppressant systems (Hamins).
- A better understanding of agent mass and heat transfer processes would provide a scientific basis for the creation of rational engineering tools and improved suppressant system design (Hamins).

Fire Protection Engineering Tools

In the context of this document, fire protection engineering tools include deterministic fire hazard analysis models and probabilistic fire risk assessment methodologies. These tools permit the hazards and risks associated with fire to be evaluated quantitatively in terms of physically meaningful units of measure. The development of these tools over the past few decades has prompted, as well as permitted, the development of frameworks for the performance-based fire safety analysis, design, and regulation of buildings. Continued development and refinement of these tools and methodologies is needed to implement more fully the rational, more economical performance-based approaches to building fire safety that are based on known levels of safety, risk, and uncertainty.

Until now, advances in fire protection engineering tools have been evolutionary. However, performance-based codes and standards, supported by a new generation of fire protection engineering tools, may truly be revolutionary advances. For this reason, research into both deterministic fire hazard assessment and probabilistic fire risk assessment is encouraged. Inputs from workshop participants and committee members included the following:

- With the increasing use of performance-based fire protection design, it is imperative that predictive tools and methodologies be available to design and analyze fire detection systems (Gottuk).
- Continued development of deterministic fire hazard analysis models and probabilistic fire risk assessment methodologies is needed to more fully implement rational performance-based approaches to building fire safety (Mowrer).
- Models, tools, and data are needed to quantify uncertainty associated with input parameters and models for conducting probabilistic fire safety assessments (Siu).
- From a national fire safety improvement standpoint, it is essential to identify the scenarios that dominate national fire risk (Siu).
- Models of gas-phase suppression are limited by the use of simple zero or one-step combustion mechanisms in large-scale simulations. Detailed numerical models of small-scale combustion systems are needed (McGrattan).
- Models of solid-phase suppression are limited by the lack of well-accepted, robust pyrolysis models that have enough physical detail to accommodate the inclusion of water impingement (McGrattan).

Structural Fire Protection

The current practice in structural fire protection in the United States is based on test methods developed a hundred years ago and test requirements based on the fire science of the 1920s. Many buildings may be significantly overprotected, while others may be unexpectedly incapable of resisting the posited fire threats. The changes in materials and construction methods over the decades have also left gaps in our fundamental knowledge of how structures perform in fire. The collapse of the two towers and Building 7 following the September 11 attacks certainly demonstrated that our understanding of structural fire protection might be incomplete for today's engineering practice. The opportunities for significant improvement in reliable and cost-effective structural fire protection are great, and there is work that needs to be done to refresh the technical basis for 21st century design. A performance-based approach to structural design for fire resistance is gradually gaining favor as an alternative to traditional prescriptive requirements such as hourly ratings and required thicknesses for fireproofing. To make performance-based methods more accessible and acceptable to practicing engineers and building officials, further research is needed, particularly in the following areas:

- A better understanding of the well-stirred reactor model, burning rate correlations, heat transfer coefficients, compartment openings, and ventilation and flame projections from windows is needed to assess fire severity for performance-based structural standards (Milke).
- The accuracy of building fuel load estimates for contemporary buildings must be confirmed (Milke).
- The high-temperature properties of structural materials, including high-strength concrete, structural steel, and fire protective coatings, must be documented (Iding).
- The performance of structural connections in fires must be better understood (Iding, Beyler).
- Analytical methods must be codified, peer-reviewed, and approved (Iding).
- Software for structural fire performance must be developed and verified (Iding).
- The role of furnace testing must be reevaluated and refined (Beyler).
- There is an urgent need to develop guidelines for assessing the fire resistance of high-performing materials in civil engineering applications (Kodur).
- There are questions about our ability to predict fire-induced structural collapse. Little research in this area has been carried out in the United States for the past two decades (Baum).

Human Behavior in Fires

The impact of fires in buildings is typically measured by their toll in deaths and injuries. These deaths and injuries are often the result of adverse interactions between people and the buildings they are trying to evacuate. This measure of impact is as much a function of how humans behave in emergency situations as it is a function of building design. Some knowledge of human behavior has been gleaned from the analysis of past disasters through survey and interview methods. The application of human factors methods also offers promise in this regard. Human response models can give a better understanding of human behavior in fire based on simulated interactions with the built environment and can lead to improved designs for notification, evacuation, and response systems. These models require different levels of input data to be able to predict the movement and/or response of people to emergency cues. Although such data are scarce and difficult to collect, human response models could prevent fires from becoming high-consequence, mass-casualty events. The prevention of a single disaster such as the West Warwick, Rhode Island, nightclub fire in February 2003 would more than justify the time and effort required for data collection and model calibration.

Workshop discussion of important research needs yielded the following insights:

- Studies should investigate the risk perceived by building occupants since September 11 and how these perceptions might change over time (Proulx).
- Studies should compare the intended response of high rise occupants during an emergency with the actual response through unannounced drills (Proulx).
- Longitudinal studies should be conducted to assess the impact of September 11th on human behavior over time (Proulx).
- Building evacuation research is needed across a wide spectrum ranging from flow and counterflow effects in stairs; effects of age and disabilities; and response to cues to decision making; training; effects of alarms; and use of elevators (Fahy).
- Research is needed to determine what levels of toxic products affect decision making (Fahy).
- Research is needed on the intersection of user needs and expectations during an emergency situation and how this impacts engineering design (Pauls/Groner).
- A number of questions from traditional human factors research apply to the emergency evacuation of buildings. Some of this work is ripe for technology transfer while other work remains to be done (Pauls/Groner).
- Complex adaptive systems that incorporate adaptive human agents in the design of performance-based fire safety systems may offer particular promise in modeling human behavior during evacuation scenarios (Pauls/Groner).

Public Policy

Fire safety in the United States is influenced to a great extent by public policy. Part of the public policy aspect of fire safety is regulation of the built environment. The regulatory system attempts to reduce risk to a level deemed acceptable by society. This presumes a political process that adopts technically informed regulations to control risk. The political process must be understood and properly integrated to achieve adequate fire safety. However, some believe that we lack the proper technical understanding and that there is little recognition of the political process by which regulation happens. Workshop participants drew attention to the following ideas:

- There is a need to further refine a risk-informed, performance-based regulatory framework that accommodates the relationship between public policy and technical issues (Meacham).
- Risk-informed, performance-based engineering and decision-making methodologies must be developed and validated (Meacham).
- Research is needed to better understand and quantify the magnitude and frequency of fire events of concern, the impact those events could have on buildings and their occupants, and overall building performance (Meacham).
- A framework is needed to link policy-level demands with technical elements, including tolerable risk (Tubbs).

- It is very hard (usually impossible) to solve a political problem with a technical solution, yet it is important to recognize that the political solution most generally will require sound science as a foundation (Kime).
- Broadly consider the criteria commonly selected for evaluating fire safety outcomes (Croce).

Data

Although "data" was not one of the original seven topics on the workshop agenda, data needs were mentioned so many times in the course of the workshop that it has been added as a separate section. The data needs to provide fire safety vary from material properties to explosion incidents to human behavior. The following are some of the data needs mentioned at the workshop:

- It is necessary to have some idea of the building contents, their distribution within the building, and their material properties (data) (Baum).
- We need an explosion incident database that contains data comparable to the data available from the NFPA and NFIRS fire databases (Zalosh).
- Without an accurate and broad-based national database, we cannot determine the success being experienced using existing explosion prevention and explosion mitigation technology and practices (Zalosh).
- Fundamental thermodynamic, thermophysical, and thermochemical property data on commercially available materials are needed to produce science-based models (Dryer, Beyler).
- There is minimal information available on material properties at elevated temperatures (Pearce).
- Data are needed to quantify the uncertainty associated with input parameters and models for conducting probabilistic fire safety assessments (Siu).
- There is a need for data on the high-temperature performance of high-performance materials (Kodur).
- Human behavior data are needed in order to design, validate, and implement building evacuation models (Fahy).
- Cost and loss data and metrics are needed to support designers, regulators, and policy makers (Meacham).
- What is needed specifically are better ways to measure accurate material property data for use in first-principle models (Croce).

OTHER TOPICS OF DISCUSSION

Other important fire safety topics were discussed at the workshop and by the committee, but since they went beyond the committee's charge they are not reported here in detail. The issue of fire-safe homes and intrinsically safe appliances was raised in the workshop by committee member Fred Dryer and others. This is an important topic because the majority of fire deaths occur in the home. The discussion revolved around the safety of consumer products how these products contribute to fires in the home and often serve as a source of ignition.

Technologies to improve firefighter capabilities and safety were of considerable interest, particularly in light of the events of September 11. The U.S. Fire Administration has submitted a report to Congress outlining a research agenda for fire service needs that was based on a workshop conducted in 1999 (USFA, 2001). Another potential research topic brought up in committee discussions was wildland fires, especially their interface with populated suburban areas. This has become a serious issue as the human population continues to encroach into areas where wildland fires are a natural and common occurrence. Such fires now displace people, cause serious damage, and place firefighters in jeopardy (of the 102 firefighter deaths recorded in 2002, 20 occurred in wildland fires (USFA, 2003)). The threat from wildland fires inspired the development of the National Fire Plan, which provided the impetus for the Joint Fire Science Program (JFSP), a collaboration between the Department of the Interior and the USDA Forest Service. The JFSP has administered and managed a large amount of fire research dealing with wildland fuel and fire management programs over the past 5 years (JFSP, 2002).

The committee decided in planning the workshop and writing this report that the topics discussed in this section, although extremely important, were not part of its charge. Robust and focused research activities are already under way to address these issues. NSF will be familiar with them and should coordinate its efforts. If NSF decides to reestablish a university grants program in basic fire research, the results of that research will certainly be of interest to those who deal with these other topics.

Interdisciplinary Research, Coordination, and Cooperation

W. J. Petak (2003) makes a strong case for a holistic to fire research similar to the approach to earthquake mitigation research. He notes that earthquake mitigation technology has advanced considerably over the years but deployment has not kept pace, even in earthquake-prone California. He believes one of the principal reasons for the gap is that earthquake risk reduction is viewed by many as a purely *technical* problem with a *technical* solution. However, despite the importance of technology, it takes institutions and people to implement workable, sociotechnical systems solutions. Figure 2.1 illustrates how the elements of such a system work together and underscores the value of interdisciplinary research that draws from the social, behavioral, and decision sciences as well as the physical sciences and engineering. For example, performance-based building codes will require realistic expectations of human behavior during a fire and must, by necessity, draw from research into human factors, the social organization of evacuation groups, and the social ties that develop within such groups.

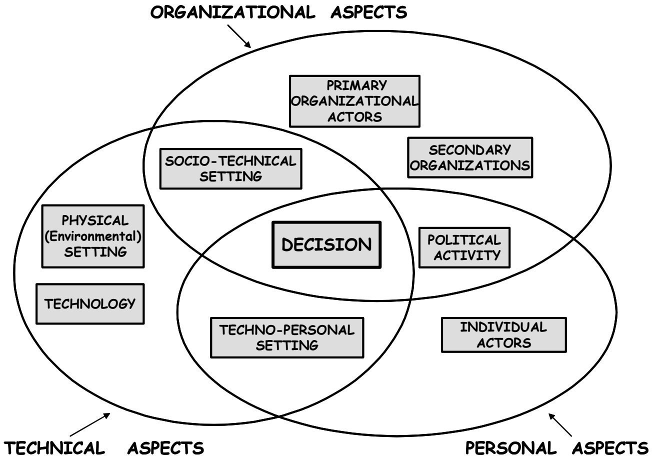

FIGURE 2.1 A sociotechnical system view for decision making (Linstone, 1984).

Presentations and discussion at the workshop also revealed the need for better coordination, cooperation, and communication among the many stakeholders in the national fire safety effort, including fire researchers and academics, the fire services, public officials, codes and standards groups, private industries, government agencies, and professional societies. Workshop participants suggested a number of possible strategies the nation could deploy for achieving this goal, including the following:

- The National Earthquake Hazards Reduction Program (NEHRP) model (Anderson),
- Use-inspired research agendas, Pasteur's quadrant (Croce),
- A national network of technology centers (Quintiere), and
- A federation of stakeholder groups with a champion (Kime, Croce, Tubbs).

Several excerpts from the workshop presentations are included to underscore this point:

- It is not clear which community owns the problem (Baum).
- Current explosion research in the United States is highly fragmented (Zalosh).
- European explosion test facilities are not only more numerous in all sizes, they are also used for integrated explosion programs with coordinated participation of government, industry, and university research laboratories (Zalosh).
- We need a coordinated university-industry-government explosion research program (Zalosh).
- It is important that a federal agency or large industrial consortium recognizes explosion protection as an important part of its mission (Zalosh).
- The Pasteur's quadrant approach to research, discussed by Croce, introduces the concept of use-inspired fundamental research and defines what should motivate all research (Dryer).
- A coordinated effort is needed between modelers, experimentalists, and manufacturers in developing detector performance metrics and accurate models for the calculation of detector responses under realistic installation conditions (Gottuk).

- There has been remarkably little interaction between researchers in the various fire communities—those involved in automatic protection, the fire service, and those in the forest fire community who are interested in the fire protection of buildings. The potential for cooperation among these various communities appears to be large (Hamins).
- A nationally coordinated network of technical centers is needed to facilitate fire safety design through education and research linked tightly to the needs of codes and standards (Quintiere).
- NSF has experience in other emerging structural engineering areas like earthquake engineering that will facilitate the process of conducting and implementing breakthrough, scientifically based engineering methods [in structural performance] (Beyler).
- A federation should be formed to identify technologies that should be adopted, to demonstrate their public value, and to generalize demonstration projects to the broader community (Kime).
- An effective stakeholder organization should be established, including a champion and societal decision makers such as the fire service and key industry, trade, and professional groups…to obtain stakeholder buy-in on key fire research directions, needs, approaches, and goals (Croce).
- A use-inspired fundamental research model should be considered (Croce).
- A group of appropriate stakeholders should be formed to help guide the process and gain acceptance for new methods in design and construction (Tubbs).
- Research priority goals, time lines, and milestones can be developed following a technology roadmap approach (Lyons).

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3

Findings and Recommendations

In accordance with its statement of task, the committee has developed a number of findings and recommendations. It should be noted that these findings and recommendations are based on the knowledge and experience of the committee members and discussions facilitated by the workshop held on April 15-16, 2002. Although the participation of the workshop attendees was invaluable for the preparation of this report, the findings and recommendations represent the opinions of the NRC committee that was appointed for this purpose. The responsibility for the final content of the report rests entirely with this committee and the National Research Council.

FINDINGS

The High Cost of Fire. Unwanted and preventable fire in the United States continues to exact an unacceptably high cost in terms of human suffering and economic losses. The threat to people, property, and economic activity is neither well understood nor fully appreciated by policy makers and the public at large.

Benefits of Performance-Based Practices. Performance-based building codes, which are now available in the United States for adoption by state and local governments, offer real promise for regulators and public officials to institute regulations that reflect a better understanding of risks and improved safety performance for buildings in their communities. However, performance-based codes depend on the ability of engineers to predict how buildings will perform under fire conditions. There are significant gaps in the data and knowledge base needed to support performance-based codes, engineering tools, predictive models, and risk assessment.

Insufficient Funding. The current funding levels and organizational infrastructure for fire research in the United States are inadequate to address even the most fundamental research needs that were raised at the workshop and subsequently discussed by the committee. The documented costs of unwanted fire, in both human and economic terms, justify substantial investment in fire safety research and the development and deployment of the products of that research. The public at large, businesses, institutions, and government agencies can all benefit from better safety at less cost.

Coordination and Cooperation. Improving fire safety in the United States depends on the combined efforts of a range of disciplines and communities, from fire researchers and academics to the fire services, public officials, codes and standards groups, private industry, government agencies, and professional societies. There is a need for better communication, cooperation, and integration of national fire safety efforts.

Important Role for Universities. University-based fire research has all but evaporated in the United States over the past three decades. In addition to choking off new scientific discovery, this turn of events has all but eliminated the production of young scholars with a career commitment to inquiry and teaching in the fire safety sciences.

Role of the National Science Foundation. The NSF has traditionally served as an incubator for coordinated, interdisciplinary research programs for hazard reduction that involve the university research community, government agencies, and the private sector. As compared with more mission-oriented agencies, an NSF commitment can be particularly beneficial in areas of basic research that will improve our understanding of the nature of fire; its detection, suppression, and control; technology applications (e.g., next-generation residential smoke detectors, material coatings, and intrinsically safe home appliances); human behavior; and interdisciplinary studies to better inform building codes, design, and regulatory/public policy processes.

The National Earthquake Hazards Reduction Program Model. Through NEHRP, the U.S. government has aggressively pursued such an integrated approach for addressing the earthquake hazard. Its approach has resulted in greatly improved building performance and reduced levels of injury and death.

RECOMMENDATIONS

The committee's recommendations are not intended to address all areas of fire safety or even all areas of fire research. They are targeted specifically to those areas where the committee believes the National Science Foundation could have a significant positive impact on the state of fire research that would enhance fire safety in the United States and are intended to suggest a path forward for NSF.

1. **NSF should reestablish and fund a program in basic fire research and interdisciplinary fire studies. Funding of approximately $10 million per year is recommended to begin this effort. This initial funding level would restore the NSF investment in fire research to its 1973 level (in today's dollars). It should be reconsidered once a robust research infrastructure is in place.**

The level of fire research at U.S. universities has declined greatly since the RANN program was terminated at NSF. Given NSF's charter to support basic research and education, the committee believes that NSF is the appropriate agency for administering a reinvigorated and robust university grants program in fire research. Funding of university principal investigators and graduate students needs to be emphasized, both to accomplish research goals and to invest in the nation's next generation of investigators and teachers—the human capital so necessary for continuous improvement in fire safety. There are many on-going initiatives and programs within NSF (e.g., nanotechnology, sensors, high-performance materials, surface chemistry, human and social factors in hazard mitigation, structural system performance) that could provide a logical nexus (not to speak of existing funding) for reestablishing a comprehensive and interdisciplinary focus on fire safety within NSF.

This report makes no attempt to suggest a national research agenda or to identify fire research priorities for the nation. Such prescription was beyond the scope of this effort. The committee believes that work previously done by others, such as the SFPE Research Agenda 2000, the United States Fire Administration (USFA), and the Joint Fire Science Project (JFSP), along with the discussion of topical areas found in this report, will serve as a valuable resource for evaluating initial research proposals. In the short term, NSF can make use of this report and recent work by others to evaluate research proposals. The committee believes that the recommended funding level of $10 million annually would be an appropriate starting point for supporting multiple investigators in the physical, social, and behavioral sciences and engineering, with an emphasis on fostering interdisciplinary activities. In the longer term, NSF should coordinate its efforts with other agencies to build an integrated and robust research infrastructure for fire safety. Once such an infrastructure is in place, higher funding levels (such as those recommended in *America Burning*—approximately $113 million in today's dollars) should be considered. The committee would note that significant resources are already available through the multiplicity of mission-directed fire safety activities currently under way in federal agencies. Better coordination of existing fire safety planning, research, and implementation and their integration under a renewed initiative by NSF could create significant opportunities to leverage research dollars, increase technology transfer, and speed deployment of new methods and products.

> **2. A coordinated national attack to increase fire research and improve fire safety practices should be launched. The committee recommends that NSF support exploratory activities to determine if a model such as NEHRP or any other model that combines integration, cooperation, stakeholder involvement, and collaboration in research could hasten the development and deployment of improved fire safety practices through more coordinated, better targeted, and significantly increased levels of fire research in the United States.**

Many workshop participants emphasized that, in addition to addressing the paucity of basic research, there also needed to be better coordination, cooperation, and communication among the stakeholders in national fire safety. The United States lacks an adequately funded and well-coordinated national fire research program such as that for earthquake engineering embodied in the NEHRP. Most federally funded fire research is mission-focused and conducted by user agencies, which show little interest in leveraging the research investment, supporting graduate students, or transferring technology. Given the emergence of performance-based design and regulatory practices, the fire safety field is desperately in need of integrated research findings targeted to the priority needs of practice. A number of possible national strategies for achieving this goal were discussed at the workshop. The committee believes that a national attack on the U.S. fire problem requires interdisciplinary communication, cooperation, and coordination supported by adequate funding. The earthquake safety movement, which began in the 1970s and has evolved into the successful NEHRP is an excellent model for the fire safety community to consider. An effort modeled on the NEHRP could engage all federal agencies currently involved with fire safety and, at a minimum, should link a reinvigorated NSF university grants program with the valuable efforts currently under way at other agencies, such as the National Institute of Standards and Technology and the U.S. Fire Administration.

APPENDIXES

Appendix A

Biographies of Committee Members

David Lucht, *Chair,* is a professor and the director of the Center for Fire Safety Studies at Worcester Polytechnic Institute. Professor Lucht began his career in Ohio, and he worked as an engineer and researcher at the Ohio State University. He went on to become the Ohio State Fire Marshal. After Congress passed the Federal Fire Prevention and Control Act in 1974, he became the first presidential appointee at the newly created U.S. Fire Administration under President Gerald Ford. He became the deputy administrator of USFA in 1975 and served until 1978. Professor. Lucht then went on to establish the first master's degree program in fire protection engineering at WPI in 1978. He is currently on the board of trustees of Underwriters Laboratories, Inc., and has been a member of NFPA's board of directors. Professor Lucht graduated with a B.S. in fire protection and safety engineering from the Illinois Institute of Technology and holds professional registration as an engineer in the state of Massachusetts. He is a fellow and past president of the Society of Fire Protection Engineers.

Craig Beyler is the technical director for Hughes Associates, Inc. He is recognized for his unique leadership in developing and implementing scientifically based methods for engineering analyses of fire phenomena. His many contributions to this area have included both theoretical and experimental work in enclosure fire phenomena and extinguishment mechanisms. Of particular relevance is his work on an analytical basis for fire detector response, SFPE´s Practice Guide on Radiation from Pool Fires, and his advancements of heat/smoke vent engineering calculation methods. Recently he received the Arthur B. Guise Medal recognizing eminent achievement in advancing the science of fire protection engineering and was elected as an SFPE fellow. Dr. Beyler holds a B.S. degree in fire protection engineering from the University of Maryland, a B.S. in civil engineering from Cornell, an M.S. in mechanical engineering from Cornell, an M.Sc. in fire safety engineering from the University of Edinburgh, and a Ph.D. in engineering science from Harvard.

David Collins is president of the Preview Group, Inc., in Cincinnati, Ohio, and manager of the American Institute of Architects' (AIA's) Code Advocacy Program. Mr. Collins has worked as regional code manager for the American Forest and Paper Association and the Portland Cement Association, as well as deputy chief building official for Hamilton County, Ohio. He is a member of BOCA, ICBO, and SBCCI as well as NFPA and serves on numerous ICC and NFPA committees. He has been on many AIA national committees and served as AIA secretary. Mr. Collins has an AAS in architecture from Purdue and a B.S. in architecture from University of Cincinnati. He is a registered architect, a certified building official, and a certified plans examiner in the State of Ohio.

Fred Dryer is a professor of mechanical and aerospace engineering at Princeton University. Dr. Dryer's principal research interests are in the fundamental combustion sciences, with emphasis on the chemistry and chemical kinetics of fuels and hazardous waste materials as related to ignition, combustion, and emissions generation and abatement; the fundamentals of formation, ignition, secondary atomization, and liquid-phase chemistry of conventional and synthetic fuel droplets as related to heavy industrial fuel combustion and emission control, gas turbine/reciprocating engines and liquid fuel fire safety-related issues on earth and in microgravity environments; and solid-phase and gas-phase interactions as related to particle burning phenomena and materials processing. Dr. Dryer recently served on two National Materials Advisory Board/National Research Council committees—the Committee on Improved Fire and Smoke Resistant Materials for Commercial Aircraft Interiors and the Committee on Aviation Fuels with Improved Fire Safety—on the NASA Scientific Advisory Panel for the Atmospheric Effects of Aviation Project, and on the National Materials Advisory Board/National Research Council. He received a bachelor's degree in aeronautical engineering from Rensselaer Polytechnic Institute and a Ph.D. in aerospace and mechanical sciences from Princeton University. He also served on the professional research staff in the Mechanical and Aerospace Engineering Department of Princeton University for 8 years.

Ken Dungan is president and cofounder of Risk Technologies, LLC, and chair of the SFPE's Scientific and Educational Foundation. Mr. Dungan served as department head of the Fire Protection Engineering Division at Union Carbide's Oak Ridge gaseous diffusion plant. He also was assistant director of engineering services for Verlan, Ltd., an insurance company for the coatings industry. Mr. Dungan then founded Professional Loss Control, Inc., in 1976, specializing in safety, fire protection, and environmental engineering. In 1995, he cofounded Risk Technologies and Performance Design Technologies, LLC. He is a past president of the SFPE and past chair of the American Association of Engineering Societies. Mr. Dungan is serving on many NFPA committees, is a member of the American Institute of Chemical Engineers, and is a licensed engineer in Pennsylvania and Tennessee.

Ofodike "DK" Ezekoye is associate professor and General Motors Centennial Teaching Fellow in mechanical engineering at the University of Texas at Austin. Dr. Ezekoye has worked on problems such as heat transfer in combustion systems, aerosol generation and filtration, and inverse design of thermal systems. He joined the University of Texas faculty in 1993 after a year as an NRC postdoctoral research fellow at the Building and Fire Research Lab at NIST. Dr. Ezekoye has published more than 70 technical articles and reports. He received a National Science Foundation CAREER Award in 1997. Dr. Ezekoye has a B.S. in mechanical engineering from the University of Pennsylvania and an M.S. and a Ph.D. in mechanical engineering from the University of California, Berkeley.

William Feinberg is professor emeritus of sociology at the University of Cincinnati and an experienced researcher of crowd behavior during fire disasters. He has been the chair of the sociology and computers section of the American Sociological Association and has been active in the ASA for over 35 years. His research has led to a computer simulation model called FIRESCAP, which simulates human reaction to a fire alarm. Dr. Feinberg has an A.B. in sociology, an A.M. in sociology, and a Ph.D. in sociology, all from Brown University.

Charles H. Kime is an assistant professor at Arizona State University, East Campus. He coordinates the fire services programs in the College of Technology and Applied Sciences; these include a bachelor of applied science degree in fire service management and a master of science in technology degree in fire service administration. Prior to joining Arizona State University, Dr. Kime spent more than 32 years with the Phoenix, Arizona, fire department, retiring in 1999 as the executive assistant fire chief. In the fire services, his experiences range from line firefighting positions to supervisory and middle management, then to executive management positions, which he held for more than 20 years. During his fire services career, Dr. Kime was very active in university education. He has taught in the graduate program of the Arizona State University School of Public Affairs and the bachelor of interdisciplinary studies degree program at the same institution, as well as myriad fire sciences and fire services administration classes. His research interests include organizational leadership, organizational behavior, and human resource management, especially within the context of the fire service. Dr. Kime holds a bachelor's degree in industrial technical education, an M.B.A., and a Ph.D. in public administration. His book *Organizational Leadership: Fire Services in the United States* was published in 2001 by Elsevier.

John Lyons (NAE) is a retired director of the U.S. Army Research Laboratory (ARL) and a former director of NIST. He was elected to the National Academy of Engineering in 1985 "for outstanding contributions to fire science and technology." Dr. Lyons helped create and launch the Advanced Technology Program and the Manufacturing Extension Partnership at NIST and the Federated Laboratory program at ARL. His particular interests are managing multiprogram laboratories, movement and diffusion of technologies, formation and management of partnerships between government labs and the private sector, stimulating consortia formation and management, technology and competitiveness, measuring research performance, justifying research efforts, and managing technical personnel. Dr. Lyons' career spans almost 20 years in the chemical industry and 25 years in government labs. The result is a broad perspective useful in today's environment of sharing and partnering between the public and private sectors.

Fred Mowrer is an associate professor at the University of Maryland. He joined the faculty of the Department of Fire Protection Engineering in 1987 after receiving his Ph.D. in fire protection engineering and combustion science from the University of California, Berkeley. Dr. Mowrer received a B.S. degree in fire protection and safety engineering (1976) from the Illinois Institute of Technology and an M.S. degree in engineering (1981) from the University of California, Berkeley. He is a registered fire protection engineer in California. He has worked as a consultant for an international fire protection engineering firm and as an engineering representative for an insurance organization. Dr. Mowrer is recent past president of the Society of Fire Protection Engineers and an active member of the International Association of Fire Safety Science and the National Fire Protection Association. He currently serves on the board of directors of the Society of Fire Protection Engineers. Dr. Mowrer's primary research interests include measurement of the contribution and response of products and materials to fire, mathematical fire modeling, development of a computer-based framework for building fire safety analysis and design, and analytical fire reconstruction. Dr. Mowrer has published papers on all these topics. He received the Harry C. Bigglestone Award for excellence in written communication of fire protection concepts from the NFPA on three occasions.

Eli Pearce is university research professor at Polytechnic University in New York, where he has served as a member of the faculty and administrator since 1971. From 1958 to 1973, he worked in industry, at DuPont, J.T. Baker Chemical Co., and Allied Chemical Corporation. Dr. Pearce received a B.S. degree from Brooklyn College (1949), an M.S. from New York University, and a Ph.D. from the Polytechnic Institute of Brooklyn (1958). His research interests are in polymer science, including synthesis, structure-property relationships, degradation, flammability, and polymer compatibility. He was president of the American Chemical Society through the year 2002.

Judy Riffle is a professor of chemistry at the Virginia Polytechnic Institute and State University (Virginia Tech) and director of its macromolecular science and engineering program. She has worked for Union Carbide as a research chemist and served as vice president for R&D at Thoratec Laboratories Corporation, a cardiovascular biomaterials company. In 1988, Dr. Riffle became assistant professor of chemistry at Virginia Tech, where she holds a tenured position. She has served as chair of the Polymers Division of the American Chemical Society. Her research has been on new polymeric materials and modifications of old polymeric materials that are flame retardant. She is active in integrating research and education through the Macromolecular Science and Engineering Program. Dr. Riffle has a B.S. in chemistry and a Ph.D. in polymer chemistry, both from Virginia Tech.

James T'ien is professor in the Department of Mechanical and Aerospace Engineering at Case Western Reserve University. He also serves as the chief scientist on combustion for the National Center for Microgravity Research on Fluids and Combustion. He has performed fundamental combustion research in a number of topics, including flame spread over solids, material flammability, and flame-radiation interaction. He is the recent recipient of a NASA public service medal for his contribution to microgravity combustion and spacecraft fire safety. Dr. T'ien received a B.S. from National Taiwan University, an M.S. from Purdue, and a Ph.D. from Princeton.

Beth Tubbs is a staff engineer at the International Conference of Building Officials, where she administers the code development process, code maintenance, and interpretation for the Uniform Building Code and Uniform Fire Code as a representative of the International Fire Code Institute. She is closely involved in code development committees, including the Secretariat of the International Fire Code and International Building Code Performance Committees, providing building and fire code technical support and assisting with related educational activities as well as acting as a liaison with other national agencies on fire protection issues. She has degrees in civil engineering and fire protection engineering from Worcester Polytechnic Institute and is a licensed professional engineer in fire protection engineering in California.

Forman Williams (NAE) is professor of engineering physics and combustion and director of the Center for Energy Research at the University of California, San Diego. He was elected to the National Academy of Engineers, Sec. 01 Aerospace Engineering, in 1988 “for contributions to the advancement of combustion and flame theory.” Before his present position, Dr. Williams taught at Harvard and Princeton. His field of specialization is combustion, and he is the author of *Combustion Theory* (Addison-Wesley, 2nd ed., 1985) and the coauthor of *Fundamental Aspects of Combustion* (Oxford, 1993). He is a member of the editorial advisory boards of *Combustion Science and Technology*, *Progress in Energy*, the *AIAA Journal*, *Combustion Science,* and *Archivium Combustionis*. Dr. Williams is currently researching many fundamental aspects of combustion, as well as combustion in microgravity. He received a B.S. from Princeton and his Ph.D. from the California Institute of Technology.

Tom Woodford is an associate professor and head of the Department of Fire Protection and Safety Engineering Technology at Oklahoma State University. He spent 12 years in the U.S. Navy, specializing in surface ship damage control and engineering. He also spent 2 years with an independent fire-testing laboratory in Washington State, where his responsibilities included work in large-scale fire testing and computer fire modeling. Mr. Woodford is an associate member of the Society of Fire Protection Engineers and the International Association for Fire Safety Science and a member of the National Fire Protection Association. He received a bachelor's degree in electrical engineering from the University of Virginia in 1983, a master of science degree in ocean engineering from the Massachusetts Institute of Technology/Woods Hole Oceanographic Institution in 1991, and a master of science in fire protection engineering from the University of Maryland in 1996.

Appendix B

Workshop Agenda

WORKSHOP TO IDENTIFY INNOVATIVE RESEARCH NEEDS TO FOSTER IMPROVED FIRE SAFETY IN THE UNITED STATES

April 15-16, 2002
Washington, D.C.

MONDAY, April 15

8:00 a.m. *Continental Breakfast*

8:30 **Welcoming Remarks: Workshop Objectives and Agenda**

Richard G. Little, Director, Board on Infrastructure and the Constructed Environment

David A. Lucht, Chair, Committee to Identify Innovative Research Needs to Foster Improved Fire Safety in the United States, Wochester Polytechnic Institute

Peter Chang, National Science Foundation

8:45 **Fire Safety Issues in the United States—an Overview**

John Lyons, Director, U.S. Army Research Lab (retired)

9:30 **Earthquake Engineering—A Possible Model of Success for Fire Safety Engineering**

William Anderson, National Research Council

10:00 *Break*

10:30 **Fire and Explosion Issues**

Moderator: Fred Dryer, Princeton University

Simulation of Building Fires—Howard Baum, NIST

Explosion Phenomena—Bob Zalosh, WPI
Flammability of liquids and gases—Fred Dryer, Princeton

11:15 **Moderated Panel Discussion**

12 noon *Lunch (in meeting room)*

1:00 **Materials and Retardant Issues**

Moderators: Eli Pearce, Polytechnic University

Performance of Polymer and Composite Materials—Judy Riffle, Virginia Polytechnic Institute, Jack Lesko, Virginia Polytechnic Institute
Possibilities for Fire Retardant Materials—Ed Weil, Polytechnic University
Thermal Decomposition of solids—Takashi Kashiwagi, NIST

2:00 **Moderated Panel Discussion**

3:00 *Break*

3:15 **Fire Protection Systems**

Moderator: Ken Dungan, Risk Technologies, LLC

Fire Signatures—Dan Gottuk, Hughes Associates
Alternate Sensors—Susan Rose-Pehrsson, NRL
Suppression—Anthony Hamins, NIST

4:00 **Moderated Panel Discussion**

5:00 *Recess for the day*

TUESDAY, April 16

8:00 a.m. *Continental Breakfast*

8:30 **Fire Protection Engineering Tools**

Moderator: Fred Mowrer, University of Maryland

Deterministic Models—Jim Quintiere, UMD
Probabilistic Methods in Deterministic Models—Nathan Siu, USNRC
Suppression Models—Kevin McGrattan, NIST

9:15 **Moderated Panel Discussion**

10:00 *Break*

10:30 **Structural Performance Issues**

Moderator: Craig Beyler, Hughes Associates, Inc.

Fire Severity—Jim Milke, UMD
Structural Dynamics—Bob Iding, WJE
High Performance Materials—Venkatesh Kodur, NRC Canada

11:15 **Moderated Panel Discussion**

12 noon *Lunch*

12:30 p.m. **Human Behavior Issues**

Moderator: William Feinberg, University of Cincinnati

Understanding Human Behavior in Stressful Situations—Guylene Proulx, NRCC
Available Data and Input into Models—Rita Fahy, NFPA
Human Factors Contributions to Building Evacuation Research and Systems Design: Opportunities and Obstacles—Jake Pauls/Norman Groner

1:15 **Moderated Panel Discussion**

2:00 **Public Policy Issues**

Moderator: Beth Tubbs, International Conference of Building Officials

Risk and Data Needs for Performance-based Codes—Brian Meacham, ARUP
Fire Service Perspective—Chuck Kime, ASU
Research to Practice—Paul Croce, FM

2:45 **Moderated Panel Discussion**

3:30 **Smart Growth for Fire Safety**

What are big opportunities for breakthroughs in research?
What kind of impact will they have?

What are the keys need in education, training, and technology transfer?
What is the role of NSF and other agencies and institutions?

5:30 *Adjourn*

Appendix C

Workshop Attendees

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Appendix D

Workshop Background Papers

Baum, Howard. Simulating Enclosure Fire Dynamics.

Beyler, Craig. Structural Fire Protection.

Croce, Paul. Public Policy Issues: Bringing Research Into Practice.

Fahy, Rita. Available Data and Input Into Models.

Gottuk, Dan. Fire Signatures and Detection.

Hamins, Anthony. Fire Suppression.

Iding, Robert. Performance-Based Structural Analysis To Determine Fireproofing Requirements: Methodology, Case Studies, And Research Needs.

Kashiwagi, Takashi. Research Needs For Flammability Of Polymeric Materials.

Kime, Charles. Transferring Fire Safety Technology Research from Academia to Practice: A Public Policy Issue at the Local Level.

Kodur, Venkatesh. Fire Resistance Research Needs For High Performing Materials.

Lyons, John. The Fire Problem.

McGrattan, Kevin. Large-scale Modeling of Fire Suppression With Water Sprays.

Meacham, Brian. Risk and Data Needs for Performance-Based Codes.

Milke, James. Research Needs For Assessing The Fire Severity In Performance-Based Fire Resistance Analyses.

Mowrer, Frederick. Fire Protection Engineering Tools.

Pauls, Jake, and Norman Groner. Human Factors Contributions To Building Evacuation Research And Systems Design: Opportunities And Obstacles.

Proulx, Guylene. Understanding Human Behavior in Stressful Situations.

Quintiere, James. Deterministic Models for Fire Protection Engineering.

Riffle ,Judy, and Jack Lesko. Polymer Matrix Composite Constitutive Properties, Evolution & Their Effects on Flame Durability & Structural Integrity.

Rose-Pehrsson, Susan. Fire Protection Systems: Alternative Sensors.

Siu, Nathan. Probabilistic Methods in Fire Safety Assessment: Potential Research and Development Needs.

Weil, Ed. Possibilities for Fire Retardant Materials-Toward Solving the Most Difficult Problems.

Zalosh, Robert. U.S. Explosion Research and Education Needs.

RISK AND DATA NEEDS FOR PERFORMANCE-BASED CODES

Brian J. Meacham[1]

ABSTRACT

The transition to performance-based codes is underway in the United States. For many on the technical side of the equation, this is a positive move, as a performance environment promises greater opportunities to apply analytical tools and methods to develop cost effective fire protection for buildings. For many on the policy setting side of the equation, however, the move to performance is being met with concern, as the certainty in design requirements provided by prescriptive regulation will no longer be assured, and the tools and data seem to be lacking to ensure that performance-based designed buildings will maintain levels of risk deemed tolerable to society. To gain a acceptable level of comfort for all involved, significant investment will be required (1) to further refine the risk-informed performance-based building regulatory framework, (2) to develop and validate risk-informed performance-based engineering and policy decision-support methodologies, (3) to develop baseline performance and risk data and databases, and (4) to provide training and education for those working in all aspects of the built environment.

Introduction and Background

The U.S. building and fire communities first seriously began to consider performance-based regulation and design in the early 1990s. A significant catalyst was the 1991 conference, Firesafety Design in the 21st Century, supported by the National Science Foundation and the Society of Fire Protection Engineers (SFPE), and hosted at Worcester Polytechnic Institute (Lucht, 1991). Through presentations and breakout group discussion, the conference participants identified goals, barriers and strategies for fire safety design in the 21st century. The outcomes included a United States national goal 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.” The primary barrier to achieving this goal was identified as a lack of fire safety goals aimed at establishing a level of safety acceptable to the public. As the conference report states (Lucht, 1991):

> “All four breakout groups identified the lack of design goals as a leading barrier to the use of emerging firesafety design methods. Each group used different words, but drove at the same point: lack of definition of desired level of safety, absence of established uniform levels of risk, lack of measurements for success/acceptability of risk, lack of performance-based objectives. Again and again, it was noted that current codes and standards do not specify the overall level of safety each is trying to achieve in the public interest. This is analogous to having sophisticated structural analysis and design methods available to structural engineers without any idea as to the live loads, dead loads or safety factors that have been established as design criteria.”

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Recognition of the need to incorporate specific goals and objectives into the regulations, which reflect acceptable or tolerable levels of risk/performance, was an important step. However, the process of incorporating these concepts is a challenge, as the concepts of risk and acceptable risk, and the use of risk analysis, are not uniformly understood or widely accepted throughout the building and fire communities. This is true for many reasons, including a poor understanding of what the magnitude of "actual" risks are, a shortage of quantified risk values that are widely accepted, and a poor understanding of the likelihood of unforeseen or "improbable" events occurring in any given building. As reported in a National Research Council supported study (McDowell and Lemer, 1991):

> "Lacking a common framework for discussion and analysis of safety, the public and government officials are often poorly prepared to deal effectively with issues that have small probabilities of occurrence and the potential for severe consequences. Development and broad application of risk analysis procedures will help facility professionals, policy makers responsible for assuring safety, and the people and property owners exposed to risk to understand more clearly the nature of those risks and to determine what levels of risk are socially and economically tolerable."

This observation highlighted another significant concern: in the early 1990s, building and fire communities lacked a common framework or process for identifying, addressing, and incorporating risk concepts into the regulatory system.

Research and Development: The Society of Fire Protection Engineers

Following the 1991 conference at WPI, the SFPE embarked on three major efforts aimed at addressing the above issues: research into performance-based design (Meacham, 1998), research into the use of risk concepts in performance-based regulation (Meacham, 2000), and the development of an engineering guide to performance-based design (SFPE, 2000). Although advancements were made through these efforts, additional needs were also identified (Meacham, 1999). This need for research motivated the SFPE to hold a workshop aimed at establishing a research agenda for fire protection engineering (SFPE, 2000a), and to co-sponsor both a United Engineering Foundation (UEF) workshop on a similar topic (Cox, 2001) and another NSF sponsored conference at WPI (Lucht, 2001). All of these efforts identified several recurring needs, including (from Meacham, 1999):

1. There is a need to consider the level(s) of tolerable risk (personal and societal).
2. There is a need for clear specification of, and agreement to, fire safety goals and objectives, and performance and design criteria.
3. There is a need to understand how fire initiates, develops and spreads.
4. There is a need to understand how various fire safety measures (active and passive), including fire department operations, can mitigate potential fire losses.
5. There is a need to understand how people react in a fire situation.
6. There is a need to have, and to apply credible data, tools and methodologies in the determination of the above factors.
7. There is a need to consider the financial impact of fire safety decisions.
8. There is a need to address uncertainties in the analysis and design process.

Research and Development: The Code Development Community

The U.S. code development community began the transition to performance-based codes following the 1991 WPI conference as well, with the formation by the International Code Council (ICC) of the Performance Code Committee in 1996, and with the National Fire Protection Association (NFPA) initiating an effort to add a performance option to the *Life Safety Code*® (Watts, 1997). In addition, the ICC and the NFPA recognized the need to address data and risk issues for performance regulation, and supported research into risk in performance regulations (Meacham, 2000) and supported the SFPE in development of fire protection engineering design guidance.

In 2000, the National Fire Protection Association published NFPA Standard 101, the *Life Safety Code,* with a performance option (NFPA 101, 2000). In 2001, the International Code Council published the *ICC Performance Code for Buildings and Facilities* (ICC, 2001). Both of these performance-based codes focus on "policy level" objectives, and refer to standards, guides and practices of professional organizations, such as the SFPE, for performance criteria, analysis, design, testing, and evaluation methods.

However, like the SFPE, the ICC and the NFPA recognized that gaps exist in data and methodologies for performance regulation, and participated in the workshops sponsored by the SFPE described above. In addition, each organization has participated in international committees and task groups aimed at sharing information and defining needs for performance regulation. The two primary such groups are the Inter-jurisdictional Regulatory Collaboration Committee (IRCC) and the International Council for Building Research and Innovation (CIB), Task Group 37. Recent papers by members of the IRCC and CIB TG37 reflect the needs of the regulatory community in terms of an overall framework, performance criteria (data), risk, and linkages (e.g., Bergeron et al., 2001; Beller et al., 2001; Bukoswki et al., 2001; Meacham, 2001; Meacham et al., 2002). These issues will be discussed in more detail later in this paper.

Risk and Data Research Needs

Even though the US has achieved the 1991 goal of developing performance-based building and fire regulations, it is widely agreed that there remains a need for a more comprehensive risk-informed performance-based regulatory framework, for risk, decision and cost analysis methodologies, and for data to support performance-based building and fire regulations. These needs are especially important from the policy perspective, for if the system is to be supported by policy makers and the public, there must be confidence in the data, tools, and methods being applied, and in the decisions that are made based on risk tolerability, performance levels, and cost.

Refined/Modified Risk-Informed Building Performance-Based Regulatory Framework

One of the key elements of understanding that has been provided by the IRCC has been the need to appropriately recognize the relationship between policy issues and technical issues. The technical community needs to understand they are working within a larger system, which must ultimately relate to qualitative goals and functions of buildings. In trying to communicate this concept, the IRCC has outlined a risk-informed performance-based regulatory model (Meacham et al., 2002). This model can conceptually be divided into two portions, qualitative and quantitative. The qualitative portion is often where the goals, functions and level of performance are described. This portion of the model sets the structure and focal point for the quantitative portion of the model. It should be noted that the qualitative portion of this model recognizes that a performance system is only useful if quantitative methods and solutions are provided. The key to the model is that quantitative methods and solutions must be specifically linked to the qualitative portion of the model to complete the system.

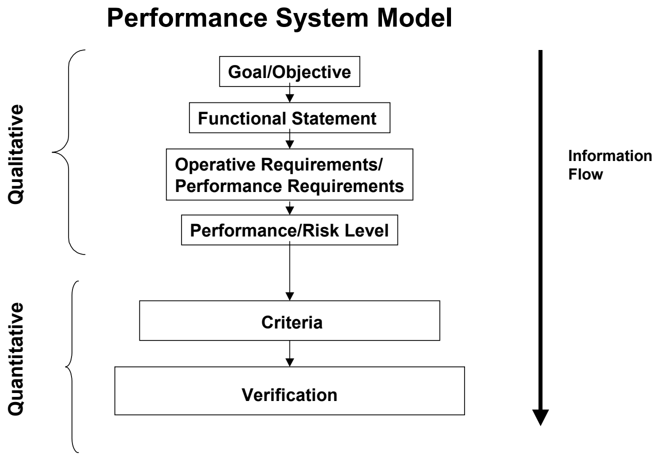


Figure 1. Outline of IRCC performance model (Meacham et al., 2002).

The intent is that the model can be viewed from the top down or the bottom-up. In other words, one should be able to start with a goal statement and be able to ultimately link to a specific quantitative requirement. Inversely, one should be able to look at a specific quantitative requirement and link to a top-level qualitative goal. If such linkages cannot be made then there is a disconnect. Generally, it should be remembered that the top-level policy/user need oriented portion of the model sets the scope for the quantitative portion.

Linking Societal Objectives, Risk Tolerability, Data, Methods, and Solutions

When designing and constructing a building, quantitative, measurable methods and solutions must be used. In the past, such methods have been available in the form of prescriptive codes, standards and design approaches. These approaches have generally been successful, but key linkages were missing (Meacham et al., 2002). Without the qualitative level, the full scope and intent of what a building code, a standard, or even a specific design provides is unknown to society, public policy makers, building owners and users. This makes it difficult to justify new and innovative approaches since it is difficult to determine what is expected. In order for the performance approach to be effective, tools are necessary which link society, policy makers, building owners and users, and the technical community. An example of the necessary linkages is illustrated in Figure 2 below, which helps to illustrate the data needs (risk and other). The desired levels of tolerable risk lead to descriptions of desired performance. To achieve desired performance, one needs to know the metrics, and needs to have test, measurement, prediction, and calculation methods to assess when the desired performance has been reached. Thus, performance criteria need to be developed within the performance framework and not in isolation.

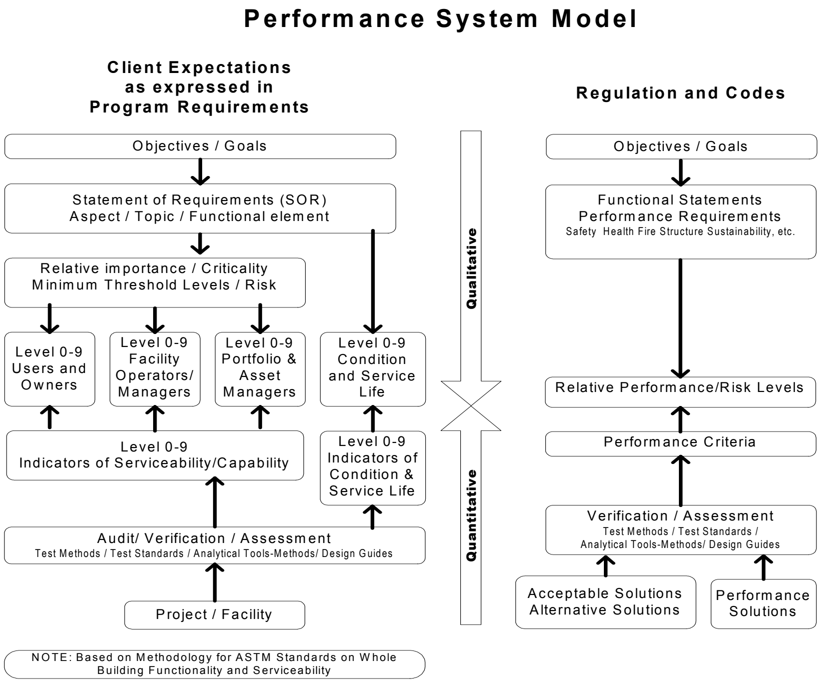


Figure 2. Linkages between qualitative and quantitative criteria (Meacham et al., 2002).

The need for the linkages outlined in Figure 2 can be further seen by going into more detail, as illustrated in Figure 3 below.

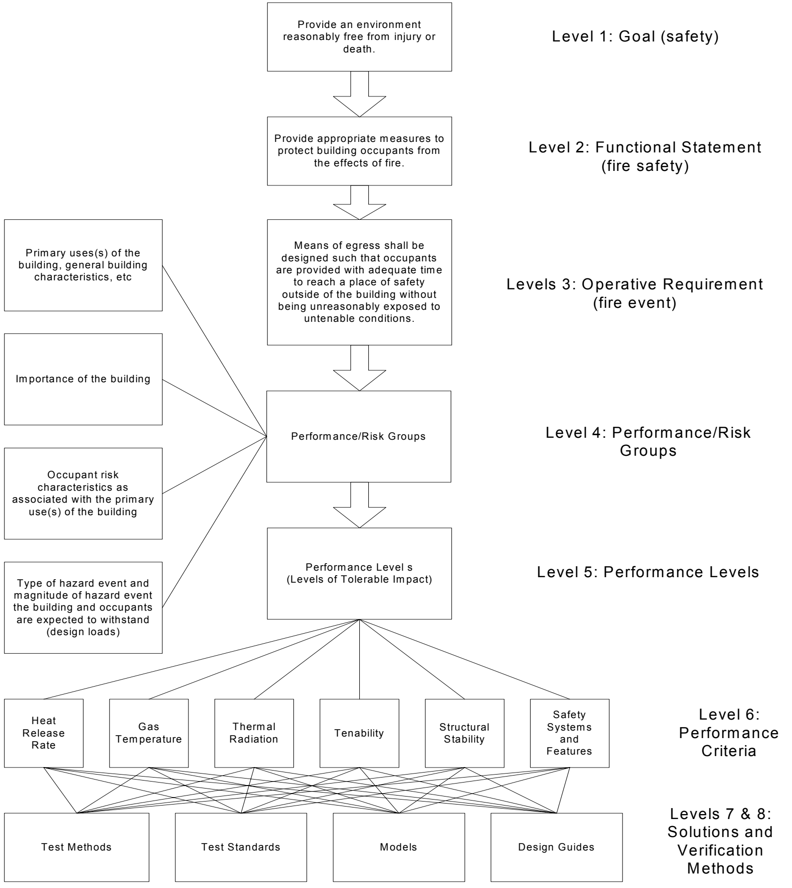
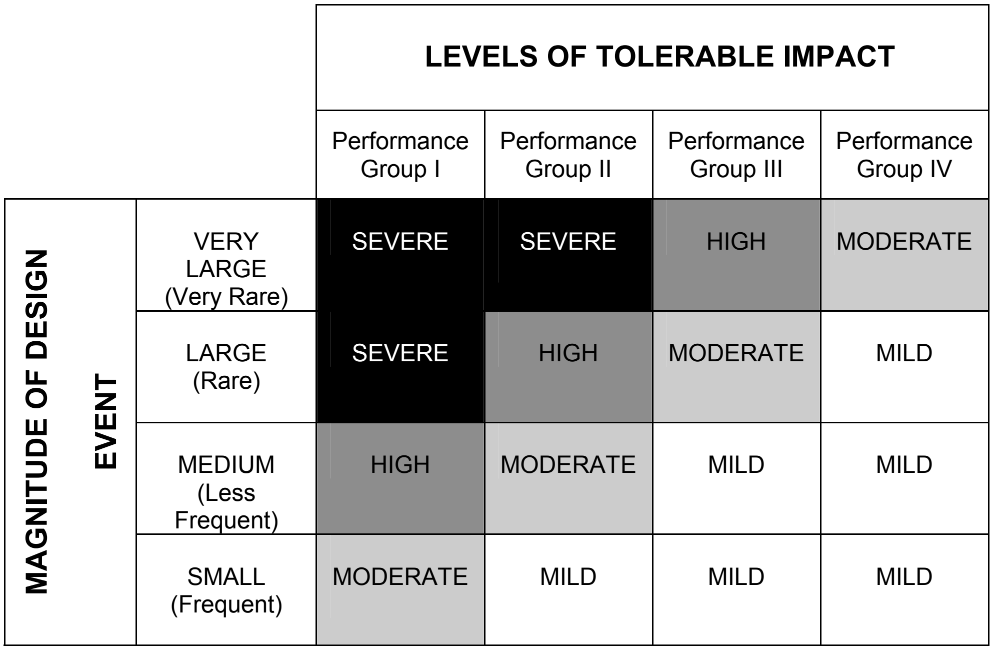


Figure 3. Relationship between components of performance system (Meacham, 1999a).

Figure 3 is a powerful visual tool for understanding just how much additional research is needed to operate successfully in a performance system. It illustrates how much data are needed to make the linkage from a goal of "safety," described in terms of "tenable conditions," to the metrics used to define, measure, construct, and evaluate buildings and building components to provide the desired level of performance and safety. *Development of test methods, standards, guides, analytic methods, and data – outside of a clear regulatory framework – leaves the door open for confusion, rather than consensus, as the linkages required to demonstrate that the necessary connections have been made may not exist.*

Events, Impacts and Performance

As part of the above stated need to link qualitative goals and quantitative methods and metrics for fire regulation, further research is needed into understanding and quantifying the fire events of concern, the impact those events could have on buildings and occupants, and the overall building performance. As illustrated in Figure 4, a mechanism for discussing these concepts for performance-based regulation has been outlined and implemented (Meacham, 2000; ICC, 2001). Performance Groups contain buildings of different uses for which similar levels of performance are desired (e.g., Performance Group I includes small unoccupied out buildings, and Performance Group IV includes critical facilities). The Levels of Tolerable Impact reflect an expectation of building performance given a specific Magnitude of Design Event (e.g., a Very Large fire is expected to result in no more than Moderate damage to a Performance Group IV building, while it is expected to result in severe damage to a Performance Group I building).



		LEVELS OF TOLERABLE IMPACT			
		Performance Group I	Performance Group II	Performance Group III	Performance Group IV
MAGNITUDE OF DESIGN 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

Figure 4. Relationship between events, tolerable impacts and building performance (adapted from Meacham, 2000; ICC, 2001).

Those familiar with seismic engineering will recognize the above, as it is derived from concepts developed by groups such as the Structural Engineers Association of California (Hamburger et al., 1995; SEAOC, 1998). Modified and incorporated into the *ICC Performance Code for Buildings and Facilities* to apply to multiple hazards (ICC, 2001; Meacham, 2000), however, *the concept has shortcomings for fire safety, as it does not adequately quantify* *magnitude and frequency of events because the required data are not currently available. Unlike a natural hazard event, fire does not impact a structure uniformly, and its impact is dependent on the structure, its protection features and its contents. Key questions include: how should fire loads be defined, how should probability of occurrence be characterized, and how can the fire loads be regulated?* Should "worst credible event" scenarios be employed, and if so, who decides what those scenarios are? Alternatively, should sets of baseline "design fire loads" be developed for specific occupancy types, building configurations, and occupant loadings? The latter more closely relates to the development and use of structural loads, and can be linked to tolerable risk and performance levels. This is an area that, as the performance concept moves forward, requires significant attention.

Development of Risk-Informed Decision Tools and Methods

To support the above effort, and to support regulatory developers, design professionals, and enforcement officials, it is becoming increasingly important to develop risk-informed decision methods and tools to help balance the critical risk, benefit and cost components. Development of a comprehensive fire risk, benefit and cost model will have to consider several factors, including how risk is defined, who is impacted and how, and how benefits and costs are to be measured (e.g., see Meacham, 2000; Notarianni, 2000).

This need for risk-informed approaches is not new. In 1972, the U.S. General Services Administration and the U.S. National Bureau of Standards jointly developed an event logic diagram that showed alternative approaches to achieving building fire safety (Meacham, 1998a). After several revisions, this tree eventually became the basic reference guide of the GSA's goal-oriented systems approach to building fire safety. Described in a document commonly referred to simply as *Appendix D,* the approach became a basis for describing a risk-informed systems approach to building fire safety design (GSA, 1972). Key features of *Appendix D* include:

- A concept of relative risk (the absence of risk is not feasible).
- Management goals as described in the context of acceptable levels of risk.
- Workable components of a fire safety system that can be adapted to any building.
- An event logic tree expressing relationships among the different system components.
- A method of calculation enabling the performance of alternative fire safety systems to be compared.
- The use of probability to describe fire safety performance.

Following the publication of *Appendix D*, activities relating to risk-informed systems approaches to building fire safety expanded considerably in the United States and internationally, including:

- Development of NFPA 550, *Guide to the Fire Safety Concepts Tree* (NFPA 550, 1995).
- Development of the Fire Safety Evaluation System (FSES) used in NFPA 101A, *Guide on Alternative Approaches to Life Safety* (NFPA 101A, 1995).
- Development of the *Building Firesafety Evaluation Method* (BFSEM) (Fitzgerald, 1985).
- Development of FRAMEworks (Bukowski et al., 1990; Hall, 1995).
- Development of CESARE-Risk (Beck, 1986; 1987; 1997)
- Development of FIRECAM (Beck and Yung, 1989; 1990)
- Development of CRISP (Fraser-Mitchell, 1994; 1997)

There are also a variety of other fire risk approaches in use or development internationally (Meacham, 2002), including in specific areas such as nuclear power (Siu, 2002) and chemical process safety (Barry, 2002). However, for the general built environment, most of the current approaches seem to be lacking from an applicability and useability perspective, either being too difficult and/or time consuming for use in practice, or lacking the sophistication required for the application, or lacking the data necessary to support the modeling and/or required decisions.

Recently, however, work undertaken by Notarianni (2000; 2002) charts a path forward for integrating risk information and uncertainty into fire engineering analysis and fire safety decision-making. In this work, Dr. Notarianni discusses the wide range of issues involved in decision-making under uncertainty, and provides an approach for cost-effectively incorporating risk and uncertainty into commonly used fire protection engineering tools. This is a significant step towards development of a tool for widespread use by the fire engineering community. Furthermore, her work in the area of decision analysis (Notarianni, 2000) nicely parallels the needs identified for risk-informed fire protection engineering design and regulation (Meacham, 2000). *Given the clear and pressing need for a risk, benefit and cost assessment and decision tool for regulation and design, as outlined above, considerable effort is required in this area.*

Data and Databases

To support all activities related to reducing the fire loss in the United States – be it in terms of life loss, economic impact, or other metric – data and easily accessible databases are needed. Furthermore, quantification of the uncertainty and variability associated with those data to be developed and catalogued in databases is required. There are numerous data needs for fire safety, ranging from material properties, to human factors, to risk data. Data needs other than for risk decisions have been discussed in many forums (e.g., SFPE, 2000; Cox, 2001), so the focus here will be on risk data issues.

The fire loss experience in the United States is generally considered well understood, as data are collected and published for such parameters as the number of fires by property class, leading sources of ignition, number of deaths and injuries, and dollar value of fire losses (e.g., NFPA, 1999). However, these data do not include all fire losses, and statistical methods are applied to infer the scope of the national fire problem. In some cases, loss data are only reported to insurance companies, and are confidential and not available to the public. In other cases, insurance companies do not get complete data either, such as when fires are extinguished when very small and only minor damage results, and when there are large deductibles or significant (or total) self insurance. In all cases, ignition frequency is severely lacking.

How one takes the available data, with its associated uncertainty, and applies it to a building fire risk problem, may differ significantly depending on one's confidence in the data and the methods applied to address the uncertainty (see, for example, Apostolakis, 1978; von Winterfeldt and Edwards, 1986; Morgan and Henrion, 1990; Notarianni, 2000). For example, consider the issue of collecting and using data aimed at understanding the fire risk situation in the United States. First, a metric to measure fire risk needs to be selected. This alone can be difficult. Consider the following ways one could measure a single metric: risk of fire death:

Deaths per million people in the overall population,
Deaths per million in a specific vulnerable or sensitive population,
Deaths per building use or occupancy type,

Deaths per hour spent in a facility,
Deaths within room of fire origin,
Deaths outside of room of fire origin,
Deaths by smoke inhalation,
Deaths due to carbon monoxide,
Deaths due to oxygen deprivation,
Deaths due to toxic substances,
Deaths due to elevated temperatures,
Deaths due to thermal radiation,
Deaths by month of year,
Deaths by day of the week, and
Deaths by time of day.

Depending on the risk metric selected, the risk of death can differ, and trends can be shown to be either increasing or decreasing. For example, in 1996, there were some 1,975,000 reported fires in the United States, resulting in some $9,406,000,000 in direct property losses, 25,550 civilian (non-fire fighter) injuries, and 4,990 civilian deaths (Karter, 1997). If one assumes a U.S. population of 250,000,000 in 1996, one could estimate the risk of death in a fire per overall population as $4990/250{,}000{,}000 = 1.996 \times 10^{-5}$. If one chooses to look at the risk of death in structure fires (4220 deaths, Karter, 1997), the risk estimate is 1.688×10^{-5}, a slightly lower figure. Looking only at non-residential structure fire deaths (140, Karter, 1997), the risk is only 5.6×10^{-7} – a significantly lower value.

In many regulated areas, a risk level of 1×10^{-6} is often targeted as being "reasonably practicable" (see, for example, Whipple, 1987; Meacham, 2000). If this were the case for fire, it would seem that the risk of death in non-residential structures is rather good. However, of the 140 non-residential fire deaths, 19 of them (13.6%) resulted from four fires in adult board and care facilities (Karter, 1997). If one were to assume a small fraction of the U.S. population occupy adult board and care facilities, say 0.5% or 1,250,000 people, the risk to life would be 1.52×10^{-5} – well above the overall non-residential structure fire risk and the 1×10^{-6} "reasonably practicable" target. Furthermore, considering that only four fires resulted in 19 deaths, one could argue that the fire risk in adult board and care facilities is unusually high (as compared with other non-residential facilities, which include hospitals, jails and other institutional occupancies, as well as offices, stores, factories and the like). Thus, when considering the overall population, the risk of death from fire in non-residential structures can appear quite low, and most would deem the risk level as being tolerable. When focus is placed on a specific subset, however (in this case adult care facilities), the risk of death from fire can appear to rise dramatically.

The above discussion on metrics becomes more complicated when injuries, economic losses, and other factors are considered. This clearly points to the need for a thorough risk characterization activity in order to understand and incorporate stakeholder input. In the end, the overall acceptability of a risk-informed performance-based code will depend on how consequences are defined, what metrics are used, what data are available, and the risk perceptions of the involved parties. Where data are lacking, judgments, and the process to elicit the judgments, are paramount to the overall acceptance of the risk characterization. In the end, whatever data are ultimately used should be well understood, including associated uncertainties, unknowns, inferences and judgments.

In addition to fire loss data and databases, comprehensive risk characterization will likely require specific information for assessment of incapacitation, death, content or structural damage or failure, environmental impact, or other losses or harms. Such information includes relevant concentrations, thresholds or tolerances, such as a maximum tolerable CO concentration, radiant heat flux or temperature. Many of these data are available in tables and text of the *SFPE Handbook of Fire Protection Engineering* (2002) and other sources. However, data are not available for numerous materials and systems, and the available data likely includes a mixture of test and/or scientific data, scientific and engineering judgment, inference and uncertainty, and the levels, types and sources of uncertainty are unknown or unreported.

One also must consider the variability in the population of concern. With respect to people, there are wide variations in age, physical ability and mental ability in the general population. This is important for risk analysis, especially when average or mean values are used to describe functions or activities, such as recognizing fire cues, making decisions and evacuating. For example, the elderly are typically more at risk from fire than the general population. This is due in part to age-related physical, mental and medicine-induced impairments, and is manifested in less overall ability to recognize fire cues, to make quick, lifesaving decisions, and to egress quickly to a place of safety. If an "average" time to hear an alarm bell is selected, an "average" decision-making time is assumed, and an "average" walking speed is postulated for an egress evaluation, what happens to those who cannot hear, make decisions or walk on their own? The more one knows about a population and how it is at risk, the better one's decisions can be regarding risk characterization, tolerability and acceptability.

Finally, the cost of fire and fire safety needs to be better defined, and associated data need to be collected and made available. Although performance-based design often promises lower costs, there has been little work undertaken to quantify the costs and verify the claim. For example, a design may claim cost savings by designing an automatic sprinkler system and reducing fire resistance. Although this may result in construction cost savings, the long-term maintenance costs may increase the total life cycle costs. Furthermore, if a significant change in use is desired for the building, the cost to upgrade the sprinkler system or add other fire safety features should be considered up front (this might be considered the cost to achieve flexibility).

From this brief discussion, it should be clear that data are needed for fire risk decisions, that work is needed to better define the types of data needed for fire safety design and regulations, and that uncertainty and variability needs to be reported with the data. As noted earlier, to assure that the "correct" data are collected and reported, data types and needs should be identified within a risk-informed regulatory framework that clearly links data to fire safety objectives.

Education and Training

Given that complex risk-informed decisions will be required in a performance-based regulatory system, a critical component of education and training for those at all levels of the regulatory, design and enforcement communities should be in the areas of risk and decision making. Such education and training should encompass risk concepts, risk characterization, uncertainty, variability, and decision-making processes and tools. *Whether part of university programs, continuing education or other, courses should be developed in the areas of risk and decision-making to support all levels of the building and fire communities.*

Barriers to Progress

As discussed above, significant barriers to progress include the lack of a common understanding of risk (and specifically fire risk), the lack of a complete framework for risk-informed performance-based regulation and design, the lack of significant databases of fire, risk and cost data, and the lack of a comprehensive fire risk and cost decision tool. If these needs are not addressed, there will be a significant challenge in implementing a performance-based building and fire regulatory system in the United States.

Conclusions

Each of the areas identified above are critical to the continued advancement of performance-based codes and fire safety design methods, and to the roles these mechanisms play in facilitating advancements in fire safety technology to reduce the fire burden in the United States. However, from a policy perspective, two areas stand out as being particularly critical for moving forward and gaining widespread and long term acceptance:

1. A framework must be developed that clearly links policy level objectives to data needs, design methods, decision tools, and building fire safety design solutions. This framework needs to clearly illustrate how the individual parts are interrelated and interdependent, and that development of test methods, standards, guides, analytic methods, and data – outside of such a framework – leaves the door open for confusion, rather than consensus, as the linkages required to demonstrate that the necessary connections have been made may not exist.

2. Decision support tools are needed, for designers, regulators and policy developers, so that all parties involved better understand the bases for fire safety requirements in the framework of levels of risk, cost and benefit acceptable to society.

The above items are closely related and desperately needed, as the current system forces too many decisions to be made without adequate justification of the bases for those decisions – by policy makers, regulatory developers, enforcement officials, and designers. In the near term, this will lead to wide variation in the application of performance concepts and criteria, and in the long term, could lead to significant differences in the level of acceptable performance, which if a significant loss occurs, could result in legal challenges to the performance system that could be difficult to defend.

From the perspective of data needed to inform technical, risk and policy decisions, two areas stand out as well:

1. Research is needed to adequately quantify magnitude and frequency of fire events for use in risk-informed performance-based decisions. Unlike a natural hazard event, fire does not impact a structure uniformly, and its impact is dependent on the structure, its protection features and its contents. Key questions that need to be addressed include: how should fire loads be defined, how should probability of occurrence be characterized, and how can the fire loads be regulated?

2. Research is needed to develop an analytic tool to describe and predict the totality of how buildings and occupants perform when subjected to design fire loads.

The National Science Foundation can play a key role in helping to reduce the fire burden in the United States by supporting research in each of the above areas – through individual research grants, and through the establishment of a multi-disciplinary center for fire performance research. Of these, support for a multi-disciplinary center would be the most important, as it would serve to link a broad cross-section of technical and policy researchers, private sector firms, and regulatory agencies to collectively identify and tackle the most important research needs. Without such cross pollination, there will remain the risk of individual research being conducted that, while in itself important to the advancement of science, does not contribute to advancements that can benefit the nation as a whole.

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Transferring Fire Safety Technology Research from Academia to Practice: A Public Policy Issue at the Local Level

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Abstract

Transferring fire safety research from academia to practice by governments at the local level is dependent upon getting issues through the public policy process. Making public policy is a political process, where public value is a critical factor. Among the many public policy making models, the rational-comprehensive model is considered the "ideal." Yet most scholars acknowledge, more practical models suggest that public policy is made incrementally. Two significant barriers exist in moving fire safety technology to the public policy agenda in local governments. First, many fire service administrators and other bureaucrats were trained and educated to stay out of politics. Secondly, many bureaucrats (fire chiefs, fire marshals, and building officials) within the system are heavily invested in the current system and often feel threatened by new technology that they do not always fully understand. Colleges, universities, and professional organizations could more effectively collaborate to offer practical courses and seminars to decision makers, in the art of transferring fire safety technology through public policy.

Introduction

The purpose of this paper is to frame the problem of transferring fire safety technology research from academia to practice within the context of the public policy making process, particularly at the local level. The fire service, fire departments in particular, play an important role in the adoption of new technologies yet there are barriers related to the political process and the adoption of new public policies. It is well known within the fire service that the adoption of codes and standards is a local issue that requires a great deal of effort and understanding among local officials and politicians. The adoption of new fire safety technology based on sound research is important to advance fire life safety and building safety in the built environment of our communities. Therefore it is important for fire service administrators, other public administrators, elected officials, researchers, scientists, and teachers to more fully understand the policy-making process at the local level.

Public Value

Bringing politics and science together to bear on the problem at hand can benefit from a discussion about public value. Public " . . .value is rooted in the desires and perceptions of individuals . . ." (Moore 1995 52). Moore continues that public value can be provided in goods or services and that one of the services is to adopt regulations that govern how things are done in the community in the name of the public good. Transferring fire safety research and knowledge into the built environment of a

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community is generally considered a public good, i.e., a good that is non excludable and non divisible. However, it would be remiss not to acknowledge that there is a considerable fire safety technology research agenda focused on materials and processes that are excludable and divisible in the private sector. These are the products and process that can be adopted by some manufacturers, but not all, or used by some building architects and engineers but not all.

Evaluating public value is a constant in any public policy debate, whether consciously or unconsciously engaged in by the actors. This debate is a mixture of the technical merits of the policy and the political merits of the policy. Some of the questions asked are as follows. Who will pay for this policy? What will this policy accomplish? How will the policy be implemented? How will the success of the policy be measured? Obviously the answers to these questions will vary from individual to individual as well as from institution to institution. It is well to understand that it is a primary role of the actors who are proposing the policy to understand these nuances and to recognize the most appropriate mix of technology and politics to get the policy adopted.

Public Policy at the Local Level

What is Public Policy?

There are a variety of definitions for public policy, however Thomas Dye (1998) provides a good working definition that is applicable to this paper. Dye defines public policy as simply what government does or does not do. Thus, public policy includes all of the policies adopted by the elected body of a local government and also includes the regulations and policies that are set by the bureaucracies within the local government, e.g., the local fire department or building department.

Who are the Actors in the Public Policy Process?

The public policy making process includes a vast number of actors, some of whom are considered official actors and some of whom are considered unofficial actors (Birkland 2001). It is the collective efforts of these actors that culminates in the adoption, or change in public policy. The official actors include the fire chief, fire marshal, building official, city manager, city engineer, and other public administrators whose roles and functions are to regulate, administer, and otherwise adopt, implement and/or make public policy. Some of the unofficial actors in the process include the members of special interest groups, e.g., the homebuilder associations, contractors, architects, builders, consultants, fire protection engineers, and scientists. Other unofficial actors include the media, citizen groups, business owners and managers, and individual concerned citizens. These actors come together in a variety of ways to make and influence public policy at the local level.

Models for Making Public Policy

Scholars have developed various public policy-making models over the years in an attempt to explicate the process and to teach students and practitioners how to make public policy. The following models represent those that are more frequently discussed and that might better illuminate the world of making public policy. A brief review of these models will help frame the discussion about how the fire service community might approach transferring new fire safety technology research into the community by changing public policy.

The Generic Model

Most public administration scholars and political scientists agree that there are some basic steps, or stages, that can be ascribed to the public policy process (Anderson 1994; Dunn 1994; Theodoulou 1995; Dye 1998; Birkland 2001). These stages generally include the following. First, a problem or issue emerges in the system and gets the attention of policy makers. Second, the issue is placed on the public agenda. This gives the agenda item legitimacy and a place in the rankings of public issues to be decided. Third, the issue is developed in the form of a proposal for consideration by the political decision-making body. Fourth, support is sought to get the proposal adopted as the government's policy. Fifth, the policy is implemented. This is normally a function of the bureaucracy. In the case of transferring fire safety technology research, and knowledge, implementation typically involves the participation of the fire service (fire department) and the building department, as well as official and unofficial actors who are involved in the development and maintenance of the community's built environment. Lastly, the consequences of actions taken to implement the policy are evaluated. It is important to examine, not only the obvious consequences, but to make a special effort to discover any unintended consequences. Unintended consequences can be either negative or positive, but in either case, should be examined before determining whether the policy was successful or not.

The Rational-Comprehensive Model

The rational-comprehensive model is generally viewed as the ideal model because it relies on rational thinking, scientific analysis, and sound logic (Weimer & Vining 1999; Birkland 2001). The underlying assumptions for this model are that the actors in the process are rational decision-makers who follow a logical path in developing public policy. The rational-comprehensive model assumes that the rational actor will be presented with a problem and a goal, gather as much information as possible about the costs and benefits, completely analyze all of the information, and select the solution that will maximize the benefits, minimize the costs, and achieve the stated goals. The rational-comprehensive model is very appealing to rational actors, especially scientists, engineers, economists, and most firefighter types because of its rationality and logic; to firefighters this is often referred to as just "common sense." However, the rational-comprehensive approach is seldom achievable because of the political and human factors that must be considered (Lindblom and Woodhouse1993; Kingdon 1995; Birkland 2001). Hence, other models have been postulated to try and capture these nuances.

The Incremental Model

Lindbloom (1959) presented an alternative to the rational-comprehensive model in his article titled *The Science of Muddling Through*. Lindbloom presents the notion that public policy is not a logical and rational process but instead an incremental process that is a function of timing and opportunity. He posits that policy-making actors are not always rational and certainly not able to develop a comprehensive approach because of so many political barriers. Therefore, public policy is a result of making small, incremental changes to existing policies, which emerge over time into a policy that often appears to be a comprehensive public policy.

The Garbage Can Model

The *Garbage Can* Model (Cohen, March and Olsen 1972) is another alternative to the rational-comprehensive model. In this model a variety of policy alternatives, issues, and solutions are tossed into the metaphorical "garbage can" where they are mixed with each other. The *garbage can* metaphorically is filled with problems, solutions, and actors all looking to find each other. Problems are looking for solutions and vise versa while actors are seeking ways to get problems and solutions together.

Bounded Rationality

The rational-comprehensive model requires all of the possible information available and the capacity to process the information in a rational and logical way. Since this is an enormous task, which typically overwhelms the capability of humans and human systems, Simon (1976) offered a concept he coined "bounded rationality." That is, Simon recognized that the capacity to process large amounts of complex and complicated information is bounded by the limitations of humans and their machines. Thus it is not reasonable to expect that all information will be available and brought to bear on any given issue nor will the system have the capacity to process such large amounts of information when making public policy.

The Streams Metaphor for Making Public Policy

John Kingdon has offered yet another approach. Kingdon (1995) offers his "streams" metaphor, which includes, a problem stream, a policy stream, and a political stream that are brought together to make public policy. He also presents the notion of "policy entrepreneurs" and "policy windows" in describing how these streams converge on an issue. Policy entrepreneurs are actors who may be official actors or unofficial actors, as noted above, and who have a solution and are looking for a problem, in which to apply it. When the opportunity arises, i.e., a policy window opens; the policy entrepreneur is ready to offer the solution to the problem. Fire protection engineers, fire chiefs, fire marshals, and building officials represent some of the official and unofficial actors that could be policy entrepreneurs.

Barriers at the Local Level

Political Barriers

Many fire chiefs, their bosses (city managers), and others within the bureaucracies of our local and state governments are reluctant to get involved in anything they determine to be politics. Yet, it is the political process that is used to set public policy and it is public policy that dictates what government does and what governmental agencies do. This process, then, has a great deal to do with the fire service communities' ability to get local governments to adopt new technologies and fire safety methods. There is a rational explanation for this dilemma. In the public administration literature it is referred to as the politics/administration dichotomy, which means that public administration scholars have debated, for over a century now, the role of public administrators.

In 1887 Woodrow Wilson published an article that was used as the foundation for the creation of a professional discipline for public administration. Wilson argued that public administrators should be professional and separate from politics, where their job is defined as carrying out the public policies that are set by elected officials in the political process. However, more recent public administration literature acknowledges that public administrators cannot, and should not, be completely separate from politics since they are a part of the larger system and have a legitimate role to play (Birkland 2001, Shafritz and Russell 2001). This includes the setting of public policy, which is a political function in our system. It is important to understand this as background in the discussion of transferring fire safety technology research and education to our communities, since the fire service community needs to use the political process to get adopted public policies that are important to transferring fire safety technology research to our communities.

The above background might explicate why many of today's public administrators, especially the more senior fire chiefs and other public administrators who were trained and educated in a system that stressed a separation between politics and administration, are reluctant to get involved in changing public policy. Although many of the younger fire chiefs are very aware that they have a political role to play, there are still a great number who believe that politics is a dirty word and it is something that they should avoid.

Investment Barriers

Many fire departments, and individual actors, have an enormous investment in their current system: an investment that they measure in terms of time, money, understanding, and application. Most departments have individuals who have invested their entire career (or a great portion of it) in the development and adoption of the codes and standards they currently use. Often they have spent many hours of personal time on committees developing these codes and standards plus an even greater amount of time learning and teaching others how to interpret and apply these codes and standards. For many of these actors, performance-based codes, fire protection engineering solutions, and the application of state-of-the-art research, and fire safety technology represent a major shift (often perceived as a major threat) in the way the have been educated and trained to do things. Some are embracing these new breakthroughs while others are standing on the sidelines viewing these new notions with much trepidation.

Adopting the latest technology presents fire departments and its members with many challenges. These challenges range from getting the dollars to train the existing workforce to use these new tools, to hiring fire protection engineers and other professionals, to dealing with the realities of managing a somewhat major shift in the existing culture. These barriers and resistors to change are not revelations but do represent significant challenges to all actors in the system. When these change resistors are added to the mixture with a reluctance to engage the political public policy making process, the challenges can be formidable.

Possible Solutions

Making public policy at the local level is not complicated but it is complex. The environment is ever changing and the actors are different from locale to locale, which is one of the oft-heard complaints by architects and engineers who do business throughout the U.S. Many of these professionals have argued for a more universal (or national) adoption of codes and standards, but that is not likely in the near future given the political system of the U.S., which places a tremendous, and historical, emphasis on the notion of local control. Understanding the public policy making process at the local level is the first step in finding viable solutions to effectively transfer fire safety technology research to the world of practice at the local level.

Rationalism Versus Incrementalism and Decision-Making

Rationalism versus Incrementalism is essentially a debate over how decisions are, or should, be made. The rational-comprehensive model is very appealing because one of its axioms is that problems are rationally and logically identified. Then a well-ordered approach to finding the best solution is based on all of the information available, followed by sound scientific analysis of all alternatives before a solution is selected. The rational approach makes a lot of sense to actors who are trying to solve a perceived technical problem, i.e., a technical problem deserves a technical solution.

Incrementalism, as described above, can take many forms (and usually does) allowing for small changes in public policy. Although, the incremental approaches do not typically provide for comprehensive solutions, they do provide for partial solutions that are politically acceptable. This is often hard for rational thinking fire chiefs, fire marshals, fire protection engineers, and researchers to accept but it recognizes the realities of the system. The incremental approach recognizes the political system and the need to find a political solution.

Technical Problems Versus Political Problems

Rational actors are often frustrated with the system when the technical solution they propose to solve the technical problem is not accepted by the system. They often go back to their department with the idea that they just need to do a better job of presenting the evidence to support their proposed solution. All they need to do is provide more data, and make their arguments more clear. After revising their report, they resubmit it only to find that it is still not acceptable. Even more frustrated they go back to their department and work even harder on providing even more data, better graphs, and strengthening all of their arguments. They resubmit their report and are again rebuked. This cycle can go on forever and when it does, the rational thinker in the system, often the fire chief or fire marshal, are broken (they can become organizational casualties) and complain that the system won't accept their proposal because it is too political.

In fact they are right about the system being political (too political may be an overstatement) but they refused (or were not able) to acknowledge that it was the political part of the system that they needed to address. In other words, they had a political problem and were trying to solve it with a technical solution. This occurs very often at the local level. All public policy issues at the local level have a political side that cannot be resolved by technical solutions, no matter how well documented and rational the technical report. This emphasizes the need to first recognize whether the problem is a political problem or a technical problem. Then, once the problem is appropriately categorized the appropriate solution can be found. This is not to minimize in any way the importance of good technology to solve technical issues. In fact, without good fire safety technology research to support the technical solutions proposed, the political solutions will most likely fail. There is a fine balance in applying the art (political) of getting an issue adopted as new or changed public policy and the science (technology) to support the policy.

Education

Another obvious solution is expanded and improved education. Often the effort is directed to train fire marshals, technicians, code enforcers, and engineers in the use of sophisticated technical tools required to use these new technologies, without any education about the political environment in which these technologies are applied. Educating decision makers, fire chiefs, fire marshals, and building officials, in the art of making public policy is less often available. This education should include some of the topics presented here and should also emphasize the need for each fire service actor in the process to understand their role and how they can contribute to the adoption of the best fire safety technology for their community. Colleges and universities can play an even greater role than they presently play by building public policy courses into their fire service curriculums. Public administration programs typically have at least one public policy course in their curriculum; however transferring fire safety technology usually is not a topic of discussion since most of the policy professors do not have any background in fire service issues. Another role for educational institutions is to partner with professional organizations like the Society of Fire Protection Engineers, the International

Fire Marshals Association, the International Association of Fire Chiefs, the International Association of Firefighters, and the International Code Council (to name just a few) to offer professional development seminars that are specifically focused on setting the public policy agenda for the transfer of fire safety technology.

Conclusion

Transferring fire safety technology research from academia to practice requires getting it adopted as part of the community's public policies. Public policy includes the regulations and policies of governmental agencies like fire departments and building departments. Getting fire and building departments to change their regulations to accommodate state-of-the-art fire safety technology is often considered a problem within the bureaucracy and not a political problem. However, as presented in this paper, setting the public policy agenda is a political process and fire service actors who recognize this will increase the probability of getting their policies adopted. Kingdon's (1995) streams metaphor explains much of what is happening in the fire service with regard to the adoption of fire safety technology. Many fire protection engineers, fire marshals, plans reviewers, building officials, educators, and consultants can easily be categorized as "policy entrepreneurs," that is they have a solution that they believe will solve (or at the very least mitigate) the fire safety problem in the United States. This can be a good thing if a concerted effort is made to educate the fire services in the public policy process.

Some specific actions may be in order. First, recognize that adopting fire safety technology research is a political problem, not just a technical problem, but that the adoption of good public policy relies on sound research. Second, it is important to identify the official and unofficial actors in the process. Moore (1995) reminds us that public managers (fire officials) have a responsibility to recognize and try to improve the value of the services they provide to the public. He also informs us that individuals define and perceive public values differently. Therefore, it is important to understand these perceptions as they relate to fire safety technology. Third, it is important for all fire service actors, especially decision makers, to understand the nuances of making public policy. This includes an understanding of the rational-comprehensive model and the various incremental models that are offered as alternatives. Lastly, it is critical that the problem is appropriately identified. This is especially true when an initial attempt to get fire safety technology on the public policy agenda is not successful. It is very hard (usually impossible) to solve a political problem with a technical solution, yet it is important to recognize that the political solution most generally will require sound science as a foundation. This may seem paradoxical to some rational actors. However, I believe it is clear that understanding the politics of setting public policy is important before we can successfully set a sound fire safety agenda at the local level, which effectively transfers fire safety technology research from academia to practice.

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PUBLIC POLICY ISSUES: BRINGING FIRE RESEARCH INTO PRACTICE

Paul A. Croce[1]

ABSTRACT

Several observations from two perspectives are used to help identify issues with implementing fire research results. These issues range from finding a way to do needed research to working with stakeholders. Practitioners need assistance now, and researchers need to bring results into practice. The management model concept of use-inspired fundamental research is more effective than the traditional "hand-off" approach. Different choices among safety criteria for desired outcomes may also be useful. A viable stakeholder organization is seen as key.

Introduction

When we look at the current state of fire research and compare it to where we started about 30 years ago, it is not difficult to say that great strides have been made, reflecting enormous achievement and tremendous progress. Huge advances have been made in knowledge, computer models, data and education. We clearly see the use of this knowledge and these data and models in the performance-based design encouraged by emerging performance-based codes and standards worldwide, coupled with a growing professional practitioner workforce composed of fire safety and fire protection engineers. Yet we still hear pleas from fire researchers that an adequate degree of fire safety has not been achieved and more research is needed. So where's the problem? From my perspective, there is little doubt that a significant part of the problem has to do with implementation, getting research results into practice.

Perspectives

I'd like to summarize some observations on the current state of affairs to help focus on needs and issues as they pertain to technology transfer, or moving research into practice. First, it will help you to appreciate my perspectives in forming the basis for my observations. FM Global is an insurer of large commercial and industrial customers worldwide, providing coverage in property protection and business interruption. Many of the Fortune 500 companies are our customers. We do not provide insurance on an actuarial basis; rather we promote loss prevention through scientifically investigated and engineered measures. Typically, our customers like and want this approach. As Vice President of Research for FM Global, it is my responsibility to assure a sound technical basis for understanding hazards and for assessing and mitigating risks… practically, cost effectively, in the field. Efforts must be balanced between trying to ascertain tomorrow's hazards and responding to today's losses.

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The International FORUM for Cooperation in Fire Research is a consortium of the heads of large fire research organizations worldwide. Members are dedicated to working together to address large, critical fire research issues. We routinely discuss the technical, organizational and management issues we face, seeking commonality as a basis for cooperation. As Chair of the FORUM, I try to find common issues to pursue and reach agreement among the members. As most of you know, many of these organizations are being privatized from independent government sponsored laboratories to commercial ones. These changes foster competition rather than cooperation. Needless to say, it is increasingly difficult to find commonality for cooperation. Yet there are still items on which we have strong agreement: the continuing need for more scientifically-based fire research, the recognition of areas needing research (though priorities differ), the benefit (and difficulty) of collaboration and the generation of position papers as a vehicle to communicate internationally.

Observations

With the above perspectives for background, I present the following observations.

1. What is fire research? I have often heard each of the following items described as or alluded to as fire research. While there may be times when each of the first three bullet items may be involved in research, it is the fourth bullet that generates new sound knowledge and is recognized as what advances the field.

   - standardized testing – routine testing conducted according to strict protocol
   - scenario testing – testing done, often at full-scale, to simulate real fire situations
   - model application
   - scientifically-based model development, experimentation, analysis
     - ✓ first principles
     - ✓ dimensionless parameters
     - ✓ generalized solutions

2. Key current drivers of fire research are performance-based design and global product testing for acceptance; to a lesser degree, loss prevention, incident investigation and improved phenomenology also provide motivation for research efforts.
3. The practice of fire safety engineering/fire protection engineering may be outpacing knowledge. The accuracy and precision of models being used in practice may not be adequate in all applications; however, uniformity and consistency of application is a key factor.
4. Global trade is a strong factor. The drive for global acceptance of products for emerging markets influences many decisions on what is done and how money is spent.
5. As a result of item 4. above, there is movement from scientific research to ad hoc testing, which not only does nothing to advance the field, but also strengthens the barrier to research needed for next generation testing.

6. Because of the commercialization of laboratories the work being done is less independent and caters more to special interest, which usually means the work is done less for understanding and more for problem-solving, and becomes less scientific and more empirical.
7. Lastly and perhaps most importantly, researchers must bring results into practice. The key word here is “bring”. In today’s environment, it is no longer acceptable or effective simply to hand off research work to practitioners. For research to be useful, it must be implemented effectively, and to be implemented effectively, researchers must work with other stakeholders from origin to (and sometimes through) implementation.

Interestingly, these observations are shared among researchers at FM Global and the FORUM.

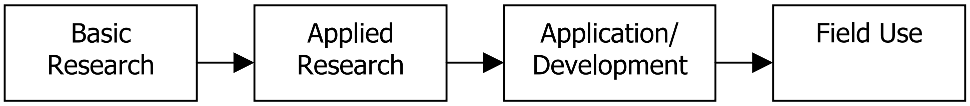
Research Needs

From a technical consideration, I believe there are two high level fire research needs; however, the achievement of both can be greatly aided through public policy positions, and both have breakthrough potential.

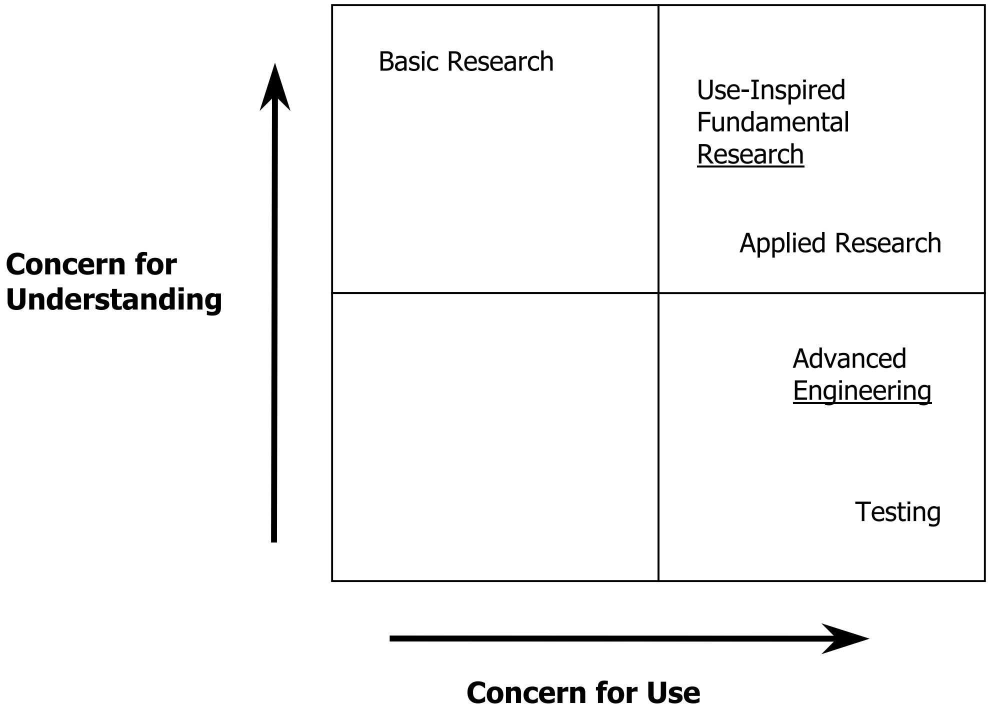
1. The ultimate goal for fire research is accurate first principle, end-use models with reliable material property data. The achievement of this goal contributes significantly to both improved performance-based design and next generation standardized tests. What is needed specifically are better ways to measure accurate material property data for use in first principle models, which also need to be developed further. (A FORUM position paper was generated on this subject.)
2. The second need is to do more focused scientifically-based research that is also more amenable to technology transfer. Two suggestions are put forth. In the current environment, researchers have to do a better job of “selling” the value of their work to other stakeholders, and get their buy-in. The management model concept of use-inspired fundamental research has proven useful to me and can be useful in a larger arena. Also, we should consider more broadly the criteria commonly selected for evaluating fire safety outcomes. These suggestions are discussed further below.

Use-Inspired Fundamental Research

Our organization recently underwent a significant merger, and there is no doubt that FM Global Research is expected to perform and be measured on useful deliverables to our business. I would like to share with you an approach I’m using to help convince our top management that funding fundamental research is both justified and beneficial to our business needs. The approach focuses on **use-inspired fundamental research**. The traditional approach for using research results has long been depicted as follows:



Instead of using this "hand-off" model, wherein basic research may not have much concern for ultimate use, I propose the following model be used:



In this chart, the ordinate shows an increasing concern for understanding, while the abscissa shows an increasing concern for use. This model clearly indicates the difference between traditional basic research and use-inspired fundamental research.

For clarity, I offer the following definitions:

- Use-Inspired Fundamental Research
  - Investigation into mechanisms or first principles with end use in mind
- Applied Research
  - New investigations into specific applications
- Advanced Engineering
  - Transferring existing knowledge to new applications
- Testing
  - Scenario – testing conducted with a simulated real configuration
  - Standardized – testing conducted according to a recognized protocol

I find this model useful because it not only shows that fundamental research can be conducted with end use in mind, but it further depicts how testing may get you an answer to a specific question but not give you an understanding of the issue. To conduct fundamental fire research in today's environment, it is essential to operate on the right side of this chart, with most work occurring in the upper right quadrant, for understanding, and validation work done in the lower right quadrant.

Possible Fire Safety Design Outcomes

When performance-based codes, standards and design are discussed, usually there is little mention of what desired outcome is being referenced or used. Most often, the focus is on people safety, sometimes inferring public safety, but still there is ambiguity if the specific outcome is not clearly stated. Oftentimes, even when the desired outcome for people safety is clearly stated, there can be a variety of solutions, with different solutions determined by different practitioners. This may not be so bad unless significant resources are being dedicated to these new solutions, in which case one must ask if there is a better way.

In fact, there are many cases when the desired outcome may not be related to public safety, per se. Listed below are a number of possible outcomes, most of which have been used in some form of performance-based design. This list is not intended to be comprehensive, but rather to illustrate that a coordinated approach among key stakeholders may produce overall better results.

Possible Fire Safety Outcomes

- safety for room-of-origin occupants
- safety for building occupants
- safety for general public
- protection for building of origin
- protection for neighboring structures
- protection for historical buildings
- protection for firefighters
- protection for infrastructure
- operability

As we have seen with recent natural catastrophes and the World Trade Center incident, protecting people and recovering from a disaster usually depend on more than a scheme that looks at people only. A viable economy and infrastructure (food, water, shelter, medical care, electricity, supplies, transportation, jobs, etc.) can be equally significant for short and long term recovery as survival itself. If the above list is rearranged as shown below, perhaps many desired outcomes can be achieved by focussing on a certain few. In this way, using what is already known and modifying it slightly for broader application can focus the application of resources and provide greater benefit to society.

Grouped Fire Safety Design Outcomes

- protection for building of origin
  - ✓ safety for room-of-origin occupants
  - ✓ safety for building occupants
  - ✓ safety for general public
  - ✓ protection for neighboring structures
  - ✓ protection for historical buildings
  - ✓ protection for firefighters
- protection of infrastructure
  - ✓ communications, utilities, transportation systems, building stock
  - ✓ operability

By focussing on two outcomes for which much work has already been done, many other outcomes can be achieved with relatively modest additional investments. Again, a dialogue among key stakeholders could produce the focus and understanding needed to achieve this kind of benefit.

Implementation Issues

Four issues relating to implementation can be highlighted.

1. Getting scientific research done toward ultimate goal – A number of factors can be barriers to getting the right work done. Decisions sometimes are strongly influenced by politics or economics, rather than science. Researchers, practitioners and other stakeholders often have different views, different approaches, different criteria, different priorities, and often compete. Lastly, the reality is that funding for fire research is too limited to pursue everything.
2. Accuracy, precision, uniformity (what's done) and consistency (how it's done) – On the one hand, performance-based design is immature, experience is limited and results can vary. On the other, how good is good enough? Questions of accuracy, precision, uniformity and consistency need to be addressed in a representative arena. It is noteworthy that key international standards organizations have technical committees working on these issues.
3. "Solutions" can create problems when all key stakeholders are not involved. We already have encountered a number of facilities whose performance-based design resulted in an uninsurable facility. Lessons can be learned from these pioneering designs, but we also expect more such examples as global markets grow.
4. Global impact and national direction – Although this workshop has a national agenda, all of these issues need to consider global concerns.

Conclusions: Fire Research Implementation Issues Needing Public Policy Support

1. Obtain agreement, buy-in on key fire research direction, needs, approaches, goals from stakeholders outside the research community. (FORUM is planning to use position papers to help gain support across boundaries.)

2. Recognize and address global concerns and influences.
3. Consider more broadly the efficacy of safety criteria for various outcomes.
4. Establish an effective stakeholder organization. This is the single most important item since success here can greatly assist with the first three. A champion is needed (preferably not a researcher), and the group should include societal decision-makers, the fire services and key industry, trade and professional groups. (FORUM is already striving for this, and is willing to work with others.)

U.S. Explosion Research and Education Needs

Robert Zalosh[1]

ABSTRACT

U.S. explosion research capabilities have been in decline since the U.S Bureau of Mines explosion research program dwindled and then disappeared. There are some isolated productive explosion research facilities and programs, but the coordinated university-government-industry programs sponsored by the European Union and by some Asian countries dwarf their size and number. It is impossible to know whether this decline in U.S. explosion research capability is affecting U.S. explosion losses and casualties because there is no broad-based national explosion incident database. It is important to develop such a database and to initiate coordinated university-government-industry explosion research projects on specific issues in gas explosions, dust explosions, and blast waves.

Introduction

The customary introduction to this type of overview paper is to provide some context; in this case, some context on how explosion hazards and challenges fit into the overall U.S. fire safety picture. Although, the lack of a reliable explosion incident database renders it impossible to provide accurate context, a rough measure can be ascertained from NFPA published accounts of reported large-loss fires (Badger 2001), and of the deadliest fire and explosion incidents (Hall 1988).

Six of the 26 losses causing at least $10 million property damage in the year 2000, as summarized by Badger, started as gas explosions. Five of the six occurred in industrial/manufacturing/storage facilities, and the sixth was ignited in a large, single-family residence. Casualties and damage in one incident were exacerbated when the gas explosion triggered a secondary dust explosion.

Hall's accounting of the deadliest U.S. fires and explosions in the period 1900 to 1987 had 59 mining incidents out of a total of 98 incidents. Most of the mining incidents were methane and/or coal dust explosions. At least eight of the other 39 incidents started as explosions, and an unspecified number started as fires that later produced explosions. Several other incidents were not listed as explosions, but actually originated as either a boiler explosion or an ammonium nitrate explosion.

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The large number of deadly coal mine explosions in the first half of the twentieth century prompted the Bureau of Mines to undertake a productive explosion research program. A large portion of our current understanding of gas explosions and dust explosions, as well as several practical explosion protection measures, stem directly from the Bureau of Mines research projects from the 1940s through the 1980s. However, the Bureau of Mines was dismantled in the 1990s, and now the U.S. needs to look elsewhere for new explosion protection technology.

Explosion Research Infrastructure

Current explosion research activity in the U.S. is highly fragmented. Figure 1 illustrates this fragmented approach in the form of a conceptual plot of explosion test scale versus number of test facilities. The test scale is important because reliable scaling laws do not exist for several key explosion phenomena such as flame accelerations. The number of facilities is also important because of the need for multiple tests with different configurations, fuels, instrumentation, etc.

As indicated in Figure 1, there are a few large-scale government explosion test facilities, such as those at Sandia National Laboratories and the Department of Energy Nevada Test Site. There are more smaller-scale industrial explosion research facilities, such as those at FM Global, Southwest Research Institute, and Fenwal Safety Systems. Finally, there are several good laboratory-scale explosion test facilities at universities such as Princeton and the California Institute of Technology. These three groupings are shown as separate areas in the plot because there is very little coordination among them.

European explosion test facilities are not only more numerous in all sizes, they are also used for integrated explosion programs with coordinated participation of government, industry, and university research laboratories. Some examples of these programs are:

- Testing Methods for Electrical Apparatus Installed in a Dusty Environment with a Potential Risk of Explosion (Participants: UK Health and Safety Executive, Polytechnic University of Madrid, and Deutsche Montan Technologie, 2001)
- Determination of Safety Categories of Electrical Devices in Potentially Explosive Atmospheres (SAFEC 2000)
- Explosive Atmosphere: Risk Assessment of Unit Operations and Equipment (RASE 2000)

In each of these programs, a project coordinator issued one synthesis report, and individual research reports and/or technical papers were issued by the participating research organizations. Furthermore, research results are being used to assist in the development of European standards for explosion protection. In some cases, international standards bodies such as the IEC are adopting these European standards.

The coordinated approach among universities, government laboratories, and industrial research facilities is also being used in European and Asian explosion research programs of a more theoretical nature. The need for such coordination in Computational Fluid Dynamic (CFD) simulations of explosions is illustrated in Figure 2. In order to conduct CFD explosion simulations involving complex chemistry and fluid dynamics (for example, for dust explosions and for multi-compartment gas explosions), the required human and machine computational resources are beyond the capabilities of virtually any single research facility. However, a coordinated theoretical approach is allowing CFD and other techniques to be applied to separate phenomena and configurations, with results leading to an improved understanding and capability to benefit the entire explosion protection community. One example is the two-dimensional CFD simulations of dust explosions reported by Zhong and Deng (2000) as their university's contribution to a coordinated research program on Explosion Reaction Engineering funded by the National Science Foundation of China.

The thriving explosion research programs in Europe and Asia and the contrasting isolated and fewer explosion research projects being conducted in the U.S. have caused the center of explosion protection technology to be transported overseas. It is creating a tremendous burden on the NFPA Explosion Protection Committee to digest the overseas research results and to adapt them along with the isolated U.S. explosion research programs (such as FM program described by Tamanini and Valiulis, 1996) to develop explosion protection guidelines suitable to U.S. facilities. The tortuous development of the most recent edition of the Guide for Deflagration Venting (NFPA 68-2002) is an example of these difficulties.

Specific Explosion Research Needs

Although there are many important specific explosion research needs, all but two apply to particular types of explosion phenomena, such as gas deflagrations, gas detonations, dust explosions, and blast waves. The two research needs that transcend individual types of explosions and explosion phenomena are 1) development of an explosion incident database that can be used to provide data comparable to the data available in the NFPA and NFIRS fire databases, and 2) establishment of a coordinated university-industry-government explosion research program to tackle the most outstanding need identified by a panel of U.S. explosion experts.

With regard to needed research on specific explosion phenomena, this author recommends the following:

- Development of a predictive capability for flame speeds and flame accelerations in non-uniform gas-air mixtures of the type that arise in buoyant gas releases, vaporization of flammable liquid spills, breaching of pressurized gas piping in a large room or building, and backdraft explosions.
- Development of a predictive capability to determine the risk/probability of deflagration-to-detonation transition for gas deflagrations in highly turbulent environments and in highly obstructed environments of the type often encountered in industrial process facilities handling flammable gases and vapors.

- Provide a realistic method to estimate the size and concentration of the dust cloud that will be formed from accumulated dust layers during a secondary dust explosion, as illustrated in Figure 3 (from Eckhoff 1997).
- Develop a predictive capability for blast waves propagating within buildings; both for blast waves produced by detonating explosives and for blast waves produced by the venting of deflagrations.
- Acquire a sufficient understanding of blast wave generated glass shards and other secondary fragments so that blast-resistant windows can be developed and the risk of secondary fragment blast injuries can be assessed.

These last two explosion research topics are particularly pertinent to the nation's terrorism threat preparedness. The first three topics are important explosion protection issues for worker safety and firefighter safety, as well as general industrial loss prevention.

Explosion Protection Education and Training

Formal academic courses in explosion protection are extremely scarce in U.S. universities and colleges. To this author's knowledge, only one of the fire protection engineering curricula offers such a course. The American Institute of Chemical Engineers (AIChE) program entitled Safety and Chemical Engineering Education (SACHE) provides educational packages on explosion protection pertinent to chemical processing facilities, and some unknown number of the 125 SACHE member colleges use these packages in their undergraduate chemical engineering courses. These packages allow professors without special expertise in explosions to incorporate the subject into a general process safety course without having to first undergo tedious self-education without benefit of a mentor or textbook.

Most safety professionals, fire protection practitioners, and loss prevention engineers acquire some knowledge of explosions through on-the-job training or self-education. Several highly protected risk insurers and some of the large oil and chemical companies are examples of corporations with formal on-the-job training. In addition, there are some continuing education explosion courses provided under the auspices of organizations such as AIChE. However, many engineers and safety personnel face their first major explosion hazard or explosion incident investigation without benefit of the fundamental knowledge needed to go beyond the regulations and consensus or corporate standards.

European universities provide a much more extensive array of formal education courses in fundamental explosion concepts and formal mentoring in explosion protection technology. Some of these universities include the University of Central Lancashire, the Univeriste' de Poitier, and the University of Bergen. The result of the more focused explosion education in Europe is inevitably to increase European capabilities in explosion protection vis-à-vis those in the U.S. Asian universities probably also provide more opportunities in explosion protection education than does the U.S. despite the abundance of excellent U.S. faculty and courses in the more general subject of combustion. It would be useful to address and reverse this widening gap between U.S. and Asian and European educational opportunities in explosion technology.

Overcoming Explosion Protection Barriers

The primary barrier to improvements in U.S. explosion protection research, explosion education, and overall explosion protection technology is the absence of either a federal government agency or a large industrial consortium that recognizes explosion protection as an important part of its mission. Although some federal agencies address explosion issues within a narrow purview, there is currently no agency that is willing to undertake the type of comprehensive explosion research that the U.S. Bureau of Mines conducted while it was active. The limited explosion research projects sponsored by the U.S. Department of Agriculture to address grain dust explosions are indeed productive, but they have not lead to advances in other explosion hazards or applications. The result is that we now have an accurate count of the average annual number (12) of grain dust explosions in U.S. grain handling facilities, but we have no idea of how many dust explosions there are in all the other U.S facilities handling combustible powders and dusts.

Likewise, despite the proprietary loss data collected by individual U.S. property and casualty insurers, we don't really know how many gas explosions there have been in industrial, commercial, and residential occupancies. Even having these overall numbers would not be nearly as valuable as having an accurate breakdown on the specific fuels, equipment, and explosion protection measures employed, as well as the size of the loss in terms of casualties and property damage.

Multi-company U.S. industry sponsored projects are underway on one or two explosion topics, such as vapor cloud explosions. The problem with this ad hoc approach entirely under the auspices of one or two specialized industries is that the research objectives tend to be short-sighted, the research is conducted only by one or two private research organizations, and publication of the results is either suppressed or substantially delayed. These are a far cry from the coordinated and widely reported research projects underway with European Union sponsorship of government-industry-university explosion research teams.

Conclusions

Although explosions contribute significantly to annual U.S. fire losses, it is not currently possible to quantify that contribution with any accuracy. The primary reasons for our lack of reliable data on U.S. explosion incidents are that the fire reports filled out using forms such as NFPA 901 do not explicitly account for explosion incidents, and the explosion loss data collected by insurers and by certain government agencies are very narrow in scope and in the number of facilities and personnel at risk. Without an accurate and broad-based national database, we cannot decipher the current level of success being experienced with existing explosion prevention and explosion mitigation technology and practices, let alone decipher any changes to that level of success. It is important to develop such a database.

The United States has fallen behind other parts of the world (particularly Europe) in the development and utilization of new explosion protection technology. Our fall from a leadership position is due in part to the U.S. shortfall in suitable explosion testing and research facilities, and in part to the extensive European Union sponsorship of coordinated government-industry-university explosion research programs. In order to re-establish U.S. leadership, there is a need for the same type of coordinated collaborative explosion research programs that are now common in Europe and Asia.

There is a need for research in the following specific explosion issues: 1) flame speeds in highly non-uniform gas-air mixtures, 2) deflagration-to-detonation transitions in congested and turbulent environments, 3) dust cloud formation that can lead to dangerous secondary dust explosions, 4) blast wave propagation in buildings, and 5) blast wave generation of secondary fragments and the development of blast resistant/compliant windows.

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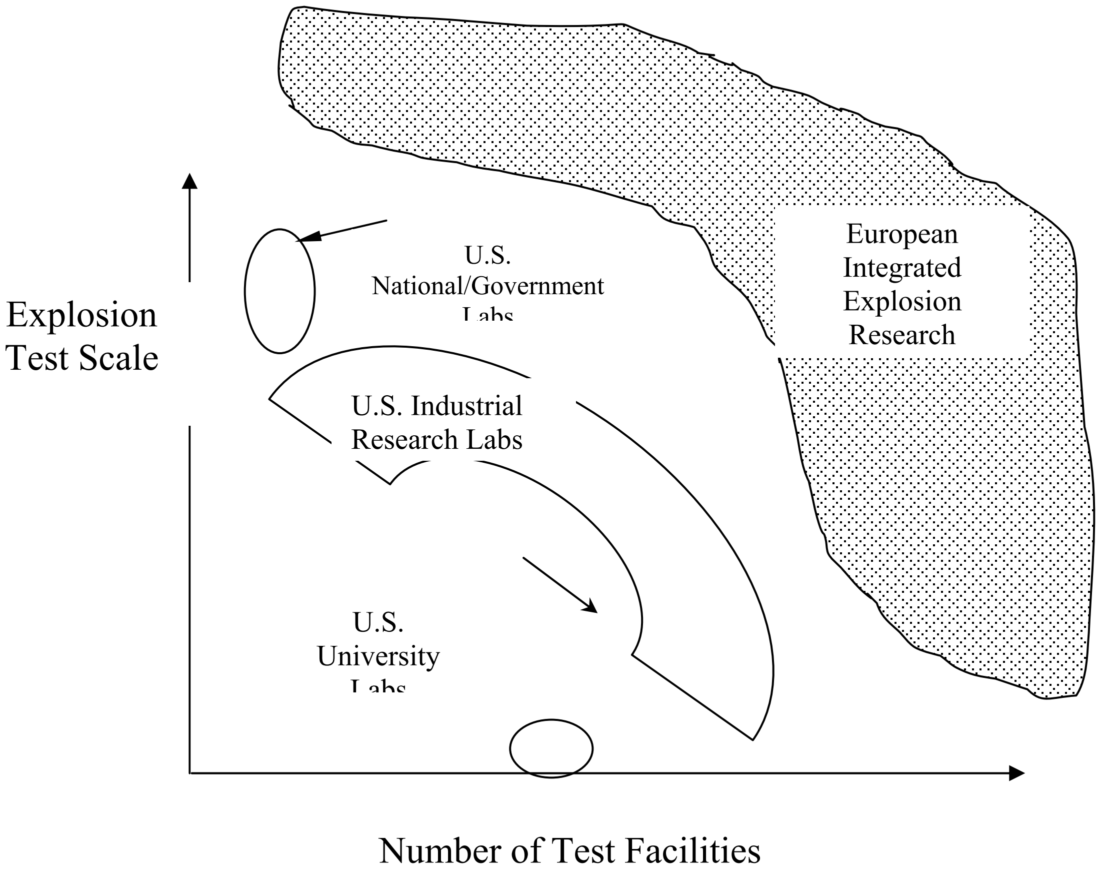

Figure 1. Conceptual Comparison of Explosion Testing Facilities in U.S. and Europe.

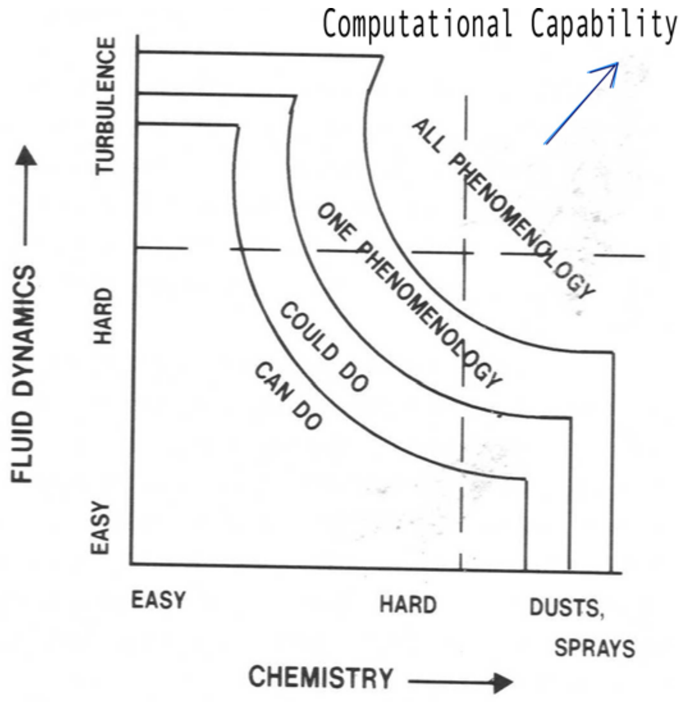

Figure 2 CFD Requirements for Explosion Simulations (adopted from Oran et al, 1982)

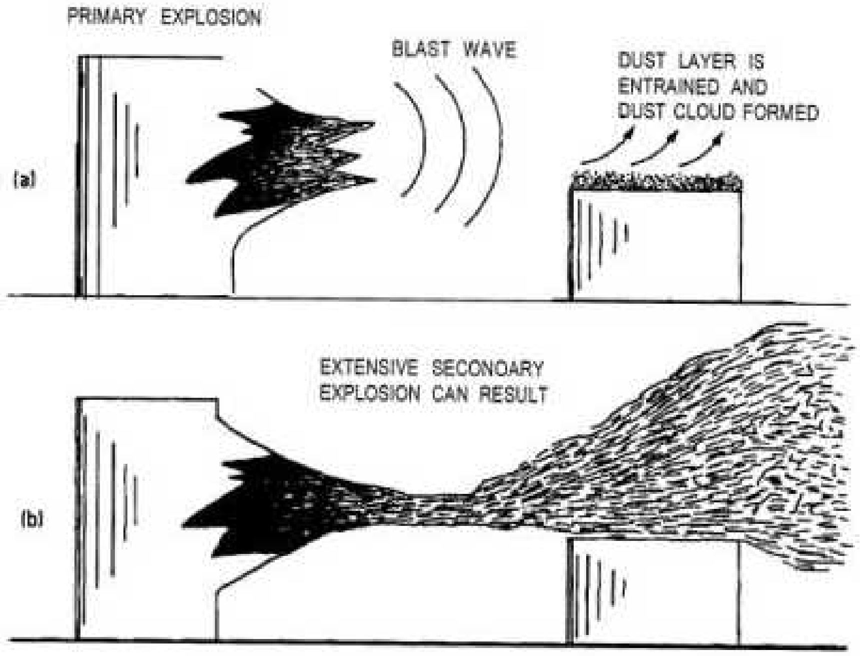

Figure 3. Secondary dust explosion caused by a) blast wave from primary explosion lifting accumulated dust, and b) flame from primary explosion igniting newly formed combustible dust cloud (from Eckhoff, 1997)

Summary of Fundamental Research Needs

F. Dryer
(07/14/02)

Current basic research is inconsistent with intent of America Burning 1974. The approximately 2 million dollar annual expenditure of the NSF Research Applied to National Need (RANN) on fundamental fire research topics in the mid 70's has dwindled to about 25 programs in 2002 supported through the NIST Center for Fire Research effort. Few of these projects concentrate on the basic aspects in the fire research area. Exemplar of the problem is that performance codes are being proposed without the necessary infrastructure, and multiple fire tests and standards are developing without a fundamental science base to remove redundancies and emphasize universality. The US cannot afford to have simply an empirical fire safety research infrastructure, and a dearth of fundamental science upon which to build new, more predictive fire modeling and performance-based design tools. The hand-off across disciplinary approaches from basic to applied research and onward into applications and development and eventually into field-use discussed by Croce in his presentation is not presently, nor has it more recently been effective. Fundamental and applied research is not interactively connected, and the connection to developers and the field is also not well coordinated. While the lack of interconnection is essentially precluded by the dearth in research funding, there is also no infrastructural organization presently active to provide the necessary communications and technology transfer. Efforts to achieve these hand-offs within the NSF-RANN program identified that a principle detractor in this process is the "language barriers" in going from fundamentals to the field. Dialogue interchange amongst fundamental data and model developers, numerical modelers, behavioral scientists, and practitioners is needed if the design of field tools is to progress. Although this process is typically painful, it is important that practitioners, applied researchers, and basic researchers interface within the fire disciplinary area. New manpower must be produced for utilizing/advancing these tools, as well as for developing the future tools; thus, an academically based fundamental research component is critical to the evolution. Such interfaces have almost entirely disappeared within the fire safety field, resulting in the present "disconnect" and nearly complete demise of basic research activity in and support of fire safety related issues. Indicative of the level to which these problems has decayed is that within the microgravity sciences programs of NASA, 10 of the principal investigations are NIST scientists involved in the Center for Fire Research. Clearly, the funding of fundamental research relevant to the fire problem is far below that required, and what remains is fragmented and tenuously supported.

NSF is likely the most appropriate agency to rejuvenate efforts and assure coupling with applied needs through approaches similar to those developed for the earthquake engineering area. If intercommunications among levels within the discipline can be strengthened, the transfer of fundamental knowledge to the field can occur in today's computer-based technological environment much more facilely than in the past. Fundamentals can be embodied within modeling tools, and advance modeling tools to real-time interactive abilities with the faster processing approaches that are continuing to evolve. It is important to realize, however, that "predictive" modeling requires continual refinement of the sub-models and fundamental descriptions within these approaches, as new and more detailed questions arise. For example, fire and smoke spread represents one level of description while toxic product evolution would require a much more sophisticated level of description. Flashover in room fire is the main contributor to death and injury of people. By slowing down the processes leading to flashover (or better preventing it to occur), more time is allowed for people to escape. The strategy is to slow down or limit the initial fire growth so that the flashover condition may not be reached. This issue represents a more complex issue than can adequately be addressed with current tools.

The "Pasteur's Quadrant" approach to research (Stokes, D.E., (1997), *Pasteur's Quadrant*, Brookings Institute Press, Washington DC; Glassman, I. (2000) Proc. Comb. Ins. 28, 1) discussed by Croce which introduces the concept of "use-inspired fundamental research" defines what should motivate all "basic or fundamental research" in engineering disciplines. It is important to note, however, that "use-inspired" basic research should still span a wide range of scales from underpinning fundamental science to the interaction of fluid transport, chemical kinetic, and heat transfer sub-models. For example, fundamental thermodynamic, thermophysical, and thermochemical property data on existing and new materials to be used in fabrication are needed to produce science-based models. Compact, but reasonably robust sub-models for chemical kinetics, molecular transport, turbulence effects and radiative transfer are needed to eventually permit the replacement of empirical heat release rate descriptions, generally input into fire models today, with an interactive fundamental description of material combustion. The large-eddy flame-spreading model in FDS from NIST has been a very useful engineering tool used by many organizations in the world. However, the necessity to use coarse grids has forced smaller-scale processes to be neglected. Sub-grid models will depend on better description of fundamental processes. These models must be appropriate for the buoyant fire situation and capable of predicting local extinction, for example.

The present fundamentals are insufficient for predicting gas-phase flame extinction issues relevant to yielding improved strategies for inhibiting inflammation, reducing rate of fire development and extinguishing fires. Laminar and turbulent extinction processes under high temperature, partially vitiated (and combustion product diluted) fuel-rich and fuel-lean conditions are poorly understood and characterized. Improved knowledge of flame speeds in highly non-uniform gas-air mixtures, deflagration-to-detonation transition in complex geometric and turbulent environments, and blast wave propagation within building constructions, garage structures, and transportation tunnels are needed. Flammability and ignition properties of vapor/aerosol mixtures as well vapor/dust mixtures must also be included within the above types of studies. Predictive capability for flame initiation, propagation and acceleration is needed for structure design. In terms of impact on residential fires, fundamentals and technology development can today produce inherently safe heating and cooking appliances, arc limited electrical systems, and further improvements in container design for liquid flammable materials.

Chemical kinetic descriptions of heterogeneous decomposition as a function of heat loading, and the gas phase species evolved are very limited, as are the thermochemical, thermophysical, and thermodynamic properties of existing flammable materials.

Describing the interactions of several materials as fuel resources for fire also needs additional fundamental underpinning. Increased understanding of methodologies to accelerate charring processes with minimal gaseous flammable evolution could lead to improved fire properties with regard to the response of materials to heat loading, to the production rate of excess pyrolyzates leading to flashover, and to the production of toxic products. A noted in the workshop papers, world-wide effort has yet to produce an effective replacement for Halon 1301. Further knowledge of the detailed mechanisms that lead to inhibition by I, P,Mn, Sn, Si, Ge, As, Sb, Ti, Sn, Cu, Cr, and Pb is needed.

As the very fundamental level of research develops, more applied, empirical descriptions of oxidative degradation and pyrolysis mechanisms of materials need to be further evolved to yield adequate short-term model inputs, as well as to characterize experimental results that can be used to eventually validate and refine the more fundamental descriptions as they evolve. Utilization of new applied mathematical approaches to perform global feature sensitivity analyses at the fundamental level as well as on large-scale systems will be critical to evaluating and directing model developments.

SIMULATING ENCLOSURE FIRE DYNAMICS

Howard R. Baum [1]

Abstract

At least three different physics based approaches to fire dynamics simulations have evolved over the years; lumped parameter or “zone models”, computational fluid dynamics models based on classical turbulence modeling techniques, and large eddy simulations. Large eddy simulations provide the most realistic description of fire phenomena developed to date. All such simulations provide descriptions of the processes that control the mixing and combustion of fuel and air at elevated temperatures. In an enclosure fire these processes are complicated by the fact that the fuel was initially part of the building or its furnishings, and the air supply is controlled by the interaction of the fire with its surroundings. The geometry of the building and its furnishings all influence the fire and are in turn changed by it. The rational prediction of these changes is one of the central issues of fire research. The key to understanding these phenomena lies at the interface separating the gas and condensed matter phases. Substantial institutional barriers hamper progress in this area of research.

Introduction

The idea that the dynamics of a fire might be studied using digital computers probably dates back to the beginnings of the computer age. The concept that a fire requires the mixing of a combustible gas with enough air at elevated temperatures is well known to anyone involved with fire. Graduate students enrolled in courses in fluid mechanics, heat transfer, and combustion have been taught the equations that need to be solved for at least as long as computers have been around. What is the problem? The difficulties revolve about three issues: First, there are an enormous number of possible fire scenarios to consider. Second, we do not have either the physical insight or the computing power (even if we had the insight) to perform all the neccessary calculations for most fire scenarios. Finally, since the “fuel” in most fires was never intended as such, both the data and the models needed to characterize both the fuel and the fire environment may be unavailable or unknown or both.

In order to make progress, the questions that are asked have to be greatly simplified. To begin with, instead of seeking a methodology that can be applied to all fire problems, we begin by looking at a few scenarios that seem to be most amenable to analysis. Hopefully, the methods developed to study these “simple” problems can be generalized over time so that more complex scenarios can be analyzed. Second, we must learn to live with idealized descriptions of fires and approximate solutions to our idealized equations. These idealized descriptions have to be based on the kind of incomplete knowledge of fire scenarios that is

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characteristic of real fires. Finally, the methods should be capable of systematic improvement. Thus, as our physical insight and computing power grow more powerful the methods of analysis can grow with them.

These issues have to be faced by anyone seeking to develop simulations of fire dynamics. Inevitably, different research groups have come to widely varying conclusions about how to proceed. The first effective simulations of fire dynamics were based on “zone models”. Each compartment is divided into two spatially homogeneous volumes, a hot upper layer and a cool lower layer. Mass and energy balances are enforced for each layer, with additional models describing other physical processes appended as differential or algebraic equations as appropriate. Examples of such phenomena include fire plumes, flows thru doors, windows and other vents, radiative and convective heat transfer, and solid fuel pyrolysis. An excellent description of the physical and mathematical assumptions behind the zone modeling concept is given by Quintiere (1984). The relative physical and computational simplicity of the zone models has led to their widespread use in the analysis of fire scenarios. So long as detailed spatial distributions of physical properties are not required, and the two layer description is a reasonable approximation to reality, these models are quite reliable. However, by their very nature, there is no way to *systematically* improve them.

The rapid growth of computing power and the corresponding maturing of computational fluid mechanics (CFD), has led to the development of CFD based “field” models applied to fire research problems. Virtually all this work is based on the conceptual framework provided by the $k-\epsilon$ turbulence modeling approach pioneered by Spalding and his collaborators. The CFD based approach has rapidly led to the development of software packages aimed specifically at fire problems. The now-classic investigation of the London Kings Cross Underground Station fire involved the use of what is now known as CFX4. The CFD portion of the investigation (Simcox et al. 1992) was a landmark in the use of this methodology in fire research. The prediction, subsequently confirmed by scale model experiments, of the “trench effect” (a Coanda effect for fire plumes in confined inclines like the escalator banks in the Kings Cross fire) led to greatly increased acceptance of field modeling in fire research. More recently, SOFIE (Lewis et al. 1997) was developed under the guidance of a consortium of European fire research organizations; a brief summary of the rationale and goals of the project is given by Moss and Rubini (1997). This description is certainly not comprehensive; a complete listing of the available CFD codes that have been used in fire research is beyond the scope of this paper.

The use of CFD models of the type described above has allowed the description of fires in complex geometries, and the incorporation of a wide variety of physical phenomena. However, these models have a fundamental limitation for fire applications; the averaging procedure at the root of the model equations. The $k-\epsilon$ model was developed as a time averaged approximation to the conservation equations of fluid mechanics. While the precise nature of the averaging time is not specified, it is clearly long enough to require the introduction of large eddy transport coefficients to describe the unresolved fluxes of mass, momentum and energy. This is the root cause of the smoothed appearance of the results of even the most highly resolved fire simulations. The smallest scale flow induced details that are computable are determined by the product of the local velocity and the averaging time underlying the $k - \epsilon$ model, rather than the spatial or temporal resolution of the computation.

Unfortunately, the evolution of large eddy structures characteristic of most fire plumes is lost with such an approach, as is the prediction of local transient events. It is sometimes argued that the averaging process used to define the equations is an "ensemble average" over many replicates of the same experiment or postulated scenario. However, this is a moot point in fire research since neither experiments nor real scenarios are replicated in the sense required by that interpertation of the equations. In practice, the $k - \epsilon$ model provides a much richer description of the spatial evolution of a fire scenario than can be obtained with a zone model. However, there is little difference in the temporal resolution achieved by this approach.

Large Eddy Simulations

The "Large Eddy Simulation" (LES) technique developed at NIST over a nearly two decade period is our attempt to carry out the conceptual program outlined above. The phrase refers to the description of turbulent mixing of the gaseous fuel and combustion products with the local atmosphere surrounding the fire. This process, which determines the burning rate in most fires and controls the spread of smoke and hot gases, is extremely difficult to predict accurately. This is true not only in fire research but in almost all phenomena involving turbulent fluid motion. The basic idea behind the use of the LES technique is that the eddies that account for most of the mixing are large enough to be calculated with reasonable accuracy from the equations of fluid mechanics. The hope (which must ultimately be justified by appeal to experiments) is that small scale eddy motion can either be crudely accounted for or ignored.

The equations describing the transport of mass, momentum, and energy by the fire induced flows must be simplified so that they can be efficiently solved for the fire scenarios of actual interest. The general equations of fluid mechanics describe a rich variety of physical processes, many of which have nothing to do with fires. Retaining this generality would lead to an enormously complex computational task that would shed very little additional insight on fire dynamics. The simplified equations, developed by Rehm and Baum (1978), have been widely adopted by the larger combustion research community, where they are referred to as the "low Mach number" combustion equations. They describe the low speed motion of a gas driven by chemical heat release and buoyancy forces.

The low Mach number equations are solved on the computer by dividing the physical space where the fire is to be simulated into a large number of rectangular cells. In each cell the "state of motion", i.e. the gas velocity, temperature, etc. are assumed to be uniform; changing only with time. The computer then computes a large number of snapshots of the state of motion as it changes with time. Figure 1 shows one such snapshot of a hangar fire simulation. Clearly, the accuracy with which the fire dynamics can be simulated depends

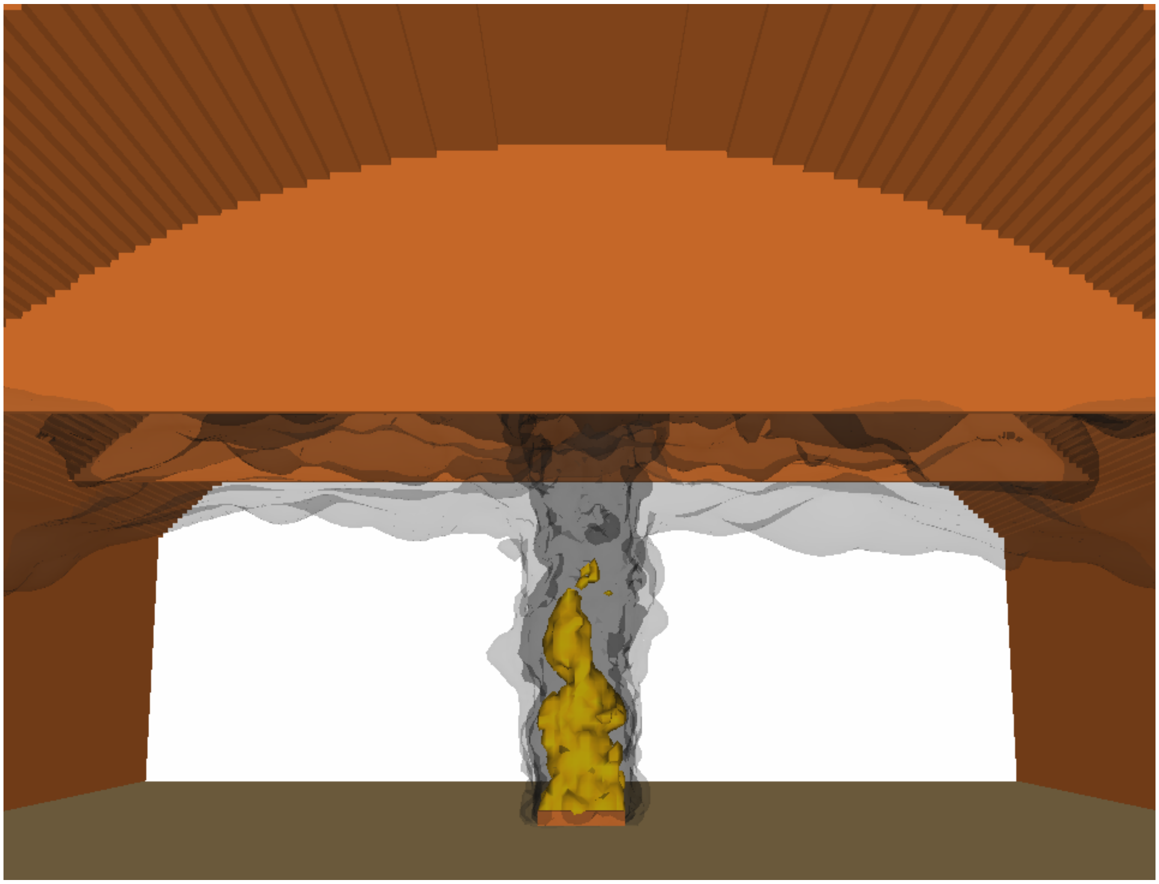

FIGURE 1: Snapshot of a simulation of 3 m square jet fuel fire in a 22 m high and 45 m wide aircraft hangar. Contours corresponding to the mean flame temperature maximum and the highest temperature non-burning region are shown.

on the number of cells which can be incorporated into the simulation. This number is ultimately limited by the computing power available to the user. Present day computers limit the number of such cells to at most a few million for an individual processor. This means that the ratio of largest to smallest eddy length scales that can be resolved by the computation (the "dynamic range" of the simulation) is roughly $100 \sim 200$. Massively parallel supercomputers are excluded from this estimate, but their existence has played no role in the development of fire research to date. Unfortunately, the range of length scales that need to be accounted for if all relevant fire processes are to be simulated is roughly $10^4 \sim 10^5$. Much of the discrepancy is due to the fact that the combustion processes that release the energy take place at length scales of 1 mm or less.

The idea that different physical phenomena occur at different length and time scales is central to an understanding of fire phenomena, and to the compromises that must be made in attempting to simulate them. The most important example is an isolated fire plume in a large well ventilated enclosure (see fig. 1). Simulations of scenarios of this kind are reported in Baum et al. (1996). The fire plume is the "pump" which entrains fresh air

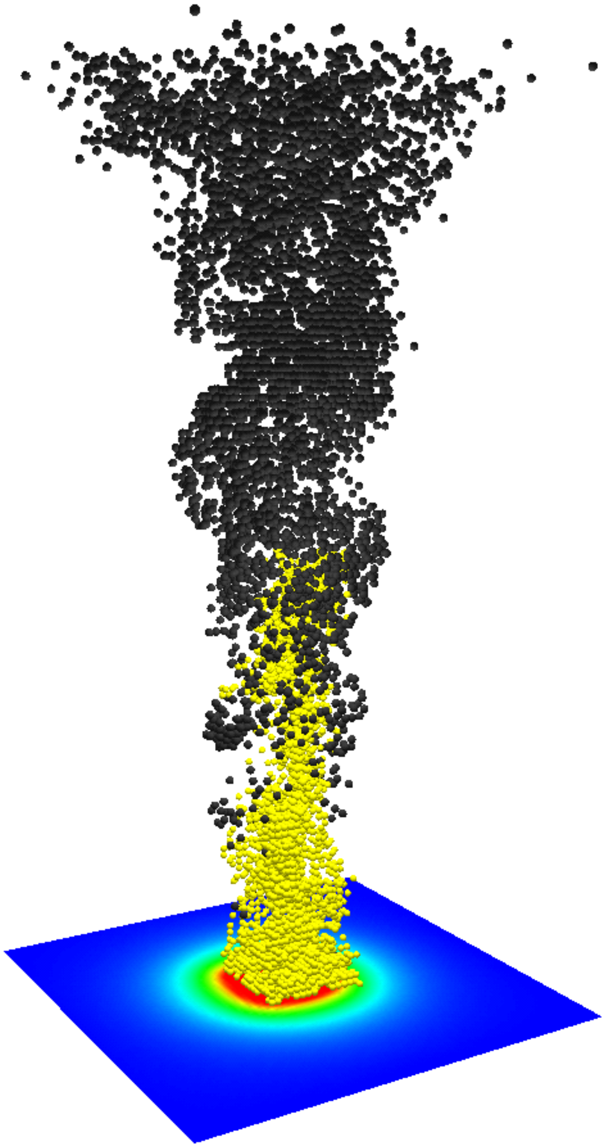

FIGURE 2: Snapshot of isolated plume structure showing burning elements (light color), burnt out combustion products (dark color), and radiation heat flux contours to fuel bed.

and mixes it with the gasified fuel emerging from the burning object. It then propels the combustion products through the rest of the enclosure. The eddies that dominate the mixing have diameters that are roughly comparable to the local diameter of the fire plume. Thus, in the above simulation, the cells have to be small enough so that many (a 12x12 array in this case) are used to describe the state of motion across the surface of the fuel bed. Since the simulation also needs to include the remainder of the hangar as well, even the 3 million cell simulation shown in Fig. 1 above cannot cope with the combustion processes without additional modeling effort.

Physical processes like combustion that occur on scales much smaller than the individual cell size are often called “sub-grid scale” phenomena. The most important of these for our purposes are the release of energy into the gas, the emission of thermal radiation, and the generation of soot together with other combustion products. These phenomena are represented by introducing the concept of a “thermal element” (Ezekoye et al. 1994). This can be thought of a small parcel of gasified fuel interacting with its environment. The concept is illustrated in Figure 2.

Each element is carried along by the large scale flow calculated as outlined above. As long as the fire is well ventilated, it burns at a rate determined by the amount of fuel represented by the parcel and a lifetime determined by the overall size of the fire. The lifetime of the burning element is determined from experimental correlations of flame height developed by McCaffrey (see Baum and McCaffrey 1989). A prescribed fraction of the fuel is converted to soot as it burns. Each element also emits a prescribed fraction of the chemical energy released by combustion as thermal radiation. This fraction is typically about 35 percent of the total. The soot generated by the fire can act as an absorber of the radiant energy. Thus, if the fire generates large amounts of soot, the transport of radiant energy through the gas must be calculated in detail . Even in the absence of significant absorption of radiant energy by the products of combustion, the radiant heat transfer to boundaries is an important component of the total heat transfer to any solid surface. Figure 2 shows a snapshot of the elements used to simuate an isolated fire plume in the absence of any boundaries. Time averages of the output of this kind of simulation must be produced in order to make quantitative comparison with most experimental data. Indeed, it is the fact that the *results* of the simulation can be averaged in a routine way while the *equations* of fluid mechanics cannot is the basis of the whole approach presented here.

The ideas outlined above have been gathered together and implemented in a publically available computer code *Fire Dynamics Simulator* (FDS) developed by McGrattan and Forney (see McGrattan et al. 2000). It has been used by hundreds of researchers and fire protection engineers around the world. An evaluation of its capacity to simulate pool fires (Joulain 1998) was summarized as follows:

> “Their computations primarily showed that large scale fire dynamics and smoke movement can be accurately calculated directly from the fundamental equations. The great ability of this approach clearly appears in (Fig. 4). At present, it can be said that the limitations of this approach have more to do with the incorporation of other physical processes like fuel pyrolysis rate, combustion model, and radiation transport than with further improvements of the description of the turbulent mixing.”

Research Needs

The limitations expressed above are very real. The fundamental properties of turbulent flow phenomena in general and turbulent combustion in particular are still poorly understood, and likely to remain so for decades to come. An improvement in the calculation of radiative transport and the combustion energy release has been incorporated in FDS (Version 2). The crude analytical calculation of the radiative transport in the original version of FDS has been replaced. The new numerical scheme accounts for both the spatial and wavelength dependence of the thermal radiation by averaging the equation governing the transport of radiant energy over each computaional cell and dividing the energy spectrum into a discrete number of broad bands. The thermal elements have been replaced with a mixing controlled model of combustion, where the energy release rate is related to the local oxygen consumption rate. The oxygen consumption is calculated by assuming that fuel and oxygen react infinitely fast when they come into physical contact. The resulting "mixture fraction" model evaluates a passive scalar quantity (the mixture fraction) which determines the degree of mixing between fuel and oxygen in each grid cell. Details can be found in McGrattan et al. (2001). These models are too new to provide any realistic evaluation of their ability to cope with fire scenarios, but they are unlikely to be the last word in these subjects.

However, even with these improvements, the basic uncertainties associated with turbulence phenomena remain unresolved. Specifically, the combustion energy release rate is controlled by small sub-grid scale mixing processes even for a well ventilated fire. The local emission of radiant energy is strongly influenced by small scale fluctuations in the temperature and the amount of soot generated by combustion. Both these topics are subjects of intense research in the combustion community. If the fire is poorly ventilated, the details of combustion chemistry become important. This too is an important research issue in combustion science, made more complex here by the uncertain characteristics of the "fuels", gasified building or furnishing materials. It is unlikely that fire research (as opposed to fundamental combustion research) is the proper venue for such studies. The fire research community has long been a borrower of ideas generated in other research areas, and will probably remain so with respect to the phenomena discussed above.

The problems peculiar to fire research that most need addressing occur at the interface between the gas and condensed phase materials. The research issues arise in both phases, and are difficult to separate. Figure 3, an early attempt by R. Rehm to simulate the fire in one of the World Trade Center towers, gives some indication of what is needed.

First, the geometry and constuction materials of the building need to be defined. If the representation of the building is simple enough, this can be done manually from building plans or other information. That is what was done here. However, the geometry used in this simulation (which is a crude representation of several floors of the damaged structure) is at about the limit of what can be done without an electronic interface between the computer codes that execute the fire simulation model and those used to design it (if any). The last caveat is quite important, since most buildings in existence today were built without the assistance of computer aided design, and this situation will remain true for decades.

Next, it is neccessary to have some idea of the building contents, their distribution

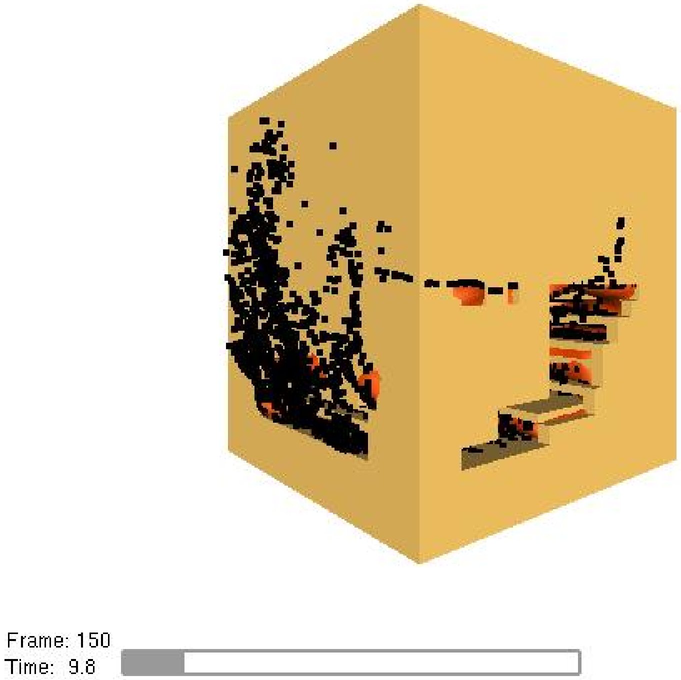

FIGURE 3: Snapshot from World Trade Center fire simulation showing smoke and flame emerging from damaged structure. (Courtesy R. Rehm)

within the building, and their material properties. While fire simulations typically consider wood cribs and combustible wall linings, any space intended for human occupation contains a rich variety of objects capable of sustaining a fire. Any substantial piece of furniture, for example, is itself a complex assembly of different materials, whose burning behavior is determined as much by their geometric arrangement as by their thermochemical properties. However, once a furniture object begins to burn, its geometry will undergo rapid change, which can influence not only the rate at which the object will burn, but its propensity to ignite other objects nearby. There has certainly been a considerable amount of furniture fire testing. However, there have been few studies oriented towards a systematic way of characterizing furniture so that the techniques used in heat transfer, combustion, and material science can be brought to bear on this problem.

Finally, the underlying geometry of the building can be altered by the fire. While most of the openings in the idealized representation in Figure 3 were caused by the initial impact of the aircraft, much of the air supply needed to sustain the fire was caused by window breaking. Although a good start has been made on this issue (see Joshi and Pagni 1994), much remains to be done. The fire changes to the building geometry alter the air supply in other ways as well. Many non-structural partitions undergo considerable warping under thermal loads, even if the materials are not combustible. While the direct impact on the structural integrity of the building may be negligible, the changes in air supply to the fire can alter its subsequent behavior.

Obviously, the fundamental technical issue in the world trade center collapse is the precise nature of the role played by the fires. While it is far to early to make any definitive statements, the very fact that the issue has been raised leads to questions about our ability to make predictions of fire induced structural collapse, even assuming that the damage caused by the initial crash was known in detail. Most large buildings are complex assemblies of steel and concrete, with protective coatings over steel surfaces. How these complexes behave at elevated temperatures, and to what extent they influence the fire behavior, is a difficult subject in its own right. Little research in this area has been carried out in the U.S. for two decades. The perception among many fire protection engineers is that this subject is well understood. Whether that opinion is shared by researchers in structural mechanics and materials science is an open question.

Insitutional Barriers

The institutional barriers to carrying out research in these areas are considerable. Problems involving turbulent combustion and its related issues have long been studied by the combustion community. However, the motivation for most of this research has been the improvement of efficiency in industrial processes and powerplants. This implies a certain degree of control over the process, and leads to many assumptions about the kind of information that will be available and the level of detail worth pursuing in any investigation. Fire, by contrast, is essentially uncontrolled combustion. Any attempt to overly constrain the processes under investigation, or postulate excessively detailed descriptions of phenomena, will prove counterproductive. They will provide information for combustion science, but not for fire research.

There have been many investigations of the thermal degradation of solids that consider an individual material in isolation. However, there is no systematic approach to the analysis of assemblies of materials. Indeed, there is no consensus as to what level of detail is appropriate for the study of thermal breakdown of individual materials. In the absence of either a conceptual framework for the analysis of complex objects under fire load, or an agreed basis for the study of individual materials, it is not clear which community "owns" this problem. Many in the fire research community think it is a non-issue, that can be addressed by the systematic improvment of synthetic "fire data" sets which provide numerical parameters for existing fire models. In the short term, this may appear to provide the best payoff for limited research funds. However, in the long term it is a recipe for the systematic elimination of fire research as a field to be taken seriously by the scientific community.

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FIRE PROTECTION SYSTEMS: ALTERNATIVE SENSORS

Susan L. Rose-Pehrsson[1]

ABSTRACT

Better sensing methods providing more sensitivity and faster responses are needed to detect fires early before they become a major problem. Work place monitoring for hazardous chemicals and indoor air population have become concerns. It would be advantageous to have a detection method that could be used for monitoring hazardous chemicals and conditions in addition to providing fast, reliable fire detection. The Early Warning Fire Detection System consisting of four commercial sensors in an array with a probabilistic neural network has demonstrated the advantage of a multicriteria approach to fire detection. The EWFD system provides fast responses to both flaming and smoldering fires with high nuisance source immunity. The next step towards improved fire sensors and sensor arrays are smart microsensor arrays. Alternative methods for fire detection are being investigated by a number of companies. The sensor types vary, but the desired characteristics are the same. Sensors and sensor systems are desired that are small, low power, robust, reliable and low cost. Methods currently under development have the potential to reduce the cost, extend the performance to include other important analytes and provide high temperature operation. Small, low cost systems allow for larger sensor networks further improving fire detection.

Introduction

Improved fire safety requires fast, reliable fire detection systems with automated fire suppression. Detectors are needed that will rapidly respond to both flaming and smoldering fires while not alarming for common nuisance sources. More reliable fire detection systems will also allow automatic control of fire suppression systems, thus minimizing damage. In addition, the ability to discriminate between fires and their byproducts (spreading fire rather than spreading smoke) would be beneficial for efficient distribution of manpower and resources. The most promising means of improving fire detection systems is through a multicriteria approach. The multicriteria approach to fire detection was demonstrated using various combinations of commercial sensors in arrays with a probabilistic neural network. (Gottuk, 1999, Rose-Pehrsson 2001) A prototype using a four-sensor array consisting of ionization and photoelectric smoke detectors and carbon monoxide and carbon dioxide sensor has been extensively tested. Compared to commercial smoke detectors, this Early Warning Fire Detection System (EWFD) was demonstrated to provide faster responses to both flaming and smoldering fires with a higher nuisance source immunity. (Gottuk, 1999, Rose-Pehrsson, 2001, Wright, Hart, Gottuk, 2002, Rose-Pehrsson, 2002)

More than a decade ago, the concept of mimicking the human nose with semi-selective sensor arrays coupled with multivariate data analysis methods gave birth to the idea of generating an electronic nose. Today, both electronic noses and electronic tongues can be found at popular trade shows. Microsensor arrays are being marketed for

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a variety of chemical problems. Recently, several companies are investigating the new sensor array systems or electronic noses for indoor air monitoring and early fire detection. (SamDetect, General Atomics, KAMINA, Cyranose) Several different sensor technologies are applicable to fire detection including, metal oxide, cermet, surface acoustic wave devices, and conductive polymer sensors. These new approaches have the potential of providing small, low cost systems that are capable of extending the performance of fire detection systems to vapor monitoring. Networks of sensors also become more feasible with small, low cost sensors. At least one of these new sensor methods can provide detection capabilities at high temperature.

Electronic Nose Concept

Driven by the need for small, portable, inexpensive instruments that can be adapted to many detection problems, electronic nose instruments were conceived. Several factors contributed to bring this about, including (1) microfabrication and micromachining techniques to fabricate sensor structures, (2) increasing interest in chemical detection for workplace monitoring, personnel protection, and process control, and (3) the increasing sophistication and decreasing size of digital components and instrumentation capable of operating sensors or using the information they provide. Electronic noses try to mimic the human nose by grouping nonspecific sensors into an array, the signal provided by the sensors are collected, preprocessed and then a pattern recognition method is used to identify a response of interest. Figure 1 schematically describes the parts of an electronic nose. Typical sensors consist of a transducer to convert chemical information into an electronic signal and a chemically selective material to interact with chemicals of interest. When chemicals are sorbed into the coating, the mechanism of the sensor or transducer is perturbed. Most individual microsensors lack the necessary specificity, but an array of sensors with different semi-selective coating can be designed where each coating responds differently to a set of chemical vapors. The combination of sensors selected to interact with different chemical properties produce a unique fingerprint for each vapor. The sensors encode chemical information about the vapors in a numerical form, which can then be analyzed by pattern recognition methods.

Pattern recognition techniques, as applied to multi-criteria or multi-sensor systems, use sensor responses to encode chemical/physical information about the by-products of a fire in numerical form. Each sensor defines an axis in a multidimensional space. Different types of fires or events can be represented as points positioned in this space according to sensor responses. Fires that produce similar responses from the set of sensors will tend to cluster near one another in space. Pattern recognition uses multivariate statistics and numerical analysis to investigate such clustering and to elucidate relationships in multidimensional data sets. Mathematical boundaries between event types can be defined and used to identify fires and discriminate nuisance sources.

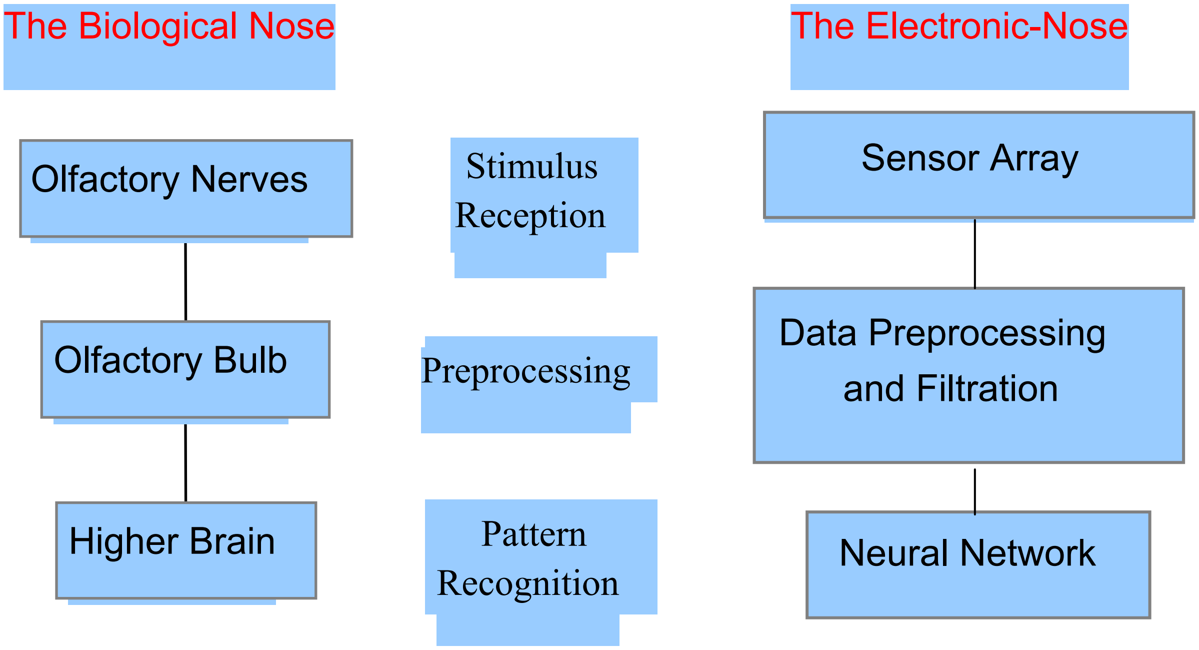


Figure 1. Comparison of electronic nose with biological nose.

Sensor Types

There are a variety of sensor types that can be used in electronic noses and can be applied to fire detection. Table 1 lists some of the types.

Table 1. Various Microsensors and Their Mechanisms for Response

Sensor Types	**Function**
Chemiresistor, Interdigitated Array	Conductivity
Conductive Polymer	Conductivity
ChemFET	Work Function
Fiber Optic/Wave Guide	Absorption
SAW/ QCM	Microgravimetric
Metal Oxide Semiconductor Sensor	Conductivity
Cermet	Electrochemical

Metal oxide semiconductor (MOS) sensors are one of the microsensors that have been investigated for fire detection and are currently incorporated in a commercial fire detection system. (SamDetect, Daimler-Benz Aerospace) The MOS can be used to measure a variety of toxic or combustible gases including carbon monoxide, nitrogen dioxide, sulfur dioxide, and methane. As shown in Fig. 2, the MOS sensing elements consist of a semiconductor such as tin oxide (SnO_2) sandwiched between two electrodes. In clean air, the conductivity is low. When exposed to reducing gas such as carbon monoxide, the conductivity increases. Selectivity to a particular gas is achieved by varying the temperature of the sensing element and the metal oxide layer. Metal oxide sensors are sensitive to toxic gases in the low parts-per-million range. The limitations of the devices are the potential for false positive alarms and effects of humidity on the sensor outputs.

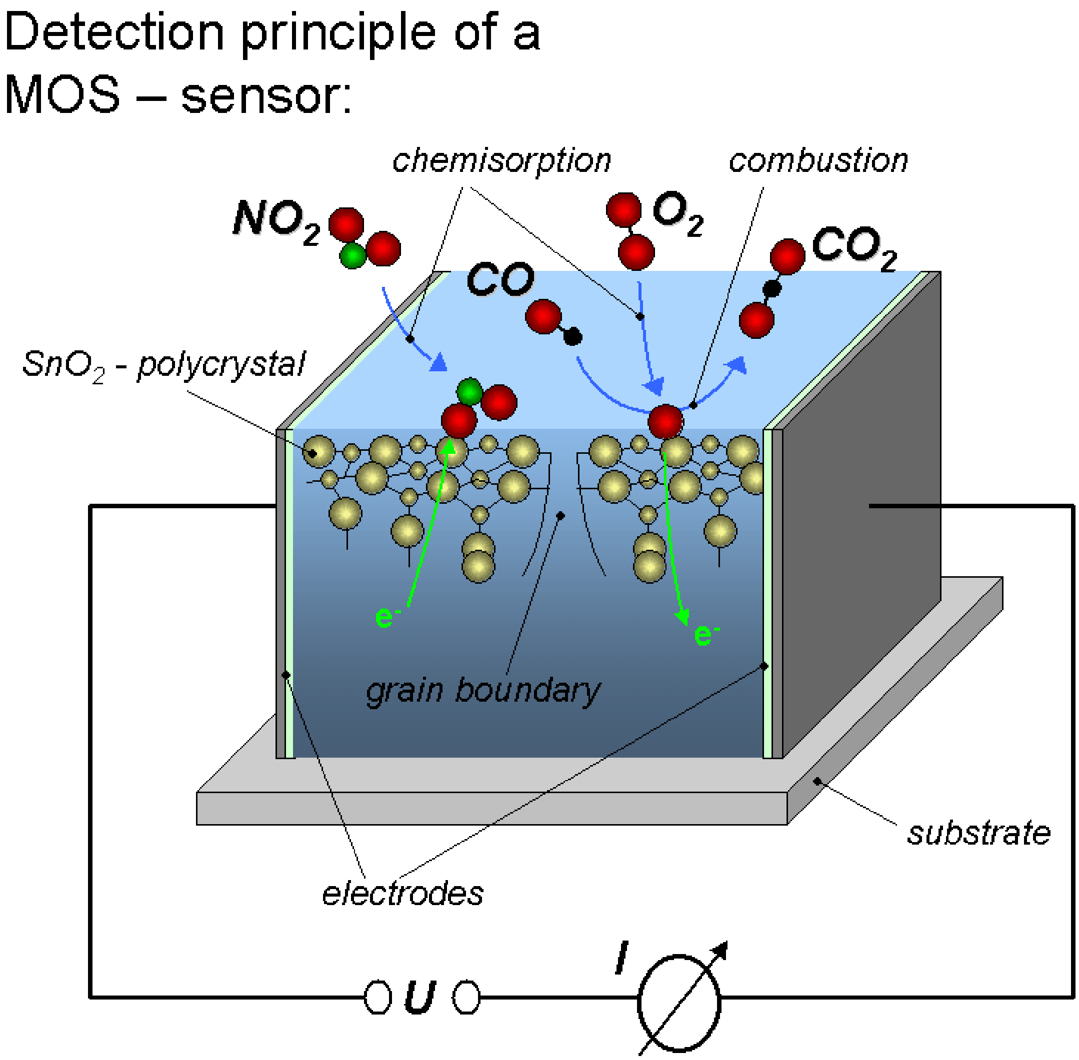


Figure 2. An example of the mechanisms involved in the sensing of chemical vapors with Metal Oxide Semiconductor Sensor.

While there are several microsensor technologies that would be applicable to fire detection, three promising methods will be described here. The sensor arrays each use a different sensor element with its own unique properties.

General Atomics – Smart Microsensor Array

General Atomics has been developing a fire detection system under the Navy's Program Damage Control Automation for Reduced Manning (DC-ARM). Voltammetric-electrocatalytic (V/EC) microsensors consisting of thick-film fabricated devices composed of various ceramic metallic (cermet) films are being used. Prototypes have been produced with both single elements and arrays. The Fig 3 below illustrates several microsensor types including the array type(s) used for fire and nuisance tests. The ceramic metallic microsensor array used was composed of four sensor elements, three of which were monitored for fire testing. The sensor elements are referred to as S0, S1, and S2 with the following compositions:

S0: tungsten bismuth oxide/platinum (WBO/Pt) (otherwise called *Sensor 1*)
S1: yttria stabilized zirconia/platinum (YSZ/Pt) (otherwise called *Sensor 2*)
S2: yttria stabilized zirconia/palladium (YSZ/Pd) (otherwise called *Sensor 3*)

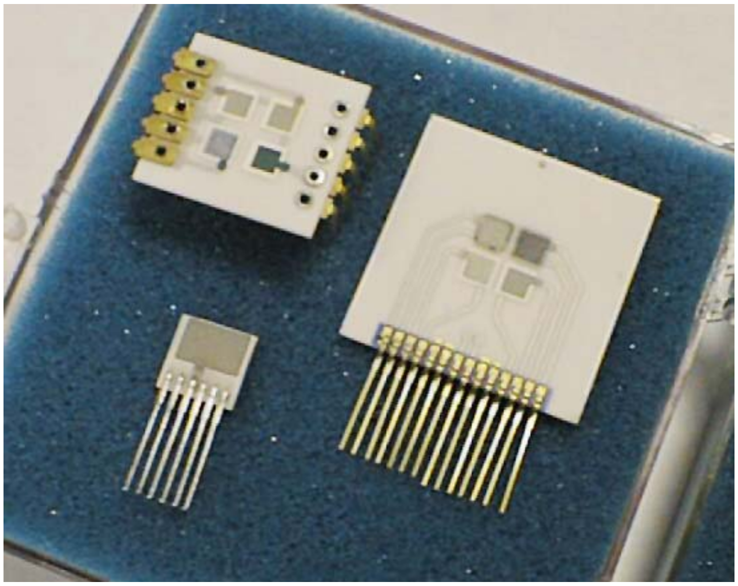


Figure 3. Cermet sensors and sensor arrays used by General Atomics.

Each sensor produced a different response to each of the test atmospheres (analytes), and the *composite array* response provided information for robust and complete classification of the samples.

The V/EC microsensor employs an electrochemical (voltammetric) measurement technique to generate its complex response waveform. Voltammetry involves applying a varying potential (typically a +/- triangular waveform) across an electrochemical cell and measuring the resultant current produced. (Chemical Sensors) The presence or absence of an analyte gas will influence the electrical characteristics of the cell (current vs. voltage). (Bard and Faulkner) Electroactive species react during both the applied waveform reduction sweep and the following oxidation sweep. This regeneration of the electroactive species allows continued reuse of the device as a sensor. The voltammetric response can be tuned by altering how the voltage is applied and the operating temperature of the cell. Voltammetry is a very well established chemical analysis technique that is particularly flexible and capable of very low level detection (part per billion) for organic, metallic, and organometallic substances. (Smythe)

Under the DC-ARM program, a breadboard system was fabricated and tested that contained an onboard power supply and temperature control. The system is shown in Fig 4. Data was collected for a set of fire and nuisance sources. The sensors were trained using the fire/nuisance data and a neural network was used to predict a subset of the sources. The preliminary results were encouraging. In addition, all the components of the breadboard system have been tested up to 300°C. (Ziegler)

Figure 4. General Atomics Breadboard for an array of cermet sensors.

The successful completion of this system would provide the following attractive features: (1) distributed network of “smart” chemical sensors, (2) small footprint with powerful capabilities including onboard processing and decision making, (3) flexible readout electronics that could accept input from a variety of sensor types, (4) capability of sensing both toxic gases and chemical agents, (5) software that can be customized to any space, and (6) the ability to collect sensor response data allowing better discrimination than standard sensors.

KAMINA

A novel type of gas sensor microarray based on the segmentation of a monolithic metal oxide layer by a set of parallel electrodes, has been developed at the Research Center KARLSRUHE, that allows sensitive detection and discrimination of gases at a very low cost. (Harms) The single monolithic metal oxide film alone forms the basis of the whole array. This film is separated into 38 sensor segments by parallel electrode strips to measure the electrical conductivity of the individual segments. (Althainz) The necessary operation temperature (usually between 200°C and 400°C) is provided by four meandering heating elements, placed at the reverse side of the chip. The heating power is controlled by two platinum thermoresistors, placed on the upper side of the chip. The whole array is coated with a permeable SiO_2 layer of variable thickness across the 38 sensor segments.

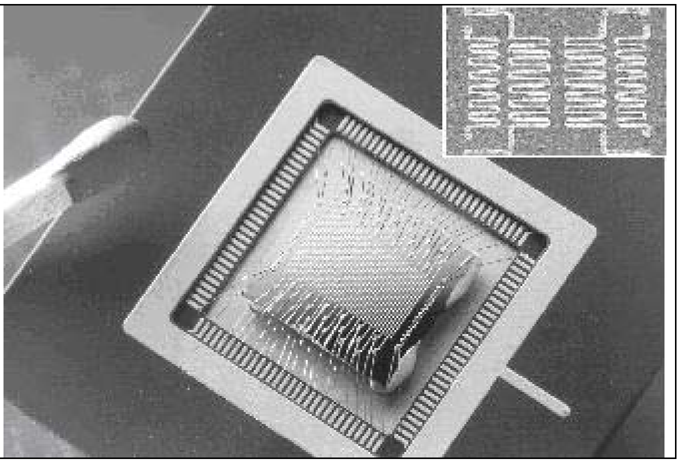


Figure 5: Gas sensor microarray mounted in its housing. The front side consists of the metal oxide detector field, separated into 38 sensor elements by 39 electrode strips. The reverse side carries four separate heating elements (on the upper right side).

The gradient technique serves to differentiate gas detection selectivity via the 38 individual sensor segments. The thickness of the ultra-thin gas-permeable SiO_2 membrane layer deposited on top of the metal oxide film varies across the array. Additionally, a controlled temperature gradient, e.g. of 50 K, is maintained across the array. Depending on the nature of the gases, due to diffusion through the membrane and the warmth caused by gas reactions at the metal oxide interface, gas detection selectivity is gradually modified from sensor segment to sensor segment. Therefore, the exposure to single gases or gas mixtures cause characteristic conductivity patterns at this gradient microarray. The dependence of the conductivity pattern on the type and quantity of ambient gases allows gas discrimination and quantification.

This gradient microarray is used in an electronic nose system called the Karlsruhe Micro Nose (KAMINA). The micro-fabrication is uncomplicated and thus inexpensive, thus making a low cost system that is reliable, stable and sensitive to a variety of chemical species. This system is being investigated for fire detection. NASA/KSC personnel are interested in the methods for space station application. The ability to measure smoldering fires at very low concentration as well as other chemical species of interest is very attractive. Fig 6 shows some of the tests conducted using the KAMINA.

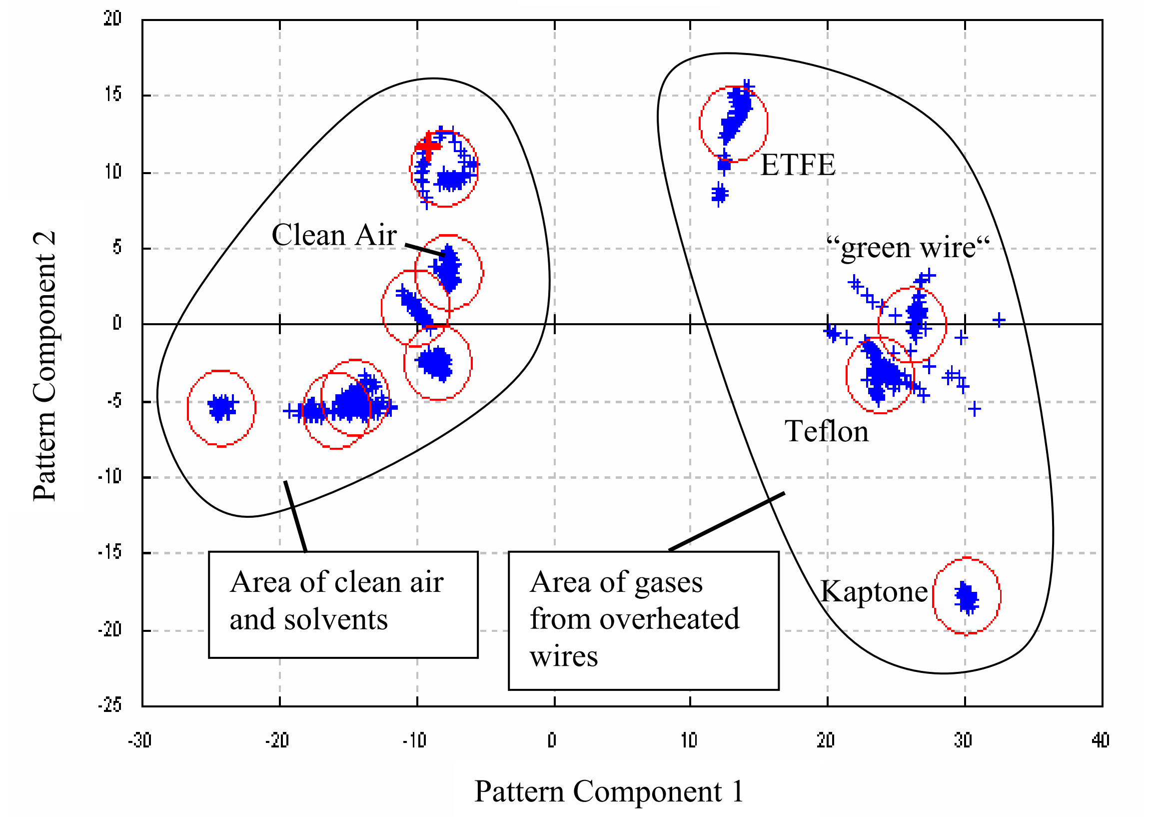
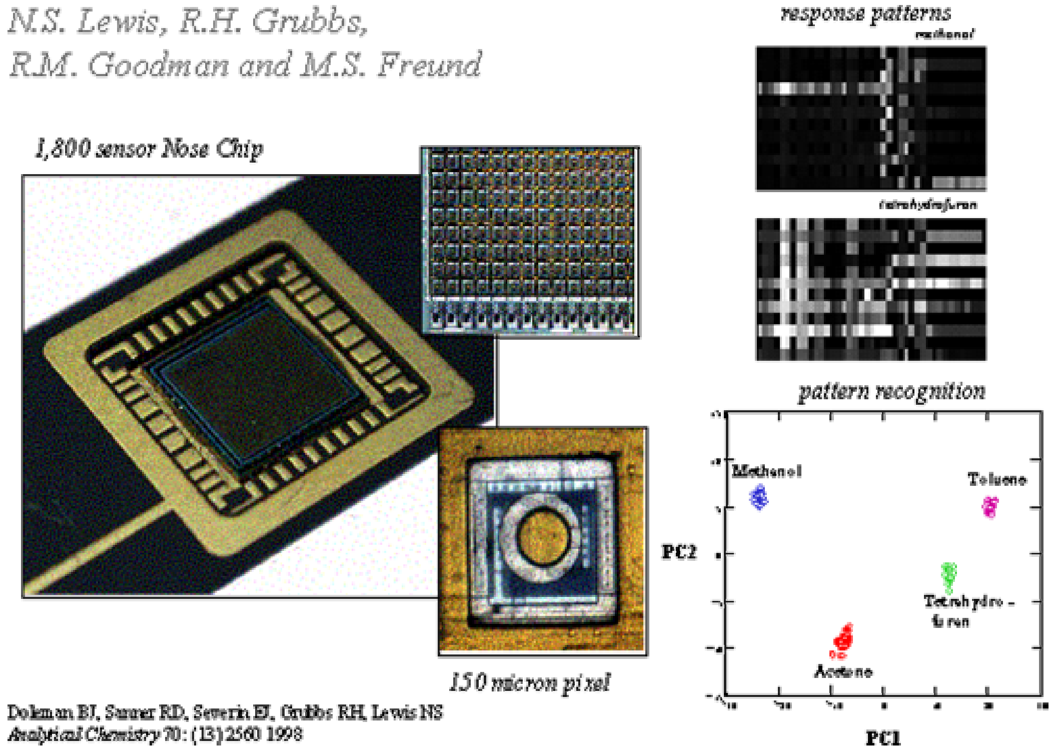


Figure 6**:** Distinction between clean air, solvents and overheated wire insulation in an LDA diagram; solvents (isopropanole, ethanole, xylene, toluene, acetone, WD40) are clearly depicted separately from pre-fire gases of hot wires mantled with kaptone, fluorine-containing and unknown materials. A gradient microarray based on Pt-doped SnO_2 was used for measurement. Its temperature was kept at 250 - 300 °C. The area limits describe a confidence range of 95 %.

CYRANOSE

Cyrano Sciences' propriety sensor technology, used in the Cyranose 320, originated in the labs of Professor Nathan Lewis at the California Institute of Technology. The technology consists of individual thin-film carbon-black polymer composite chemiresistors configured into an array. The collective output of the array is used to identify an unknown analyte using standard data analysis techniques. Each individual detector of the sensor array is a composite material consisting of conductive carbon black homogeneously blended throughout a non-conducting polymer. The detector materials are deposited as thin films on an alumina substrate each across two electrical leads creating conducting chemiresistors. The output from the device is an array of resistance values as measured between each of the two electrical leads for each of the detectors in the array. When a composite is exposed to an analyte, the polymer matrix acts like a sponge and "swells up" while absorbing the analyte. The increase in volume changes the resistance because the conductive carbon-black pathways through the material are broken. When the analyte is removed, the polymer "sponge" off-gasses and "dries out". This causes the film to shrink and the conductive pathways are reestablished. The response from the chemiresistor during an analyte exposure is measured as a bulk relative resistance change. Since an analyte will absorb into the different polymer matrices to different degrees, a pattern of response is observed across the array.

Fig 7 shows an example of an array developed and tested by Dr. Lewis. Response patterns are observed and selectivity for various gas vapors is shown in a principal component plot.



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Analytical Chemistry 70: (13) 2560 1998

Figure 7. Good selectivity for several different vapors is clearly shown in the principal component plot for this array of chemiresistors produced by in Nathan Lewis' laboratory. Two examples of characteristic response patterns are also shown.

Conclusions

Electronic noses are being used in limited applications such as the food industry or chemical warfare detection at this time. Current limitations on sensors require highly controlled sampling or highly specific analyte detection such as chemical warfare detection. In many cases, the humidity effects are too great to be used in ambient conditions. Many of the attractive sensor technologies need better understanding of the underlying science before the responses will be completely correlated with wide variety of varying chemicals present in the ambient environment.

More mature sensors and sensor arrays are not being widely used today as fire detectors because the industry demands long-term stability and reliability. Fire detection methods are expected to operate for ten years with little or no maintenance. Methods are needed to improve sensor robustness. Alternatively better calibration schemes are needed to compensate for changes in sensors over time and varying conditions. Other techniques that would advance the technology are adaptive updating, robust modeling, fault/outlier detection and diagnostics, and sampling theory (point verses volume). New discrimination algorithms and signal processing methods are also needed.

The multicriteria approach could be extended even further to include different sensor types, expanding the orthogonality of information generated. Sensor systems could also begin to mimic "man" by combining a variety of different senses similar to man's eyes, ears, nose, and touch. A new ONR program, "Advanced Damage Countermeasures, Volume Sensor" has begun studies towards a multicriteria fire detection system that incorporates optical, acoustic, pressure, and electronic nose sensors.

Integrating sensor information beyond the individual sensor to a global or neighborhood approach will broaden the information available to allocate resources and fight fires more effectively. Preliminary studies with a multivariate statistical processing algorithm to monitor a network of sensor arrays have been successful. (JiJi, 2002). The method uses the sensor location and temporal data to identify events, determine source location and monitor fire rate of growth. Hotelling's statistic and the *Q*-statistic are employed initially for event detection. Subsequently, contribution plots are used to determine source location, rate of growth and to discriminate between actual fires and their byproducts in adjacent compartments. Multivariate statistical process control is shown to be an efficient method for continuous monitoring of the EWFD systems.

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FIRE SUPPRESSION

Anthony Hamins[1]

Abstract

This paper briefly reviews the history, design limitations and research needs of automatic suppression systems. Over the last 35 years there have been great advances in our understanding of the mechanisms of fire suppression. There are, however, still huge gaps in our ability to predict suppressant requirements and design effective inexpensive suppression systems.

In the future, innovations in suppression systems could involve a combination of early fault-free detection, a directed response matching the quantity of the agent precisely to the requirements of the fire, and reduced negative side effects such as water damage, environmental insult, and agent toxicity. These resolutions lend themselves to smart suppression based on scenario-specific engineering analysis.

To provide a foundation for the future, research is needed on the complicated multi-phase processes by which a condensed phase agent extinguishes a fire. In addition, further understanding of chemical mechanisms associated with halon replacements is needed to provide a scientific basis for improved suppressant system design. As an example of a novel approach to fire suppression, a description of solid propellant gas generators is provided. These promising devices illustrate the need to support the development of new suppression technologies.

Introduction

During the last 35 years, there have been great advances in the understanding of the mechanisms of fire suppression. During this period, there have been numerous conference proceedings dedicated to fire suppression research and many articles reviewing the status of suppression research and suggesting future directions (Fristrom 1967; Heskestad 1980; Emmons 1986; Friedman 1986; Gann 1991; Yao 1997; Grosshandler 1998; Grant 2000). There are, however, still huge gaps in our ability to predict suppressant requirements, and design effective inexpensive suppression systems.

The world of fire suppression applications is extremely broad. It is composed of several communities. The first is automatic fire suppression systems. This community is represented by two distinct camps: the water sprinkler industry, which protects occupied building spaces, and the camp involved with protecting unoccupied or easily evacuated spaces. The latter camp uses halocarbons, carbon dioxide, or similar systems to protect buildings and structures (e.g., trains, boats, aircraft, motor vehicles). A second distinct fire suppression community deals with forest and wildland fires including the protection of buildings at the urban-wildland interface. For this community, a completely different scale of effort is required with potentially huge ecological consequences. A third community is the fire service with more than two million members located in every city and town in the U.S. The Fire Service overlaps with the first two communities, as its members handle every type of fire activity. The diverse applications associated with each of these communities exemplify the complexity of the suppression problem.

Fires addressed by each of these communities are turbulent by nature, which complicates the understanding of the physics of suppression. Much progress, however, has been made through the examination of simple laminar flames. This is true of the theory of gas-phase flame extinction, which significantly advanced the understanding of

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the mechanisms of flame extinction. The ratio of the characteristic residence time of a parcel of fluid in a flame to the characteristic chemical reaction time is known as the Damköhler number (Da), which reflects the flow-chemistry interaction. Liñan (1974) used asymptotic analysis to analyze the extinction of laminar diffusion flames and showed that as Da decreases, the maximum flame temperature decreases until a critical value of the Da is obtained when the flame abruptly extinguishes. The Damköhler number criterion suggests a number of strategies for extinguishing fires, that include increasing the flow field strain rate, cooling the reactants, reactant removal, separation, or chemical inhibition (Williams, 1981). The elegance of the theory is its applicability to fire suppression phenomena addressed by each of the fire communities, involving advanced suppressant designs such as a solid propellant gas generator or just plain water, forest fire fuels or jet fuel.

This paper addresses some limitations in the design of current fire suppression systems, suggested research needs and barriers hindering research advances. The paper is broken into several parts. The first deals with the history, design limitations and research needs of automatic water sprinklers. The second section discusses halon replacements and the need for further understanding of chemical mechanisms. The third section discusses features of a specific halon alternative, the solid propellant gas generator, which represents a novel approach to fire suppression. The fourth section discusses barriers that are inherent limitations to progress in suppression research. Each section makes suggested research recommendations.

Water Sprinklers

Any structure that does not have an automatic sprinkler system is vulnerable to the effects of fire as manual fire fighting is often limited in its ability to control a fire. One of the great technological innovations associated with fire protection is the water sprinkler, which has prevented the loss of a tremendous amount of lives and property (Rohr 2000). Major A. Stewart Harrison of the First Engineer London Volunteers was the inventor of the first modern automatic sprinkler (Fig. 1) in 1864 (Woodbury 1892). The sprinklers were to be hung pendant style from water pipes on the ceiling. The modern fire sprinkler would have had a very different history if it weren't for systematic research on the behavior of materials.

By 1670, Isaac Newton's interest in alchemy led him to perform many experiments in inorganic chemistry (Christianson 1984). This interest influenced his scientific achievements including crafting a high quality mirror for the first reflecting telescope and the invention of solder, which he created in 1699. As Master of the Mint in London, Newton discovered that the alloys of Bismuth, Lead, Cadmium and Tin had significantly lower melting temperatures than the pure metals themselves (Woodbury 1892). These materials found many new applications over the next hundred years and when Harrison created the water sprinkler, the fusible solder link played a critical role. Are parallel breakthroughs possible today that would facilitate effective fire suppression?

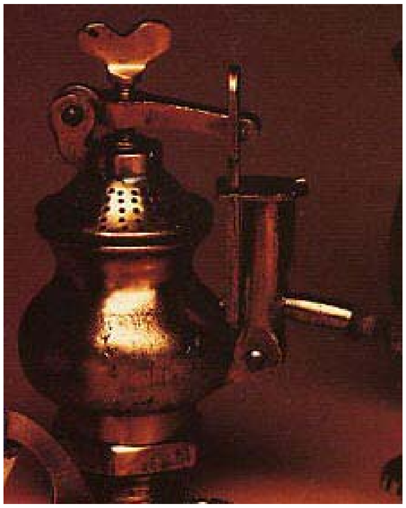

Figure 1. Perforated sprinkler head with a fusible solder link.

Historically, water has been the most common medium used for suppressing fires. Some have suggested that nature could not have designed a better suppressant. It is relatively inexpensive, non-toxic, environmentally friendly, chemically stable, compatible with many materials, pumpable, and typically available in large quantities.

Residential fire sprinklers are fairly effective. In an analysis of fires in homes, NFPA estimates that the current generation of water sprinklers reduce the chance of death by 73% (Rohr 2000). But few residences (1% to 2%) have sprinkler systems. The barrier to improved fire safety in this instance appears to be cost and of course politics. If the current generation of sprinklers will not penetrate the residential market, is it possible to develop an effective and less-expensive suppression system?

Although sprinklers are generally effective, there are some special problems and gaps in performance associated with water sprinklers under particular situations (Rohr 2000). This includes, for example, fires that initiate in proximity to a person or in a concealed space. Fast spreading fires can "overpower" a fire sprinkler system. Smoldering can be deadly for an immobile person in its vicinity. Water is expensive if it has to be handled and stored in large quantities for emergency purposes, for instance in rural areas.

There is a level of crudeness used in the design and approval of automatic water sprinklers. Currently, sprinklers are designed by empiricism, by filing metal and banging with a hammer until the water (with and without a fire present) appears well distributed at a particular plane below the sprinkler head. Because sprinklers are not directed towards the fire, water is often over-applied. There are environmental problems associated with over-use of water in suppression activities. An extreme example is the 1986 Swiss case when approximately 20,000 m^3 of extinguishing water containing pesticides and mercury ran into the Rhine River, runoff from a chemical warehouse fire (Holemann 1994). Although there has been an evolution in sprinkler design, the original strategy remains essentially unchanged since its origins.

To provide a foundation for the future, research is needed on several fronts including the complicated multi-phase processes by which a condensed phase agent extinguishes a fire. This includes the droplet/spray interaction with the gas-phase flames and the burning fuel. Future innovation in suppression system design could involve a combination of early fault-free detection and directed suppressant deployment, which matches the quantity of the agent more precisely to the requirements of the fire with reduced negative side effects such as water damage, environmental insult, and agent toxicity. These resolutions lend themselves to smart suppression based on scenario-specific engineering analysis.

During the last 20 years, the laser diagnostics needed to address some of these issues has become commercially available. Particle imaging velocimetry (PIV) is a non-intrusive field measuring technique that has been used to characterize the velocity field in a planar field of droplets as large as 1 m x 1 m. Water (or agent) droplets scatter light from imposed light sheets. The spatial displacement of the drops corresponding to two images separated by a known time period is measured and the velocity deduced. Phase Doppler interferometry (PDI) can provide point measurements of droplet size, velocity distribution, and number density. Other laser based techniques are available or under development for characterizing droplet sprays. A number of studies have used these diagnostics to begin to examine water distribution patterns from sprinklers (Sheppard

2001). Some preliminary work has looked at the flow of droplets past obstacles (Presser 2001). Yet, details of the flows associated with the interaction of evaporating drops with a fire or an isothermal plume have not been characterized, nor the large-scale flow structures associated with the momentum of a sprinkler spray. Whereas an improved understanding of the processes of suppressant transport, distribution, and interaction with obstacles is important, so too is the interaction of a suppressant with a burning surface.

Magee and Reitz (1986) report on the water spray suppression of burning thermoplastics with radiant heating. To extinguish the burning PMMA slabs, a critical amount of water must be applied such that the burning rate is reduced to 4 g/m^2-s. Similar results were found for other thermoplastics, except at low water application rates when the burning rate of PE and PS was found to increase as the water droplets penetrated the molten plastic surface and then vaporized, causing molten fuel to be thrown into the gas phase. What is the ideal drop character needed to extinguish a burning material?

Although the interaction of a liquid drop with a surface has been studied for more than 100 years, the complicated fluid mechanic processes associated with liquid droplet/surface interactions are not yet well understood (Manzello 2001). Some studies have shown that the impact energy, surface temperature and surface roughness controls drop behavior and its tendency to spread, splash, or rebound. To address suppression of burning materials, the complex heat transfer processes associated with droplet/surface interactions need to be better characterized.

A better understanding of agent mass and heat transfer processes would provide a scientific basis for the creation of rational engineering tools and improved suppressant system design. The exact form of the ultimate suppression system is not clear, but it might integrate detection and a smart nozzle with water additives, water mist, or alternative agents.

Halon Replacements

The world-wide effort over the last decade to find a suitable replacement or alternative for Halon 1301 for use in unoccupied spaces has not identified a gold star replacement, but many advances in the understanding of fire suppression have been made. The development of a number of advanced agent systems, screening methods, and knowledge about the physics of flame suppression has been developed. In particular, work sorting out the chemical and physical behavior of fire suppressants is noteworthy (Sheinson 1989; Ewing 1994).

An intriguing summary of 40 years of flame inhibition experiments in premixed flame systems is shown in Figure 2 (Babushok 2000). Here, the additive effectiveness is defined as the relative agent concentration required to diminish flame speed by 10% as compared to Halon. There is almost a three order of magnitude difference between the most effective metallic compounds and the least effective inert compounds. The grouping together of agents that contain a specific element implies that inhibition is caused by a specific atom, relatively independent of the ligands associated with the agent molecule. Linteris (2002a) has investigated the super metallic agents in Fig. 2 and shown that while the metal compounds can be very effective in premixed flames, their marginal effectiveness decreases rapidly above a volume fraction of a few parts per million and their effectiveness in (coflowing nonpremixed) cup burner flames (NFPA 2001) is much less than expected. Through a series of light scattering experiments, Linteris postulates that some metallic compounds involving Fe and Mn condense to form particulates in the coflowing diffusion flames, which then do not participate in flame inhibition in an effective manner. This is in contrast to Na and K containing compounds, which when introduced into cup burner flames as solid powders are very effective, even more than CF_3Br on a mass basis (Hamins 1996). Linteris (2002b) concludes that the regions of cup burner flames, which are most sensitive to chemical inhibition should be investigated to better understand the mechanisms of flame suppression. Further information on the detailed chemical kinetic mechanisms involving compounds containing Br, I, P,Mn, Sn, Si, Ge, As, Sb, Ti, Sn, Cu, Cr, and Pb (Tapscott 2001) would promote the accuracy of such models. These recent studies demonstrate that fundamental investigation of suppression kinetics is a rich field, deserving further attention. The design of more effective suppressants may be possible through improved understanding of the kinetic mechanisms of fire suppression coupled with bench-scale experimentation.

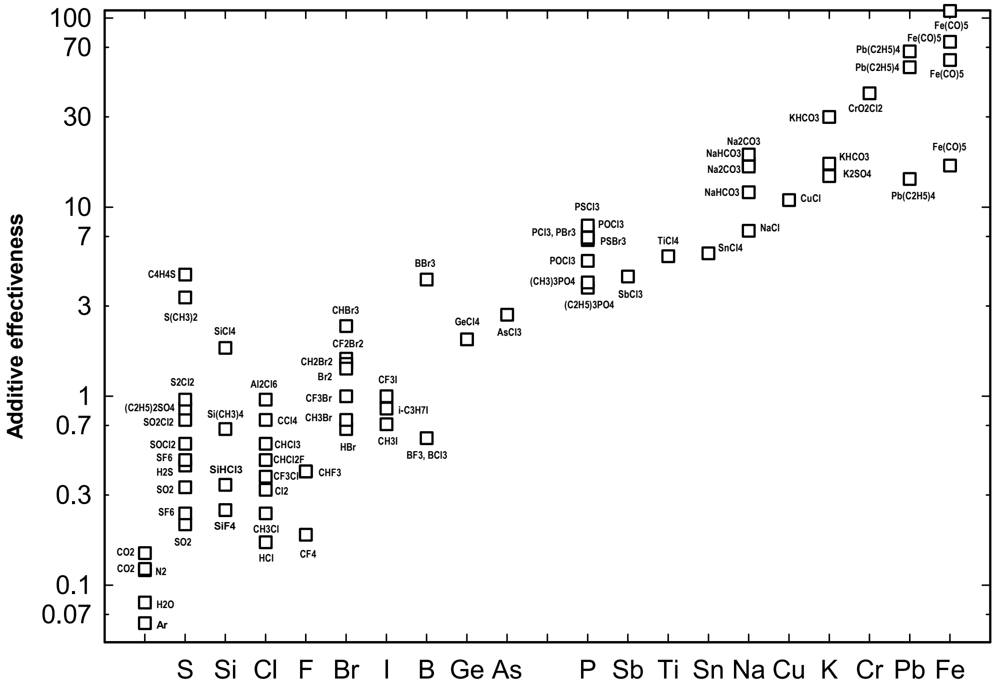

Figure 2. The relative additive effectiveness for various agents.

Solid Propellant Gas Generators

In the search for a suitable halon alternative, novel types of extinguishing agents and delivery mechanisms have been developed. One class of such devices is the solid propellant gas generator (SPGG). Through solid-phase combustion, the device rapidly yields hot exhaust products (principally gaseous N_2, CO_2, H_2O vapor, and potassium salt particulates) that can be used as fire suppressants. A number of experiments were undertaken to examine the effectiveness of SPGG in full-scale and laboratory-scale configurations.

Figure 3. Dripping and pooling underbody gasoline fire suppressed by SPGG.

Vehicle Fire Suppression

Vehicle fires represent approximately one-quarter of the total number of fires responded to by local fire services (U.S. Fire Administration 1997). Although fires represent only a small percentage of vehicle related injuries, they account for a significant percentage of fire injuries. In 1994, of the 15,000 fire-related injuries in the U.S., approximately 10 % were vehicle related (U.S Fire Administration 1997). For the years from 1989 to 1993, there was an average 425,000 fires in vehicles per year (Stewart 1996). A large proportion of fires occur after rear-end collisions, likely related to fuel system leaks and underbody fuel-fed fires (Tessmer 1994). Depending on the fire scenario, conditions in the passenger compartment can become untenable after several minutes. Post-collision fires are particularly dangerous because evacuation of the vehicle is often impossible (e.g., broken bones, jammed doors).

There are many parameters that might affect the suppressant distribution and effectiveness in a vehicle fire including the nozzle type, number, placement, orientation, reservoir size, and pressurization. In addition, ambient effects (wind), geometric effects (flow field obstacles; enclosure openings), fuel effects (fuel type, location, flow rate) and the flow field velocity (as influenced by vehicle movement or operation of the engine fan) may play a role. The intricacy of these real-scale effects is difficult to appreciate until observed through experimentation.

It is conceptually possible to successfully suppress almost any fire, if enough of a suitable suppressant is utilized. In practice, however, penalties such as system mass, volume, and cost will limit the fire scenarios that can be addressed. The experimental results showed that it is highly improbable that a practical on-board fire suppression system will be able to extinguish all possible engine compartment and underbody fires (Hamins 2000). Full-scale underbody suppression experiments (see Fig. 3) showed that suppression of a (333 mL volume) gasoline dripping pool fire was achievable when the fuel was located under the vehicle footprint for low wind conditions. The SPGG was effective under conditions of low to moderate winds, even for fires burning approximately 1 m beyond the footprint of a vehicle, when the fuel puddle was not behind a tire. The rapid agent delivery provided by these unique devices proved advantageous for the transport of agent past obstacles in the flow field.

Aircraft Engine Nacelle Fire Suppression

A series of suppression experiments investigated the relative effectiveness of halogenated agents and solid propellant gas generators (SPGG) in suppressing a series of spray fires with and without a fuel re-ignition source (Hamins 2002). Figure 4 shows a schematic diagram of the test facility. Several agents were tested including CF_3Br, C_2HF_5, and two basic types of SPGG, including one that produced inert gases in conjunction with a fine solid particulate composed of K_2CO_3 and one that produced inert gases only. The effectiveness of the SPGG was dependent on its composition and delivery rate. The SPGG effluent, which contained a significant percentage of K_2CO_3 particulate was particularly effective for re-ignition protection, a scenario which dominates agent mass requirements for the halogenated agents.

SPGG is currently operational on-board the V-22 aircraft. The success of the SPGG in the V-22 and the F-22 test programs exemplifies the importance of supporting novel approaches to fire suppression. The support of new advanced agents should continue as novel design ideas address fire scenarios that pose a significant publics safety concern.

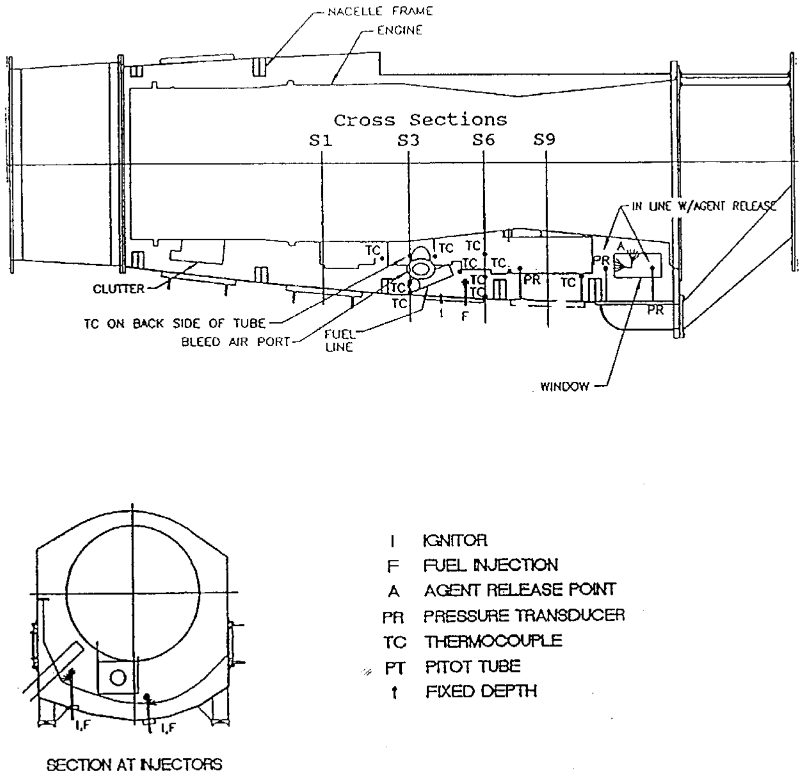

Figure 4. Cross-sectional view of the simulated F-22 engine nacelle fire suppression test facility.

Barriers to Change

There has been remarkably little overlap between researchers in the various fire communities; those involved with automatic protection of occupied and unoccupied spaces, the Fire Service, and those in the forest fire community interested in building fire protection. There may be even less interaction between a different pair of communities - those researchers involved in bench-scale suppression research and those involved in full-scale suppression testing. Lab-scale experiments benefit from better control of conditions, yet the issues of scale-up are not trivial as some important phenomena in full-scale may have been over-looked in the design of a reduced–scale experiment. The potential for cooperation among these various communities appears to be large. After all, the essential physics of suppression is scenario independent. The exchange of research insight beyond these barriers, from one community to another, could be supported by encouraging grant proposals by teams of researchers from different research communities. For example, overcoming cost as a barrier to change might best be addressed by a team composed of researchers from industry with those from academia.

Conclusions

In a time frame of one hundred years, it is possible to imagine an array of high density nano-sensors that trigger early fault-free fire detection, an array of suppressant release nozzles that facilitate directed suppression that matches the quantity and location of the agent precisely to the requirements of the fire with reduced negative side effects such as water damage, environmental insult, and agent toxicity. Today, issues of cost shatter this fantasy, but in the future that may not necessarily be the case. Innovations in suppression will likely come about from a combination of research on transport processes, advanced agent kinetics, innovation in engineering design and serendipity. These resolutions lend themselves to smart suppression based on scenario-specific engineering analysis.

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FIRE SIGNATURES AND DETECTION

D. T. Gottuk[1]

ABSTRACT

Fire detection systems are used for both life safety and property protection and have saved thousands of lives in the United States. Despite its wide spread use in residential to industrial applications, there is still much that can be improved, leading to increased life safety and the reduction of property loss. Continued research is needed in the area of multi-signature detection, particularly gas and smoke combinations which hold the greatest promise for improved performance compared to smoke detectors alone. This research includes the identification of low concentrations of chemical species from fire and nuisance alarm sources. Achieving the goal of detailed signature identification will require the development of new sensor technologies (e.g., electronic nose sensors). The development of low cost gas sensors, particularly CO and CO_2, that are stable with a functional life of ten years or more is needed to produce marketable multi-signature detectors. The development of multi-signature detection will also benefit from advancements in multivariate analysis techniques that allow more efficient development and testing of fire alarm algorithms. Lastly, a coordinated effort is needed between modelers, experimentalists and manufacturers in developing detector performance metrics and accurate models for the calculation of detector responses under realistic installation conditions.

Fire Detection

Fire detection is an integral part of fire safety in the United States. Fire detection is used for life safety (evacuation), property protection and for automatic suppression activation in a wide range of applications from residential housing to aircraft hangars. The early notification of occupants to a fire is a key component to the life safety features of a structure. This early notification is dependent on several factors: 1) sensing a signature of a fire prior to life threatening conditions, 2) determining that the signature represents a fire and not a nuisance source, and 3) distributing an alarm notification signal to the occupants.

Fire signatures can be defined as any fire product that produces a change in the environment, such as electromagnetic radiation (e.g., light), heat, acoustic energy or particular gases. A common signature used for fire detection is smoke, the condensed phase component of products of combustion from a fire. Even this fire signature

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represents a range of conditions. The character of smoke is dependent on the type of fuel burning, the mode of burning (smoldering or flaming) and the environmental conditions. Smoke can consist of distributions of many small particles, few larger diameter particles, spherically shaped aerosols or irregularly shaped agglomerates (Mulholland, 1995).

Although fire detection has played a significant role in improving fire safety in the U.S. (Hall, 2000), there is a recognized need for improvement. A main objective is to increase detection sensitivity and increase the reliability of the detection system through improved nuisance alarm immunity. Improved reliability is needed such that fire detection systems can automatically control fire suppression systems. For example, in the past nuisance alarms have caused expensive releases of fire suppression systems in aircraft hangars. The U.S. Airforce deemed the problem serious enough to prohibit the use of automatic detector-controlled suppression systems. The use of only manually controlled suppression implies that a higher risk of property damage was accepted given the potentially increased time to respond.

In addition to increased reliability for property protection, reduced nuisance alarms would translate into more lives saved, particularly in residential occupancies. Given that 73 percent of civilian fire deaths and 71 percent of civilian fire injuries occur in residential fires [FEMA, 2001], improvements in residential fire alarm equipment has the potential for the greatest impact of improving life safety against fire in the U.S. A Consumer Product Safety Commission study found that approximately 30% of fires in the United States occurred in instances where smoke detectors were either nonexistent or inoperable (Smith, 1994). The CPSC research found that nuisance (false) alarm sources caused many people to remove, disable, or otherwise alter their smoke detection equipment, thus defeating its very purpose as a life-saving device. Therefore, improving nuisance alarm immunity should be a key objective for new fire detection technologies. Though limited research is focusing on nuisance alarm immunity, the development of new devices and test methods to provide better immunity and to recognize the benefits has not really materialized in the industry (FPRF, 2002). Addressing the nuisance alarm problem needs to be a priority. As further evidence, a National Fire Protection Association (NFPA) survey showed that 69 percent of the public assumes “no fire” and only 7 percent assume “fire; leave now” when a smoke alarm sounds (Hall, 2000). This poor response is attributed greatly to peoples experience with nuisance alarms.

Particularly over the past decade, improvements in detection have been enabled by cheaper and more sophisticated computational processing (Gottuk, 1998). These advancements have also led to research and development of multi-criteria detection systems. These systems generally have two main components: the combination of sensors and advanced processing schemes for using the sensor output. In the broadest definition of the term, multi-criteria detection can consist of processing the output from a single sensor to yield multiple parameters (e.g., absolute value, rate of rise or fluctuation). For example, Pfister (1983) reports on work in which better discrimination between smoke and water vapor is achieved with an ionization smoke chamber (the most common type of residential smoke alarm) by comparing ion current output at both low and high voltages. By measuring multiple outputs from a single sensor, better discrimination between a real fire (smoke) and nuisance alarm (water) source can be achieved. To the author’s knowledge, this technology is not being used in commercial devices. The vast majority of research work in the area of multi-criteria fire detection has focused on processing data from multiple sensors (i.e., multi-signature detection).

The most common type of fire warning equipment are smoke detectors, which are found in residential to industrial applications and encompass multiple smoke sensor technologies. Other than smoke detectors, the most common detection technologies are heat detectors and optical fire detectors (flame detectors).

Currently there are primarily two types of smoke detectors, ionization and photoelectric (Gottuk, 1998; Bukowski, 1994). These detector types respond differently to different smoke properties. For example, ionization smoke detectors generally respond faster to flaming fires than smoldering fires because flaming fires have a larger number of particles. Photoelectric smoke detectors generally respond faster to smoldering fires than flaming because the smoke is characterized by larger particle sizes. The two detection technologies illustrate the diversity of smoke measurements. Although some may consider smoke a single signature, there are multiple parameters that can be used to characterize it. These parameters include the particle size distribution, the number density, mass and optical properties. These parameters are dependent on the type of fuel burning, the mode of burning (smoldering or flaming), the environmental conditions and the time during smoke transport, during which particles can agglomerate. Smoke detection technologies have changed little over the past 20 years in part because of a lack of knowledge regarding the character of smoke from fire and nuisance sources. A quantified characterization of smoke properties for a range of applicable sources would provide the basis for improvements or the development of new smoke measurement technologies. The majority of fire detection testing performed has not included measurements of smoke properties, such as particle number density and size distribution, because of the difficulty of making these measurements. The development of reasonably priced experimental techniques for making in situ transient smoke property measurements is needed.

Heat detectors respond to temperature changes in the surrounding gas. A fixed temperature heat detector will signal an alarm when the active element of the detector reaches the designed alarm temperature. Depending on the application, activation temperatures may range from approximately 38 C (100 F) to 302 C (575 F) (Bukowski, 1994)). Other types of heat detectors include rate compensated and rate-of-rise. Heat detectors are not considered early warning detection devices since a reasonable size fire is required to achieve the alarm threshold [Bukowski, 1976]. The use of temperature measurements as part of a multi-signature fire detector is discussed below.

Optical fire detectors measure the radiant energy from a fire. These detectors utilize both single sensor and multi-sensor technologies, which detect light in the ultraviolet (UV), visible and/or infrared (IR) spectrum. The most common types in use today are UV/IR, dual IR, and triple IR devices. The majority of units are UV/IR, but newer triple IR technologies have been gaining wide spread use. In a Navy research program, triple IR detectors provided the best detection response to fuel spill fires and the very good nuisance alarm immunity compared to the other optical fire detectors (Gottuk, 2000). One manufacturer has a device that detects in the UV, visible and IR. These combined sensor units are multi-criteria detectors. Besides detecting energy at multiple wavelengths, the IR detectors also evaluate the fluctuations (frequency) of the incoming energy which correspond to the pulsations of a fire plume. Both the combination of sensors and the use of energy pulsation frequency have contributed greatly to developing more nuisance alarm resistant fire detectors.

Optical detectors can provide very fast response to flaming fires depending on the distance from the fire, the line of sight, and the particular detector technology. Optical detectors are not well suited for smoldering fires or in applications where the field-of-view of the detector may be obscured. The high cost of this technology and its particular applicability to wide open spaces and flaming fires does not make optical fire detection suitable to many applications, such as residential housing and office buildings.

Due to the relative magnitude of residential fire deaths and injuries, improving detection for residential applications should be an area of increased research. Advances made for the residential applications would translate to a broad range of applications where smoke detection is currently used. Generally, the use of smoke detection is in applications primarily focused on fire detection for life safety. Optical fire detection and heat detection are associated with property protection more so than smoke detectors.

Multi-Signature Fire Detection

The use of multiple signatures for fire detection is an active area of research (Gottuk, 1998; AUBE, 2001). The concept of multi-signature detection is a logical progression in the advancement of automatic fire detection. In many aspects, a person represents the best fire detector because of his/her ability to detect a wide range of fire signatures. A person's senses allow for the detection of sound, heat, light, smoke and odors (gases) from a fire. In addition to being able to detect multiple signatures, the person has a high level processing capability to input and analyze these signatures to yield very good discrimination of real fire and nuisance events. Ultimately, the science of fire detection is an effort to mimic man. The two main areas of research have been to identify useful fire signatures and to develop the advanced processing for accurate nuisance/fire source discrimination and alarm. A review of the state of the art is provided in Gottuk (1998).

Multi-signature fire detection technologies continue to offer the most promising means to achieve both improved sensitivity to real fires and reduced susceptibility to nuisance alarms (Conforti, 1999; Gottuk, 1998; Meacham, 1994; Fischer, 1994; Hagen, 2000). Based on the work to date, the use of gas sensors in combination with smoke sensors holds the greatest potential for successful multi-criteria detectors. Temperature sensors are used in a number of commercially available combination detectors (primarily photoelectric smoke and heat), but most experimental data shows little to no improvement in fire detection capabilities with the addition of the temperature sensor (Wakelin, 1997; Gottuk, Hill et al. 1999, Rose-Pehrsson 2000).

Most research with gas signatures has focused on the utilization of species that are prominent products of combustion, such as carbon monoxide (CO) and carbon dioxide (CO_2), and to a lesser extent oxygen and general hydrocarbons. These species have been used because they are key products of combustion and are easily measured in the lab with standard measuring techniques, i.e., bench-top equipment. It is important to note that not until about the last 10 years were CO or CO_2 sensors available that had the potential to be incorporated into typical detector heads. The most promising CO sensors are electrochemical cells, and the most promising CO_2 units have been NDIR sensors. Costs for both sensor types has been decreasing considerably over the past decade, making the use of these sensors a more practical consideration. However, more work is needed in the manufacture of cheaper sensors with better performance specifications. For example, low cost CO electrochemical cell sensors with part-per-million (ppm) concentration resolution and a ten year life are desirable. Carbon dioxide sensors are still rather costly relative to the price of smoke sensors. The scarce availability of cost effective gas sensors with stable operation and long life has been a deterrent for manufacturers to developing multi-signature detectors.

There are several advantages to developing a combined CO/smoke detector. One of the primary advantages is the ability of a combined sensor algorithm to produce faster alarms to fires while reducing many nuisance alarms (Gottuk, 1999). Most nuisance alarms which are not related to hardware problems are the result of non-fire aerosols. Cooking aerosols, dusts, tobacco, and aerosol can discharges are examples of sources which cause nuisance alarms (Breen, 1985). Cooking aerosols and steam (e.g., from a shower) are the most common nuisance alarm sources (Smith, 1994; Kuklinski, 1996). Of these examples, only tobacco smoke and possibly gas fired cooking are expected to contain carbon monoxide. This makes carbon monoxide an attractive fire signature for detection purposes. The fact that carbon monoxide is the causative agent in a majority of fire deaths further enhances the desirability of using CO as a fire signature. Given the toxic properties of CO, a combination CO/smoke fire detector can also serve as a CO alarm for exposure safety. Currently, there are no combination gas/smoke detectors on the market. However, several manufacturers have or are still working on developing units. In some cases, the manufacturers have put the development programs on hold for both marketing and technical reasons. One of the impediments has been the availability of cost-effective gas sensors that are stable with a functional life of ten years or more.

Detection of Low Concentrations of Chemical Species

Several studies have investigated the use of hydrocarbon sensors (typically metal-oxide type) and oxygen measurements, but the inclusion of these signatures in a multi-signature detector has not been demonstrated to yield a marked improvement over standard smoke detectors. Only a few studies have investigated the use of a wide variety of gas species (e.g., Chen, 2000; Gottuk, Hill et al., 1999). Chen et al. used a FTIR analyzer and measured CO, CO_2, H_2O, CH_4, CH_3OH, Formaldehyde, HCl, C_2H_4, N_2O, NH_3, CF_4, NO, methyl methacrylate, IPA, C_2H_6, C_3H_6, C_6H_{14}, C_2H_2, and C_6H_6. The resolution of these measurements was on the order of ppm. However, for many of the fire and nuisance sources, species concentrations were below the detectable levels. Gottuk et al. measured CO, CO_2, O_2, H_2, C_1-C_6 hydrocarbons, HCL, HCN, H_2S, SO_2, NO, NO_2, relative humidity and smoke. The majority of the gas species were measured using electrochemical cells with ranges from 5 to 200 ppm. Species such as HCL, HCN, H_2S, SO_2, NO, NO_2 had measured values of only fractions of a ppm for many fire and nuisance sources. Because of the small or non-existent values measured for the fire and nuisance sources, some of the species were not useful for an alarm algorithm. The results indicated that the more primary products of combustion (CO2 and CO) and smoke were the key signatures. Both of these experimental studies indicate that the use of many gaseous signatures is hampered in part by the inability to measure low levels, on the order of parts per billion.

As illustrated with our sense of smell, a fire can be detected and even classified using the nose (a multi-signature sensor) which can detect gases at much lower concentrations than can be feasibly measured by a potential fire detector sensor. The development of an electronic nose (a multi-sensor array) for fire detection purposes is an area of research that warrants more attention. Particularly, work is needed in developing low cost, compact sensors that can measure a wide range of chemical species at low concentrations. In addition, there is also much work needed in the development of the data processing that will accompany the sensor development. This data processing will most likely entail much experimental testing to be able to interpret the outputs of the multi-sensor arrays.

The development of a fire alarm algorithm for an electronic nose can be accomplished in one of two ways. One, establish a database of specific individual gas species (and other signatures) from fire and nuisance source events using general measurement equipment. Then develop a multi-sensor array that can be used to provide outputs specifically correlated to the measured species in the database. This approach provides a means for wider use of data in the development of alarm algorithms. That is, one set of tests (database) can be used for multiple sensor arrays. However, many multi-sensor array technologies may not provide species-specific concentrations that match the database. This leads to the second method.

A sensor array is developed and is exposed to fire and nuisance sources to develop a database of sensor outputs (fingerprints) for the different events. This method requires an extensive set of tests for each sensor array developed. Tests may even need to be repeated for any significant design change that alters the output characteristics of the sensor array. Though there is significant research in the area of electronic nose technology, little has focused on fire detection. Because of the complexities of being able to accurately discriminate between fires and nuisance events, a concentrated effort is needed in both the development of sensor arrays with alarm algorithms and establishing a quantitative understanding of the low level concentrations (< 1 ppm) of chemical species characteristic of both fire and nuisance sources.

Nuisance sources

In general for any combination of sensors in a fire detector, the key is to have a good understanding of the signature patterns from fire events and to know how to discriminate between these fire signatures and those from nuisance sources. This problem becomes quite difficult for nuisance sources, such as controlled combustion events, that have similar characteristics to fires. Examples include occasional smoke from fireplaces, use of acetylene torches, and burning food in a kitchen. The problem is compounded by cases in which a nuisance source, such as slightly burning toast, transitions into an actual fire, i.e., the toast chars and starts to flame in a malfunctioning toaster. The key question is how to make the judgment call as to when the situation becomes a potential fire threat and not just a nuisance event if an alarm occurs. This judgement is often difficult for a person; now an alarm threshold must be established based on limited sensor data. Besides these difficulties, the science of characterizing nuisance sources (those actually causing smoke alarms to respond) has been very limited and warrants more attention. As new multi-signature detectors are developed to provide better nuisance alarm immunity, test standards (e.g., UL 217 and UL 268) need to be improved to evaluate the detectors for these features in order to recognize the benefits (FPRF, 2002). Without a means to quantify and document improvements in nuisance alarm immunity, manufacturers have difficulty convincing consumers to pay higher prices for detectors with supposedly improved performance.

Development of Alarm Algorithms

As more signatures are identified, the development of high level processing becomes even more important. The development of fire algorithms has been an area of research as evidenced in the literature, but the amount of work has been limited and much has been outside of the U.S. (AUBE '99 and AUBE '01). The research areas of artificial intelligence, the use of neural networks and fuzzy logic algorithms, is playing an important role. Much of the fire detection research has focused on the development of alarm algorithms using fuzzy logic and neural networks for event classification and discrimination between fire and nuisance sources (McAvoy, 1996; Milke, 1995; Okayama, 1991, Okayama, 1991a; Okayama, 1994; Nakanishi, 1995; Rose-Phersson, 2000, Wang, 2001). Current work by the U.S. Navy has employed probabilistic neural networks (PNN) developed for non-fire applications and applied them successfully to fire detection (Rose-Pehrsson, 2000, Rose-Pehrsson, 2002 and Gottuk, 2001). Using a PNN with a four sensor combination (ion, photo, CO and CO2), a prototype fire alarm system was demonstrated to provide overall improved performance compared to conventional smoke detectors (generally faster response to fires and better nuisance source immunity).

The success of developing these alarm algorithms can require substantial testing. Particularly for neural networks, which are developed from a database of fire and nuisance signatures, the question arises whether the database is substantially broad enough to yield a robust fire alarm algorithm suitable for the majority of applications. It may be possible to employ different or new multivariate techniques in the development and validation of fire alarm algorithms which would require fewer experimental tests.

Other approaches for developing alarm algorithms have relied on more simplified mathematical correlations based on signature patterns and methods specifically linked to a knowledge of fire dynamics (e.g., Gottuk, 1999, Ishii, 1991; Richards, 1997; and Davis, 2001). As noted previously for the numerically-driven multivariate alarm algorithms, all algorithm development requires the availability of signature data. This results in large databases of information that are proportional to the number of signatures being evaluated. In the case that multiple aspects of signatures are evaluated (i.e., magnitude and rate-of-change), the databases can become quite cumbersome to process, particularly when trying to manually review from a fire dynamics perspective. The development of generic tools, such as data processing software, to aid in the development and validation of alarm algorithms would be helpful.

Perceptions and Education

The education of the public (both consumers and installers) is an area in need of improvement. The first hurdle is the problem that fire alarm systems are installed to meet code not to provide the best life safety protection possible. This is particularly true for many commercial and industrial installations. Manufacturers estimate that about 95 percent or more of the programmable detection systems are never changed from factory default settings. Many of these systems could be optimized to provide better performance by implementing standard features in the system or adjusting alarm sensitivity levels.

Many consumers take fire detection for granted. For instance, smoke alarms[2] in a home are frequently not tested nor maintained. However, these electronic devices are expected to always work. People expect a smoke alarm to be able to save a person from a fire regardless of particular conditions within the residence (e.g., closed doors and relatively long distances between potential fires and the alarm). The National Fire Alarm Code (NFPA 72) provides minimum standards for smoke alarm installations in residential occupancies. Particularly with larger houses, the use of more than the required "one smoke alarm per floor" would be warranted. Unfortunately, many installers (and homeowners) are not aware that more smoke alarms maybe needed, despite this being a recommendation in NFPA 72 and in instruction manuals.

An informal consensus of industry experts and manufacturers is that much of the public is very cost sensitive in implementing fire alarm equipment (i.e., this fits the misconseption that minimum requirements provide all the safety needed). This is a problem for introducing new advanced smoke alarms which may cost more but provide significantly higher levels of safety (faster response time and less nuisance alarms). Both the education of the public as well as the quantification of the level of safety provided are needed to address this problem. Quantifying the level of safety provided requires the development of engineering performance metrics (Cholin, 2002) and standardized test methods (FPRF, 2002).

Detector Response

One means of quantifying the level of safety provided by a detection system is to be able to calculate the response of a smoke detector. With the increasing use of performance-based fire protection design, it is also imperative that predictive tools and methodologies be available to design and analyze fire detection systems (Cholin, 2002, Schifiliti, 2001). Without the technical tools for calculating the response of a fire detector (particularly smoke detectors), performance-based analyses can not fully account for or weigh the benefits of a fire detection system relative to other fire safety systems.

Presently, there are two basic methodologies in use for estimating the response of smoke detectors – the Temperature Rise Method and the Optical Density Method (Schifiliti, 1995; NFPA 72). Unfortunately, neither provides very accurate results. In fact, only recently was the potential accuracy for alarm estimation using the second methodology evaluated (Geiman, 2002). Schifiliti (2001) reports on the problems associated with detector response modeling and suggests several research objectives. One is to further develop, test and verify models that describe smoke entry into a detector sensor from outside the housing. Secondly, further test and refine Newman's model for ionization detector response. In general, a coordinated effort is needed between modelers,

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[2] A smoke alarm is a device that has both a smoke sensor and a horn. Smoke alarms are typically used in residential occupancies. A smoke detector is generally only a sensor and is wired to a control panel that typically distributes the alarm notification. Relative to this paper, the terms can be used interchangeably.

experimentalists and manufacturers in developing a consistent approach to creating accurate models that can be applied to general classes of detectors at different alarm sensitivity levels. As discussed by Cholin (2002), the development of performance metrics are also needed to achieve the objectives of developing useful detector response models. Establishing these performance metrics will only be possible with the cooperation of detector manufacturers and testing organizations.

Conclusions

Fire detection systems are used for both life safety and property protection and have saved thousands of lives in the United States. Despite its wide spread use in residential to industrial applications, there is still much that can be improved, leading to increased life safety and the reduction of property loss. Improvements include research objectives, education and training and the development of engineering methodologies.

Continued research is needed in the area of multi-signature detection, particularly gas and smoke combinations which hold the greatest promise for improved performance compared to smoke detectors alone. Multiple studies have demonstrated both faster detector response to fires and better nuisance alarm immunity with multi-signature detection. The research needed includes the identification of low concentrations of chemical species from fire and nuisance alarm sources. Achieving the goal of detailed signature identification will require the development of new sensor technologies (e.g., electronic nose sensors). The development of low cost gas sensors, particularly CO and CO_2, that are stable with a functional life of ten years or more is needed to produce marketable multi-signature detectors. The development of multi-signature detection will also benefit from advancements in multivariate analysis techniques that allow more efficient development and testing of fire alarm algorithms.

The ultimate manufacture and use of advanced multi-signature detectors will depend on further education of the general public, installers and engineers to the benefits of the new detection systems. This education should include a better understanding of current fire alarm systems and the means to optimize them using currently available features. A potential problem is a general attitude that a fire alarm system is just code required equipment not a valued piece of life safety equipment. Improved fire detectors (multi-signature or otherwise) will not be widely accepted unless consumers are willing to pay higher prices for increased life safety. In order to educate and convince consumers and engineers of the value of improved detectors, detector performance metrics and test standards must be developed to document the added benefits. For instance, the improved nuisance alarm immunity of a multi-signature detector needs to be demonstrated and recognized by listing agencies.

Lastly, but potentially the most important, a coordinated effort is needed between modelers, experimentalists and manufacturers in developing detector performance metrics and accurate models for the calculation of detector responses under realistic installation conditions. With the increasing use of performance-based fire protection design, it is imperative that predictive tools and methodologies be available to design and analyze fire detection systems. Without the technical tools for calculating the response of a fire detector (particularly smoke detectors), performance-based analyses can not fully account for the benefits of a fire detection system relative to other fire safety systems.

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PROBABILISTIC METHODS IN FIRE SAFETY ASSESSMENT: POTENTIAL RESEARCH AND DEVELOPMENT NEEDS[1]

N. Siu[2]

ABSTRACT

Probabilistic methods of analysis provide an important means for conveying information regarding analysis uncertainties to fire safety decision makers. A broad range of issues (e.g., the likelihood of challenging accidental fires, the uncertainties in current predictions of fire environments) can be addressed using these methods. Current research and development (R&D) needs regarding the use of these methods include the development of tools and data for quantifying input parameter uncertainties, and the development of methods, tools, and data for quantifying model uncertainties. From a fire safety improvement perspective, it is essential to identify those scenarios that dominate nationwide fire risk, in order to identify potentially effective mitigation approaches as well as to better focus R&D activities..

Introduction

Probabilistic methods of engineering analysis[3] are playing an increasingly important role in fire safety assessment. These methods are designed to quantitatively address the uncertainties inherent in safety analyses. They not only provide a language and tools to support analysts in making clear statements about the limitations in their results, they also provide a means to convey important information to decision makers who wish to assess and use the analysis results.

The term “probabilistic methods” comes from, of course, the choice of using the theory of probability to develop quantitative statements of uncertainty. The basic unit of measure is the conditional probability, denoted by $P\{X|C\}$, which quantifies the analysis team’s belief[4] that a particular proposition $\{X\}$ is true, given that a specified condition $\{C\}$ holds. Typical propositions of interest can be discrete (e.g., N fires of a certain class occur over the course of a year) or continuous (e.g., the temperature at a particular point in space at a particular point in time falls in the range $[T,T+dT]$) in nature. The conditions of interest reflect both the analysis boundary conditions (which indicate the area of

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[1] The views and conclusions in this paper are those of the author and should not be interpreted as necessarily representing the views or official policies, either expressly or implied, of the U.S. Nuclear Regulatory Commission.

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[3] In this paper, “probabilistic methods” are defined as methods of analysis whose results are stated in terms of probabilities (or related quantities, e.g., frequencies). They are distinguished from probabilistic solution methods (e.g., Monte Carlo simulation methods), which can be used to solve deterministic as well as probabilistic problems.

[4] This paper follows the subjective interpretation of probability, as discussed by Apostolakis (1978, 1990) in the context of engineering analyses performed to support decision-making.

applicability of the results) and the evidence (e.g., empirical data) shaping the analysis team's belief. The theory of probability provides the means to develop the conditional probability of compound propositions in a manner consistent with logic and with the available evidence.

Current Level of Understanding

The application of probabilistic methods to fire safety assessment can range from complete scope probabilistic safety assessments (PSAs), which identify potential scenarios, their consequences, and their probabilities, to focused assessments of the uncertainties associated with the prediction of a particular phenomena under tightly specified conditions.

The models used in these assessments can be deterministic or probabilistic in nature. In addition, the solution methods used to solve these models can also be deterministic or probabilistic. Table 1 provides a number of examples illustrating the various combinations of deterministic and probabilistic models and methods.

Table 1. Example combinations of models and solution methods.

		Solution Method	
		Deterministic	Probabilistic
Model	Deterministic	Zone model Finite difference method	Finite, homogeneous gas layer model Monte Carlo transport method
	Probabilistic	Event tree model Minimal cutset upper bound method	Rule-based evacuation model Discrete-event simulation method

Despite the differences across the various combinations shown in Table 1, some broad statements can be made regarding the current understanding of probabilistic methods (in the context of fire safety assessment applications).

First, the development of efficient probabilistic solution methods has been a subject of active research for a number of decades, and will likely continue to be a subject of research even as current computing capabilities allow us to tackle increasingly complex problems using currently available methods. Examples of methods developed over the years include object-oriented, discrete-event simulation for rule-driven systems, and advanced Monte Carlo sampling schemes to support the application of Bayes' Theorem in the statistical estimation of multiple dependent parameters.

Second, research to develop methods for assessing the uncertainties in model predictions is also underway. This research applies to the probabilistic as well as the deterministic models identified in Table 1, because the predictions of probabilistic models, which address "aleatory uncertainties" (also referred to as "random" or "stochastic" uncertainties), are naturally themselves uncertain to some degree. The methods for uncertainty analysis are aimed at quantifying the "epistemic uncertainties" (also referred to as "state-of-knowledge" uncertainties) in the accuracy of the model predictions.[5]

A complete, formal uncertainty analysis for both deterministic and probabilistic models requires: a) an assessment of the uncertainties in the model input parameters, b) the propagation of these uncertainties through the model structure, and c) the estimation of uncertainties associated with the model structure itself. Methods are available to perform the first and second steps in relatively routine applications. On the other hand, considerable development work remains to be done on methods supporting the third step.

Regarding input parameter uncertainties, widely available statistical techniques can be used when large amounts of directly relevant, unambiguous data are available. When the data are sparse, only partially relevant, or even ambiguous, as may be the case for safety assessments of many actual situations, Bayesian techniques (including expert elicitation) can be used, as discussed by Siu and Kelly (1998). The technical issues remaining involve questions concerning the application of these techniques to specific problems, e.g., how to assign probability values to different potential data sets given a set of evidence. There is also a need to develop, where practical, stronger sets of data. This will reduce the need to use the more elaborate estimation techniques mentioned above.

Regarding the propagation of uncertainties, a wide variety of tools and techniques have been developed over the years. As an example, Helton and Davis (2000) provide a summary discussion of a number of sampling-based methods (e.g., direct Monte Carlo, importance sampling, Latin Hypercube sampling) that can be used.

Regarding the estimation of model uncertainties, the current level of understanding is far less mature. In a 1993 workshop discussing the treatment of model uncertainty in risk assessment applications, even the definition of "model uncertainty" was the subject of considerable discussion (see Mosleh et al, 1995). The conceptual frameworks underlying the various definitions suggested addressed such concepts as the probability of a given model being "correct" and the accuracy of the model in predicting the true (but unknown) value of the output variable(s). The workshop discussions also addressed, to a limited extent, the operationalization of the various definitions.

More recent work by Droguett (1999) argues for a Bayesian approach that uses two forms of evidence: evidence from the model (i.e., the model's predictions for the situation of interest), and evidence about the model (i.e., information about the model structure, and information from previous uses of the models, including benchmarking and validation calculations). This approach, which is represented in Figure 1, expands on discussions held in the previously mentioned workshop and is consistent with the philosophy of current PSAs. Droguett also proposes a number of computational methods for applying the approach that may be useful in a number of fire safety assessment applications. Work remains to develop tools for routine practitioner use, and to develop the data needed by these tools (e.g., comparisons of model predictions against

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[5] "Aleatory" uncertainties are those uncertainties that are, for the purposes of the analysis, treated as being irreducible. Thus, if repeated trials of an idealized thought experiment (where the conditions are kept constant from trial to trial) will, assuming no measurement error, lead to a distribution of outcomes for the variable, this distribution is a measure of the aleatory uncertainties in the variable. "Epistemic" uncertainties are those that can be reduced with additional knowledge. Uncertainties in a deterministic variable whose true value is unknown are epistemic. Repeated trials of a thought experiment involving the variable will, in principle, result in a single outcome, the true value of the variable.

experimental observations).

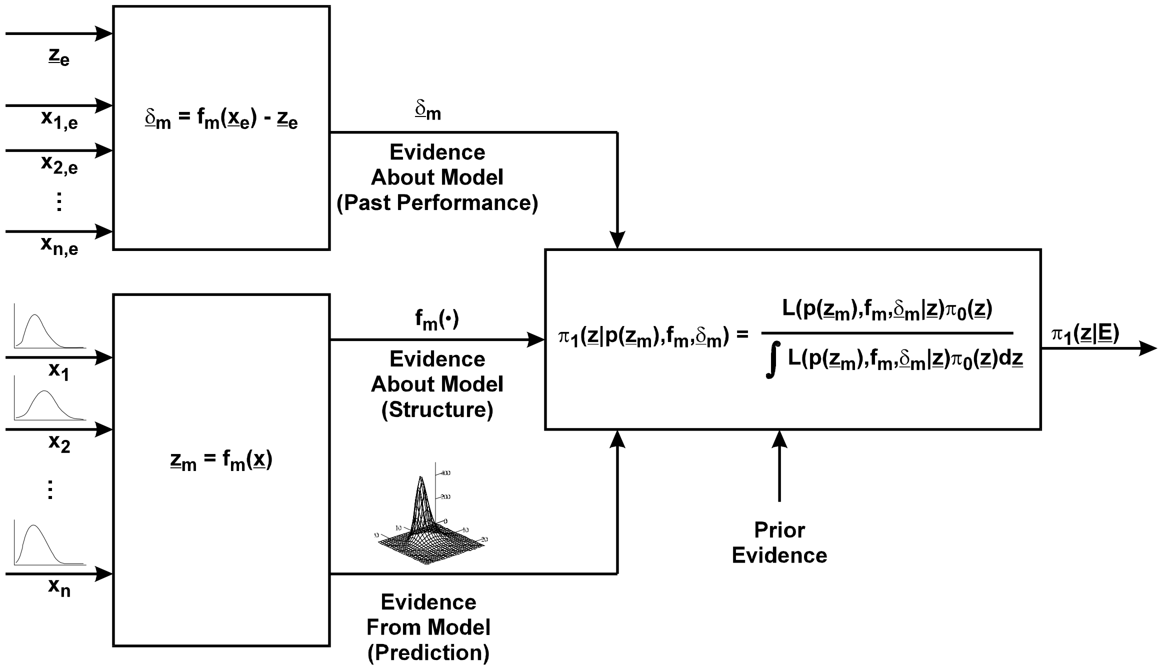

Figure 1. Bayesian Approach to Treating Model Uncertainty

Key Research Needs

From the preceding discussion, it can be seen that improvements could be useful in a number of areas relevant to probabilistic methods. These areas include: the development of efficient numerical methods for solving complex problems (as well as guidance for selecting methods appropriate to the specific problem at hand), the quantification of uncertainty in a set of model parameters when current evidence is weak, and the quantification of uncertainties associated with the structure of a given model.

From a fire safety perspective, however, it may be that improvements in these areas will not have the same benefit as an improvement in a non-methodological area, namely the current state of knowledge regarding the dominant contributors to fire risk.

As indicated by the background notes provided for this workshop, there clearly is a general understanding of the nation's current fire risk (both in terms of life safety and in terms of economics). It is less clear if there is an understanding of the risk-dominant scenarios sufficiently detailed to identify and evaluate potentially effective risk management strategies (which can include R&D aimed at developing improved models, methods, and data for analyses in areas where uncertainties need to be reduced). If a more detailed understanding is needed, then work to reach this understanding may well require a large number of fire safety assessments covering a broad range of building and facility types. It may also require focused R&D activities aimed specifically at developing tools to support the identification of key scenarios. This is not a particularly innovative activity, not is it necessarily a big opportunity for "breakthrough" research. Rather, it is an enabling, and crucial, step in the identification of measures that should lead to real improvements in national fire safety.

Role of Key Institutions

If, as suggested in the preceding section, it is decided that a number of fire safety assessments should be performed to identify key scenarios for all of the buildings and facilities of interest, this could require a substantial investment of resources. Resources would be needed to develop the methods, tools, data, and guidance supporting the performance of consistent analyses, to perform the analyses, to review the analyses, and to implement the results of the analyses. Key institutional support would likely be needed in this major undertaking to develop stakeholder buy-in, to ensure the availability of resources, and to coordinate the various technical and non-technical activities.

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DETERMINISTIC MODELS FOR FIRE PROTECTION ENGINEERING
The Thermal and Fluid Mechanics of Fire

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ABSTRACT

A brief review is presented for deterministic modeling which is taken here to mean predictive methods for the thermal-fluid aspects of fire. This research in fire dominates the output from the fertile period of 1974-1983. It calls for support of fire research at levels that made it productive. Modeling here includes formulas developed by the experimental process at that period which has been invaluable to the engineer. Research funding has been all but eliminated for fundamental studies in fire. These fundamental studies are essential for developing the infrastructure of the discipline and practice of fire protection engineering. A plan is proposed to establish federally funded national centers to support and conduct research for better standards, conduct education and training, and dispense advice and information.

Introduction

Deterministic modeling is a term used often in fire research to mean predictive methods for fire phenomena. Generally this pertains to the physics of fire, since the chemistry in this modeling is relegated to stoichiometry from the known fuel, or data and correlations based on measured yields of the major products of combustion. This modeling deals with the thermal flow properties induced by combustion. Hence a much better title for this discussion might be "the thermal and fluid mechanics of fire". It includes the processes of ignition, flame spread, combustion extent, and burning rate. These processes depend on geometry and fuel properties, and therefore the form and definition of the latter must be addressed. They pertain to processes that occur in the ambient and in confined spaces where the environment can affect their behavior. This includes the behavior of fire in compartments, buildings, structures and vehicles. They may be terrestrial or beyond. In short, the thermal sciences in concert with the combustion processes of uncontrolled fire pertain. As a consequence, the interaction of these processes with people (burn injury, heat stress, inhalation toxicology), structures (fire resistance), special equipment and manufacturing (nuclear reactors, electronics, chip making), and special hazards (radioactive waste fires, pollution, nuclear winter) all come into play. More importantly, the ability to address such issues cannot rest on a response to emergencies. The infrastructure for a knowledge-base needs to be sufficiently developed to deal with issues as they arise, whether they are in the normal scope of fire protection design and analysis or new situations due to disaster or the development of new technologies. In short, fire engineering cannot be relegated to codes and standards

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that have no foundation in science; they must be part of the main stream of science and engineering.

Historical Developments

Fire science has developed slowly and in spurts. The thermal-fluid aspect has dominated the subject of fire science for most of its development thus far. In order to understand the evolution of fire science, it is useful to examine its historical development. The study of fire could not adequately begin without the development of some key areas of science. It is useful to put these developments in perspective. Table 1 shows the birth of significant science disciplines that were necessary for the development fire science. Fire research activities may have begun as early as 1920. These early studies were focused on the establishment of engineering design practices to insure the adequate fire resistance of building structural elements. It is noteworthy that not much has been done in this area over the last 50 years, resting on what was done before. Yet the WTC building collapses have raised our sensitivity to the needs in structural fire resistance. At about 1945 to 1950, a more broad fire research effort began. The studies from this period began to address the dynamics of the fire and the movement of smoke. Damage to people and contents were now considered more important than just the building structure.

Table 1. Suggested Dates for the Development of Modern Science Disciplines

Date	Discipline
1780	Chemistry (Lavoisier)
1850	Thermodynamics (Clausius, Gibbs)
1890	Fluid Mechanics (Reynolds, Prandtl)
1920	Heat Transfer (Nusselt, McAdams)
1930	Combustion (Semenov, Zeldovich)
1950	Fire (Kawagoe, Thomas, Emmons)

In the USA a presidential commission report in 1973, “America Burning”, outlined the needs of the fire service, the fire problem in the USA, and the research needs [1]. The report advocated the need “to strengthen this grounding of knowledge about fire in a body of scientific and engineering theory, so that real-world problems can be dealt with through predictive analyses.” This report, in a time of an acute consumer interest in the safety of products, brought fire research to the forefront in the USA. It helped secure the fundamental grants program of $ 2 million per year from the NSF RANN Program to the newly formed Center for Fire Research at NIST, then the National Bureau of Standards. (Incidentally, Ralph Long, who established the NSF fire program, did a masterful job at enlisting the best scientists and academicians of the country. Also I learned a research management tenet from him when I critically asked him why he had so many grants in flame spread. He replied that it was the only way to make progress through productive debate and convergence on the right answer to issues. This tenet is at odds with modern management that strives to remove redundancy.) The NIST program employed nearly 125 at its peak, but at about 1983, it came under attack due to changing government policies. The fundamental grants program dropped from \$ 2 million as initiated in 1974 to \$ 1.2 million where it stands today. Fire research and safety has suffered accordingly as government attitudes changed and funding waned.

State of Thermal-Fluids Fire Modeling

The state of the art for fire modeling can be measured by the ability to present a consistent and generalized mathematical formulation for its phenomena. This state can be measured by the number of recognized handbooks and textbooks that exist. These are few in number and not couched in the same pedagogical form as familiar texts in the thermal-fluid sciences. It is interesting to note that the NRC underwrote the McAdams text for McGraw-Hill in 1933, because McGraw-Hill did not want to publish it [2]! The SFPE Handbook of Fire Protection Engineering [3] probably is the best barometer of the state of the art. Published first in 1986 it is now in its 3rd edition. However, in my opinion, the new editions only build sales and do not disseminate any significant new knowledge. The primary development of knowledge occurred when the basic research program of Ralph Long and the good funding years of the Center for Fire Research existed (1974-1983).

Some discussion of the form of modeling results should be discussed. Many associate modeling with computer prediction. This is a narrow view and misses the significant contribution from experimental results. The latter leads to correlations, based on theory, which provide the backbone of formulas for analysis and design. They are the main substance of the thermal-fluids science of engineering and populate the fire literature as well. These correlations are necessary because the phenomena are too complex to be predicted directly from the fundamental laws of physics. Issues of turbulence, radiation and chemistry prohibit exact solutions. These correlations provide the ingredients of system models, known as zone models for compartment fire analysis. In them, the correlations provide the transport relationships for the conservation equations. In the more fundamental CFD approaches, these correlations provide the experimental basis for validation. Hence, the need for specific experimental studies and accurate measurement techniques should be at the forefront of any modeling discussion. I will not address the CFD approach, except to say that these require their own modeling, and direct simulation will have to wait for larger computers. Even when such computers exist, the need for individual formulation of the physics is necessary for engineering application. In fire investigation analysis, I rarely resort to the computer. The physics needs to be estimated first, before seeking improved resolution without, necessarily, an increase in accuracy.

Progress over the last 50 years of fire research has laid a good foundation to demonstrate that a wide range of engineering methods have been developed. Like all areas of engineering, the methods can be improved and refined to improve their generality and accuracy. Some used to think fire was too complex to synthesize by engineering formulae, but this has been dispelled. Current knowledge will allow prediction in the following areas:

1. Dynamics of fire plumes for simple geometries.
2. Dynamics of smoke flow under ceilings.
3. Dynamics of room fires and flashover.
4. Dynamics of ignition, flame spread and burning rate for simple geometries.
5. Primitive results for the suppression of fire and its agents.
6. Smoke movement in simple building geometries from room to room.

Given sufficient funding in fundamental research, prediction accuracy in these areas can be improved and expanded. But fundamental research must be systematically conducted or the knowledge-base will weaken, and the needed expansion will not occur. I emphasize that this research, although some see fire as an applied area, is fundamental, and is essential for this neglected, immature area of science. Although the above list of areas demonstrates competence in predictive methods for fire phenomena, they are far from complete. For example, one might be able to predict flame height in the open, but not its length along a ceiling, out of room, or out of a building. This is incomplete knowledge that tantalizes the practicing engineering, and leads to potential errand analysis. However, in addition to extending the knowledge in 1-6, I list several distinct areas that have been neglected or bear study:

7. Ventilation-limited and fully-developed fires in confined spaces.
8. Heat flux by fire.
9. Turbulent combustion application to fire and buoyant phenomena.
10. Smoldering
11. Measurement techniques for flow and thermal measurements in fire.

This research is necessary to provide the engineering infrastructure to insure society with proper assessment of fire behavior for safety design and for investigation. One can count the fire deaths and the cost of fire as motivators for change, but how can we afford to live in a technicological world and still be subjected to medieval fire tests and regulations.

Flammability Testing.

There is no uniformity in the methods to assess the flammability of materials. Tests vary between countries, and even within government agencies. Rarely can a scientific rationale can be made for the flammability test method. There is no universal criterion to assess flammability, nor can it be directly related to the fire scenario of relevance. This is a serious and a complex problem. Scientists work on idealizations of products and materials, and regulators demand robust, reproducible tests. This is an area that demands more science and more connection to reality. A recent GAO report on Fire Safety says: "The nation's system for developing standards and testing products to certify their compliance with those standards is complex. The system consists of a decentralized, largely self-regulated network of private independent standards-development organizations, testing laboratories, and government agencies."[4] Technical objective input needs to be provided in this development process. The federal government needs to insure that this happens.

Fire Safety Design and Performance Codes.

Motivating factors for including engineering methods in fire safety design are (1) the reduction of cost, (2) the maintenance of architectural integrity, and (3) the elimination of constraining regulations. Government policies on deregulation have led to legislation in the United Kingdom and in New Zealand to promote the seeking of alternatives to the specific fire regulations. Australia and Japan have also introduced fire safety performance practices into its national building codes. This has opened the door to engineering as an alternative to the "plank-by-plank" language of regulations. Consequently, there has been increasing interest by regulators and standards organizations to embrace the use of engineering methodology in fire safety design. Most regulatory codes provide for an alternative to the prescriptive requirements if equivalence can be demonstrated. This is a challenge for the engineer, and is becoming a bigger part of the dialogue between the fire protection engineer and the authority responsible for administering the regulations. As a result, the knowledge-base of fire science has become more disseminated, but its potential for being used incorrectly has increased.

Just as with the measurement of product flammability, there is a challenge here for fire science. The current fire science knowledge-base has demonstrated and has stimulated the use of engineering methods. In the USA, litigation claims in fire damage suits have encouraged a progressive view of engineering methods for fire. Indeed, the US Supreme Court has required that testing and analysis form the allowable expert opinion in court testimony. This is a natural consequence of fire science becoming available, and lawyers recognizing that valid scientific expertise could help them. Unfortunately, the legal community does not contribute to open research. The ability for the performance code process to grow and have economic and safety benefits can be a catalyst for more needed fire research. A process is necessary for insuring that fire safety design and performance codes are the standards of the future. This will insure measurable safety and more clearly display the weakness of the codes.

Fire Investigation.

Fire science expertise has been recognized to help explain fire accidents and crimes of arson. Governments have convened boards of inquiry that have included fire scientists to help understand fire tragedies of significant public impact. Examples include the fires following the earthquake in Kobe, the Kings Cross fire in London, and the recent TWA 800 explosion. In the USA, the National Transportation Safety Board (NTSB) has unique authority to investigate any significant transportation accidents including fire. In recent years the Bureau of Alcohol Tobacco and Firearms (ATF) was given the federal authority to investigate federal arson crimes, and as a consequence has established a trained nationwide team that can immediately respond individually or in force to a fire scene. Their interest in fire science has culminated in federal funding of the first national laboratory for the study of fire pertaining to arson. The lack of an appropriate investigative analysis for the fire-induced collapse of the WTC buildings (3) dramatically underscores the attention that fire safety receives at the science level. It is great that NSF stepped up with fast-track grants for WTC research, but more is needed.

Fire Engineering Education.

Institutions formally granting degrees in fire safety (protection) engineering, or providing special subprograms in fire engineering, are increasing around the world. I count about 25 programs and growing. They include, beyond the USA, Sweden, UK, N. Ireland, Japan, China, New Zealand, Australia, and Russia. Our program at the University of Maryland has graduated about 700 with a BS degree since 1956 and about 60 MS students since 1990. I am told that the fire program at the University of Lund is the most popular curriculum in Sweden, apparently due to its career path into officer positions in the fire service. The fire service has recently motivated the University of North Carolina at Charlotte to begin a fire engineering program with the same objective. Unfortunately this is not a view shared by all, but it is clear that the general support for fire safety engineering education is growing. Yet as an engineering discipline it has a challenge to demonstrate its scientific competence and market its profession into traditional and new career paths. While in some countries the fire service is recognizing the need for trained scientific personnel, in general the fire service has lagged in its appreciation of fire safety engineering. Yet the fire service is an area that can absorb a large population of students. Current educational institutions in the US cannot fill this potential need.

Issues

Opportunities for Research.

Research in fire does not start at the high-tech level; it is an immature science but has demonstrated its viability as a discipline in its own right. An investment must be made to develop the same systematic knowledge-base for fire engineering that the field of thermal science has experienced. It must catch up. This knowledge-base is essential for sound engineering design and fire investigation. The impact to society is an assured measure of safety that is more realistic than our current practice, and more flexible in its application. This should and must be done through a scientific process. The routine design should still be done by specifications based on engineering, but the extraordinary design needs a performance code process.

Needs in Education and Training.

The field of fire protection engineering is virtually unknown. Many positions are filled without the proper background. This will continue as long as the practice is empirical and code driven. The educational process must keep pace with the demands for change. Those currently in the practice of fire safety must have access to available professional education to afford them the ability to understand and react to this change. Formal engineering education needs to be supported through the development of research and texts.

Barriers.

The barriers to change are the entrenched practices of standards bodies and testing laboratories, and the intransigence of industry to objectively promote safety. The administrative standards infrastructure is sound and working, but it needs to develop a technical infrastructure based on science. Industry is astute enough to digest change with scientific rationality.

Role of the Federal Government.

NSF needs to examine its reluctance to support education and basic research for fire. I was told by a NSF program manager "fire was applied, but combustion was basic research". This of course is ridiculous, but these biases stifle fair consideration. There is much that NSF has done to promote and develop basic research in fire through its program in the 1970's and its evolution to the NIST grants program for fire. But those funds have withered, and need to at least be brought back the to intent of "America Burning".

Certainly, NIST should continue to be the focal point of fire research and development in the USA, and standards should be its focus. Currently, the NIST effort plays an ineffective role in the development of standards. This is not by choice, but by funding ability.

In 1998 I convened an ad hoc group of interested parties (FMRC, NFPA, NIST, SFPE, UL, USFA, etc) for a discussion on the needs of fire research, education and safety in the USA. My concept for a national plan was aired and received significant, but not unanimous, support. I still believe it may still be a way for the US to assume its responsibilities to the public for assured fire safety. This responsibility is one of the federal government. It transcends conservative and liberal philosophies since it helps those that need it, and those that need it (including large corporations and agencies) do not have the ability to develop the safety technology and standards themselves. I propose a nationally funded effort to establish regional centers.

My specific proposed concept is to establish a **nationally coordinated network of "technical centers"** to facilitate fire safety design through education and research linked tightly to the needs of codes and standards. These regional national centers would help to facilitate the implementation and development of performance codes and their evolution from our current prescriptive practices, and would provide the technical bases for input to the standards processes, and needed educational support. I see four components to the centers:

1. **Input to codes and standards**.

   This component would provide support for the needed objective technical input to the normal standards committee processes that currently exist. Those committee processes have an infrastructure and framework for operating. However, they do not necessarily provide technical input from the scientific community. The basic science community in fire is almost decoupled from this process because of the incentives that drive it and the lack of funds to provide the technical base. A direct connection should be made between the standards process and the scientific research community.

This will provide a needed technical dialogue with a clear relevance for the scientific community. This activity can be coordinated between the national centers and standards bodies.

2. Education.

Both degree and continuing education elements are needed. The current set of fire safety practitioners know that science is affecting their practice, but have not had the opportunity to learn from these developments in a deliberate manner. Hence, distrust, anxiety, and over-expectations are emotions that arise among the field of practitioners. In the USA, we have 1 UG fire-engineering program, 2 graduate programs, and several 4-year fire technology programs. These are insufficient to promote the accurate implementation of a performance code. I conceive that the proposed centers could dispense educational programs at all levels and could network distance learning programs as well.

3. Technical Advice.

Just as programs involving manufacturing and agricultural extension services provide information, I would see that a component of the fire safety centers could follow a similar practice. This can be done in many ways. It could consider doing work under contract, directing people to qualified firms, or provide technical information. This is an essential component that is needed for local fire safety approvals and enforcement agencies try to deal with the demands of code modifications, alternatives and interpretations.

4. Research.

Although a sufficient knowledge-base on fire science and engineering methods has developed since the 1970's, it is insufficient to sustain a complete performance code process. Actually, much of the U.S. knowledge-base was established when funding for fundamental research was plentiful in the 1970's. Since then we have seen a significant reduction in a national investment for fire safety research. In 1974 -1981 the research budget for university research from NSF, and then from NIST, was $ 2 million; now in 2002, is a paltry $ 1.1 million. A minuscule amount of the costs of fire safety are invested back into research to answer key questions. As technology advances, the economic and human threats from fire change in ways that prescriptive codes do not anticipate. We can not afford to have immeasurable, non-technically-based fire safety prescriptions for new technologies that can have such widespread potential impact on life safety, economics and security.

I would envision a new research program established to capture the interests of leading scientists in order to maintain a scientific community-base on the subject of fire for a direct link to applications in the codes and standards.

Conclusions

1. Deterministic models for fire have demonstrated the viability of useful engineering analysis and are key to the implementation of performance codes.

2. The current regulatory process needs to create a mechanism for producing scientific information to support current and future standards.
3. The funding for fire research is woefully inadequate in insure a measured level of fire safety.
4. A plan is proposed to establish national centers to develop the infrastructure for technically based fire standards.

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Fire Protection Engineering Tools

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Introduction

Within the context of this document, fire protection engineering tools include deterministic fire hazard analysis models and probabilistic fire risk assessment methodologies. These tools permit the hazards and risks associated with fire to be evaluated quantitatively in terms of physically meaningful units of measure. The development of these tools over the past few decades has prompted, as well as permitted, the development of frameworks for performance-based fire safety analysis, design and regulation of buildings. Continued development and refinement of these tools and methodologies are needed to more fully implement rational performance-based approaches to building fire safety, which hold the promise of permitting more cost-effective fire safety designs with better known levels of safety, risk and uncertainty.

Fires of hazardous proportions are extremely complex chemical and physical phenomena involving turbulent reacting flows at high temperatures, where the highly nonlinear effects of thermal radiation dominate. Unlike controlled combustion processes where the mixing of fuel and oxidizer are regulated, such as in internal combustion engines and furnaces, fires involve unregulated mixing and reaction of fuel and oxidizer. Thomas [1] has suggested that fire be defined as “gaseous combustion without taps,” in recognition of its uniquely unregulated nature. As noted by Thomas, the fire controls the air flow, through buoyancy-induced entrainment and chimney effects, while also controlling the supply of gaseous fuel by the thermal feedback to the condensed fuel from the gaseous combustion zone and the hot smoky gases. Despite the complexity of the problem, substantial progress has been made in characterizing the environments produced by fires in enclosures. Considerably more progress can be made with additional research.

Deterministic fire hazard analysis models

Quintiere [2] notes that the term deterministic modeling is often used in fire research to mean predictive methods for fire phenomena, commonly referred to as fire modeling. Generally, this pertains to the physics of fire, with modeling of the chemistry of fire relegated to specification of the stoichiometry of a known fuel or to the development of data and correlations based on measured yields of the major products of combustion. The physical modeling of fire generally deals with the temperatures, flows, smoke concentrations and smoke movement induced by combustion. Hence, Quintiere suggests that a more descriptive term for fire modeling might be the thermal and fluid mechanics of fire.

Fires in enclosures develop in a series of stages, which Mowrer [3] has called:

- The fire plume / ceiling jet stage;
- The enclosure smoke filling stage;
- The preflashover ventilated stage;
- The postflashover ventilated stage.

In terms of this sequence of fire development in enclosures, fire models have been developed in reverse order, with postflashover fire models developed first, followed by models of the other stages. To a large extent, this sequence of model development has followed and been motivated by increasing computer power.

The first enclosure fire models addressed the postflashover ventilated stage of fire development in terms of a one-zone well-stirred reactor concept. As noted by Thomas [1], interest in postflashover fire conditions was driven in large part by pressure from structural engineers to deal in a quantitative way with the loads imposed by fire on a structure. Following the fire-induced collapses of three high-rise buildings at the World Trade Center in New York on September 11, 2001, there is renewed interest in this issue on the part of structural and fire protection engineers.

In many respects, the postflashover stage of enclosure fires has been the easiest to analyze for a number of reasons, including:

- thermal conditions within the enclosure are relatively uniform throughout the volume of the enclosure, permitting a one-zone, well-stirred analysis to be relatively accurate for predicting average gas temperatures within the enclosure;
- the burning rate within the enclosure is regulated by the rate of air flow into the enclosure, i.e., the fire intensity is ventilation-controlled;
- The rate of air flow into the enclosure is regulated by the ventilation factor, $A_o\sqrt{H_o}$, that arises due to the buoyancy of the hot gases within the enclosure.

As a consequence of these last two points, the burning rate within an enclosure is known to a higher level of accuracy during the post-flashover stage than during the earlier stages of an enclosure fire.

Models based on the one-zone, well-stirred reactor concept were developed in the 1950s by Kawagoe in Japan [4], in the 1960s by Magnusson and Thelandersson in Sweden [5] and in the 1970s by Babrauskas and Williamson in the United States [6]. Relatively little notable work was done on the modeling of post-flashover fires in the 1980s, but during the 1990s, Thomas and Bennetts in Australia [7] performed small-scale experiments in long and wide enclosures with single ventilation openings that call into question many of the long-standing assumptions regarding the behavior of post-flashover fires, particularly with respect to the duration of such fires. This work had stimulated renewed interest in the topic of post-flashover fire severity even before the events of September 11, 2001.

Modeling of the pre-flashover vented stage of enclosure fires began in earnest in the United States in 1972, with the NSF-RANN sponsored Home Fire Project under the direction of Emmons at Harvard University in collaboration with Factory Mutual Research Corporation. This work [8], and related work [9] at the National Bureau of Standards (now NIST), gave rise to the conceptualization and development of the two-zone enclosure fire model. The two-zone modeling approach uses the concept of thermodynamic control volumes, with the application of conservation equations to assess the relatively uniform conditions within different control volumes. In a two-zone fire model, the control volumes nominally include the hot smoke layer beneath the ceiling and the cool lower lower above the floor of a room. These zones, assumed to be separated by a distinct interface, arise due to thermal stratification caused by the buoyancy of the fire gases. Quintiere [10] provides an overview of the zone modeling approach, including discussions of the application of the conservation equations and of the various submodels typically used to address different phenomena such as fire heat release, plume entrainment, vent flows and boundary heat transfer.

A large number of two-zone enclosure fire models were developed and refined through the 1980s and early 1990s [11], with the FAST/CFAST model developed at NIST [12] representing the current state-of-the-art of multi-room two-zone fire models and probably the most widely used zone model in the world today. With the emergence of CFD fire models as practical engineering tools, the development and use of zone fire models is beginning to diminish.

Modeling of the enclosure smoke filling stage of enclosure fires was an early outgrowth of the two-zone modeling effort. Zukoski [13] published the seminal paper on enclosure smoke filling in 1978 and Cooper [14] developed the ASET model shortly thereafter. Walton [15] adapted the ASET model for use on the personal computers that were just starting to come into widespread use in the early 1980s. Even today, almost 20 years later, variants of the simple ASET model are still used in fire protection engineering practice, to such an extent that the computer model evaluation task group of the Society of Fire Protection Engineers is currently evaluating the accuracy of the ASET model.

Preliminary analysis of the fire plume / ceiling jet stage of enclosure fires was undertaken by Thomas during the 1950s [16]. Considerable work on ceiling jets was done during the late 1960s and early 1970s, principally at Factory Mutual Research Corporation. Axisymmetric fire plume and ceiling jet temperature and velocity correlations developed by Alpert in 1972 [17] are still widely used, particularly in the predominant model for predicting fire detector and sprinkler activation times, the DETACT model, the concept for which was initially developed by Heskestad [18] during the mid-1970s before being developed in its current form by Evans and Stroup [19] during the mid-1980s.

Models of preflashover vented fires as well as enclosure smoke filling models require plume entrainment submodels in order to calculate the transport of mass, species and energy from the lower layer to the smoke layer. This need stimulated increased interest in the topic of fire plume entrainment during the 1970s and 1980s, with a number of investigators [20-22] performing experiments and developing correlations for the entrainment of air into axisymmetric plumes based on the seminal work of Morton, Taylor and Turner [23] on buoyant plumes during the 1950s.

One significant limitation of zone models is that they do not predict fire-induced flows from first principles. For example, a zone model requires a plume entrainment submodel in order to calculate the rate of mass flow from the lower layer to the upper layer. Plume entrainment correlations have only been developed for a limited range of idealized plume geometries, including axisymmetric plumes and line plumes. Consequently, the accuracy of zone models diminishes as real conditions diverge significantly from the idealized conditions upon which the submodel correlations are based. This imposes a significant limitation on the accurate application of zone models and has been a motivating factor in the development and application of field fire models.

During the 1980s, the application of computational fluid dynamics (CFD) models to enclosure fire simulation began in earnest, with much of the early work performed in the United Kingdom. As noted by Cox and Kumar [24], many of the assumptions and simplifications associated with zone fire modeling are unnecessary for CFD modeling because in CFD modeling the full set of field equations, expressing the conservation principles for mass, species, momentum and energy, are solved numerically, subject only to the boundary conditions of the problem, at least in theory.

CFD models come much closer to first principles than zone models in terms of expressing the conservation principles, but for practical problems they still require elements of modeling because full resolution of the time and length scales involved in the reacting turbulent flows associated with fire is not practical with current computers. In particular, turbulence, combustion and radiation typically require the specification and selection of appropriate models. Direct numerical simulation (DNS) of combustion is now used for research purposes [25], but is expected to remain a tool of the basic combustion research community for many years to come [24].

Two types of CFD model are now in fairly widespread use in fire protection engineering. These modeling approaches differ in their treatment of turbulence. The Reynolds-averaged Navier-Stokes (RANS) model solves only for time-averaged properties, with the turbulent fluctuations and transport processes in these averages addressed by means of turbulence models. The k-e turbulence model is typically used in RANS models. Large-eddy simulation (LES) rigorously computes the larger vortices associated with fire-induced flows, but requires models to address sub-grid scale phenomena, including combustion. As noted by Novozhilov [26], LES provides a level of accuracy closest to DNS because it resolves the large scale motions of the flow while requiring modeling only for the smaller scales.

In LES, large-scale flows are solved exactly, with modeling needed only for the small-scale motion. Because the small eddies that are being modeled rather than calculated contain only a small portion of the total turbulent kinetic energy, the flows computed by LES are usually less sensitive to the approximations involved in the small scale turbulence modeling. The LES approach to modeling fire using CFD has become the most popular approach in recent years due to the release by the National Institute of Standards and Technology of the Fire Dynamics Simulator fire model based on LES [27].

Initial applications of CFD models to fire generally were directed towards smoke movement and smoke control problems. These problems typically involve relatively small fires in relatively large spaces, where the effects of radiation and oxygen vitiation on combustion are negligible. For these applications, details of the fire itself are not too important; the fire simply serves as a source of heat (buoyancy) and combustion products. For these applications, the fire is typically specified and the movement of smoke resulting from this specified fire is calculated by the CFD model. For this type of application, hydrodynamic aspects of the models are most important. It is these hydrodynamic aspects of the models that are closest to first principles, so this type of application can be addressed with a relatively high level of accuracy, provided the boundary conditions are well known.

There is increasing interest in application of the CFD models to predictions of ignition, flame spread and burning rate, including the important effects of thermal radiation and oxygen vitiation on these processes. These are significant issues for many, if not most, hazardous fire situations. These topics are at the cutting edge of fire science and considerably more research is required to permit the prediction of fire development. The ability to accurately predict fire development, rather than just the consequences of a specified fire, represents the greatest challenge, as well as the greatest opportunity, for advancing the scientific basis of fire hazard assessment.

So far, this discussion of fire hazard assessment has only addressed the modeling of fire development and consequences. A key aspect of fire protection engineering is the design of systems to mitigate the consequences of fire. These include fire detection and alarm systems, as well as fire suppression systems, with automatic sprinkler systems being the most popular form of automatic fire suppression. The topic of fire detection and alarm systems is addressed elsewhere in this report.

McGrattan [28] and Grant, et al. [29] provide overviews of fire suppression with water sprays. McGrattan notes that relatively crude water suppression submodels have been incorporated into various CFD-based fire models over the past decade, while in their comprehensive review, Grant, et al. note that relatively little research had been done on fire suppression following World War 2 until a resurgence of interest in water mist as a replacement for Halon in fixed fire protection systems. Both reviews reflect the relative lack of knowledge on detailed fire suppression mechanisms and the currently empirical nature of fire suppression system design. Further research can reduce this empiricism and provide a more scientific basis for fire suppression system design.

Probabilistic fire risk assessment methods

Fires in buildings are relatively rare events, but they can have very large and extreme consequences. From an economic standpoint, it can be argued that the objective of fire protection engineering should be to minimize the total expenditure for fire, including the costs of direct and indirect fire losses as well as the costs of public and private fire protection. Evaluating these costs is a daunting task; determining the proper levels and allocations of expenditures for cost effective fire protection is even more daunting. Evaluating the costs of fire is made even more difficult by the life safety aspects of the fire problem. While precise cost optimization may be an unattainable goal, probabilistic fire risk assessments are important to the understanding of fire safety, particularly the state of knowledge regarding the dominant contributors to fire risk.

Internationally, a number of countries have been moving in the direction of risk-based fire safety regulation. Notable among these countries are Australia and Canada, where researchers have been collaborating for many years on a comprehensive risk-cost assessment model. In Australia, this work is embodied in the Fire-Risk (formerly CESARE-Risk) model [30], while in Canada, a model called FiRECAM (for Fire Risk Evaluation and Cost Assessment Model) [31] is being developed. These risk-cost assessment models employ an event-based modeling approach in which events are characterized by discrete time and probabilities of occurrence [32]. The models have been applied to office and apartment buildings, with the performance of the fire safety design assessed in terms of two decision-making parameters: 1) the expected risk to life (ERL) and 2) the fire cost expectation. Similar concepts have been espoused in the United States [33], but have not been developed in terms of a comprehensive model.

In the United States, performance-based approaches to fire protection design has been developed fairly recently in terms of a framework guidance document [34], performance-based options to prescriptive code requirements [35] and performance-based codes [36]. These performance-based approaches depend on the selection of design fire scenarios. One of the distinguishing aspects of fire scenario selection is the potential for intentional acts of incendiarism as well as accidental ignitions. Another is the dynamic interaction between the fire scenario and the level of protection provided. These distinguishing features require different types of analyses than used for natural hazards such as earthquakes.

Siu [37] provides an overview of potential research and development needs for probabilistic methods in fire safety assessment. Siu defines “probabilistic methods” as methods of analysis whose results are stated in terms of probabilities (or related quantities, e.g., frequencies). They are distinguished from probabilistic solutions methods (e.g., Monte Carlo simulation methods), which can be used to solve deterministic as well as probabilistic methods. Siu notes that probabilistic methods of engineering analysis are designed to quantitatively address the uncertainties inherent in safety analysis. They provide an indication of central tendencies as well as a measure of the uncertainties associated with the central tendencies. They not only provide a language and the tools to support analysts in making clear statements about the limitations in their results, they also provide a means to convey important information to decision makers who wish to assess and use the analysis results.

As noted by Siu [37], the application of probabilistic methods to fire safety assessment can range from complete scope probabilistic safety assessments (PSAs), which identify potential scenarios, their consequences and their probabilities, to more focused assessments of the uncertainties associated with the prediction of particular phenomena under tightly specified conditions. The models used in these assessments can be deterministic or probabilistic and the solution methods used to solve these models can also be deterministic or probabilistic. A complete, formal uncertainty analysis for both deterministic and probabilistic models requires: a) an assessment of the uncertainties in the model input parameters, b) the propagation of these uncertainties through the model structure, and c) the estimation of uncertainties associated with the model structure itself. Methods are available to perform the first and second steps in relatively routine applications, but considerable development work remains to be done on methods supporting the third step.

Siu [37] identifies a number of key research needs in the area of probabilistic methods for fire safety assessment. These include: the development of efficient numerical methods for solving complex problems as well as the guidance for selecting methods appropriate to a specific problem at hand, the quantification of uncertainty in a set of model parameters when current evidence is weak, and the quantification of uncertainties associated with the structure of a given model. He notes that it is not clear if there is an understanding of the risk-dominant fire scenarios for different buildings and facilities in sufficient detail to identify and evaluate potentially effective risk management strategies. He argues that a large number of fire safety assessments may be necessary if a more detailed understanding of these scenarios is needed. While not necessarily an opportunity for "breakthrough" research, this is a crucial enabling step in the identification of measures that should lead to real improvements in national fire safety.

Summary and Conclusions

The term "fire modeling" is a misnomer for most applications because the fire itself is typically specified and it is the consequences of this specified fire that are being calculated. Thus, a more accurate term for most applications would be "fire consequence analysis" rather than "fire modeling." Herein lies the most fundamental limitation of fire modeling and the area where substantial improvements are needed to advance the current state of fire hazard analysis modeling.

The current state-of-the-art in predicting fire development is not nearly as advanced as the current ability to calculate the consequences of a specified fire. Significant improvements are needed in the understanding of the chemical and physical processes involved in the unwanted burning of combustibles in buildings, including the high-temperature and flammability properties of materials. Continued development is also needed in the models used to predict fire development, particularly in their treatment of the combustion process and radiative heat transfer in enclosure fires.

In order to develop cost-effective engineering designs for fire protection, risk-based, or performance-based, analyses are needed. Performance-based approaches to fire safety design are just now emerging and are not yet comprehensive. Much of the development of performance-based approaches to fire protection has borrowed from other low-probability high-consequence hazards, such as earthquake. But it is important to recognize that fire has some significant differences when compared with extrinsic hazards such as earthquakes. Foremost among these differences is the potential for intentional fires, which renders meaningless the concept of a return period for fire (i.e., the concept of a 100-year building fire is meaningless). The interaction between fire protection design and fire magnitude is also an important difference that needs to be explored.

Developments in fire protection engineering tools are expected to be evolutionary, not revolutionary. Nonetheless, significant progress can be made with research into both deterministic fire hazard assessment and probabilistic fire risk assessment.

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LARGE-SCALE MODELING OF FIRE SUPPRESSION WITH WATER SPRAYS

Kevin McGrattan[1]

Abstract

The mechanisms underlying fire suppression by water can be divided into gas and solid phase phenomena. Numerical models of these phenomena are dependent on the level of detail given to the combustion and the fuel pyrolysis processes. Presently, models of gas phase suppression are limited by the use of simple zero or one-step combustion mechanisms in large-scale simulations. Detailed numerical models of small-scale combustion systems exist, but these models are hard to apply at room or building scale. Models of solid phase suppression are limited by the lack of well-accepted, robust pyrolysis models that have enough physical detail to accommodate the inclusion of water impingement. Several lumped parameter models of solid phase suppression by water have been developed over the past decade, but these models do not necessarily work well within a CFD model framework. The challenge to the modeler is to inject more physics into the solid phase suppression models and to simplify the physics of the gas phase to bring the two parts of the problem into the same conceptual framework.

Introduction

The problems inherent to modeling fire suppression are, not surprisingly, similar to those inherent to fire modeling in general. Indeed, the governing mechanisms can be divided into two categories – gas phase and solid phase. In the gas phase, an agent – water, CO_2, *etc.* – interacts with the fire, slowing or stopping the reaction of fuel and oxygen. The equations describing the transport and mixing of the various species are not subject to debate, and there exist fairly good numerical solvers of these equations for small-scale combustion systems. On the other hand, the solid phase phenomena, even without the introduction of the suppression agent, is not well-characterized by a set of equations accepted by the research community. Ironically, solid phase suppression phenomena are more amenable to engineering correlations in large-scale simulations, even though gas phase phenomena have a better theoretical foundation. The challenge to the modeler is to inject more physics into the solid phase suppression models and simplify the physics of the gas phase to bring the two parts of the problem into the same conceptual framework.

In the discussion to follow, we will discuss the challenges associated with modeling both gas and solid phase fire suppression by water after first discussing the often non-trivial modeling of the suppression device, *i.e.* sprinkler, fire hose, extinguisher, *etc.*, and the transport of the agent to the fire. The suppression agent of interest here is water simply because the author has more experience with it. More information about suppression of fire by water can be found in an overview article by Grant *et al.* (2000). Suppression with gaseous agents is primarily a gas phase problem, and these issues will be discussed in terms of water vapor as a suppressing agent. The detailed chemistry of suppression agents will

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not be discussed. Finally, we will include some examples of fire suppression calculations performed to date at NIST to point out the possibilities and limitations of modeling fire suppression.

Getting the Water to the Fire

Before we can discuss suppression in either the gas or solid phase, we must consider how the agent is delivered to the fire. The most common fire suppression technique is via a water spray, either from a fire hose or an automatic sprinkler system. An entire industry is built around designing, installing and maintaining sprinkler systems in buildings. A good design requires that the sprinklers activate in a timely manner and deliver water to the fire in sufficient quantities to at least control its spread. Numerical models are used in the design process to predict activation times, and to a limited extent the subsequent suppression of the fire by the water droplets. Predicting activation is the least difficult part of the problem, followed by the calculation of the water spray, followed by the suppression of the fire. In the discussion to follow, we will follow these different steps.

Sprinkler Activation

The temperature of the sensing element of a given sprinkler is estimated from the differential equation put forth by Heskestad and Bill (1988) at Factory Mutual

$$\frac{dT_l}{dt} = \frac{\sqrt{u}}{\mathrm{RTI}}(T_g - T_l) - \frac{C}{\mathrm{RTI}}(T_l - T_m) \tag{1}$$

Here T_l is the temperature of the thermally-sensitive mechanism (link), T_g is the gas temperature in the neighborhood of the link, T_m is the temperature of the sprinkler mount (assumed ambient), and u is the gas speed flowing past the link. The sprinkler is assumed to activate when the link temperature reaches a prescribed value. The sensitivity of the detector is characterized by the value of the Response Time Index (RTI), a roughly constant parameter for a given sprinkler which is a measure of the link's thermal capacity divided by the heat transfer efficiency between the hot gases and the link.

$$\frac{\mathrm{RTI}}{\sqrt{u}} = \frac{\rho_l \, c_l \, V_l}{hA} \tag{2}$$

The amount of heat conducted away from the link by the mount is indicated by the "C-Factor", C. Both are empirically determined from a test device in which a sprinkler is quickly "plunged" into a small, hot wind tunnel. Recently, Ruffino and di Marzo (2001) have provided an additional heat sink to the equation due to small water droplets from other activated sprinklers. The term is proportional to the mass flux of water in the neighborhood of the sprinkler, and the proportionality constant has been found to be relatively constant for different types of sprinklers.

This activation model for a sprinkler is widely used in the fire protection community in both CFD and lumped parameter ("zone") models. Given the variety of sprinkler designs, it provides a relatively simple model whose accuracy is comparable or better to the governing flow calculation. Except for the addition of source and sink terms, like the water droplets or radiation heat flux, it is not anticipated that a better model will be developed in the next decade.

Sprinkler Spray Characterization

Sprinkler spray characterization will remain largely empirically-based because each sprinkler has its own unique design that makes predicting the initial water spray difficult. To simulate the sprinkler spray, we need to know the initial distribution of the droplet size and velocity. Measuring these quantities has proven to be very difficult and still very expensive. The most promising technique for measuring droplet size is through Phase Doppler Interferometry (PDI) (Widmann, 2001); and droplet velocity through Particle Image Velocimetry (PIV) (Sheppard, 2001) Both are non-intrusive, laser-based techniques that require very expensive equipment and skilled technicians with a high level of training in laser diagnostics. This is worrisome because calculations of this type should be cheaper than experiments. If high level modeling of challenging industrial fire scenarios becomes more routine and starts to show potential benefits to sprinkler manufacturers and building owners, there ought to be more investment in the measurement techniques required for input data. The Catch-22 is that it is hard to show benefits with little information about the various sprinkler designs and fuels.

Water Droplet Transport, Heat and Mass Transfer

Once the initial distribution of water droplet size and velocity distributions have been provided, the transport of the droplets through the hot, smoke-filled gases and the exchange of mass and energy between the droplets and the gas can be handled using fairly well-accepted correlations found in most any heat transfer text book. The droplets are treated in a Lagrangian fashion, where a single computed droplet will represent many more actual droplets. This approach has been called the “superdrop” concept (Kumar *et al.*, 1997). Again, one may argue that any of the half-dozen different empirical relations is too simplistic, and in response the modeler can systematically refine the treatment of the droplets. However, a point of diminishing returns will soon be met because uncertainties associated with the suppression of the fire will far out-weigh those associated with the tracking and evaporation of largely spherical water droplets. Indeed, one of the biggest challenges in modeling a sprinkler spray is not the flight of the droplet through the hot gas, but rather the pooling, dripping and absorption of the water onto and into a complicated pile of burning and non-burning commodity. Indeed, the goal of many sprinkler systems is not necessarily to extinguish the fire but rather to control it and stop its spread. What happens to the water on non-burning surfaces is thus equally important to what happens to it on burning surfaces. Moreover, burning objects rarely maintain their original shape and consistency, and trying to model every aspect of the process is an exercise in futility.

Solid Phase Suppression

The fundamental physics and empirical relations describing the heat transfer between a droplet of water and hot gas are fairly well-accepted and reasonably easy to apply in a

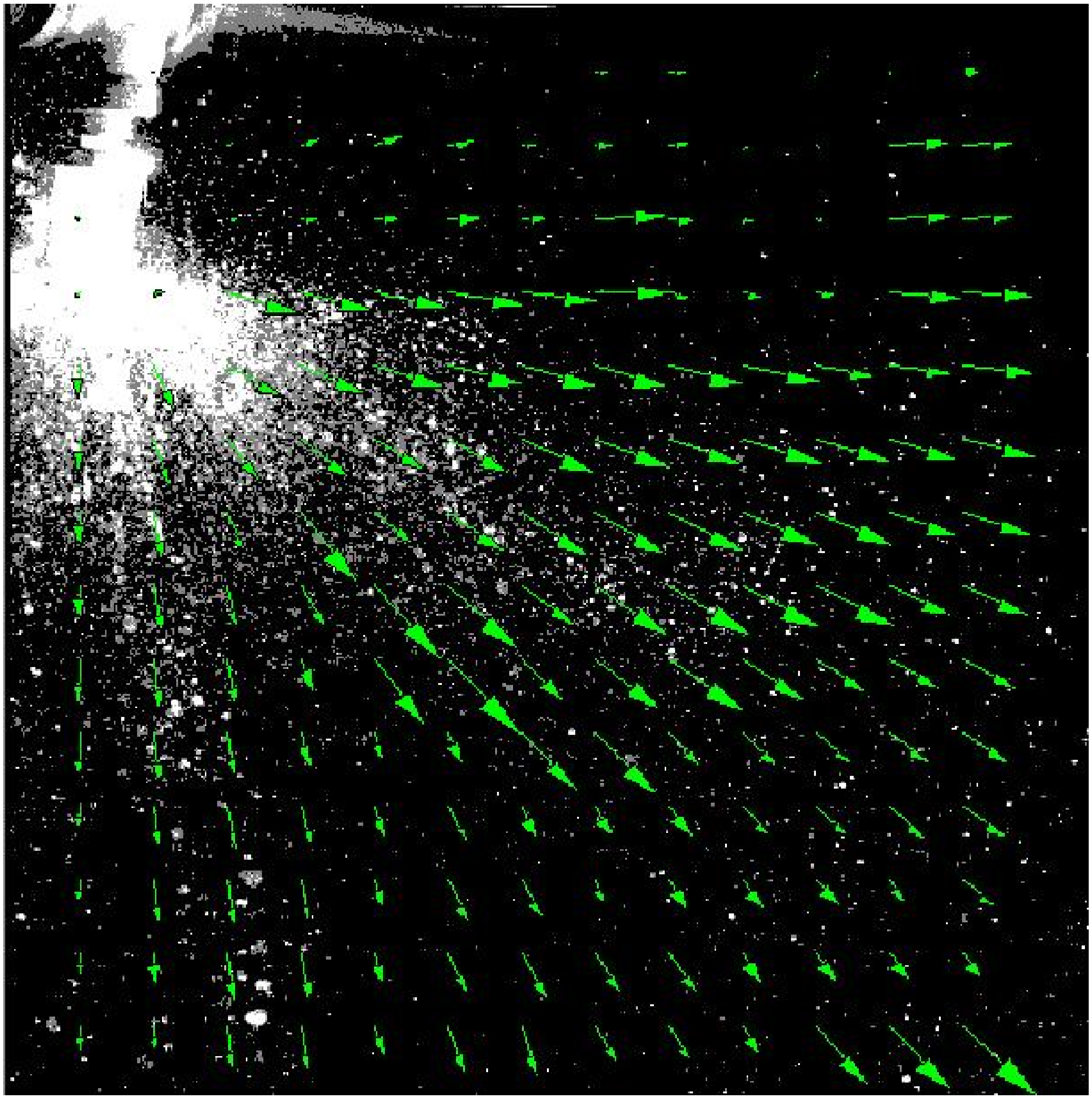

FIGURE 1: PIV image of a pendant sprinkler, showing the velocity vectors of the droplets. Reprinted courtesy of David Sheppard, Underwriters Laboratories and Richard Lueptow, Northwestern University.

numerical model. However, when the water droplets encounter burning surfaces, simple heat transfer correlations become more difficult to apply. The reason for this is that the water is not only cooling the surface and the surrounding gas, but it is also changing the pyrolysis rate of the burning fuel. If the surface of the fuel is planar, it is possible to characterize the decrease in the pyrolysis rate as a function of the decrease in the total heat feedback to the surface. Unfortunately, most fuels of interest in fire applications are multi-component solids with complex geometry at scales unresolvable by the computational grid.

To date, a significant amount of work in developing engineering models to describe the decrease in burning rate by water application has been performed at Factory Mutual. An important paper on the subject is by Yu *et al.* (1994). The authors consider dozens of rack storage commodity fires of different geometries and water application rates, and characterize the suppression rates in terms of a few global parameters. Their analysis is based on energy balances at the fuel surface, and it yields an expression for the total heat release rate from a rack storage fire after sprinkler activation

$$\dot{Q} = \dot{Q}_0 \, e^{-k(t-t_0)} \tag{3}$$

where $\dot{Q}_0$ is the total heat release rate at the time of application t_0, and k is a fuel-dependent (usually linear) function of the water application rate. The exponential nature of the decrease in heat release rate has been observed in a wide variety of fire tests. It is not surprising that there is an exponential relationship since the fuel pyrolysis rate is tied to the heat fed back from the fire.

Unfortunately, this type of analysis is based on global water flow and burning rates. Equation (3) accounts for both the cooling of non-burning surfaces as well as the decrease in heat release rate of burning surfaces. In a CFD model, the cooling of unburned surfaces and the reduction in the heat release rate are computed locally and separately, thus it is awkward to apply a global suppression rule. However, the exponential nature of suppression by water is observed both locally and globally, thus it can be assumed that the local burning rate of the fuel can be expressed in the form (Hamins, 1999)

$$\dot{m}''_f(t) = \dot{m}''_{f,0}(t) \, e^{-\int k(t)\, dt} \tag{4}$$

Here $\dot{m}''_{f,0}(t)$ is the burning rate per unit area of the fuel when no water is applied and $k(t)$ is a linear function of the local water mass per unit area, m''_w, expressed in units of kg/m^2,

$$k(t) = a \, m''_w(t) \quad \mathrm{s}^{-1} \tag{5}$$

Note that a is an empirical constant.

Understanding how various standard commodities burn and how they respond to water ought to be less empirically-based. Solid phase pyrolysis models need to be developed that retain enough of the fundamental physics to accommodate a better description of suppression, yet that are consistent with the assumptions and limitations of a large-scale simulation. A strategy for doing this is to apply current CFD techniques to model relatively small-scale standard test apparatus, and eventually move to larger scale. It is unclear how to describe the burning of real commodities, which are mixtures of cardboard, plastics, woods, *etc.*, other than with the simple lumped parameter models developed to date. It is hoped that at a minimum, we will have a way of relating the burning rate of the fuel to the heat feedback to the surface based on the thermo-physical properties of the fuel rather than simply an exhaustive series of experiments that are often too expensive to perform given the wide variety of fuels burning in a single fire. This is possible now with a limited number of pure fuels, liquids especially, but hopefully this list can be extended in the future.

Gas Phase Suppression

Most large-scale fire models track fuel and oxygen, and the major products of combustion, via a single mixture fraction variable or by way of multiple transport equations for the individual species. Because the flame cannot be resolved on grids whose cells are on the order of tens of centimeters, empirical rules must be used to ascertain the chemical heat release rate. Often the burning rate is closely tied to the parameters used to model the subgrid scale turbulence. In the case of a mixture fraction approach, it is assumed that fuel and oxygen burn instantaneously when mixed. Regardless of the combustion model, in cases of large-scale, well-ventilated fires, the various models work in a reasonable way in the sense that the fuel is consumed and the energy is distributed onto the computational grid. However, if a fire is in an under-ventilated compartment, or if a suppression agent like water mist or CO_2 is introduced, fuel and oxygen may mix but may not burn. The physical mechanisms underlying the phenomena are complex, and all the simplified models suffer from an imprecise estimation of the temperature and local strain rate in the neighborhood of the flame sheet. A good overview of the physical mechanisms behind water mist suppression is given by Mawhinney *et al.* (1994).

Sub-grid scale modeling of gas phase suppression and extinction is still an area of active research in the combustion community. Until reliable models can be developed for building-scale fire simulations, simple empirical rules can be devised that prevent burning from taking place when the atmosphere immediately surrounding the fire cannot sustain the combustion. In such a model, a single set of state relations can no longer be applied, since now some fuel may be mixed with the other combustion products. To account for the deviation from the ideal state relations, at least one other scalar quantity in addition to the mixture fraction would have to be tracked in the calculation. This increases the cost of the calculation, but may provide enough information to make reasonable assessments of the affect of the water vapor on combustion.

Examples

Following are two examples of calculations performed at NIST with the Fire Dynamics Simulator (FDS), a CFD model that uses large eddy simulation techniques to model fire (McGrattan *et al.*, 2001). The first example looks at the performance of a sprinkler system in a large warehouse. The issues here are the activation of the sprinklers, the trajectory of the water droplets, and the suppression of the fire that consumes box loads of commodities stored on steel racks. Suppression is achieved mainly through direct contact between the water and the burning surfaces. The second example looks at the suppression of a large heptane spray fire within a mock-up of a shipboard machinery space. Mist nozzles are used to flood the entire compartment volume with very fine water droplets. The rapid evaporation of the droplets cools the hot gases and displaces the available oxygen within the compartment. Here suppression is almost all gas phase.

Rack Storage Fires

A few years ago, in parallel with large scale tests conducted by the NFPA Research Foundation, computer fire models were used to predict the outcome of fire suppression tests in mock-ups of large warehouses and warehouse retail stores (McGrattan, 1999) (Figure 2). A series of bench scale experiments was conducted at NIST to develop necessary input data for the model. These experiments generated data describing the burning rate and flame spread behavior of the cartoned plastic commodity, thermal response parameters and spray pattern of the sprinkler, and the effect of the water spray on the commodity selected for the tests (Hamins, 1999). It was found that the outcome of the large-scale calculations was very sensitive to these inputs, especially the thermal properties of the commodity. In addition, predicting the spread of the water over and between the pile of boxes was very difficult, nullifying any gain in accuracy achieved by the bench-scale tests.

What made the model work reasonably well was the fact that the water spray and “dripping” behavior parameters were tweaked until a match between computed and observed water density patterns on the floor was obtained. Hundreds of hours were needed to roughly characterize one fuel and one sprinkler because the characterization was almost all empirical – little of it was based on fundamental physical models because the phenomena were so very complex. As a result, users of the FDS model were not able to apply it easily to other commodities and sprinklers; a problem that persists to this day.

Water Mist

A more complex example of the new algorithm is shown in Fig. 4. Here a mist sprinkler system is installed in a simplified machinery space whose dimensions are 16 m by 10 m by 8 m. The 6 MW fire is fueled by a series of heptane spray burners lined along the top of a steel box centered in the compartment. Eight mist nozzles are positioned at the ceiling, 4 m apart. Four nozzles are positioned above the 2 m by 2 m opening centered along the longer wall, 0.5 m above the floor. The nozzles are activated a short time after the ignition of the fuel burners. The small water droplets evaporate due to both the high temperatures in the upper smoke layer, and the absorption of thermal radiation from the fire. The water vapor displaces oxygen and the water evaporation cools the compartment, both of which weaken the fire. The numerical algorithm appears to handle the evaporation and transport of the water vapor, but a problem remains in predicting the change in burning behavior. Presently, the FDS contains a mixture fraction combustion model that assumes an infinitely fast reaction between fuel and oxygen regardless of temperature. Dilution of the air by smoke, exhaust gases and water vapor is predicted in the model, but the unburned fuel due to a lack of oxygen eventually burns somewhere in the compartment, even though the lower temperature in reality would not sustain this burning. Thus, the focus of attention needs to be turned back towards the combustion routine so that the suppression of the fire in an underventilated space can be handled better. Even in the absence of a sprinkler system, there is a need to better understand the weakening of a fire in an underventilated

FIGURE 2: Photograph of a rack storage fire, courtesy Underwriters Laboratories, Northbrook, IL.

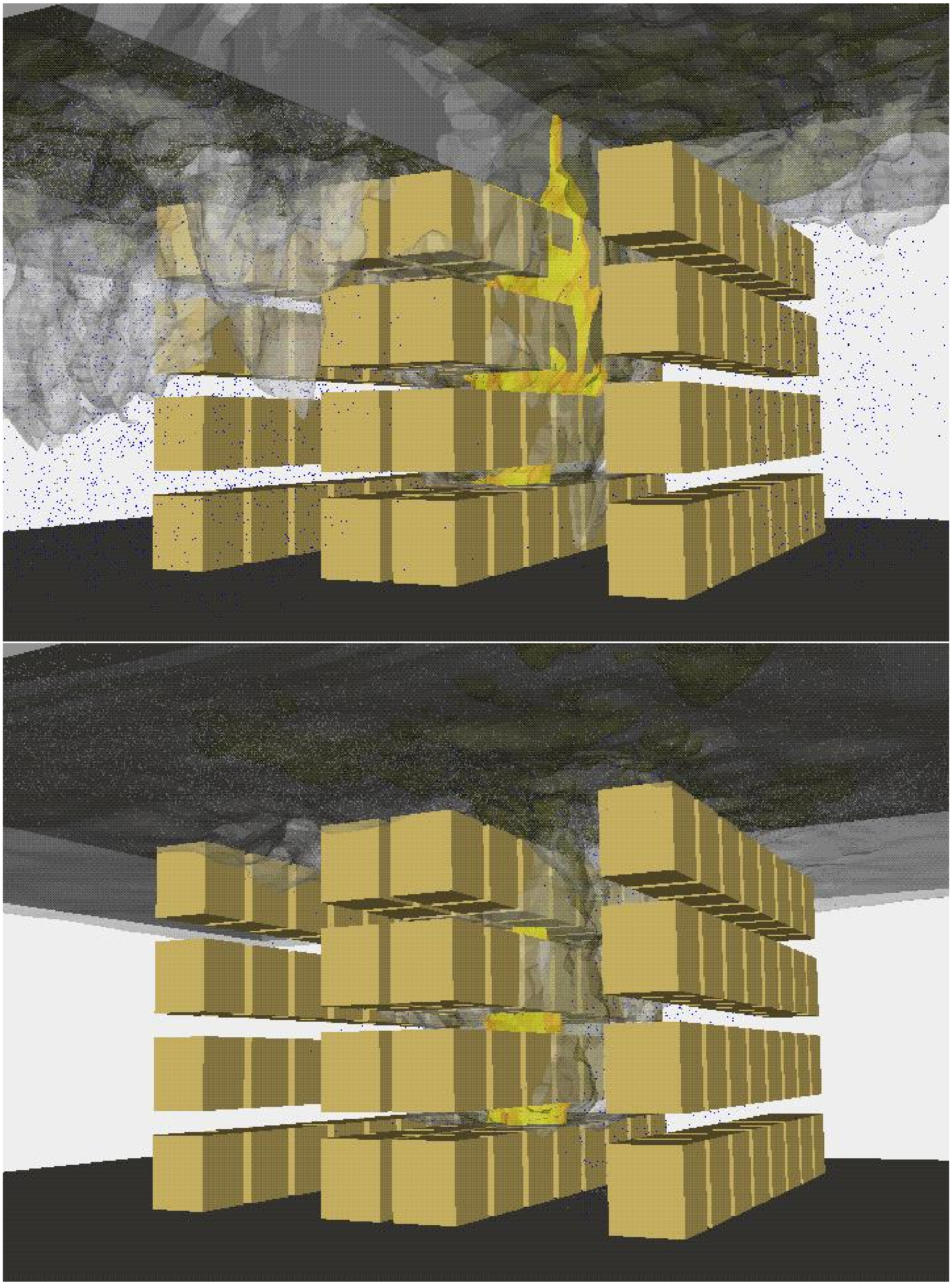

FIGURE 3: Snapshots of two simulations of a rack storage fire. In the top picture, the fire is ignited beneath a draft curtain, which interferes with the sprinkler activation. In the bottom picture, no draft curtains are present.

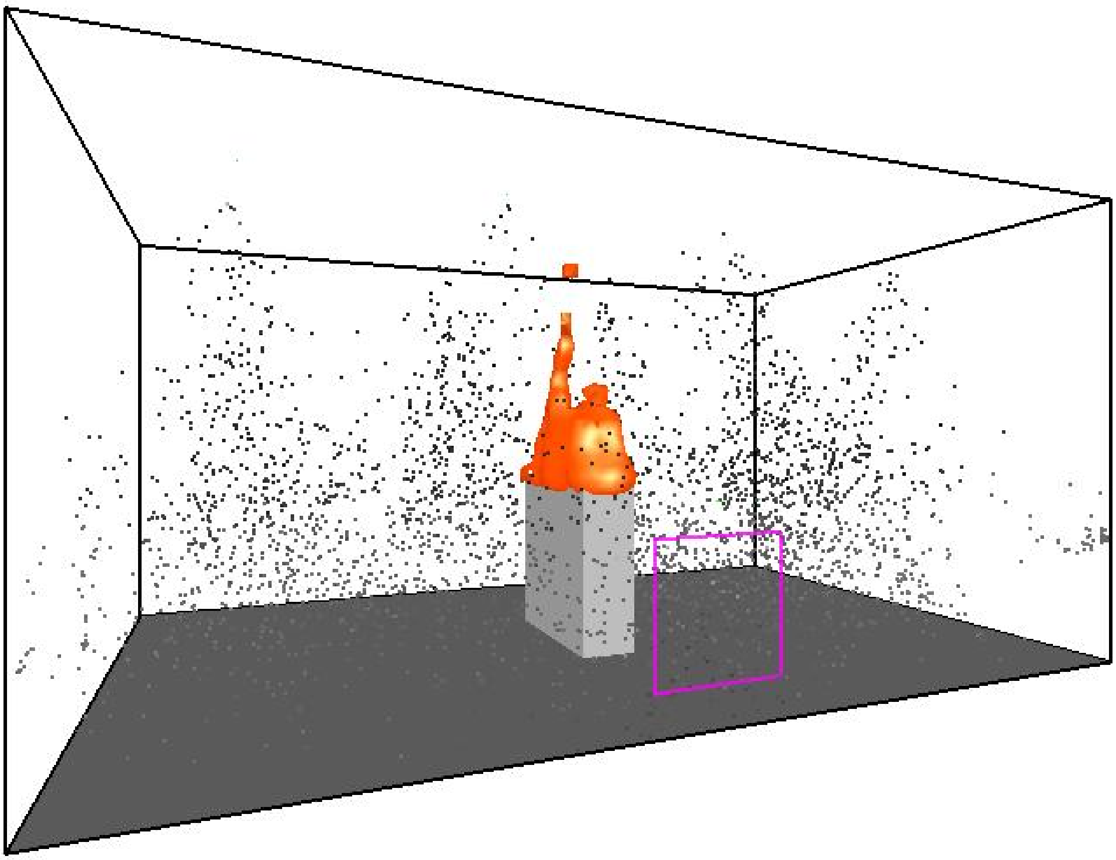

FIGURE 4: Simulation of a mist system suppressing a large heptane spray burner fire. Shown is the outline of the flame and the water droplets.

compartment.

Conclusions

Relatively crude water suppression sub-models have been incorporated into various CFD-based fire models over the past decade. Thus far, the models can be used for qualitative analysis of sprinkler and mist suppression systems. In some cases, it is possible to carefully select the necessary parameters to match the results of actual large-scale tests, then use the model to simulate similar large-scale tests that cannot be performed because of cost. As research in this area continues, it is inevitable that some physical features of the problem will receive a more detailed treatment than others. The challenge to modelers is to develop the various physical sub-models at the same pace, so that no one part of the problem outpaces another. The degree of accuracy of the overall model is determined by its weakest element. Maintaining a consistent level of accuracy is difficult in an academic environment because of the highly specialized nature of most university endeavors. Consider the chemical kineticist, the fluid dynamicist, the material scientist all being told that what they are doing is not of use in a particular fire model, not because it is bad research, but rather that it is inconsistent with the overall level of accuracy in the model. Of course, eventually these detailed mechanisms may be of use, but when? To get to that point, the models that have been developed to date have to be used for both research and practical problems. CFD still remains out of reach for many because of cost, limited computer power, difficulty of use. Getting beyond this obstacle means making CFD models run faster, cheaper and easier. Simply making the computer program run is not always easy, and it takes time and a critical mass of users to iron out numerical bugs even before the real problems inherent to the limitations of the sub-models can be addressed. Once one gains experience with a given model, the research needs will become clearer because the limitations of the model will be understood in terms of a concrete application.

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UNDERSTANDING HUMAN BEHAVIOUR IN STRESSFUL SITUATIONS

Guylène Proulx, Ph.D.[1]

ABSTRACT

The events of September 11, 2001 have shocked the public imagination regarding the safety of highrise buildings. Prior to these events, the reluctance to evacuate upon hearing the fire alarm signal was regularly observed in highrise buildings. Following the tragic events of September 11, many highrises were totally evacuated on minimal cues. The perception of risk seems to have been heightened right after the event but will this condition last over time? Highrise buildings are seldom meant to be totally evacuated. The strategy used instead is phased evacuation or a protect-in-place approach. Today during an emergency, are highrise building occupants prepared to stay in and wait to be instructed before leaving the building? Studies should investigate the risk perceived by highrise building occupants since September 11 and how these perceptions might change over time. Further studies should compare highrise occupant intention of response during an emergency and actual response through unannounced drills. Authorities, architects and engineers need these findings in order to appropriately design buildings, fire safety systems, training materials and instructions provided to occupants during an emergency.

Background

The content of this paper was greatly inspired by discussions with different colleagues, particularly with Drs. Rita Fahy, Brian Meacham and Jim Flynn. In partnership with these scientists, a study proposal was submitted in December 2001 for a Small Grant for Exploratory Research Proposal to the National Science Foundation (Fahy et al., 2001). Although the proposal was unsuccessful at the time, the questions and variables tackled are still of the utmost importance for the future of fire safety in highrise structures. Consequently, these issues are reiterated here in a different format.

Highrise Evacuation

The events of September 11, 2001 and particularly the World Trade Center towers attack, fire and subsequent collapse have had a significant impact on the public perception of risk and safety in highrise buildings. In the days following these events a large number of highrise buildings were totally evacuated on minimal cues, in some cases a simple rumor was sufficient to vacate thousands of office workers to the street. This heightened state of perceived risk could not last forever, people would not be able to function under such a high level of stress (Seyle, 1979). However, the question remains: are there some

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lasting effects that could influence occupant response during a future emergency? If such effects exist how do they impact fire safety engineering and will this affect change over time?

It is important to understand that modern highrise buildings which are over 25-storeys in building height are seldom meant to be fully evacuated in the event of a fire. The evacuation strategy in such highrises is usually to instruct building occupants through a voice communication system to remain in place while the emergency is dealt with, whereas a phased evacuation or relocation of occupants is carried out. In a phased evacuation the occupants closest to the fire are evacuated or moved to other floors first, while floors above the fire floor evacuated successively upon receiving instruction. Occupants on some floors, particularly under the fire floor, may not need to evacuate at all and might essentially protect-in-place.

In the September 11 incident, many occupants of the South Tower began to leave the building, on their own, right after the first plane struck the North Tower. For the survivors from the uppermost floors of the South Tower, this decision saved their lives since, later on, a plane hit their floors. This is particularly important in light of reports that occupants of the South Tower were told, through the voice communication system, that because the incident was contained to the North Tower, they did not need to evacuate and it was safe to stay or return to their desks. Although this instruction may have been appropriate at the time it was issued, many occupants who followed the instruction could well be among the victims. After the second plane struck, and after the two towers collapsed, many members of the public have been left with the impression and mistaken belief that the instructions given to the building occupants were erroneous. Many people have also taken from the events of the day a new expectation that the collapse of a highrise building may be inevitable during any fire, failing to appreciate the extreme differences between a “typical” highrise fire and one caused by a large aircraft loaded with fuel.

The events of September 11, which received unprecedented and sustained media coverage, may have changed the public perception of risk in highrise buildings (Finucane, 1999). People who work or live in highrise structures may be fearful that a similar attack will be made on their building or that a fire could bring the structure to collapse. If people have developed a new attitude toward safety in highrise buildings, their response in case of an emergency might be different from what could be expected prior to September 11. The design of buildings, fire safety features and fire safety plans might need to be modified to accommodate the new attitude of highrise building occupants.

Behaviour in Stressful Situations

It is recognized that every person involved in an emergency will feel some form of stress regardless of their age, gender, past experience, training or cultural background. This stress is not an abnormal reaction; on the contrary, stress is regarded as a necessary state to motivate reaction and action (Seyle, 1979). The performance of the person in dealing with a stressful situation will depend on the task demands, the environmental conditions and the subject himself or herself (Wesnes & Warburton, 1983). In order to make a decision the person will process information, perceived in the environment or drawn from past experience (Janis & Mann, 1977).

Decision-making during an emergency is different from day-to-day decision-making for three main reasons. First, there is much more at stake in emergency decisions - often the survival of the person and of the people he or she values the most is at play. Second, the amount of time available is limited to make a decision before crucial options are lost. Third, the information on which to base a decision is ambiguous, incomplete and unusual, further it is usually impossible to look for more appropriate information due to the lack of both time and means to get information (Proulx, 1993).

During a fire, the nature of the information obtained, the limited time to react and the assessment of danger will create a feeling of stress. It is argued that this stress will be felt from the moment ambiguous information is perceived until well after the event when the person has reached safety (Lazarus & Folkman, 1984). During the course of the event, the intensity of stress experienced will vary as a function of the information newly-perceived and the assessment of the decision taken. The media and public in general often mentioned the potential of mass panic, imagining a crowd that suddenly wants to flee danger at all cost, even if it implies getting trampled or crushed in the process. Although these types of behaviour are extremely rare in fires and have never been reported in highrise fires, the expectation that people will panic is very strong. This schemata is very much nourished by the media and movie industry who like to play on strong emotional images. In fact, 'panic' in the form of irrational behaviour is rare during fires and researchers have long ago rejected this concept to explain human behaviour in fire. From around 200 accounts of the World Trade Center survivors published in the media, panic was seldom mentioned instead many emphasized the calm and altruistic behaviour of the evacuees.

The expectation of 'panic' has been a favored argument put forward to delay warning of the public during emergencies (Sime, 1980). Such delays in informing the occupants have contributed to subsequent flight behaviour and crush of people who had only a few seconds left to react and escape once the situation unexpectedly got out of hand. Consequently, researchers are pleading for early warning to the public, providing occupants with as much information as possible to support them in their decision making process (Donald & Canter, 1990; Proulx & Sime, 1991).

The reality of human behaviour in highrise building fires is somewhat different from the 'panic' scenario. What is regularly observed is a lethargic response to the fire alarm, voice communication instruction or even the initial cues of a fire (Proulx, 1999). Unless very well trained, occupants are usually reluctant to leave their floor and are prepared to stay on location. Phased evacuation or a protect-in-place approach are seen as less disruptive by occupants. Staying on location during actual fires is sometime the official fire safety plan (Proulx, 1998) or the chosen response by occupants (Proulx, 1996).

In modern highrise buildings over 25-storeys in building height, it is neither practical nor feasible to conduct full evacuation of the building. Not all occupants have the capacity to travel down so many floors. Further, in order to obtain reasonable evacuation times, wider or multiple means of egress would be necessary which would make the building economically non-viable. Therefore, the buildings and fire safety features are designed to allow occupants to stay on location or to evacuate in sequential order.

If people believe they are not safe in highrise buildings and choose not to comply with fire safety instructions telling them to evacuate only when directed, the risk to all occupants of the building could increase tremendously due to injuries associated with uncontrolled egress. For people living and working in highrise buildings, how they perceived their risks, process information, and make decisions for their safety will impact on how engineers should design buildings and safety systems.

Safety systems in buildings have to account for what can realistically be expected from people in emergency situations. For example, if it is known that it takes on the order of 2 or 3 minutes for people to leave their apartments in a highrise tower, it would be inappropriate to make assumptions that people will leave within seconds. Likewise, if it is known in highrise buildings that all people will leave on every floor at once instead of a few floors at a time, the ratio of egress capacity to egress time will change, and building design will need to accommodate this response. If the events of September 11 have affected people's confidence in the structural integrity of highrise buildings, it is possible that they will not remain in place for phased evacuation, no matter what they are told, and the impact could be significant.

Research Needed

There are 5 dimensions needing immediate attention regarding human behaviour in a highrise building fire. This research should focus on the impact of the attack, fire and collapse of the World Trade Center towers have had on issues of risk perception, communication, and trust in the information given for occupants of highrise buildings.

1. Study how perception of risk in highrise buildings has changed since September 11, 2001.
2. Explore the impact of highrise risk perception on intended behaviour in future emergencies.
3. Observe unannounced emergency evacuations in highrise buildings varying evacuation strategy and information provided to occupants to access actual response.
4. Compare actual evacuation behaviour with intended behaviour.
5. Conduct longitudinal studies to assess the impact of September 11 over time.

This research effort could involve developing and conducting surveys of highrise occupants, planning and monitoring emergency evacuations, conducting post-evacuation surveys and post fire surveys.

Conclusion

To understand the implications of September 11, it is necessary to investigate the actual occupant perception of risk in highrise buildings and how people intend to react during an emergency while assessing how these factors might change over time.

To conduct such studies, appropriate funding is required. There is still this myth out there that social science is easy and shouldn’t cost as much as applied sciences. Research into human behaviour is certainly not easy and tends to be lengthy and costly. Funds should be readily available to start investigation immediately after fires.

Authorities, architects and engineers need these findings in order to appropriately design highrise buildings, fire safety systems, training materials and instructions provided to occupants during an emergency. The way highrise buildings are designed today, may very well change in light of the events of September 11. If occupants are no longer prepared to comply with the procedure elaborated in the fire safety plan, important changes will be necessary in existing and future highrise buildings to prevent major disasters.

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HUMAN FACTORS CONTRIBUTIONS TO BUILDING EVACUATION RESEARCH AND SYSTEMS DESIGN: OPPORTUNITIES AND OBSTACLES

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Abstract

Human factors research and design methods provide data collection and analysis methods relevant to a wide-range of evacuation research questions, from higher-order cognitive processes to basic design issues such as egress widths. Research questions include the discovery of human goals and the cognitive demands imposed by their pursuit, the achievement of situational awareness and its influence on decision making processes, cooperation among people with different roles, and the inclusion of adaptive human agents in the design of performance-based fire safety systems. However, many obstacles are evident, the foremost of which is the lack of funding directed towards research into the human factors fire safety systems. Other difficulties include the over reliance on codes and standards and the lack of user-centered design curriculum for fire safety researchers, engineers, and practitioners.

Introduction

The field of human factors (alternatively called “ergonomics”) has contributed to solving many design challenges where people interact with technological systems. The human factors field has a remarkable record of contributions to other engineering fields—including aviation and military systems, computer-human interactions, and workplace safety. The potential for cost-effective innovation is great, especially in view of the large stock of existing buildings. The field of human factors can yield designs that better support the actions and decisions that enable safety systems adapt to chaotic events that play out in unforeseeable ways.

The National Research Council recognized the importance of the field by organizing a standing committee on human factors in 1980. “Ample evidence exists—from aviation accident reports to job task analysis—documenting the importance of investing in human factors and the sometimes tragic results of failing to consider its contributions.” (Rouse, et al., 1997)

Advantages of user-centered system design

We maintain that the fire safety community needs to broaden its view of what constitutes a fire safety system where the actions of people largely determine successful outcomes. In our view, a fire safety system is comprised of *all* relevant components, *including* people, that play significant roles in mitigating the effects of fire. (Groner, 2001). Everything that can support the goals of an evacuation should be the concern of the systems’ designers—including procedures and training.

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Systems-centered approaches traditionally used by fire protection engineers are ill suited to designing systems that take full advantage of human as well as technological agents. “Traditional system-centered design treats users as just another resource to be assigned and optimized to meet operational goals” (Stanney, et. al, 1997; p. 639) However, favorable outcomes from building evacuations necessarily depend on the actions taken by people, and people are not mechanical systems components that dependably react with assigned predetermined responses. Instead, people select and process information that helps them pursue their goals of adapting to stressful, ambiguous, and dynamic situations. To account adequately for the goal-seeking information-processing reality of human behavior, we believe fire protection engineers should understand how and when to change from systems-centered design to user-centered design. “User-centered design…considers users’ roles and responsibilities as the key design objective to be met and supported by advancing technologies.” (Stanney, et. al, 1997; p. 639)

Example: Alarm signals

Non-vocal alarm signals provide an example of the limitations of systems-oriented design. If people were “just a resource…to meet operational goals,” alarm signals would evoke the assigned responses from building occupants. However, from a user-centered perspective, alarm signals provide little information on which to base human responses. There is no information about the likelihood that the threat is real, its location and severity, and the viability of response options. From a user-centered perspective, poor responses are to be expected. From the user-centered perspective, the designer is responsible for building a system that provides information sufficient for people to choose a reasonable course of action. Human factors provides the research and design tools that can guide this expanded view of systems design.

Research questions addressable using human factors engineering approach

To help explain the potential for designing fire safety systems from a user-centered perspective, the following section presents a few research questions concerning building evacuations, along with speculation how human factors professionals approach the problems.

How can we discover what goals people pursue during evacuations, along with the relevant physical and social features of their environments that influence their actions?

The behaviors of people are responses to the situations in which they find themselves. It follows that systems design should take into account people’s understandings of social and physical attributes of the situations in which they are likely to find themselves. Many human factors professionals use “contextual inquiries” to obtain relevant data, and to consolidate it into “work models” that describe informational flows, the use of artifacts, constraints imposed by social roles and the physical environment, etc. (Beyer and Holtzblatt 1998).

Example: Deference Behavior in Evacuations

Methods adapted from contextual inquiries can be applied to the understanding of deference behavior exhibited by people using stairways in high-rise office buildings. Based on evacuation drill observations by Pauls and Jones (1980), evacuees coming down an exit stairwell tend to defer their progress to people entering the stairwell from a lower floor. Deference behaviors imperil people on higher floors who have a more-urgent need to evacuate than do those on lower floors. Do people believe they are relatively safe in the stairwell and people entering need the same security? Do they believe that people from lower floors take precedence in getting out? Do people automatically apply tendencies to be "polite"? We need to understand why this occurs to design systems that will reliably hold some people back so that those most endangered have priority access to the exits.

How can we research the cognitive demands imposed by pursuing goals in emergencies situations?

In understanding how we can research and design systems that support building evacuations, human factors professionals commonly rely on cognitive task analyses to develop systems requirements (Schraagen 2000). A conventional task analysis describes the steps required to accomplish a goal, producing a standard operating procedure to be applied *without variation* in response to a defined scenario. However, given the stressful, chaotic, and ambiguous situations generated by real emergencies, the importance of cognitive demands imposed by tasks is transparently important. Cognitive task analyses are used to understand how expectations, perception, memory, mental models, and decision-making influence human performance in responding to building emergencies.

Example: finding safe routes of egress

Cognitive task analyses can provide insights into how systems designers support the real goals of people during an evacuation. For example, Groner (1998) discussed the use of smoke detection systems to inform building occupants about which routes of egress are tenable. Similarly, simple devices can inform persons in residential units whether it is safe to leave doors in a more effective manner than the problematic process of feeling the door for heat.

How can we build models that integrate human performance and physical engineering representations into overall systems views of building evacuations?

Ideally, Performance-based design solutions would reflect an integrated systems understanding that includes how people adapt to achieve desirable systems goals. Deterministic probabilistic representations that model the probabilities of events are inherently limited, because they can only model fixed responses to defined scenarios (Groner, 1999). However, in the real world, emergencies are started and play out in unpredictable ways.

Example: Integrated systems representations of building evacuations.

Groner and Williamson (1997, 1998) have investigated the use of desirable system states to model systems that integrate physical engineering and human behavioral responses to emergencies. Other human factors professionals have examined similar problems in other contexts. These types of representations are needed to optimize the allocation of functions between human and manufactured agents. (Sharit, 1997)

What factors enhance and inhibit the achievement of situational awareness?

Situational awareness refers to the person's perception of context, especially as regards to how the environment helps or hinders them in their pursuit of goals. An important part of situation awareness concerns a person's ability to project how the environment will change in the future. In a fire emergency, mistakes can be avoided by achieving good situational awareness.

Example: When to direct people to leave a residential high-rise building.

Incident commanders need to achieve good situational awareness to know when and where to order building occupants to evacuate or relocate. Proulx (2001) discussed an incident where an evacuation was ordered after exits stairs were no longer tenable, injuring people and forcing many to abandon their evacuations and seek refuge. Investigations of the factors that facilitate and interfere with incident managers' understanding of situations would help systems designers support this crucial decision.

What factors impact the quality of cooperation among building emergency teams, management, operational engineers, and emergency responders?

Building evacuations involve complex and dynamic relations among people in many roles. A significant body of research has revealed that social roles are important during responses to fire emergency. The extent to which these people can successfully collaborate is important to achieving good situational awareness and finding a viable response. Social roles can facilitate or interfere with these crucial tasks.

Example: How to do social roles affect what information is used in achieving situational awareness of incident managers?

Human factors professionals have been making progress in their understanding of how systems design can improve the effectiveness of inter- and intra-team cooperation (McNeese, et al 2001). For example, Cockpit Resource Management concerns the cooperative work of aviation flight crews (Wiener, et al. 1993), and provides a useful model for research that can reveal problems and suggest solutions in the role relations among building emergency teams, managers and operating engineers, tenants, and emergency responders.

How do people really make decisions and how can training, procedures, and technology be used to support them?

Naturalistic decision-making refers to the process of how people decide of courses of action in real world settings. Klein (1989) observed firefighters to discover that decision-makers did not consider the value and probabilities associated with alternative courses of action. Instead, they try to achieve a fit between the perceived situation and their memory store of mental schema. Accordingly, good situational awareness results from the availability of schema that match well to situational features. An example of current salience is the development and use of expert schemas that can help incident commanders predict progressive building collapses.

Example: Video Monitoring of Egress Activity in Exit Stairwells

Pauls (1994) proposed the use of video monitoring of exit stairwells as a means to improve decision-making during building evacuations. Video cameras in the exit stairwells, especially at the exit discharge area, can potentially help incident managers to adjust the numbers of people using particular stairwells, assess interference between descending evacuees and ascending emergency responders, etc. Human factors research is needed to understand how to design video systems that enhance decision making rather than adding to an overload of information.

Obstacles to the Use of Human Factors in the Design of Building Evacuation Systems

More than anything, research into the intersection between human factors and fire safety needs funding. For a decade or so, starting in the mid-1970's, the National Institute of Standards and Technology funded seminal research into human behavior and fire that yielded important insights. For example, "panic" was once believed to be prevalent during fire emergencies. We now know that altruism is common during emergency evacuations, and that people spontaneously form "convergence clusters." We also know that prior role behaviors carry over to emergencies, that people persist in their tasks even when confronted with seemingly obvious signs of danger, and that ambiguous information leads to confusion and mistakes. (For a review of fire-related human behavior research, including a focus on evacuation, see Pauls, 1999.)

Even while funding for research into human behaviors and fires diminished, the field of human factors made notable advances. We believe that adequate funding of research on human factors related to evacuations will yield insights that can significantly improve the design of fire safety systems.

We are failing to conduct timely research about human and organizational factors during emergency building evacuations. The 9/11 World Trade Center evacuations are only the most recent and salient examples. During these evacuations, we do not know whether deference behavior was common, the evacuees' reasons for their decisions, how well building emergency teams and professional responders worked together, whether people anticipated the impending structural collapse, the role of changes made subsequent to the 1993 bombing—the list is too long to complete here.

We need funding to support the technology transfer of human factors methodologies to better understand and design fire safety systems. The video monitoring recommended by Pauls (1994), especially in relation to the 1993 evacuation of the World Trade Center towers, would have permitted rapid determination of exactly how many people came out of each exit as well as the exact flow volume over the course of the evacuation. Following the 2001 terrorist attack, the recommendation gained even more potency as it became very important to identify the evacuees (and emergency responders) individually as well as to determine the exact number, something that was in dispute both in the 1993 and 2001 incidents.

Unfortunately, research related to human factors applications to fire safety has been largely ignored. For example, there are several university-based centers for the research of natural disasters, and the National Science Foundation supports rapid responses to such events. However, there is nothing to support a similar response to building evacuations, as evidenced by the recent hearings conducted by the Congressional Science Committee. (http://www.house.gov/science/ hot/wtc/wtc.htm)

Fire safety engineering curricula needs to include human-centered design and associated methods. We believe that fire protection engineers needlessly limit themselves by only recognizing the validity of methods that conform to "standards of engineering practice." A related obstacle is the longstanding professional reliance on legally enforced building codes and safety standards that limits the scope of attention given to safety issues, including fire-related human behavior. Current codes and standards do not take a user-centered approach, even when so-called systems approaches or performance-based approaches are used. One exception to this is found in the *Life Safety Evaluation* applicable to large places of assembly addressed by the *Life Safety Code,* NFPA 101.

Conclusions

The human factors field introduced in this paper provides, in our opinion, the best discipline with which to address evacuation. As described by Pauls (1994, 1999), user-centered systems design should be based on a much better understanding of the five W's of evacuation: What, Who, Where, When and Why. The "One Thing that Absolutely Needs to be Done" is to quickly and carefully study emergency evacuations in large buildings (such as the World Trade Center towers). We can make immediate progress by picking the "low-hanging fruits" of evacuation research. Researching more challenging topics dealing with the cognitive and cooperative demands posed by evacuations will yield more valuable advances.

Fire safety researchers and design professionals will need to change attitudes and broaden their orientations to take advantage of this promising intersection of disciplines. This can best be accomplished through education in user-centered design principles and methods adapted from the field of human factors research and design.

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AVAILABLE DATA AND INPUT INTO MODELS

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ABSTRACT

There is a need for better data to improve our knowledge of human behavior in fire. This data can be used in the development and refinement of evacuation models and in the use of such models. Once collected, human behavior data must be published in peer-reviewed journals and conference proceedings. A central repository should be created to store the data in a format that enhances its use by researchers, fire safety engineers and the regulatory community. The data collection itself must be adequately funded. We need a coordinated effort to collect this sort of information, rather than ad hoc projects when major incidents occurs. Valuable time can be lost in the pursuit and processing of funding. One important method for collecting this data is post-incident surveys and interviews. Although there are some disadvantages to this technique, it provides valuable insight into actions and behaviors in real-life emergencies.

Introduction

Evacuation models are key tools for the evaluation of engineered designs. Fire growth models can predict the spread of smoke and other toxic products throughout a structure. Evacuation models can predict the location of people as they exit the structure. Used together in the evaluation of a design, these models can provide some indication of the risk that occupants might face under a modeled scenario.

Evacuation models vary in complexity, but all rely on data, either in their development (i.e., they are calculation methods based on observations) or as input. The models may simply provide estimates of evacuation times, or they may be intended to more fully simulate occupant behavior, including decisions.

Brief Overview of Evacuation Models

There are different types of evacuation models. There are simple straightforward calculation methods for estimates of evacuation times. These equations or simple computer models may be based on observed movement from drills and experiments.

The next level of complexity is network flow models that handle large numbers of people. These models are useful for benchmarking designs, but they cannot be used to predict what any one person might experience, since they treat the occupants like water in a pipe rather than as individuals.

Behavioral simulation models are the most complex, treating more of the variables related to both movement and behavior. Their added complexity requires tremendous amounts of data for their development, if the assumptions they contain

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regarding behavior are to be based on reality rather then expediency. Their users also need a fuller understanding of the components of human behavior in fire in order to choose appropriately among available options.

Types of Data Needed for Models

Data can be used to develop the equations or algorithms in models or to serve as input to the models. Data is also needed to test the validity of the models.

All evacuation models require data on the characteristics of occupants, their actions during evacuation, delays that may occur, and travel speeds for different types of occupants. Data is needed on, for example:

- delay times, i.e., the time that elapses between when people are first alerted to an incident and when they begin to leave, including the time they may take to prepare for evacuation;
- walking speeds on different types of surfaces, up and down stairs, under different degrees of crowdedness, and for people with a range of physical abilities;
- occupant characteristic, including age, gender, degree of training, familiarity, etc., to account for differences in actions and reactions among the different types of people for different types of occupancies;
- the variety of specific actions people may engage in during evacuation, since these will impact the time people take to leave the building;
- effects of obstructions in travel paths, which can cause delays or block egress; and
- exit choice decisions, which determine travel paths and affect travel times.

Sources of Data

The appropriate methods for collecting the needed data vary, and each collection method has its advantages and disadvantages.

Videotaped observations of actual evacuations are ideal, since they show exactly what different people did, and the elapsed time can be calculated directly from the tape. They will show how long it takes people to react to cues, to seek information and/or prepare to evacuate, and will record their movement (including queueing, walking speed, flows through doorways, in corridors or on stairs, precedence behavior at merges, etc.) The characteristics of their individuals, including any mobility impairments, can be determined from the tape, or can be obtained later in interviews. However, videotapes are rarely available for actual fire incidents, so what is obtained is information that, though valuable, is not directly applicable to decisions and movement of people under actual stressful conditions. Regardless of its limitations, extensive and valuable work in this area has been undertaken in recent years in mid- and high-rise apartment and office buildings. [Proulx et al 1994, 1995a, 1996]

Laboratory experiments have been done to test the effects of smoke on decision-making and travel speed. [Jin 1997, Kubota 2001] Because of ethical issues and increasing restrictions and outright bans on the use of human subjects, however, researchers rarely undertake such experiments.

Post-incident surveys and interviews can be used to obtain information from survivors of actual fires. This method has been used for a great many years (Bryan 1977 and 1983, Woods 1990, Best 1977, Proulx et al 1995b, Fahy and Proulx 1996). A methodology for conducting post-fire interviews is detailed in (Keating and Loftus 1984). Although these methods will give real-life evidence, there are disadvantages. Recollections and descriptions will be subjective. The elapsed times are not recorded objectively, and the reported times may be distorted. Details can be lost as time passes after an incident, making timeliness of data collection an important issue. Recollections of a group of people may converge over time as they share their stories and meld details.

Research Needs

In order to better understand human behavior in fire, to enhance the effectiveness and completeness of evacuation models, and to provide better information for the users of evacuations model, additional study is needed in a range of areas.

The areas of study involve the need for more data on all the time components of behavior, particularly those that are not a simple matter of speed and distance; data on the variability of those time components; and data or models on the factors driving behavior choices and the variability in time to perform certain actions. Some of the more specific areas are listed and described here:

- effects on counterflows in stairs: what do we know about the impact of firefighters going upstairs while occupants evacuate or of rescuers (e.g., in hospitals or nursing homes) returning for more people?
- movement capabilities of a wide cross-section of society: how much do we know about variations in movement capability by age or by walking impairment?
- evacuation of disabled people: how are wheelchair users expected to evacuate and how long with that take; how might their evacuation impact the overall evacuation flow?
- differences in response to a range of cues: do people respond differently to different types of alarms or different fire cues?
- waking effectiveness of a range of cues: what would be the most effective method or design to awaken people and alert them to a fire?
- delay times before beginning evacuation: what is the effect of being alone, being with others, the types and number of cues, the type of occupancy, a person's experience with false alarms?
- flows on different types of stairway configurations: what do we know about the use of space on stairs, flows on spiral stairs, the effect of the geometry of stairs?
- behaviors: who decides to stay and who decides to go; what is the basis for exit choice; how can we predict stopping and turning back behaviors; who

queues and who doesn't; do we know how to predict an individual's need for rest during long evacuations?
- effects of training of staff and/or occupants: how can we begin to quantify the impact of training of staff or occupants on reducing delay times and/or improving travel times?
- perception of risk: what factors impact perception of risk and how does risk perception impact judgment?
- toxic effects: at what levels do toxic products affect decision making, movement speeds and survival and how do those effects vary among people?
- interaction between people -- how do the presence of social groups impact evacuation delays and movement?
- elevator use: assuming they were safe to use, how would they be used effectively for evacuation, and would they be used by everyone or only by those with mobility impairments?
- alarms: can building occupants recognize alarms and how audible are they throughout a building, given ranges in ambient noise and light levels?

Education and Training

Research in human behavior is a discipline that could benefit greatly from improved partnerships with researchers in the behavioral sciences. (Horasan and Saunders, 2001) Differences in approach to research between physical and social sciences must be bridged so that the best information can be identified and applied to the fire problem.

Once data is collected, it must be put in the hands of the people who can use and apply it. Two international symposia were held in recent years which have helped to focus attention on this research field, which has been an essential first step and the proceedings from the symposia are valuable resources (ISHBF 1998, 2001). However, there were few practitioners in the field of fire safety engineering present at either symposium. They need a place to find the current state of knowledge in human behavior so that they can effectively and appropriately apply available evacuation models. Model developers need access to the data so that they can use it as the basis for assumptions and calculations. Building and fire regulators need the data so that they can better understand and evaluate the analyses of engineered designs. In the overall field of fire safety sciences, researchers studying the physics and chemistry of fire need to appreciate the role of human factors in the use of products, the maintenance of systems, the response to real-world fires, and their vulnerability to fire's effects. This all points to the need for a cross-disciplinary approach to the study of human behavior in fire.

Barriers to Improved Collection and Use of Data

We lack a central repository for research on human behavior in fire. A central storage system for data would require that efforts begin to standardize the collection or reporting of collected data so that retrieval would be simplified. A first attempt to consolidate some of the available movement and delay time data has been proposed, but that was only a very preliminary first step (Fahy and Proulx, 2001).

There are several barriers that exist today that limit our ability to create such a clearinghouse. Much of the data collected over the past few decades was never published, and so, cannot be used. Any data collection project must be published in peer-reviewed literature.

A standard reporting mechanism would allow data from various sources to be compared, without unduly constraining the approaches researchers choose to use. For example, every data set should include a description of the occupancy, the capabilities of the occupants, their number, the fire safety systems present, the effectiveness of those systems and any other information that supplies a context for the data. This would enable researchers to identify the similarities between data sets and allow comparisons or aggregations where appropriate. Aggregated data should be reported in terms of distributions that will capture the range of observations, rather than just summary statistical measures.

And finally, data must be shared. This is difficult when the research is funded by an entity that will claim a propriety right to the data. Government-funded research, however, should be disseminated as widely as possible, so that all can benefit.

Conclusion

Human behavior in fire is clearly an area that would benefit from increased research efforts. If only one aspect of the research had to be given top priority, it should be the timely collection of post-fire incident data. The U.S. Fire Administration of the Federal Emergency Management Agency contracts for the investigation of significant fires. The incidents to be investigated are agreed upon by the contractor and contract officer, with the cooperation of the responding fire department. Very little delay occurs after notification of the fire and the dispatch of the investigation team.

A similar program for the collection of survey or interview data could be instituted. This would reduce the delays that now occur while proposals seeking funding are developed and reviewed. General agreement on approach (which can vary from incident to incident) can be reached beforehand. A schedule for completion of reports and planning for their dissemination would also be agreed. Every incident needs a methodology tailored to that incident, and that unavoidable customization step takes long enough. Coordination with USFA may be necessary, since an on-scene incident investigation, including information on the fire, the geometry of the structure, the presence and performance of fire protection systems, etc., bear on the actions of the occupants in attempting evacuation.

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POSSIBILITIES FOR FIRE RETARDANT MATERIALS - TOWARD SOLVING THE MOST DIFFICULT PROBLEMS

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ABSTRACT

Flammable materials are increasing in our workplaces and in our homes. Flame retardants, although shown to save lives and property, are not used in most plastics and textiles due to cost and adverse effects on other properties. Progress in flame retardant materials has been mostly evolutionary. There are pressing needs particularly for better means for flame retarding the large volume commodity polymers.

Many flame retardant modes of action can be demonstrated, but most have not been fully exploited, for example, heat reflecting additives, endothermic additives, improved char formers, non-carbonaceous barrier formers, dehydrogenation and oxidative dehydrogenation catalysts, improved intumescent systems, char morphology improvers, radical scavengers, and char oxidation inhibitors. Systematic quantitative measurements and basic mechanistic studies of the contribution of multiple additives are needed to find optimum and synergistic combinations.

Training and academic research in flame retardant chemistry in the U. S. has been quite limited. At Polytechnic University, we have been dependent on industrial funding resulting in mainly short-term research goals, and high-risk approaches have generally not been pursued.

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Introduction

There is a pressing need for advanced technology for ignition-resistant, self-extinguishing or slow-burning plastics and wood. The environment in which we live and work is increasingly being loaded with materials with high heats of combustion. At the same time, potential ignition sources such as electrical wiring and devices are proliferating. In housing, urbanization and crowding results in more human involvement in fire ignition. The fastest growing commodity plastics, the polyolefins and the styrenics, are also the ones most difficult to flame retard, especially where cost is a large factor. Present technology uses mainly brominated additives which work well as flame retardants but tend to increase visible smoke and corrosive vapors, and require fairly substantial loadings. Alternative flame retardants for the hydrocarbon-rich polymers, namely aluminum hydroxide and magnesium hydroxide, require very high loadings such that polymer properties are badly impaired. Wood, despite over two centuries of effort, still lacks fully satisfactory flame retardants; those which are used can sometimes cause serious strength loss.

Research Needs

From several decades of personal experience, I believe that aggressive research on new flame retardant systems to find a way out of this problem has been insufficient. Leading research centers are few in the U. S.; NIST is doing a respectable job, and amongst universities,

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Marquette University and Polytechnic have been conducting modest sized projects in this area over the last two decades. Industrial efforts have been more evolutionary than revolutionary. Newer products coming out of industry, particularly phosphorus and bromine types, are improved but still recognizable descendants of older types. One of the more novel systems, the nanoclays seem to have had their start at Toyota in Japan. These seem to be more useful in suppressing heat release than in retarding ignition or bringing about self-extinguishment, although we recently found that we could achieve self-extinguishing properties by using nanoclays plus other selected flame retardants to provide a synergistic action (Weil and Rao, unpublished).

Some excellent flame retardancy research depends on the development of novel polymers. Prof. Pearce and I reviewed "fire-smart polymers" which are designed to crosslink when exposed to fire (Pearce, Weil and Barinov, 1999). Prof. Riffle at this meeting describes flame retardant thermoset composites. Much elegant work was done in the Cold War period on highly fire-resistant designed polymers, costly enough that virtually none of them have found civilian use. Indeed, when cost, processability and other industrially important factors are considered, the "fire-smart polymers" are unlikely to replace the commodity polymers. Thus, we are left with a serious problem. We have proposed at various times several aggressive approaches to the problem (Weil, Hansen and Patel, 1990, Weil, 1995). With limited time and effort applied to some of these suggested approaches, our experimental results have given us encouragement that we may be on the right track.

One approach makes use of catalysis. In principle, there is no limit to the efficiency of a catalyst. Nature's enzymes show what can be done in catalyzing chemical reactions by many orders of magnitude of velocity. We have suggested that dehydrogenation or oxidative dehydrogenation catalysts should in principle be useful in flame retardancy. A rare example is the finding at GE that parts per million of platinum in some silicone systems provides flame retardancy (discussed in Weil, Hansen and Patel, 1990, *loc. cit.*). In our own laboratory, pursuing a catalyst lead, we found that iron compounds exerted, in proper combinations with other additives, a strong flame retardant effect in some non-halogen systems (Weil and Patel, 1991) As time and manpower permits, we continue to look at this lead further. We observed flame retardant effects, seemingly catalysis of crosslinking, in some rubber blends with small additive amounts of potassium carbonate (Weil and Patel, 1996).

In using catalysts in flame retardancy, there is a dilemma: on one hand, polymers do not penetrate well into the pores of heterogeneous catalysts and char easily deactivates such catalysts, while, on the other hand, many homogeneous catalysts are not thermally stable enough to survive the pre-ignition temperatures. One way out, which has not been much explored, is the use of nano-sized heterogeneous catalysts which have their active sites mainly on the outside surface of the particles rather than in pores.

In classical petrochemical catalysis, combinations of elements are frequently superior. A typical catalyst for dehydrogenation of ethylbenzene to styrene has three or four active oxides in an empirically found optimum combination. We can expect to see similar relationships in the flame retardant catalyst area. This topic has been scarcely explored. In research at Polytechnic, some remarkable examples have been found showing synergism of low levels of certain metal salts with char-forming phosphorus-based intumescent systems (Lewin and Endo, 2000). The new high-throughput methods being researched at NIST could be ideal in searching for effective catalysts. Just as catalyst theory is adding more design and less trial and error to petrochemical catalyst development, in the same way catalyst theory could point to fruitful avenues for flame retardant research.

Turning to a second avenue to much more efficient flame retardants, I propose intensified efforts along the lines of synergism (strong positive interactions) of additives (Weil, 2000). This approach has been tried and proven in the classical halogen systems where antimony oxide combinations are the "workhorses" of the established flame retardant systems. We have been looking for new synergists for phosphorus systems. Some encouraging results have come from combining volatile (vapor-phase active) phosphorus compounds with non-volatile (condensed phase active) phosphorus compounds.

Prof. Lewin at Polytechnic has had some excellent results with a wide range of sulfur compounds as synergists for ammonium polyphosphate in polyester and polyamide thermoplastics (Lewin, 2001). Reviewing our own work and our recent review of the literature (Weil, Lewin and Barinov 2002), we see that sulfur compounds have often been reported and even used in effective combinations with phosphorus for flame and smoke suppression, but no extensive exploration of the mode of action and possible optimization seems to have been done. In view of the low cost and toxicologically favorable character of many sulfur compounds, this looks like a fruitful area for research.

Thirdly, we turn to a solution to the efficient flame retardant problem which is often relegated to the plastics compounder who generally arrives at a workable solution by diligent trial and error. We propose a combination of a mechanism-driven and a data-driven (iterative) solution to building flame retardant systems from multiple components, some synergistic, some just cooperative. The tools for this purpose are surprisingly varied: Even if the polymer must be a commodity polyolefin or styrenic, the potential additive range is broad. We have available the following tools for use in assembling flame retardant systems:

- Materials which could retard ignition, such as non-flammable materials which might bloom to the surface such as fluoro-surfactants, heat-reflective materials, surface antioxidants, surface barrier-formers, and the like.

- Heat sinks of various types in the condensed phase. The "workhorse" materials are alumina trihydrate (ATH) and magnesium hydroxide. Other heat sinks that are used are hydrated zinc borate, hydrotalcite, gypsum and melamine. Some tailored ATH varieties with controlled endothermic regions have been made. Synergism has been sporadically studied, but we think much more could be accomplished. For instance, optimized fitting of the endotherms to the thermal decomposition profile of the polymer by use of a series of such additives could be effective.

- Heat sinks in the vapor phase. This may be a main part of the action of the halogen and melamine systems. Computational approaches show a remarkable relation of heat capacity plus heat of dissociation of flame inhibitors to their efficiency (Larsen, 1980; Ewing, Hughes and Carhart, 1988; Ewing, Beyler and Carhart, 1994).

- Char-forming additives, such as the intumescent types, and there are many ranging from relatively small molecules such as pentaerythritol to oligomers such as novolacs to high polymers such as polyphenylene oxides.

- Silicate barrier forming types. Remarkable efficiency has been shown by some solid polysiloxanes in reducing rate of heat release, probably by barrier formation (Hshieh, 1998), and we have lately found these same siloxanes can contribute strongly in certain self-extinguishing formulations. Nanoclays and their synergistic combinations are promising.

- Char inducing catalysts. The classical material for intumescent systems isr ammonium polyphosphate, which has thermal and hydrolytic stability limitations. Moderate improvement has been made by encapsulation. We have evidence that much more stable materials of this class (for example, phospham and phosphorus oxynitride) are possible (Weil, Patel and Huang, 1993).

- Intumescent systems, which usually comprise a char-forming ("carbonific") component, a char-inducing catalyst, and a blowing agent ("spumific"). In some cases, the main polymer can be the carbonific or the spumific component (Ballistreri, Montaudo, Scamporrino, Puglisi, Vitalini and Cucinella, 1988). The general principals are understood but much experimentation is usually necessary to balance the formulation (Anderson, Dzuik, Mallow and Buckminster, 1985).

- Char-barrier morphology improvers. We have observed that in some non-halogen formulations, iron compounds act as synergists, and our preliminary observations indicate that the char is more coherent. The literature gives further support to the idea that iron, and some other metals such as molybdenum, aid the structuring of carbon.

- Radical scavengers in the condensed phase. One of the several modes of action of red phosphorus is believed to be radical scavenging (Weil, 2000), and some hindered amines may perform similarly.

- Radical scavengers in the flame phase. This is the generally accepted mode of action of hydrogen bromide and antimony halides, and is one of the several modes of action of those phosphorus compounds which can volatilize (Lewin and Weil, 2001).

- Rheology control. There are melt-flow inducers such as peroxides and tetrasubtituted ethanes which act as flame retardant synergists. These additives can help self-extinguishment by dripping, where the flammability standards permit such a mode of extinguishment, or where the drips are non-flaming.

- Drip preventatives such as powdered PTFE. These are useful where melt flow is undesired, particularly where the drips are flaming.

- Char protectants such as some borates and phosphorus compounds, and possibly synergistic phosphorus-nitrogen additives. Inhibition of the combustion of solid carbon permits a char barrier to be maintained, and/or prevents afterglow.

- Ceramic or glassy barrier formers, usually silica- or boron-based, and we have found that delving into commercial glass and glaze technology provides some very useful additives.

I have tried to enumerate in broad classes the many tools which are available for use in flame retardancy. Moreover, there is a strong likelihood of interactions between them, often synergistic, sometimes antagonistic. Therefore, it is very advantageous to use some version of experimental design and statistical data evaluation in the discovery of highly effective systems. We have done this in a number of studies using multivariate regression analysis.

Fourthly, in approaching plastics flame retardancy, we would like to call attention to a powerful approach to flame retardancy which is old with regard to wood and structural protection, but remarkably unexplored in regard to plastics, namely flame retardant intumescent coatings. These coatings, as used to protect wood or sometimes structural steel, pipes, tanks and the like, are able to expand to many times their thickness by forming a foamed char. These char barriers can provide long lived thermal protection and are used, for example, in off-shore oil drilling platforms, refineries and the like. It can be shown by heat transfer measurements that a 27 mm-thick layer of suitable foamed char can protect a substrate from ignition against flame temperatures as high as 1500°C and a 1 cm-thick foamed char can protect up to 4600°C (Weil, Hansen and Patel, 1990, *loc. cit.*). Thinner versions are often used as fire-protective interior paint for wood. Applications of intumescent coatings to plastics are hard to find. One reason is the adhesion problem. With polyolefins, this is a challenging problem for any coating.

The advantage of solving the plastic flammability problem this way is that the interior of the plastic can be optimized for its physical properties, processing characteristics and cost, while the exterior (the coating) can be optimized for fire barrier action. This area has had very little research, mostly just optimization by compounding with a narrow range of ingredients.

In general, flame retardant coatings have hydrophilic ingredients to catalyze and form the char, and this hydrophilicity aggravates the adhesion problem, water resistance and washability. We think this shortcoming is solvable, and there are clues as to how to solve it, for example by building self-intumescent polymer additives, not needing inorganic polyphosphates to catalyze the charring. We also think the relatively under-researched area of phosphorus-nitrogen chemistry will be productive in making available better (more water-resistant) ingredients for intumescent coatings (Weil, Patel and Huang, 1993).

Although in the foregoing discussion, I have tended to emphasize additives, it is important to mention that minor polymer modifications may have a beneficial effect on flame retardancy.

Many of these proposals can be carried out with relatively benign chemistry. By lowering the level of additives, the environmental questions are alleviated. By preventing fire efficiently, the environmental pollution which occurs from fire, such as polycyclic aromatic hydrocarbons in soot, is prevented. It is practically futile to try to make the fire atmosphere breathable, since in the final analysis it seems that CO is the main killer (Hirschler, Debanne, Larsen and Nelson, 1993; Nelson, 2001), but by preventing or slowing down fires, toxic combustion gases are certainly avoided or minimized. There is no credible case of a flame retardant causing any fire casualties, and there is ample evidence that the use of flame retardant chemicals saves lives (Stevens and Mann, 1999).

So far in this paper, I have addressed research needs. Turning to educational needs, we perceive a shortage in this country of people trained in the chemistry and materials side of fire sciences. Regarding flame retardant additives research in the U. S., besides our Polymer Research Institute at Polytechnic, mention should be made of Marquette University (Prof. Charles Wilkie) and Florida Institute of Technology (Prof. Gordon Nelson). Inherently flame retardant polymers and composites are researched at Virginia Polytechnic, and we will hear more about that work from Prof. Riffle. But, altogether, the numbers of students doing graduate research and studying flame retardancy seems small relative to the importance of the problem. Other speakers at this meeting will address a similar situation regarding fire engineers. I think it is fair to say, judging from perusal of the current literature, most of the students doing graduate work in the chemistry and materials science aspect of fire sciences are from overseas, and of course we lose many of these when they return home. Young people at the assistant professor or associate professor level in this area of applied science or related basic science are practically non-existent in this country. In the speaker's judgment, the UK, France, Italy, China, Japan and Russia appear to be training more young people in this area of applied science than is the US.

Some of the barriers to progress in the field of fire-resistant materials are: cost (extremely important in the highly competitive commodity plastics), unfavorable effects on physical properties and processability, lack of compelling regulations to flame retard many kinds of combustible products, inadequate basic research to support and stimulate innovative approaches, increasingly short-term focus in industrial research.

One important, and rather obvious, need for action is to initiate more university research projects in the US on innovative flame retardant additives and coating for plastics. Having some NSF projects in the chemical and material aspects of fire sciences would elevate the attractiveness and productivity of this field. My preference for the main thrust of the research would be to try to make use of catalysis, synergism and intumescence to reach highly efficient flame retardant additive systems for the most important plastics.

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Polymer Matrix Composite Constitutive Properties, Evolution & Their Effects on Flame Durability & Structural Integrity

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Abstract

Fiber-reinforced polymer composite materials (FRP) are gaining acceptance in civil and building infrastructure applications worldwide. Most FRP implementations in building structures are experimental and compliance with fire codes has either not been the focus, or this has been dealt with through application of protective coatings. Recognizing that this is not a long term solution, this paper seeks to summarize the general state of knowledge in the area of FRP composites and their response to fire conditions. With the polymer as the primary concern, there is a clear correlation between the matrix material and the resistance and response to damaging heat flux. Glass transition temperatures for commercially available matrix materials are typically 120-400°C; no match for the higher temperatures observed in realistic fire situations. Fire resistance is designed into these materials through one of two methods: (1) A gas phase mechanism whereby gaseous decomposition products inhibit approach of oxygen to the flame, and (2) Via char formation. In either case the property evolution (reversible and irreversible) is influenced by the loss in stiffness and strength from temperatures which exceed the glass transition temperature, and loss in sections from ablation. Charring of the surface plies and ply delaminations can insulate the composite underneath, thus extending the life. With temperature driving the evolution in properties, spatial knowledge of the incident heat flux, knowledge of property evolution, and the ability to incorporate property evolution to describe structural integrity, are central to simulating structural response of building structures under a fire threat.

Introduction

The recent interest in fiber-reinforced polymer composites (PMC's) for civil infrastructure and building applications has generated a need for a closer look at their performance and stability under fire conditions. Design engineers typically express concerns about the integrity of PMC bridge structures exposed to fire. Walls and columns strengthened with FRP retrofits for seismic considerations have relied on the ASTM equivalents to the Uniform Building Code (UBC) as a qualification for building materials when considering fire. Specifically, the standards for fire resistance (ASTM E119 = UBC 43-1), flame-spread and smoke density (ASTM E 84 = UBC 42-1) and non-combustibility of building materials (ASTM E 136 = UBC 4-1) form the basis for selecting building materials.

As of yet, there are no comprehensive codes, or guidelines for specifying codes, concerning fire resistance and structural integrity. This is with exception to safety provisions in the ACI 440F code which requires a new factored nominal moment larger than 1.2 dead plus 0.85 live load to address structural integrity of bonded repairs [1]. More comprehensive and validated guidelines will be required as routine use of these materials is sought. Such provisions will be introduced as the industry matures and other PMC housing structures are designed and evaluated for routine use. In particular there are several companies moving forward with the development of modular structures fabricated from reinforced polymers [2, 3]. These structures have been enabled through innovative production and joining features that reduce the cost of component manufacturing and construction as compared to the "stick built" homes. "Snap joining" technology, for instance, can be efficiently manufactured and field constructed with integrated features (e.g. panels incorporating snap joining/sealing features, electrical and plumbing traces) that will serve multiple functions (Figure 1).

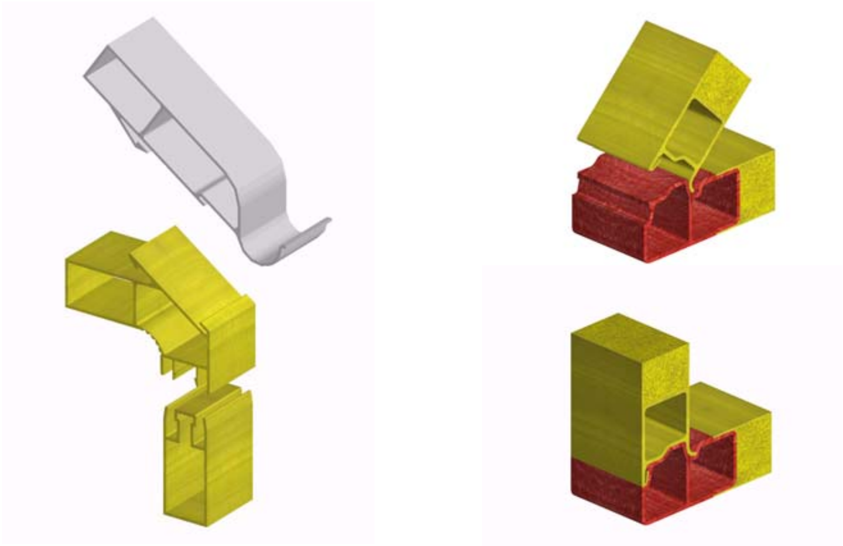

Figure 1. Snap-joining technology: **Left** - wall-ceiling-roof connection with integrated gutter, **Right**– Tilt installed wall-to-floor joint

Flame Properties of Polymer Matrices for Structural Composites in Construction and Infrastructure

Cone calorimetry can provide information on burning rate (indicated by the peak in the heat release rate and the average heat release rate) and char formation [4-7]. While there is limited experience from which to specify PMCs in fire critical areas [7], the performance of various classes of fiber/polymer composites have been studied or at least screened [8, 9]. There are two major mechanisms by which neat polymers are rendered flame retardant: (1) A gas phase mechanism whereby gaseous decomposition products inhibit approach of oxygen to the flame, and (2) Via char formation.

Polymer	Flame Performance	
	Time to Ignition	PHHR
Polytetrafluoroethylene	**No ignition**	**13 kW/m^2**
Poly(vinyl chloride)	**85 sec.**	**183 kW/m^2**
Polystyrene	**97 sec.**	**1101 kW/m^2**
Nylon 6,6	**65 sec.**	**1313 kW/m^2**

Figure 2. Flame properties from cone calorimetry (measured at an incident heat flux of 40 kW/m^2) of halogenated vs. non-halogenated aliphatic polymers [4]. Note the order of magnitude improvement in the peak heat release rates (PHHR) of the halogenated vs. non-halogenated materials.

Halogenated polymers burn relatively slowly due to the gas phase mechanism (Figures 2-3), but such materials do not necessarily form high char yields. One major detraction when considering halogenated materials, however, is that dense smoke usually results upon burning, and in at least several cases, the concentrations of toxic carbon monoxide are unusually high. One can note at least an order of magnitude improvement in burning rates (i.e., lower PHHR) for all of the halogenated polymers vs.

non-halogenated materials. For example, oligomers from tetrabromobisphenol A and epichlorohydrin provide the base materials for commercial flame retardant vinyl esters and epoxies (figure 3). Flame retardant vinyl ester resins are typically blends of brominated with non-brominated oligomers diluted with styrene. Networks from such compositions have relatively slow burning rates but they typically only exhibit about 9 weight percent char (Figure 3) [10]. When brominated epoxies or vinyl esters burn, they also evolve high concentrations of toxic carbon monoxide.

Polymer	Flame Performance			
	Incident Heat Flux	Time to Ignition	PHHR	Char
Polytetrafluoroethylene	40 kW/m^2	No ignition	13 kW/m^2	
Poly(vinyl chloride)	40 kW/m^2	85 sec.	183 kW/m^2	
Fluorine-containing PEEK*	50 kW/m^2	138 sec.	87 kW/m^2	25%
Brominated vinyl ester**	50 kW/m^2	44 sec.	290 kW/m^2	9%

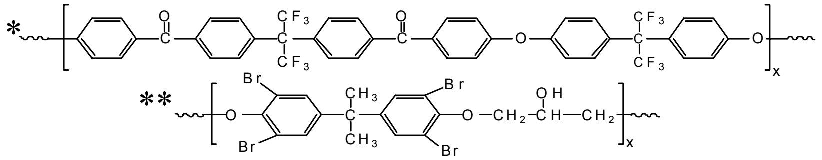

Figure 3. Cone calorimetry results for halogenated polymeric materials illustrating the slow burning rates [4, 11, 12]. There is a need to better understand effects of smoke density and the nature of the by-products.

Polymers with highly aromatic chemical structures in their backbones are flame resistant due to formation of substantial char upon pyrolysis (Figure 4). Polymers with aromatic backbones comprised of "ladder" structures, exemplified by the aromatic polyimides, also exhibit these properties. This is undoubtedly related to the fact that these materials lack thermally labile, aliphatic C-H bonds in the polymer backbones, and are thus inherently more thermally stable. Moreover, the aromatic rings lead to char, which may be important for forming protective surface layers during the pyrolysis process. Quantification of this aspect will require a better understanding of the behavior of these materials during pyrolysis.

Polymer	Flame Performance			
	Incident Heat Flux	Time to Ignition	PHHR	Char
Ultem polyetherimide	50 kW/m^2	160 sec.	128 kW/m^2	79%
Poly(dimethylsiloxane-b-etherimide)	50 kW/m^2	97 sec.	210 kW/m^2	32%
Fluorine-containing PEEK	50 kW/m^2	138 sec.	87 kW/m^2	25%
Polysulfone (UDEL)	40 kW/m^2		170 kW/m^2	
	50 kW/m^2	126 sec.	431 kW/m^2	56%
	70 kW/m^2		310 kW/m^2	

Figure 4. Polymers with all-aromatic backbones are highly resistant to burning and protect their underlying substrates via formation of large amounts of char [4, 13, 14].

Although it is known that aromatic polymers such as those described in figure 4 have good flame retardance, these materials can be expensive, and this detracts from their desirability for composite components in construction and infrastructure. The military and civilian aircraft communities have developed methods to functionalize aromatic polyimides and poly(arylene ether)s with thermally stable, crosslinkable terminal groups (e.g., phenylethynyl functional oligomers) [15-19], which could provide processible, corrosion resistant, flame resistant, PMC matrices. Such materials have not really been considered as construction materials due to their potential costs, but this may be attractive for flame resistant components.

Structural polymer matrix composites are typically comprised of about 60 volume percent fiber and 40 volume percent of the polymer matrix. Fibers utilized in applications requiring flame resistance are limited to carbon and glass, both of which exhibit excellent performance in a fire.

Thermosetting polymer matrix materials suitable for structural applications can be classified in terms of their thermal performance (Table 1), which often parallels their applications (and price). The vinyl ester and unsaturated polyester matrix materials are utilized to produce rapidly manufactured parts for construction and infrastructure. Their free radical curing mechanism and low viscosities make them ideal for pultrusion or low temperature VARTM processing. The resultant networks are highly crosslinked which leads to good environmental and corrosion resistance, and the materials are inexpensive. Unfortunately, unless they are halogenated, they lack flame resistance and residual integrity, and pose a health threat in enclosed spaces. It is clear from the flammability tests that these materials are not the most desirable systems in that regard (Figure 5). Phenolic novolac or resole networks have inherently low flame-spread, slow burning rates, and the materials are cost-effective [20]. They are highly aromatic and also have hindered phenol units along the backbones, which may effectively protect the materials through oxygen scavenging. The viscosities and curing chemistries for undiluted phenolic resins, however, do not allow fabrication of void-free composites by methods typically used for manufacturing construction components (i.e., pultrusion or VARTM). Conventional thermal curing of resole oligomers evolves water and produces voids in the composites which detract from structural properties. One approach to overcome some of these issues is to cure novolac resins with epoxy or even phthalonitrile crosslinking reagents [21-25]. Some of these matrices have excellent structural properties combined with good fire resistance.

Table 1. Thermal performance often dictates the applications for thermosetting polymer matrix systems.

System	**T_g (°C)**	**Current Applications**
Vinyl esters – styrene Unsaturated polyesters – styrene Low temperature epoxies Phenolics	Moderate (≈120-160)	Civil engineering (e.g., construction, infrastructure), automotive, ships
Cyanates	High (≈260)	Electronic materials, adhesives and matrices, civilian aircraft
High modulus epoxies	High (≈240)	Military
Functionalized poly(arylene ether)s	High (200-280)	Tougheners, military
Functionalized polyimides Phthalonitriles	Very high (200-400)	Aerospace, electronic

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Resin	Flame Performance			
	Time to Ignition	PHHR	CO/CO_2	Char
Unsaturated polyester-styrene	**53 sec.**	**710 kW/m^2**	**0.025**	**13%**
Vinyl ester-styrene	**69 sec.**	**619 kW/m^2**	**0.028**	**11%**
Epoxy-DDS		**1230 kW/m^2**	**0.04**	**5%**
Phenolic	**272 sec.**	**124 kW/m^2**	**0.02**	**54%**
Phenolic Resole		**116 kW/m^2**	**0.01**	**65%**
Phenolic-epoxy (65:35 wt:wt)	**75 sec.**	**263 kW/m^2**	**0.02**	**26%**
Phenolic-phthalonitrile (85:15 wt:wt)	**102 sec.**	**137 kW/m^2**	**0.02**	**54%**
Polysiloxane network	**45 sec.**	**80 kW/m^2**	**0.02**	

Figure 5. Flame properties of thermoset polymer matrices for composites measured by cone calorimetry with an incident heat flux of 50 kW/m^2 [5, 21, 23, 25, 26]. PHHR is peak heat release rate.

Finally, several extremely fire resistant thermosetting resins have been developed and studied by the Navy, including bis-phthalonitriles matrices [27]. These materials must be cured slowly at elevated temperatures, but indeed have extremely good flame properties.

Modeling of Fire Damage Mechanisms in Polymer Matrix Composites

A considerable amount of work has been completed to begin examining materials that do hold promise under conditions of fire, e.g., the phenolic matrices. Mechanics that describe the thermochemical and the resulting mechanical properties have been expanded over the years (first studied by Bumford et al. [28]). This work has motivated examination of fire durability and structural integrity in anisotropic composites [29-35]. Although the community still lacks a complete description of relationships between polymer composition/microstructure and fire behavior [36], some success at combining the thermochemical processes to residual properties of composites has been achieved.

We understand that upon exposure to the flame/heat, the matrix material of the polymer composite first undergoes reversible changes in physical properties (lowering of the elastic modulus by transitioning from the glass to a rubber and thermal expansion). These reversible changes occur in the early stages of a fire and can cause the structure to exceed buckling or deflection-driven limit states. A review of glass transition temperatures for various polymer composites in Table 1 shows that the temperatures at which the greatest change in mechanical properties takes place (i.e. the T_g) can vary by nearly 300°C depending on the polymers and their economics. At higher temperatures (200-300°C) irreversible, multi-stage, decomposition reactions (pyrolysis) occur causing evolution of gases [37] and formation of carbonaceous char, particularly at the surface directly exposed to the heat flux [31]. The process of polymer material evolution and response to intense thermal conditions are summarized in a National Research Council Report [6]: *Thermal degradation, char formation, transport of degradation products, ignition and fire growth.*

The above described phenomena alter the thermal/physical properties of the polymer, and also result in ply ablation, introduction of additional stresses, and reductions in lamina strengths. Delaminations commonly result from combined thermal expansion of the surface lamina due to thermal gradients, and gas evolution between plies of the laminate [33, 34, 38]. As a result of the changes to the laminates, the structures lose stability (reductions in moduli) and undergo reductions in load-carrying capacity (increases in ply stresses and reductions in the ply strengths).

However, some of the damage modes and material changes can be beneficial to the laminate for fire resistance. The formation of char, the char itself, and delaminations within the laminate surface region reduce thermal conductivity and protect the underlying lamina from further damage and exposure to higher temperatures [34]. This self-insulating [39] process leads to a "slow burn-through" process in thick laminates [38]. The factors that influence this process are chemical structure of the matrix material, the nature of added flame retardants, heating rate, ultimate temperature, manufacture-induced flaws/porosity of the virgin material, moisture content, and the initial and evolving thermal conductivity and permeability in the fiber and transverse directions. It is therefore clear that the type of fiber, fiber volume fraction and the quality of the manufacturing process, in addition to the character of the matrix, can affect this evolving thermo-chemical interplay.

Models to describe residual strength

Recent work by Burdette and Reifsnider [40, 41] have attempted to bring together some of these issues to configure an approach that assesses residual strength and predicts structural integrity. A clear concern in making predictions of residual structural performance for composites in intense heat conditions lies in the description of incident heat flux for a given fire condition. The Fire Dynamics Simulator [42] provided the necessary input for subsequent thermal-mechanical modeling. The incident heat flux was used to describe the thermal distribution in a bending-loaded, unidirectional AS-4/polyphenylene sulfide, semi-crystalline polymer composite. Compression strength micromechanics were augmented with a description of polymer stiffness as a function of temperature (20 to 200°C) where the T_g was approximately 90°C. Time-to-failure was subsequently predicted when the bending strain reached the critical compression strain in the fiber of the unidirectional composite. Through this approach, the fire size could be directly related to structural failure given the proximity to the fire and the surrounding boundary conditions. This study demonstrated the importance of relating incident heat flux from a fire state to the temperature distribution in a composite sample. Moreover, knowledge of the temperature distribution within the structure allows for determining failure, given an appropriate failure prediction methodology, purely based on the evolving thermal-mechanical properties of the polymer.

A feature of the degradation and property evolution process of the PMC laminate that may not be fully appreciated involves tracking the heat and the resulting temperature distribution. As pointed out above, temperature controls both reversible and irreversible composite properties. More importantly, temperature distribution is influenced by the local heat flux, both internal and external. If we consider extreme incident heat flux conditions for a jet fuel pool fire, the measured heat flux ranged from 90 to 160 kW/m^2 [6]. Although these values are extreme, they are realistic considering the response of the twin towers to fuel fires. Comparing this range in extreme incident heat flux to cone calorimetry measurements (Table 2) for average heat release (over 300 sec.) for various composites, we find the internal heat generated from burning is equal to or greater than the incident flux [8]. Moreover, if we consider the data of Table 2 relative to its incident heat flux (25, 50, 75 and 100 kW/m^2), in most cases the average heat generated is greater than the incident. One should not overlook, however, that the peak heat release (1200-1300 kW/m^2) is multiples of the incident heat for 10's of seconds, and this could produce considerable irreversible damage to the composite. If this re-irradiated heat is properly included in the estimate of temperatures, the acceleration of property loss and damage will be significant.

This suggests that tracking the internal heat generated is critical to modeling stiffness and strength changes in PMC's that burn. Cone calorimetry data can be used empirically to supply this needed information. Moreover, it also suggests that polymer matrix materials which develop sufficient char upon burning could impart considerably better chances for structural integrity in those composites (as opposed to those composites that have matrices which do not produce significant char).

Table 2. Cone calorimetry peak and average heat release (average over 300 seconds) for various composites material systems relative to the incident heat flux [8].

Composite Material System	*Incident Heat Flux (kW/m^2)*	*Peak Heat Release (kW/m^2)*	*Average Heat Release (kW/m^2) (300 seconds)*	*Average Heat Release/Incident*
Glass/VE, brominated, flame retardant	25	75	29	***1.2***
	50	119	78	***1.7***
	75	139	80	***1.1***
	100	166	-	-
Glass/VE, non-flame retardant	25	377	180	***7.2***
	50	-	-	-
	75	499	220	***2.9***
	100	557	-	-
Glass/Epoxy S2/3501-6, (0/90)	25	39	30	***1.2***
	50	178	98	***1.9***
	75	217	93	***1.2***
	100	232	93	***1.0***
Glass/Epoxy, E-Glass/F155	25	-	-	-
	50	40	2	***.24***
	75	246	1	***.01***
	100	232	5	***.02***
Glass/Epoxy, S2/F155	25	20	4	***.2***
	50	93	-	-
	75	141	99	***1.3***
	100	202	108	***1.1***
Glass/Epoxy, RTM 9405/9470	25	159	93	***3.7***
	50	294	135	***2.7***
	75	191	121	***1.6***
	100	335	122	***1.2***
Graphite/Epoxy, AS-4/3501-6	25	105	69	***2.8***
	50	171	93	***1.9***
	75	244	147	***1.9***
	100	202	115	***1.2***

Fire Durability and the Development of Design Guidelines

With the goal of developing an understanding of residual performance of a composite structure under fire conditions (while ensuring compliance with smoke and toxicity requirements), the development of design guidelines is in question. While the response of a structure to a specific fire may be considered deterministic, the fire conditions that will cause structural failure are not. Thus, a stochastic approach should be considered where simulation of residual structural performance is estimated for various fire scenarios. In this way, guidelines can be derived that account for variability in fuel load, geometry and flame propagation in a given space. A first step in accomplishing this depends on the ability to integrate various elements of fire simulation, the mechanics of material evolution, and how material property evolution influences the load carrying capacity of a structure given a set of limit states.

Conclusions and Recommendations

Review of presently available literature suggests that the buildings community does not possess the necessary polymer matrix materials to produce fiber-reinforced polymeric materials ultimately suitable for all critical fire applications. The glass transition temperatures of the materials presently under consideration for construction components are low (e.g., vinyl esters and unsaturated polyesters) and these materials do not form significant char upon burning. However, with lower thermal conductivity and the ability to char, FRP structural materials could potentially serve as reasonable reinforcements for repair and retrofit of primary structural elements in building structures. For enclosed spaces, it is also necessary that these materials meet basic smoke and toxicity standards.

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Research Needs For Flammability Of Polymeric Materials

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After a steady decline in the number of civilian fire deaths in homes in the US from 1977 (5865) to 1999 (2895), it appears that the number of deaths remains at around 3000 (the estimated number of the deaths in 2000 was 3420)[1]. In these fires, two classes of items that were first ignited and subsequently caused most civilian deaths are upholstered furniture (average of 658 deaths from 1993 to 1997) and mattresses or bedding (552 deaths)[2]. In order to understand the fire growth processes of upholstered furniture and mattress fires, detailed observation have been made of fire growth behavior on furniture mock-ups using the California Technical Bulletin 133 test protocol[3] and full scale fire growth tests of selected mattresses ignited by a gas burner system simulating burning bedclothes[4]. The tests showed splitting and melting of thermoplastic fabrics, and melt flow of polyurethane foam products to form the complex phenomena of a "basal melt fire". These phenomena significantly affected fire growth and heat release rate of the mock-ups of upholstered furniture. The extensive European study of the fire safety of upholstered furniture also made a related conclusion[5]. When a charring fabric is exposed to fire, it forms a char shell that protects the foam from direct fire exposure, whereas, a melting fabricmelts away to expose the foam to flames. Dripping materials are quite common. It was also observed that flaming melt drips were clear contributors to the spread of flames in the mattress interior, which tended to enhance fire growth and increase heat release rate of the mattress fire. Another example of significant effects of polymer melt flow on fire growth is the flame spread along a thin polypropylene, PP, wall lining. These linings are used in food processing plants, industrial kitchen and similar establishments to prevent work place contamination. It was observed that PP linings in a wall configuration, when subjected to a small ignition source at the bottom, generated a pool-like fire fed by PP melt flow and the pool-like fire controls the growth and spread of fire[6].

The behaviors of polymer melt, melt flow, and dripping have been observed by other studies in addition to those described above studies and their significance on fire growth has been recognized. Despite this recognition, the literature contains only a few systematic studies to understand the mechanisms of these behaviors and to determine their quantitative effects on fire growth[7,8]. Since thermoplastic polymers are widely used in consumer products such as fabrics, electronic devices, automobiles, appliances, and others, in the event of fire, the involvement of thermoplastic materials as a fire growth contributor is highly expected. However, current understanding of the effects of polymer melt flow on fire growth is very limited. Some results from the literature are presented to demonstrate the complex behavior of the polymer melt effects[8]. Figure 1 is a schematic illustration of heat release rate and mass loss rate measurement for a vertically mounted

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thermoplastic polymer sample (5.7 cm wide by 25 cm high by 2.5 cm thick). A small methane fed gas burner was used to initiate ignition across the sample width. Two weighing scales were used to simultaneously measure the sample weight and the accumulated weight of polymer melt drips in the catch pan. Figure 2 shows the results of a commercial PP placed just above a calcium silicate board as the catch pan. As the pool fire grew (see width in the top graph), a self-accelerating process was initiated in which the pool flames enhance the flame growth on the sample face and the rate of polymer melt flow arrival on the catch pan. The pool fire thus boosted its own growth rate and the overall heat release rate from the pool plus sample face fire grew in an accelerating manner. This observation of the dominance of the pool flame over the sample face fire is consistent with that of fire growth over a much larger PP wall lining[6]. Figure 3 shows a plot of the heat release rate versus time for various polymers, using the same experimental configuration. There is a wide variety of behavior influenced by the melt characteristics and the thermo-chemical properties of these polymers. PMMA is the only material that did not yield a melt pool at all because its melt viscosity was so high as to overcome the force of gravity. Nylon 66 was reluctant to burn at all in these experiments, which included no external radiant flux.

The polymer melt flow behavior described above is complex; even the simple two-dimensional configuration described here poses a challenge to model its behavior. The geometry of the problem changes significantly with time. The surface of the melt is a free surface that may undergo considerable deformation, including dripping, and the internal interface between the solid and melted polymer changes its location as the material heats and flows. Unfortunately, there is little modeling of such polymer melt flow except preliminary results of the melting and dripping behavior of the low molecular weight PP in the above experimental configuration under an external radiant flux of 20 kW/m^2 without burning[8]. The study was conducted using the filling capability of the commercial finite-element program FIDAP to model flow processes involving arbitrary changes in shape, including breakup and merging of fluid volumes[9]. The results show the same qualitative behavior of polymer melt flow and dripping as were observed in the experiment. However, the model did not include any thermal degradation of the polymer and thus the polymer melt viscosity was treated as only a function of temperature without including the change in molecular weight.

As described above, the burning mechanism of thermoplastic based consumer products can be very complex but currently fire researchers often characterize flammability properties of polymeric materials (not only thermoplastics but also natural polymers such as wood) with four global parameters. They are material ignition temperature, thermal properties (the value of product of $k\rho c$, where k is thermal conductivity, ρ is density, and c is specific heat), specific heat of combustion, and global heat of gasification. The global heat of gasification is well defined for a liquid and a unique value for each liquid is available in a physical chemistry handbook. However, such value is not well defined for a solid material such as synthetic and natural polymeric materials. Many polymeric materials degrade through complex thermal degradation reaction steps during burning. However, at present it is very difficult to determine the kinetic constants of each chemical reaction of the complex multiple reaction steps.

Additional complexity is inherent in the transport processes, heat and mass transport, in the material. The heat transfer process is probably the easiest to analyze and this could be predicted with a reasonable accuracy. However, the data on thermal properties as a function of temperature up to ignition/burning temperatures of many materials are needed. Although the importance of the transport process of thermal degradation products through wood or charring materials in combustion and biomass research has been demonstrated[10], such a process has been rarely considered or recognized by the fire research community. At present, it is not clear whether the transport process of the products in the form of bubbles through a molten layer of a thermoplastic material has significant effects on gasification (burning) rate of the polymeric material. However, some experimental study[11] and theoretical studies[12,13] indicate its importance. Therefore, fundamental understanding of complex chemical and physical mechanisms in the condensed phase during burning of polymeric materials is severely lacking compared with that in the gas phase. Such understanding is critically needed to develop new flame retardant additives which mainly act in the condensed phase.

At present, it is not clear how much detail of the chemical and physical processes should be included to predict the fire behavior of polymeric materials with reasonable accuracy. Therefore, the term “global heat of gasification” for polymeric materials is the least well characterized among the four parameters described above. All complexities of thermal degradation chemical reactions and of transport processes are lumped into this term. It has been recognized that the validity of a constant global heat of gasification is highly questionable for char-forming polymeric materials such as engineering plastics and natural polymers. Thus, the overall accuracy of a fire growth model depends on the accuracy and validity of a constant global heat of gasification even if it uses a sophisticated gas phase model with high order accuracy. Furthermore, the effects of polymer melt flow on fire growth described above cannot be determined by the four listed parameters. More detailed studies in the condensed phase are needed to determine the important chemical and physical processes which control the gasification rate of polymeric materials. Then we can determine in what detail we need to model the condensed phase processes to be able to predict gasification rate of polymeric materials to comparable accuracy with that of the gas phase.

One important characteristic of the polymer is its molecular weight which has strong effects on polymer melt viscosity and surface tension in turn controling polymer melt flow. Although molecular weight was included for surface pyrolysis of vinyl polymers as early as 1970[14], molecular weight were rarely measured or calculated during the burning of polymeric materials. The change in molecular weight for polymeric materials during burning depends strongly on their degradation mechanisms. A severe reduction in the molecular weight of burning polyethylene occurs due to numerous random scission initiations and extensive melt flow can occur for this polymer. A significant reduction in molecular weight and subsequent melt flow can occur for burning polypropylene and polystyrene. However, polymethylmethacrylate, PMMA, does not significantly reduce its molecular weight during burning due to its dominant depropagation reaction in its degradation mechanism and little melt flow is expected for this polymer. Unfortunately, many systematic flammability studies in the fire research community have been conducted with PMMA in order to avoid the complex melt flow behavior. Since there have been extensive studies of molecular weight modeling[15] and size exclusion chromatography is available to measure molecular weight, it is time that such measurement and modeling of this should be included in the condensed phase study. Without these studies, polymer melt flow effects on fire growth over polymeric materials will not be properly characterized, understood, and modeled.

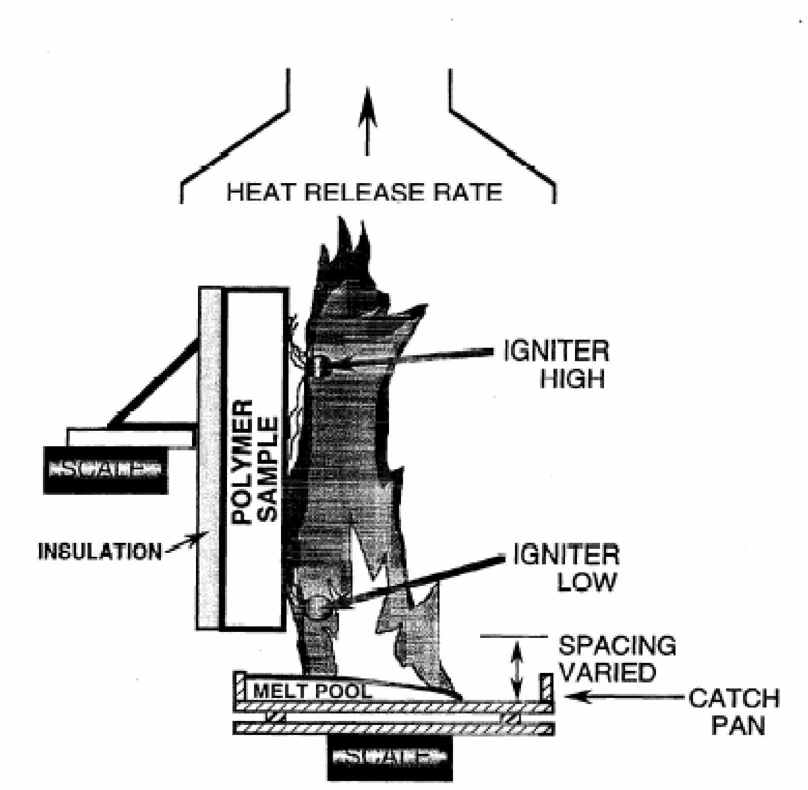

Figure 1. Experimental set-up for polymer melt-drip fire [Ref. 8].

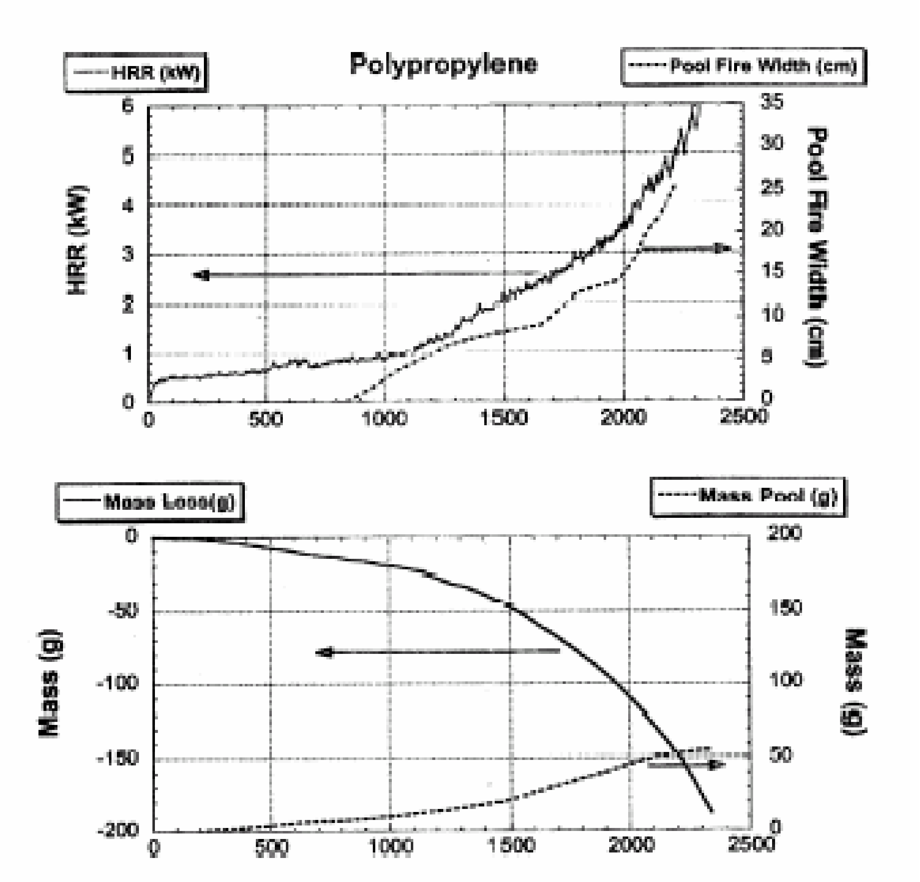

Figure 2. Melt/drip fire behavior of PP, low ignition location, close catch pan spacing [Ref. 8]

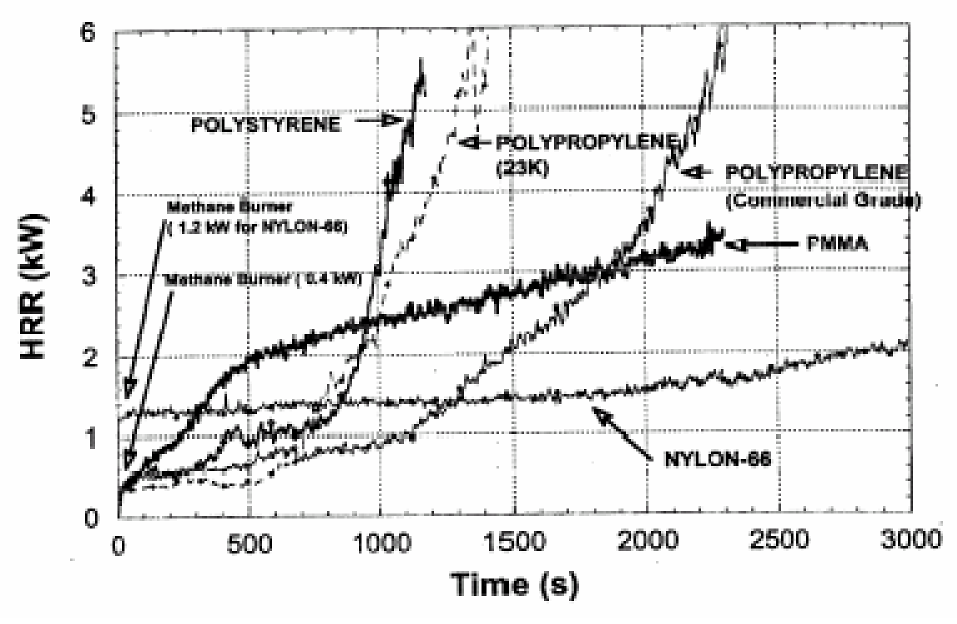

Figure 3. Heat release rate behavior of several thermoplastics, low ignition position, close catch pan spacing [Ref. 8].

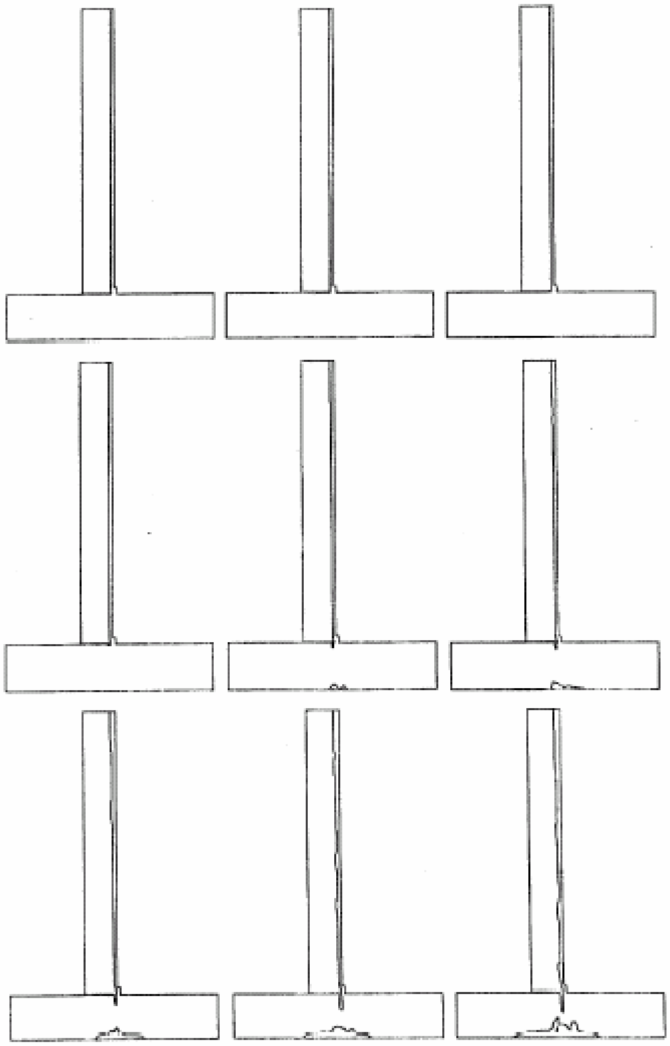

Figure 4. Calculated profiles of low molecular weight PP including dripping into catch basin, from t=20 s to t= 100 s at 10 s intervals without combustion. Incident heat flux on the surface of the vertical PP sample is 20 kW/m^2. [Ref. 8]

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RESEARCH NEEDS FOR ASSESSING THE FIRE SEVERITY IN PERFORMANCE-BASED FIRE RESISTANCE ANALYSES

James A. Milke[1]

Introduction

Fire resistance is a characteristic of a building assembly referring to the ability of the assembly to perform the following two objectives despite exposure to a fire:

- restrict the spread of fire beyond the compartment of fire involvement
- support a load

Restricting fire spread is accomplished by limiting heat transmission to the unexposed side of the barrier and preventing crack development. Heat transmission limits are established to prevent the ignition of combustibles in contact with the unexposed side of the assembly (Schwartz and Lie, 1985). The standard test method, ASTM E119 (2000),[2] expresses heat transmission limits as a maximum increase in temperature on the unexposed side either as 139 °C averaged over the entire surface or 181°C at a single point The ability to support the applied load(s) requires the load-capacity of the structural member to exceed the applied or induced loads and the structural member to maintain its stability. Failure of a load-bearing member may result in local collapse or initiation of progressive collapse.

Typically, fire resistance analyses are performed by conducting a standard test (ASTM, 2000). In the ASTM E119 test standard, the severity of fire exposure is expressed solely in terms of the temperature-time history of the exposure, without reference to the radiative or convective aspects of the exposure. A more recently developed fire resistance test standard, ASTM E1529 (2001), specifies an incident heat flux that is to be applied to the test sample.

The standard test provides a comparative measure of performance and is not intended to predict the response of an assembly exposed to actual fire conditions. Consequently, where an assessment of the expected performance of a building assembly exposed to an actual fire incident is desired, an engineering analysis of the thermal and structural response of the fire-exposed assembly is required. An engineering analysis of the response of fire-exposed structural assemblies involves consideration of:

- fire exposure conditions
- material properties at elevated temperatures of structural members in the assembly
- thermal response of the assembly

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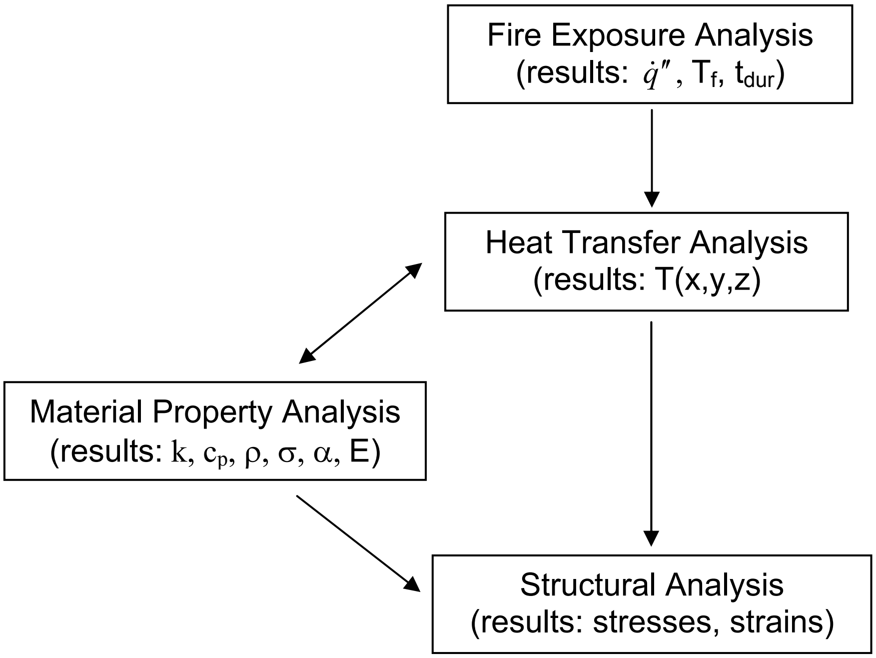
[2] The standard test method is documented in ASTM E119, NFPA 251 and UL 263. For simplicity. the standard test method will be referred to as ASTM E119 throughout this paper.

- structural response of the heated assembly.

The relationship of these four issues in a performance-based design approach for evaluating fire resistance is reflected in Figure 1. The issues are inter-related, *i.e.* a description of the fire exposure provides a description of the boundary conditions for the thermal response analysis and a duration of the proposed fire incident. Results from the thermal response analysis are important for the structural response analysis to determine the temperature rise in the assembly, which affects material properties and results in the development of thermal strains.

Figure 1. Process of Performance-Based Analysis of Fire Resistance



Fire Resistance Analysis Methods

In a recent survey for the American Society of Civil Engineers, Milke and Hill (1997) identified several existing analysis methods to determine the fire resistance of building assemblies. Included in the documentation of these methods is a description of a "natural" fire exposure, i.e. a non-standard exposure as a means of assessing fire severity (Pettersson, *et al.*, 1976)(AISI, 1979)(ECCS, 2001)(ENV 1993, 1995). In these documents, the heat transfer and structural analyses were either described or results provided for a selected group of fire exposures.

Fire Exposure

The fire exposure needs to be characterized in a manner that establishes the boundary conditions for the heat transfer analysis. In addition, the duration of the fire exposure needs to be determined.

In general, acceptable statements of the boundary conditions for heat transfer analyses include either a specified surface temperature or incident heat flux. The incident heat flux can either be explicitly specified or may be implicitly specified by providing the temperature of the exposure and the relevant heat transfer coefficients.

Stipulation of a surface temperature is applicable when the exterior surface temperature of the fire protection material is approximately equal to the exposure temperature, as occurs for steel columns protected with low density insulating materials. This boundary condition is applied in the lumped heat capacity method used to determine the temperature rise in steel columns protected with low density spray-applied protection materials (Lie and Stanzak, 1974).

Another possible boundary condition includes stipulating the exposure temperature in addition to the radiative and convective coefficients associated with the exposure. This statement implicitly describes the incident heat flux on the assembly. An expression for the net heat flux associated with radiative and convective heating conditions is provided in equation (1).

$$\dot{q}'' = F\varepsilon\sigma\left(T^4 - T_s^{\,4}\right) + h_c\left(T - T_s\right) \tag{1}$$

where:

F: view factor

h_c: convection heat transfer coefficient

$\dot{q}''$: heat flux

T: temperature of exposing fire/smoke

T_s: temperature of surface of exposed object

ε: emissivity of exposure

σ: Stefan-Boltzmann constant

This approach is used in most heat transfer analyses applied to assess fire resistance (Pettersson, *et al.*, 1976)(Jeanes, 1982)(ECCS, 2001)(ENV 1993, 1995). Consequently, in order to determine the incident heat flux, the analyst needs information on the temperature of the exposure in the vicinity of the building assembly being studied as well as the convection heat transfer coefficient and emissivity of the exposure.

The last means of stipulating the boundary condition is to specify the incident heat flux explicitly. This is commonly applied for cases where radiation is the only mode of heat transfer, such as structural members exposed to radiation from a flame plume from a pool fire. Harmathy's normalized heat load approach is an example of specification of a heat flux (1981). Recent efforts by an SFPE task group involved in developing a design guide to estimate heating conditions for performance-based fire resistance analyses have indicated that a constant heat flux may also be specified as an upper limit to describe the heating conditions associated with fully-developed compartment fires.

Research Needs

Research needs for fire severity are best presented for the specific scenarios considered in fire resistance analyses. Hurley (1999) described three categories of scenarios for fire resistance analyses:

- exposure of interior structural members to fully-developed compartment fires
- exposure of exterior structural members by flame projections from fully-developed compartment fires.
- exposure of structural members to localized, but not fully-developed, fires

Fully-developed Compartment Fires

Traditionally, an expression of fire severity for compartment fires is based on the temperature within the compartment. For example, the Swedish design guide by Pettersson, etal. adopted a set of figures from Magnusson and Thelandersson (1970) that presented temperatures for ventilation-controlled, fully-developed compartment fires as a function of fuel load and ventilation.

For use as a boundary condition, specification of a temperature in the compartment may also require the convection heat transfer coefficient and emissivity. Some guidance is available in the literature on an estimate of the emissivity (Tien, et al., 1995). Often, a value near 1.0 results such that a black body assumption may provide a reasonable estimate of the heating conditions. However, while a value for the convection heat transfer coefficient in the furnace test is suggested (Milke, 1995), little information is available on a reasonable value for the convection heat transfer coefficient in fully-developed compartment fires. Further, unlike the emissivity, a value for the coefficient which provides an estimate of a “most severe” condition does not exist. The lack of guidance on the convection heat transfer coefficient is often dismissed as being unimportant because convection heat transfer is not the dominant mode of heat transfer in fully-developed compartment fires.

The approach by Magnusson and Thelandersson is based on a well-stirred reactor model of the interior environment. The method is applicable to situations where natural ventilation was provided by one or more openings positioned on the same wall of the room.

The well-stirred reactor model assumes that the conditions are uniform throughout the space. Consequently, all structural members in the space are assumed to receive the same thermal insult. Thomas and Bennetts (1999) observed significant variations in the behavior of fires in large spaces or for spaces with high aspect ratios. Neither uniform burning nor uniform temperatures was observed. While the maximum temperatures observed were comparable to predictions using a well-stirred reactor model, the observed duration of the exposure was significantly greater than that predicted using the well-stirred reactor model.

Generally, the duration of the exposure is estimated by the ratio of the fuel load to the mass loss rate. The significant studies of fuel load were conducted several years ago, with the most recent study conducted in the 1970's (Culver, 1976). Fuel composition has changed notably in contemporary office buildings from the initial fuel load survey conducted in the 1940's. Usage of interior spaces has also changed appreciably, especially in the office environment where computers are present at most workstations and desks and chairs are comprised of synthetic materials (and less steel and wood). Large open-office pools of clerical workers have been replaced by open-offices with portable partitions.

In summary, the research needs to assess the fire severity for fully-developed compartment fires include:

- assess the applicability of the well-stirred reactor assumption for spaces
- develop methods to assess the local exposing temperature for those situations where the well-stirred reactor model does not apply
- review applicability of correlations of burning rate for a broad range of fuels
- conduct experiments to study fire development in spaces with openings on multiple walls or from a combination of natural and mechanical ventilation
- confirm the accuracy of fuel load estimates for contemporary buildings from previous surveys especially office buildings where changes in fuel load have intuitively experienced a significant change from the era of the previous surveys
- develop insights for radiative and convective heat transfer coefficients in fully-developed compartment fires.

Exterior Fires

This scenario envisions an exposure of exterior structural members to radiation from flame projections from windows in addition to radiation from internal compartment fires that is emitted through the window opening. Based on work by Law (1978), a design guide has been available for over 20 years to assess the exposure of exterior structural members by flame projections from interior compartment fires (AISI, 1979). Recently, this method was incorporated into the Eurocodes (1995). Law's method requires an estimate of the length of the flame projecting from a ventilation opening based on an empirical correlation. The empirical correlation is based on compartment fires involving wood cribs. The method also considers the estimate of radiation from the flames inside the compartment based on a well-stirred reactor model. In addition, the correlations are based primarily on fires in compartment fires with natural ventilation from a single ventilation opening.

In summary, the research needs to assess the fire severity for exterior fires:

- study flame projections from windows, relative to the dimensions of the compartment, fuel composition, and ventilation characteristics.
- See list for fully-developed compartment fires.

Localized Fires

Localized fires are associated with situations involving a non-fully-developed compartment fire or an exterior fire involving a liquid pool or a storage commodity. An SFPE task group has developed a guide on analyzing the hazard posed by thermal radiation from pool fires (SFPE, 1998). Stipulating the heat transfer boundary condition in this case can be done either by specifying the heat flux emitted from the fire either explicitly or implicitly. A explicit statement of heat flux can be estimated as the product of the radiation fraction and the heat release rate of the fire. The radiation fraction for hydrocarbon pool fires is provided by Mudan and Croce (1995). The implicit statement of heat flux requires that the plume temperature and emissivity are known. Plume temperatures can be estimated from plume centerline temperature correlations (Heskestad, 1995).

In summary, the research needs to assess the fire severity for localized fires include:

- determine the radiation fraction for a broader range of fuel arrays.

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FIRE RESISTANCE RESEARCH NEEDS FOR HIGH PERFORMING MATERIALS

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ABSTRACT

In recent years, there has been a growing interest in the use of high-performing materials (HPM), such as high strength concrete (HSC) and fibre-reinforced polymers (FRP), in civil engineering applications. HPM are often used as structural members in buildings, without fully addressing the fire related issues. At present, there is very little information available on the performance of HPM under fire conditions. Many of the HPM have special characteristics and hence, traditional fire protection measures, as well as conventional fire resistance assessment methods (prescribed in standards), may not be applied to enhance or evaluate their fire resistance. There is an urgent need for the development of fire resistance design guidelines, for the wider application of HPM in buildings and other infrastructure projects where fire resistance requirements are to be satisfied. The research needed for the development of such guidelines include: improved methods for fire resistance assessment; data on material properties (thermal, mechanical, deformation) as a function of temperature; fire resistance experiments on large/full scale structural systems; validated numerical models and parametric studies. The output from this research will be simplified design guidelines that can be incorporated into codes and standards to facilitate integration of fire resistance design with structural design. Undertaking of this research, followed by technology transfer, should lead to wider use of HPM, and result in cost-effective and fire resistant structural systems.

Introduction

Worldwide interest in the use of high-performing materials, such as high strength concrete (HSC), and fibre-reinforced polymers (FRP), in civil engineering applications has increased significantly in recent years. This is mainly due to the advantages, such as high strength and durability (non-corrosive), that HSC and FRP offers over traditional materials, such as normal strength concrete (NSC) and steel (Mufti et al. 1991, Kodur 2000). Further, the costs associated with the use of these HPM in construction have lowered in recent years, thus making them cost-effective in civil engineering projects.

One such HPM is HSC which is widely used in high rise buildings due to the improvements in structural performance, such as strength and durability, as compared to traditional NSC. Generally, NSC structural members exhibit good performance under fire situations. Studies show, however, that the performance of HSC is different from that of NSC and may not exhibit good performance in fire. Further, the spalling of concrete under fire conditions is one of the major concerns due to the low porosity (low water-cement ratio) in HSC. The spalling of concrete (HSC) exposed to fire has been observed under

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laboratory and real fire conditions (Diederichs 1995, Kodur 2000). Spalling, which results in the rapid loss of concrete during a fire, exposes deeper layers of concrete to fire temperatures, thereby increasing the rate of transmission of heat to the inner layers of the member, including to the reinforcement. While many of the design standards for concrete structures have been updated with detailed specifications for the structural design of HSC under normal conditions, there are no guidelines for the fire resistance design of HSC structural members (ACI 1999, CSA 1994).

Another example of HPM is FRP which are used as internal (rebars) or external (wrapping and sheeting) reinforcement in new or exiting (refurbishing) concrete structures because of their high strength, non-corrosive, non-magnetic and light-weight properties. However, preliminary studies indicate that the performance of FRP under fire conditions is well below that of traditional materials. One of the main impediments to using FRP in buildings is the lack of knowledge about the fire resistance of FRP (Kodur and Baingo, 1998).

HPM are being developed to overcome shortcomings in traditional materials and are provided with superior properties under ambient temperatures. This is achieved through significant research activities, funded by organisations such as NSF and CERF, to address the problems related to long term durability and material behaviour of HPM. However, there is not much research, at present, to address fire-related issues of HPM in spite of serious problems with fire performance. Addressing the fire-related issues is critical for the wider application of these HPM in buildings and other infrastructure projects where fire performance requirements are to be satisfied. In this paper the fire resistance research needs for HPM, mainly HSC and FRP, are outlined.

Fire Resistance Requirements

One of the major safety requirements in building design is the provision of appropriate fire resistance to structural members. The basis for this requirement can be attributed to the fact that, when other measures of containing the fire fail, structural integrity is the last line of defence. Fire resistance is the duration during which a structural member (system) exhibits resistance with respect to structural integrity, stability and temperature transmission. Typical fire resistance requirements for specific building elements are specified in building codes (UBC 1995, NBCC 1995).

Fire resistance can play a crucial role in buildings as seen in the collapse of WTC twin towers and surrounding buildings as a result of the September 11 incidents. Many older buildings were generally built with larger cross-sectional areas (required by structural design considerations alone), and with traditional materials, such as concrete and masonry, which enhanced the fire-proofing capacity of the buildings. However, in modern buildings, the use of HPM, together with sophisticated design techniques based on non-linear methods of analysis aimed at optimizing the structural design, often lead to thin structural members, that might result in lower fire resistance characteristics. Hence, there is an urgent need for establishing the fire resistance of structural systems made of HPM.

Fire Resistance of Traditional and High Performing Materials

The fire resistance of conventional materials, such as steel (with appropriate protection) and concrete (NSC), is superior to those of HPM. The fire resistance assessment of these traditional materials is well established and can be made through simplified measures, such as the concept of critical temperature. However, due to inherent properties of HPM, the fire protection and assessment techniques used for traditional materials may not be applied to HPM. This is illustrated by comparing fire resistance assessment and protection techniques for two conventional and two HPM .

Steel Members: When exposed to fully developed fires, fully-loaded unprotected structural steel components attain their critical load-bearing capacity after approximately 15 minutes. Fire protection measures are, therefore, necessary for load-bearing steel structures and is achieved through membrane protection (external insulation) or capacitive protection. The fire resistance of a protected/unprotected structural member is often estimated based on the time required to reach a critical temperature in steel under standard fire exposures.

The membrane mechanism (external insulation) works by delaying the transfer of heat to the steel members. In this method, a fire resistant barrier (insulation) is placed between the potential fire source and the member to be protected. Commonly used insulating materials are: gypsum, pelite, vermiculite fibre, and concrete. Also, intrumescent coatings are often applied in a layer that has the approximate thickness of a coat of paint, to provide the required fire protection.

The method of capacitive protection is based on the principle of using the heat capacity of a protective material to absorb heat. In this case, the supplementing material absorbs the heat as it enters steel and acts as a heat sink. Common examples are: concrete-filled hollow steel columns and water-filled hollow steel columns (Kodur and Lie 1995).

Concrete Members: Concrete (NSC) is less conductive and, therefore, attains higher temperatures at a lower rate than steel. Hence, concrete structural members can often be used unprotected. In reinforced and prestressed concrete structural members, the required fire resistance is generally obtained through the provision of minimum member dimensions and minimum thickness of concrete cover. The minimum concrete cover thickness requirements are to ensure that the temperature in the reinforcement does not reach its critical temperature for the required duration. The critical temperature is defined as the temperature at which the reinforcement loses much of its strength and can no longer support the applied load. For reinforcing steel, the critical temperature is 593°C, while for prestressing steel the critical temperature in 426°C (Lie, 1992). By providing the minimum member dimensions, the unexposed temperatures are kept within the allowable limits for the required fire resistance rating.

If the required fire resistance cannot be achieved with these two provisions, then external insulation, where a fire resistive barrier (insulation) is placed between the potential fire source and the member to be protected, can be used.

HSC Members: The main advantages of using HSC, as a replacement of NSC, are improved durability (corrosion free condition) and strength (thinner structural members).

Hence the current fire resistance criterion for NSC, which is generally obtained through the provision of minimum member dimensions and minimum thickness of concrete cover, may not be applicable to HSC structural systems.

Further, the fire performance of HSC is significantly different from that of NSC due to the occurrence of spalling and faster degradation of mechanical properties at elevated temperature (Phan 1996, Kodur 2000). Spalling results in the rapid loss of concrete during a fire exposing deeper layers of concrete to fire temperatures, thereby increasing the rate of transmission of heat to the reinforcement. The occurrence of spalling limits the use of critical temperature criterion for evaluating fire resistance of HSC structural members. Also, any fire protection techniques for NSC may not be adapted for achieving the required fire resistance ratings of HSC structural members, since spalling will alter the overall response of the system.

FRP reinforced Members: Unlike steel and concrete (NSC), FRP as a material is often combustible and might even alter the fire characteristics. Further, there is wide variation in the composition of FRP (Glass, carbon, aramid) and the orthotropic nature of these materials makes the fire resistance evaluation quite complex and simple fire resistance estimation techniques, such as critical temperature concept, cannot be applied (Gates 1991). Also, commonly used fire protection techniques for concrete and steel may not be adapted for achieving the required ratings of FRP structural members, since there are some major differences, such as combustibility and orthotropic property, associated with FRP as a material (Kodur and Baingo 1999).

Also, in steel-reinforced and prestressed concrete structural members the concrete cover thickness requirements, for the steel reinforcement, are complemented, to a certain extent, by the requirements for corrosion control. For FRP-reinforced concrete structural members, no special concrete cover thickness provisions are required for corrosion control. Furthermore, FRP-reinforced concrete members are often thinner than steel-reinforced structural members, thus the provision of minimum concrete cover to FRP reinforcement to satisfy fire resistance requirements may not be practical or economical (Kodur and Baingo, 1999).

Research Needs

For the effective use of HPM there is an immediate need to develop fire resistance design guidelines for use by the design engineers, architects and regulatory officials. The following research is needed to develop such guidelines.

Fire resistance assessment: There are a number of drawbacks in the current approach of evaluating fire resistance, such as single elemental tests, not accounting for connections and support conditions, and unrealistic definition of failure (basing it on critical temperature of rebars) (ASTM 1988). Hence, the current fire resistance evaluation methods may not be directly applied to HPM due to the complexities (spalling in HSC, burning in FRP) associated with these materials. A new approach should be established and standardised methods be developed, which include evaluating fire resistance based on structural systems and defining failure based on the failure of the overall system (deflection and strength criterion).

Fire growth: The fire growth in the case of structural members made of HPM might be entirely different (as compared to traditional materials) since HPM such as FRP are combustible and alter the fire characteristics, as they act as a fuel source. Hence, for the benefit of design professionals, for use in models and experimental studies, design fire curves should be developed by accounting particular characteristics of HPM.

Computer models: For assessing fire resistance, computer models should be developed, and validated, based on structural systems (not single elements). The models should be flexible enough to allow users to define various scenarios in terms of fire growth, material characteristics (spalling in HSC, burning in FRP) and failure criterion (deflection, strength).

Material properties: For modelling the behaviour of HPM, the effect of heating on the following properties is needed as a function of temperature:

- Thermal properties: thermal conductivity, specific heat, mass loss
- Mechanical properties: tensile strength, compressive strength, modulus of elasticity, ultimate strain
- Deformation properties: thermal expansion, creep
- Transport properties: porosity, pore pressure (for HSC)

Further, many of the HPM (FRP) are combustible and produce off gasses. The toxicity associated with these gasses should also be established.

Experimental studies: To validate the computer models, and to better understand the behaviour of HPM, fire resistance experiments need to be carried out on large/full scale structural systems under realistic fire exposures.

Numerical studies: Using the validated computer models, detailed numerical studies should be carried out to determine the extent of influence of different parameters, such as the concrete cover, on the fire performance of structural systems made of HPM. Data generated from such studies could be used to develop simplified design recommendations, including any additional fire protection measures, for achieving fire resistant systems.

Fire-proofing materials: Since many of the HPM have poor fire resistance characteristics, innovative solutions need to be developed for enhancing their fire resistance properties. This can be achieved either by developing innovative solutions, such as modifying tie configuration and adding fibers to HSC (Kodur 2000, Kodur et al 2002), or by developing innovative fire-proofing materials. Such fire proofing materials should be thoroughly checked for durability characteristics (adhesion, cohesion).

Technology transfer: The above research should lead to: new test methods for evaluating fire resistance; validated computer models for predicting fire resistance performance; innovative fire-proofing materials, fire resistance design guidelines and highly trained professionals. The simplified design guidelines have to be incorporated into codes and standards for design of structural systems.

The technology transfer can be modelled on the same line as that of changes that were implemented into building codes and standards following the San Fernando earthquake in 1971. This should be followed by appropriate training, though seminars, courses etc. of material and structural engineers in fire related design issues. The availability of such guidelines in codes and standards, and trained personnel, will facilitate integration of fire resistance design with structural design. This will lead to wider use of the HPM in buildings and infrastructure projects and result in cost-effective and fire resistant structural systems.

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PERFORMANCE-BASED STRUCTURAL ANALYSIS TO DETERMINE FIREPROOFING REQUIREMENTS: METHODOLOGY, CASE STUDIES, AND RESEARCH NEEDS

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ABSTRACT

A performance-based approach to designing structures for fire resistance is gradually gaining favor as an alternative to traditional prescriptive requirements such as hourly ratings and tables of required fireproofing thicknesses. A performance-based code permits engineers to use thermal and structural analysis to predict the performance of a building during the types of fires it could actually be exposed to rather than a code-specified standard fire. In the USA, performance-based codes have been used for many years in seismic design and other areas of structural engineering, and in the next few years will also be enacted for fire protection design. The methodology for performing these fire analyses is well established and is summarized here. In addition, some typical case studies taken from engineering practice are presented. To make these performance-based methods more accessible and acceptable to practicing engineers and building officials, further research is needed, particularly in identifying high-temperature material properties, codifying approved analytical methods, developing and verifying software, and training engineers in the use of these methods.

Introduction

The basic concept underlying performance-based fire analysis is that a building should be designed for the fire severity that might actually occur in the building rather than for a code-specified "one-size-fits-all" fire such as ASTM E-119. Using factors such as fuel load and ventilation, the maximum credible fire in different locations in the building is calculated and the structural response to these fires is calculated. The key elements of the performance-based approach are:

- Perform a Fire Hazards Analysis to identify all potential fire scenarios and determine the impact of each scenario on adjacent structural members, particularly the fire gas temperatures each member would be exposed to. This involves conducting fire combustion analysis to predict site-specific fire curves (temperature vs. time) and the spatial distribution of these fire curves.

- Evaluate the response of the structural members to the imposed fire hazards assuming varying levels of fireproofing. This involves a Fire Thermal Analysis to calculate temperature history in each member and a Fire Structural Analysis to determine forces and stresses in each member and

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whether local or progressive structural collapse would occur during any of the fire hazard scenarios.

- Where required, develop a risk mitigation plan or revised fireproofing scheme to ensure that performance of the structural system is acceptable for the type of building being designed.

Fire Hazards Analysis

The first step in evaluating a building's response to fire and resulting fireproofing requirements is to perform a Fire Hazards Analysis. All significant individual fire hazards are identified and the resulting fire exposure to surrounding structural elements determined. In line with the general intent of fire codes, the exposure is conservatively developed without taking credit for suppression systems, such as sprinklers. Hazards are worst case credible fires resulting from both fixed and transient sources. A transient hazard could result from trucks or refuse containers that could move about a building. The fire hazards analysis method comprises the following steps:

- Definition of fire areas or compartments to establish how far a fire could potentially propagate within the structure and how much of the structure could possibly be impacted by the fire.
- Identification of potential fire hazards and ignition sources within each fire area. These could be from ordinary building contents, fuel tanks, or possible terrorist attacks or arson.
- Definition of potential fire scenarios (sequence of fire ignition, propagation to adjacent combustibles, and the intensity of the resulting fire).
- Calculation of the resulting exposure temperatures as a function of time for structural members in the vicinity of the postulated fires.

Characterizing a fire scenario requires defining the amount of material involved in the fire, the intensity of burning, and the location of the fire and its plume with respect to targets (structural members). The burning characteristics of materials involved in the scenarios can be derived from published data from the Society of Fire Protection Engineers and a variety of other sources and are based on conservative interpretation of fire test data for actual combustion materials. For each scenario these calculations result in a time-temperature curve for the hot gases in the fire. Also calculated will be how fire temperatures decrease at varying distances from the center of the fire if flashover does not occur. These fire curves serve as input for the next phase of analysis, predicting temperatures in the structural members.

Fire Thermal Analysis

Structural members exposed to hot gases from fires gradually heat up and can reach very high temperatures. The temperature rise always lags the fire temperature because of the thermal inertia inherent in the material and the tendency for heat to flow to cooler material adjacent to the heated area. Fireproofing or other forms of insulation, of course, can greatly slow the temperature rise in protected steel. When the fire starts to cool, the temperature drop in a structural member will lag the falling gas temperature, again because of thermal inertia and fireproofing.

Basic heat conduction theory can predict temperature history in fire-exposed structures when thermal material properties of concrete, steel and insulation are known. The heat conduction field equation for a three-dimensional steel member is:

$$\rho \, C \; \partial T / \partial t \; + \; K \, \nabla^2 \, T = Q \tag{1}$$

where

ρ = density of steel
C = specific heat capacity of steel
T = temperature distribution in member
t = time
K = heat conductivity of steel
Q = heat input into member
$\nabla^2 (\,)$ = $\dfrac{\partial^2 \; (\,)}{\partial x^2} + \dfrac{\partial^2 \; (\,)}{\partial y^2} + \dfrac{\partial^2 \; (\,)}{\partial z^2}$

In a fire, the heat input is due to a combination of convection and radiation into the fire-exposed surfaces. This heat flow can be calculated using the equation:

$$Q = A \, [C \, (T_f - T_s)^N + V * \sigma \, (\alpha \varepsilon_f \theta^4{}_f - \varepsilon_s \theta^4{}_s)] \tag{2}$$

where

A = surface exposed to fire
C = convection coefficient
N = convection power factor
V = radiation view factor
σ = Stefan-Boltzmann constant
α = absorption of surface
ε_f = emissivity of the flame associated with fire
θ_f = absolute temperature of fire (°R)
ε_s = surface emissivity
θ_s = absolute temperature of surface (°R)
T_f = fire exposure temperature
T_s = surface temperature

There are a number of finite element computer codes that solve the heat conduction field equation with this fire boundary condition. The code most commonly used is FIRES-T3 (Iding 1977). All of these codes discretize the field equations into a set of linear equations expressed by the matrix relationship.

$$[C]\,\{\dot{T}\} + [K]\,\{T\} = \{Q\} \tag{3}$$

where

$[C]$ = Capacity matrix (temperature-dependent)
$[K]$ = Conductivity matrix (temperature-dependent)
$\{Q\}$ = External heat flow vector (depends on exothermic reactions and fire boundary conditions)
$\{T\}$ = Temperature vector (time-dependent)

The FIRES-T3 code uses an iterative approach to account for the nonlinearities in the fire boundary condition in Equation 2.

All thermal analyses start with discretizing the structural members into finite elements and defining boundary conditions, both fire-exposure boundaries and other boundaries where heat may escape from the member into adjoining parts of the structure or into the environment. The thermal material properties are defined for all components of the model and the time-dependent fire curve (gas temperature T_f) from the particular fire scenario to be considered is specified. The equations are then solved to obtain the temperature history in all parts of the structural member during the fire. Such temperatures form the basis for a structural analysis of each member and the structure as a whole.

Fire Structural Analysis

Once the maximum temperature loading in each structural member is known, calculations to determine the structural response of these members to the fire can be made, particularly to determine whether any member will fail during the fire. Standard structural analysis methods and computer codes can be used, but they must take into account the special characteristics of materials at high temperatures:

- Thermal expansion (coefficient of expansion multiplied by temperature change), which can be very large in a fire. When there is restraint acting very large stresses can be generated by this thermal expansion, leading to buckling or crushing.
- Effect of temperature on material properties, such as modulus of elasticity and yield strength. When steel becomes hot enough the yield point can drop so much that the member cannot support the loads on it during the fire and collapse will occur. The degradation of yield strength with temperature for A36 mild steel is shown in Figure 5. It can be seen that between 1000°F and 1100°F, the yield point has fallen to only 60% of its room-temperature value. Typical maximum design loads produce about 60% of yield stress, so collapse of a fully loaded member could occur once this temperature is reached, although most steel structures would be much more lightly loaded during a fire and would fail at higher temperatures.

- High-temperature steel creep. Increase in deflection in a flowing manner when loads are not increased is called creep. Steel does not creep at normal temperatures, but when the material reaches 1100°F-1300°F creep becomes important.
- Nonlinear behavior. Structural response during a severe fire can quickly lead to high stresses, yielding, creep and local or general failure. A complete analysis must take these nonlinear effects into account.

Several computer programs were specifically designed to model these special high-temperature phenomena, including FIRES-RC II (Iding 1977) and FASBUS II (Iding 1987 and 1990). General purpose linear programs can sometimes also be used, particularly if steel temperatures are not very high or if there is little restraint to thermal expansion.

Simplified approaches are also possible. For example, in relatively unrestrained steel members, a temperature threshold can be set (typically 800°F-1000°F) at which the yield point is well above the stresses the member must carry during the fire and the member can be considered acceptable. This is the type of acceptance criterion used in ASTM E-119 furnace tests when assemblies are not loaded during the test.

Case Study Number 1 - Transient Trash Fire in Power Plant

The subject of this case study is a steel braced-frame power plant located in Healy, Alaska. The entire power house enclosure can be considered one very large fire compartment, with the exception of the plant administrative and control area separated from the rest of the enclosure by rated fire-resistive occupancy separation walls and doors. The steel-framed enclosure is as high as a 20-story office building. However, its behavior in a fire will be very different since only its lower portions can be impacted by any possible fire. The upper reaches of both the interior and exterior of the frame are not close to combustible materials. In addition, the space inside the enclosure is so large that flashover and other characteristics of compartment fires cannot occur. Therefore, prescriptive code requirements for fireproofing, which are based on the ASTM E-119 compartment fire, are not well suited for designing the fire protection for most of this structure. A performance-based approach which looks at the actual fire exposures this building could be subjected to can give a more rational and economic design.

There are a very large number of both fixed and transient fire hazards to be considered in this plant and much calculation was necessary to determine the effects of each one on the structural steel frame. Some examples of these hazards are shown in Figures 1 through 4 (Lee 1996). To demonstrate the performance-based analysis procedure, one typical fire hazard will be studied here in some detail.

The fire hazard to be examined is a transient trash or refuse fire. Such a fire can occur when transient combustible materials come into contact with ignition sources such as hot surfaces, portable heaters, hot slag from welding and cutting operations, or carelessly discarded cigarettes. A pile of refuse could accumulate wherever there is a floor or grating to support the transient material. Therefore, this is an important scenario to consider since there are many places in the structure which could be impacted by a fire of this type. If the refuse is placed directly against an unfireproofed steel column, and the fire were large enough, the structural integrity of that column might be affected.

The first step in the analysis is to conservatively estimate the quantity of transient material that could be adjacent to a column. The fuel package selected is typical maintenance refuse composed of a cardboard box, Kimwipes, acetone, and a plastic wash bottle. The burning characteristics of this fuel package (about 110 Btu/sec heat release rate) were calculated, from which the gas temperatures of the fire plume impacting the surface of the column were also calculated (Lee 1996), as shown in Figure 6. Note that for this fuel load the fire duration is about 13 minutes and the peak plume temperature is 1600°F. Also note in Figure 6 that the temperature of the gas enveloping the column decreases at higher elevations above the fire, so that only the first few feet of column above the refuse pile are exposed to very high temperatures.

The next step in the analysis is to determine the temperature rise in the steel column itself during the trash fire. A three-dimensional heat conduction analysis using FIRES-T3 is performed for a typical bare, unfireproofed W14 x 90 column, which is the smallest size column in the steel frame and, therefore, would be most severely affected by the trash fire. Also modeled is the base plate and adjacent concrete slab. Note that a fully three-dimensional thermal analysis is necessary here because heat transfer along the length of the column must be considered as well as convective losses from the steel to the surrounding air. Such three-dimensional analysis produces much more accurate results when only a localized area is exposed to fire heat input. In this case, it is assumed that the trash is piled at ground level against one side of the column's web and adjacent flanges, thereby exposing these surfaces to the full radiation from the fire, as expressed in Equation 2. The finite element model is shown in Figure 7 and makes use of the symmetry of the fire and associated heat flow.

Calculated temperatures within the hottest cross-section of the column (about 18 inches from the floor) are plotted in Figure 8. Maximum steel surface temperature of 900°F is reached after 13 minutes of fire exposure, after which the fire begins to cool. Average temperature within the hottest steel cross-section peaks at 715°F, also at 13 minutes of fire exposure.

The final step in the analysis is a structural evaluation of the ability of the steel column to support superposed load when subjected to these temperatures. In this case, temperatures are so low that complex nonlinear failure analysis is not needed. At 715°F, the A36 steel columns retain more than 90% of their room-temperature yield strength (Figure 5), so there can be no significant weakening of the frame from this fire scenario. In addition, the configuration of this frame and its connections will not offer much restraint to the thermal expansion in the columns and thermal stresses would not be important. Therefore, these columns will continue to support full design loading demands at these steel temperatures.

The fire hazard analysis for a typical transient trash fire shows that such fires are too small to significantly affect the load bearing capacity of columns anywhere in the steel frame, even if they are unfireproofed. Therefore, spray-on fireproofing is not necessary for this fire hazard.

Case Study Number 2 - Fireproofing Requirements for the Eiffel Tower II

The Eiffel Tower II in Las Vegas, Nevada, as shown in Figure 9, is a half-scale replica of the original Eiffel Tower in Paris. The primary structure is comprised of steel tubular members which were originally intended to be left bare with no spray-on fireproofing, as was the case on the original Eiffel Tower. However, early in the design process questions were raised about fire safety and compliance with prescriptive building codes. Since this structure was completely unlike typical steel high-rise buildings and would not be subjected to the type of fire envisioned in the code, it was a perfect candidate for performance-based analysis.

Working with the local building officials, credible fire scenarios were postulated, including several based on possible terrorist attack and arson. Following the methodology discussed earlier, fire time-temperature curves were developed for each of these scenarios and affected steel members identified. Since members were relatively light and unfireproofed, thermal analysis was not necessary because steel temperatures would closely follow fire gas temperatures with minimal thermal lag. Maximum steel temperatures in affected members for four different fire scenarios are shown in Figure 10, including a truck fire at the base of one leg and a contents fire in the casino or elevated restaurant. Structural analyses were conducted using the same computer model developed for the general design of the tower by inputting thermal expansion and taking into account loss of steel strength at elevated temperature. An iterative process was followed, conservatively removing or softening members as they buckled, yielded, or fractured. If a stable equilibrium taking into account removed or compromised members could be found, then one could be confident that the tower would not go into progressive collapse from the fire scenario and damage would be localized. This iterative approach was used because a fully nonlinear analyses using one of the specialized fire computer programs was not economically feasible for a structure of this size. After examining all the fire scenarios it was decided that portions of the structure near ground level and above the restaurant and casino areas needed fireproofing and that these areas should be protected by intumescent paint. The majority of the tower would not be adversely affected by fire and was left unfireproofed.

Recommendations for Research

Performance-based fire codes and associated analysis will not find universal acceptance as easily as seismic analysis has. Earthquake structural analysis arose unrestrained by previous practice. Buildings had essentially not been designed specifically for earthquakes, and engineers, architects and building officials gratefully adopted the new methods as they found their way into engineering literature and the building codes. Performance-based fire analysis, however, finds the field already occupied by a long established prescriptive code based on a hundred years of furnace tests and engineering practice backed by a huge industry. The new methods must be highly developed and extensively verified before they can supplement or replace the traditional methods. The following types of efforts would aid in this process:

- Better identification of material properties at elevated temperatures, particularly those of spray-on fireproofing and intumescent paint.
- Research on the performance of structural connections in fires and the development of analytical tools to evaluate such connections.
- Development of peer review protocol for the transitional period when performance-based analysis is first being presented to building officials.
- Incorporation into commercial computer codes the basic capabilities to conduct fire analysis, especially as nonlinear programs come into greater use. This is necessary if fire is to be treated as an additional load case that must be considered in building design.
- More exposure of engineering students and practitioners to the basics of structural fire performance and analytical methods to predict it. Sponsorship of workshops and seminars for non-specialists.
- Some sort of codification of methods to calculate fire curves for the most common fire scenarios so design engineers do not have to engage a specialist for routine structural design.
- More emphasis on examining the fire safety of a building as a whole. Current practice is to consider the fire safety of individual building elements (floor assemblies, columns, etc.) without considering how the fire response of each assembly affects the rest of the building. Research is needed to develop practical methods to avoid progressive collapse in a severe fire and incorporate them into future performance-based codes.

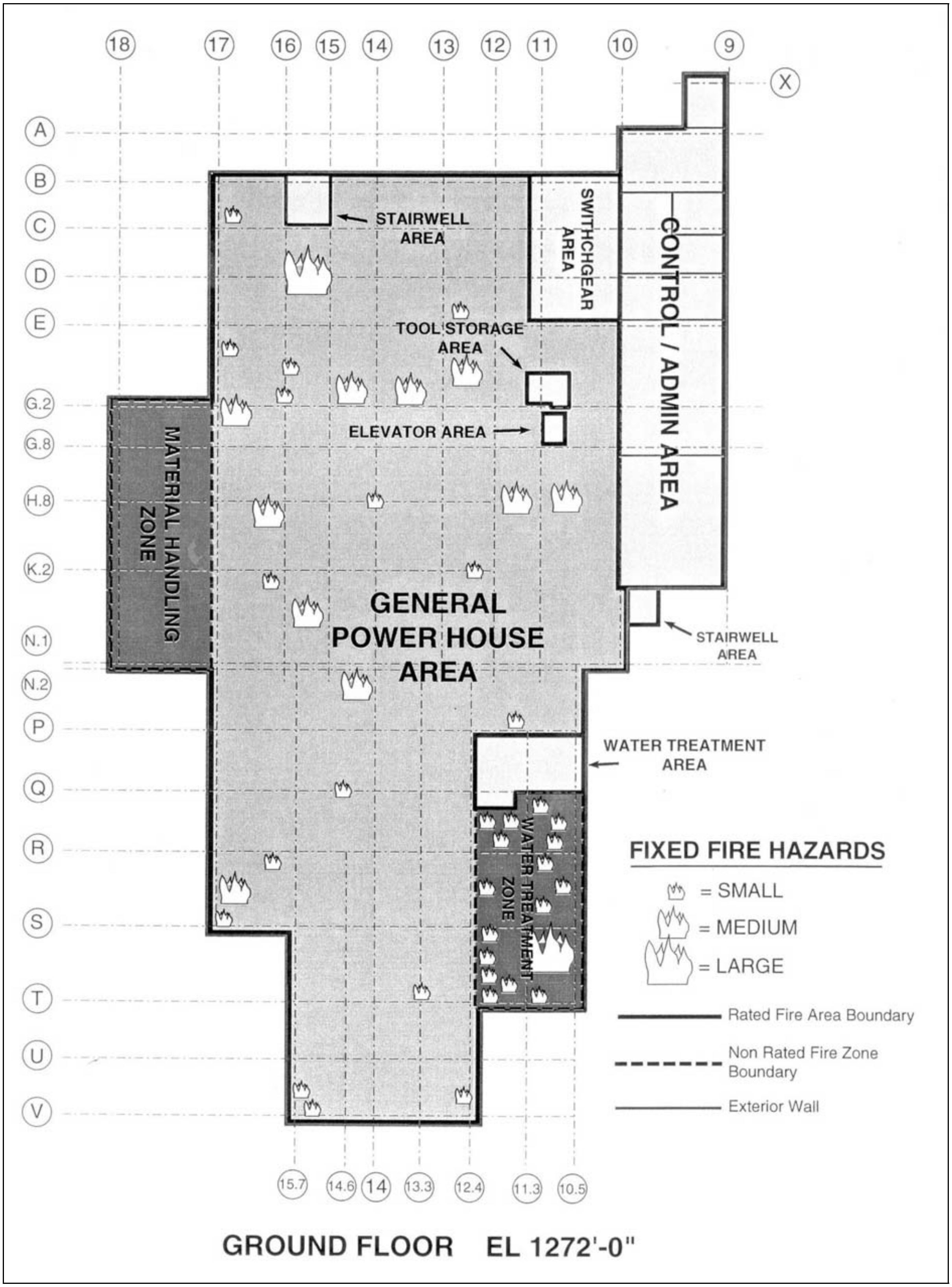

Figure 1. Fixed Fire Hazards on Ground Floor of Healy Power Plant.

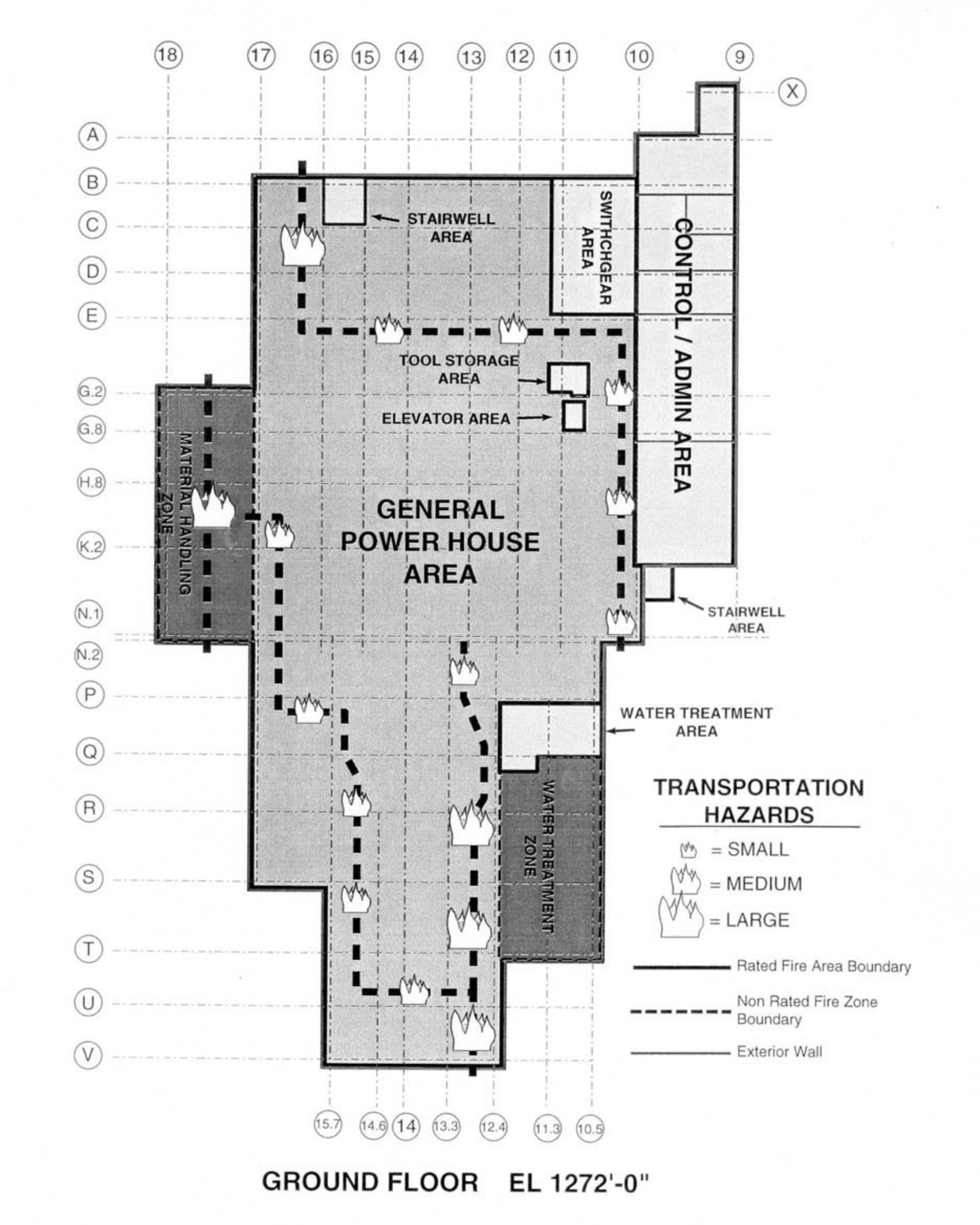

Figure 2. Transportation Fire Hazards on Ground Floor of Healy Power Plant.

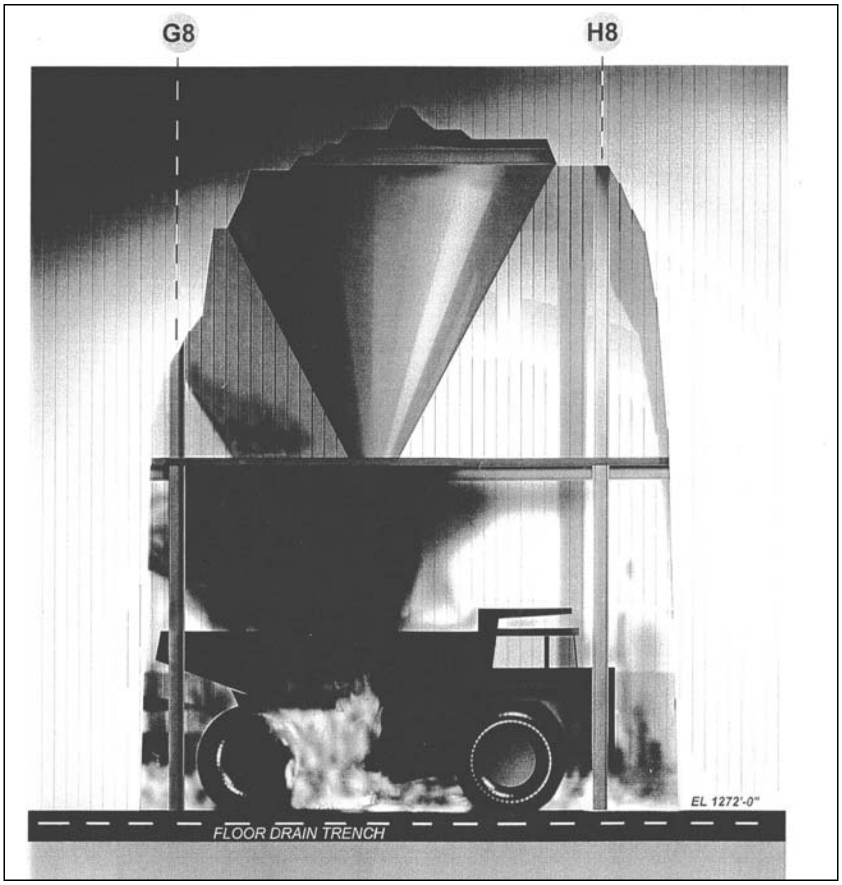

Figure 3. Large Truck Fire Scenario.

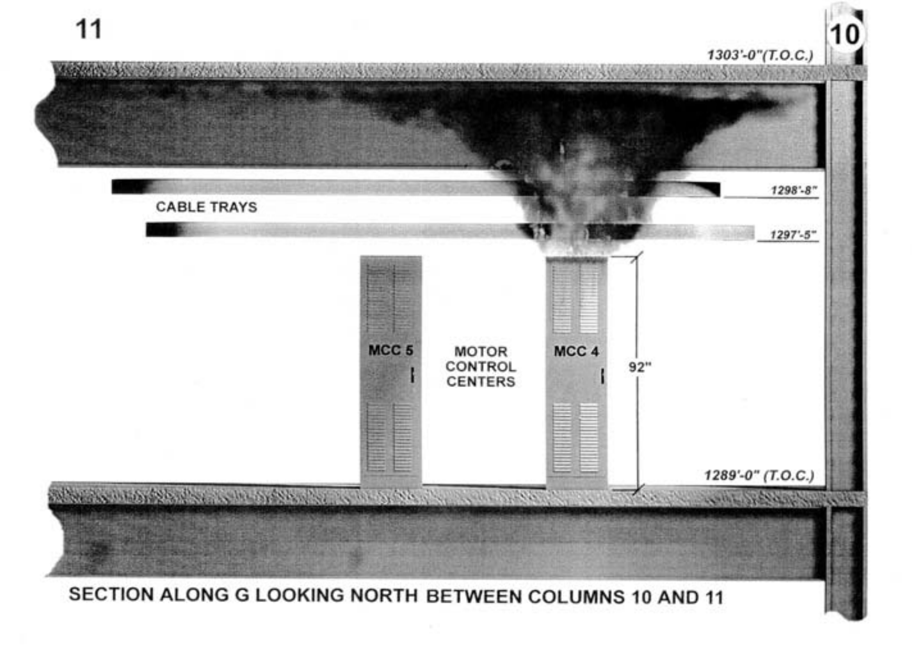

Figure 4. Motor Control Center Fire Scenario.

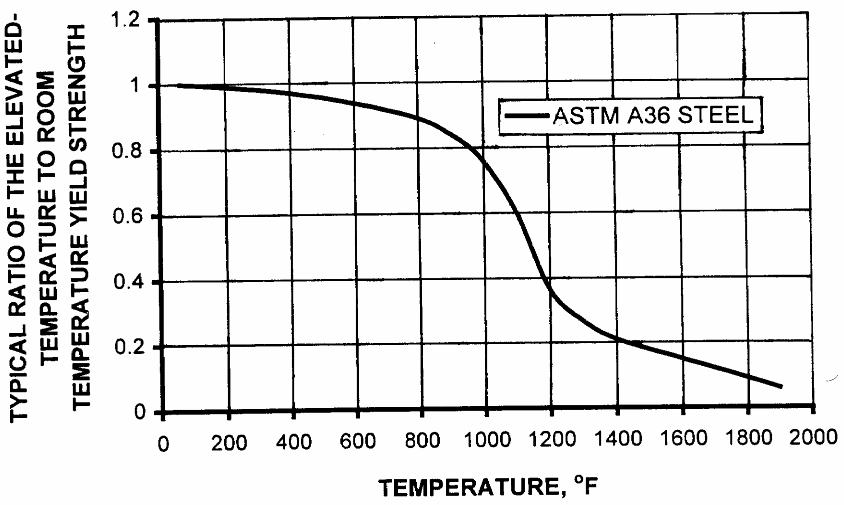

Figure 5. Effect of Temperature on the Ratio Between Elevated-Temperature and Room-Temperature Yield Strength of Steel.

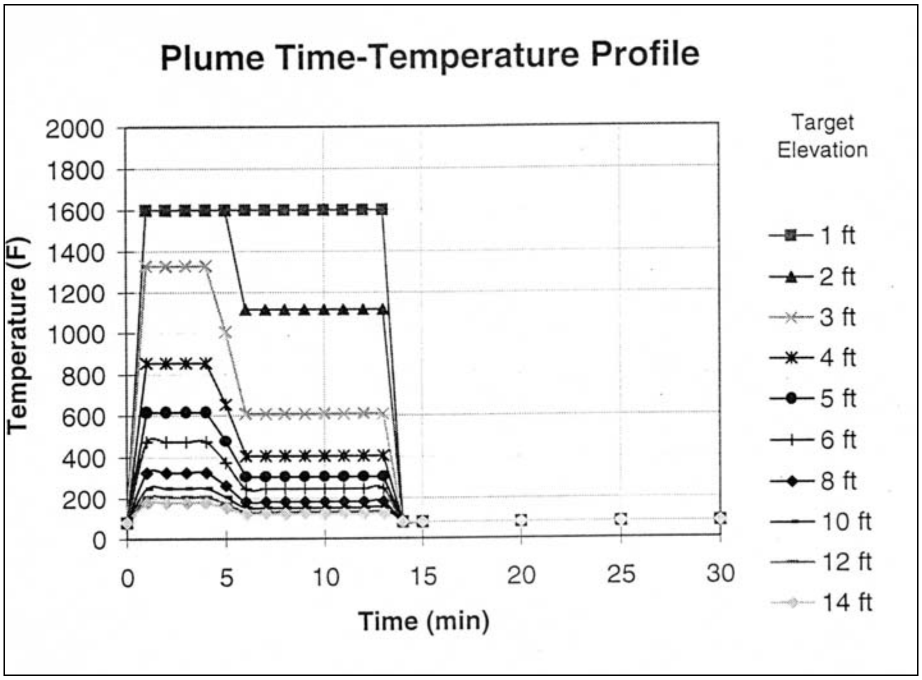

Figure 6. Column Exposure Temperatures from Maintenance Refuse Fire.

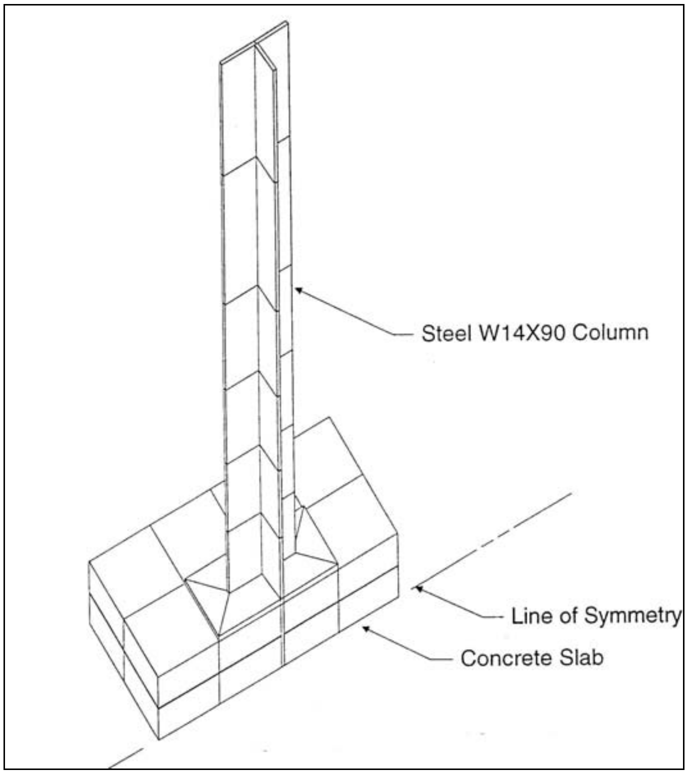

Figure 7. Column, Adjacent Base Plate and Floor Slab Discretized into Finite Element Mesh.

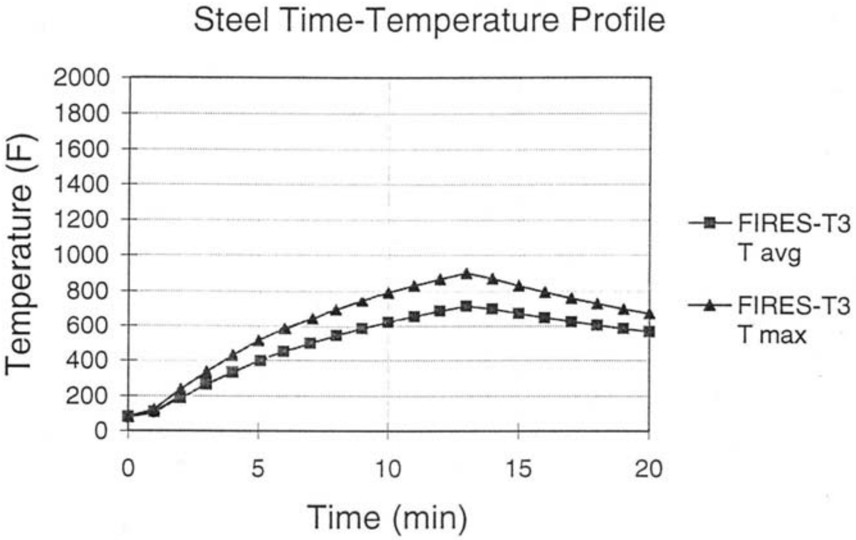

Figure 8. Steel Temperature History for Maintenance Refuse Fire.

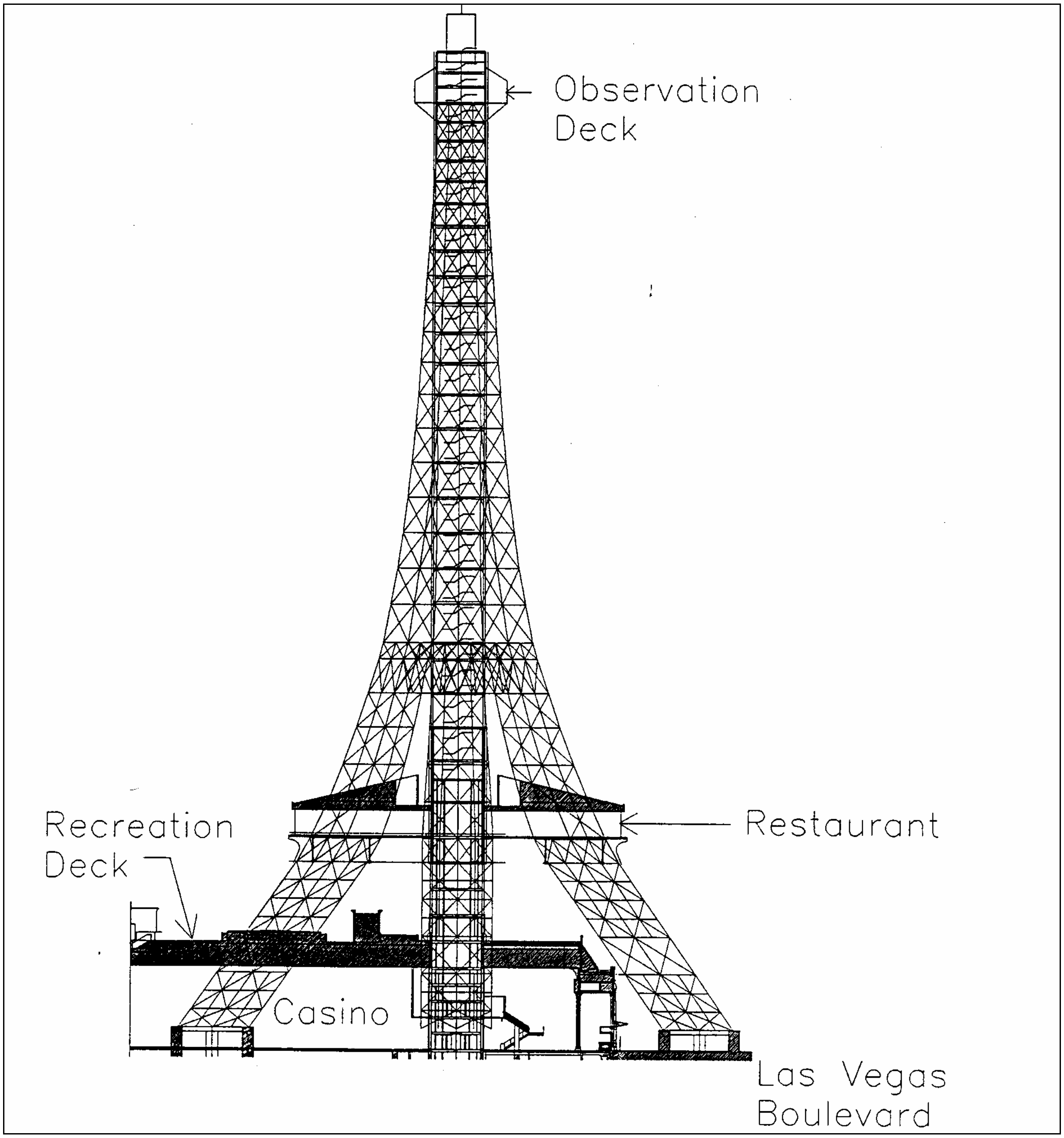

Figure 9. Eiffel Tower II.

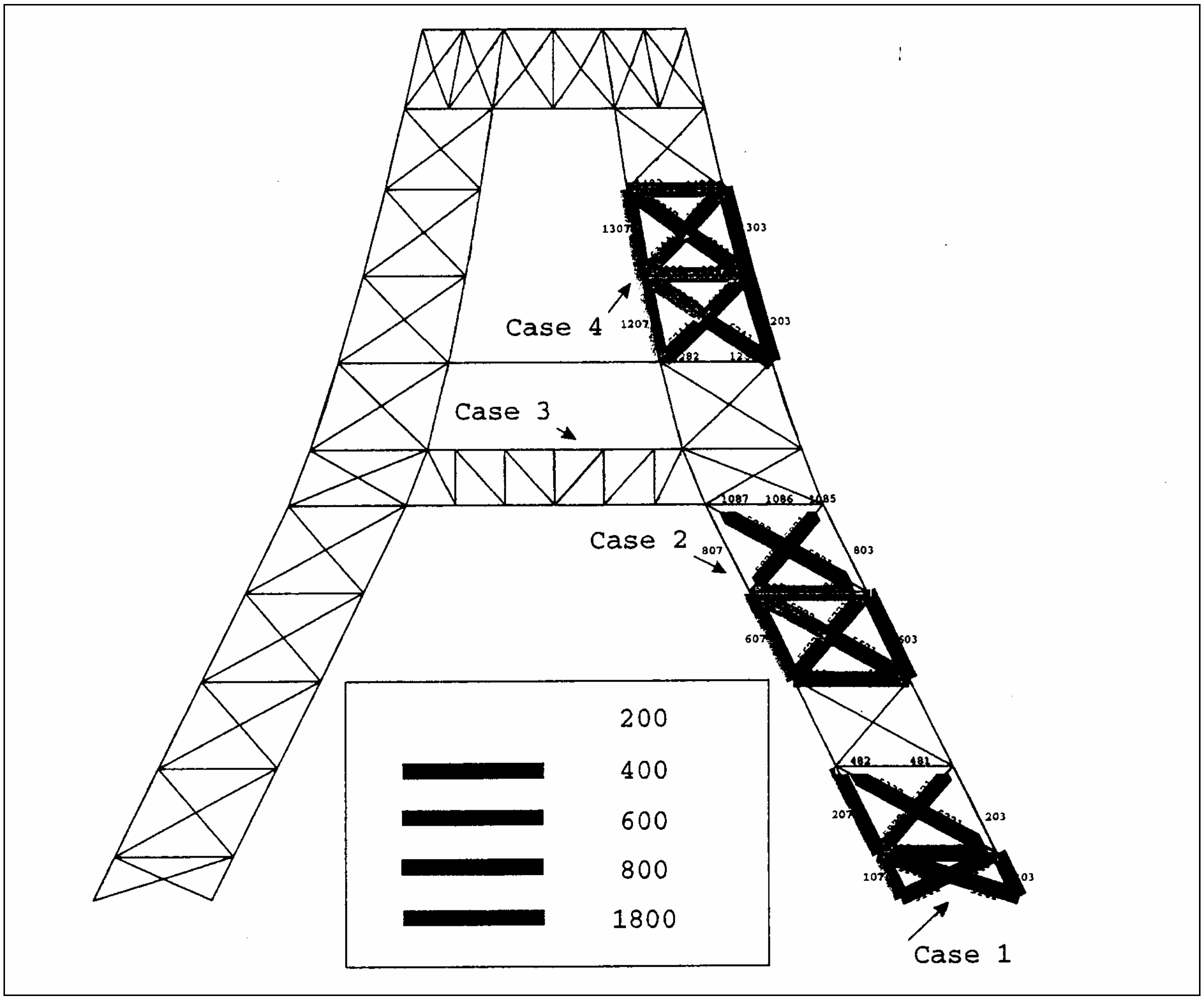

Figure 10. Calculated Steel Temperatures in Eiffel Tower II for Four Fire Scenarios.

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Structural Fire Protection

The current practice in structural fire protection in the US is based on test methods developed a hundred years ago and test requirements developed on the basis of the fire science of the 1920's. While changes in the test methods and the requirements have evolved over the years, the bases and principles have not changed. Thus, the opportunities for significant innovation in reliable and cost effective structural fire protection are great.

NAS workshop papers and presentations in the area of structural fire protection were provided by Milke, Iding, and Kodur. The committee thanks these individuals for their contribution to the work of the committee.

Historical Perspective

At the turn of the century there was intense interest in structural fire protection as a result of many severe urban fires that destroyed whole areas of the respective cities. Furnace test methods to assess the structural performance of elements of building assemblies were developed and over time the many different furnace testing protocols were integrated to form the basis of the furnace test methods used throughout the 20th century. Out of this process arose the standard time-temperature exposure curve that is still used today (AISI 1979). In the 1920's Ingberg, at the National Bureau of Standards, developed test duration requirements in the then standard time-temperature exposure based on expected fuel loads for various occupancies (Ingberg 1928). These developments predated modern fire science and do not reflect our modern understanding of the role of ventilation on the severity of fires environments.

In the 1950's Kawagoe and others recognized the role of ventilation in fire severity. The buoyant flow of air to support combustion was mathematically modeled by Kawagoe (1958) and the primary role of the opening factor, $A\sqrt{H}$, was recognized. A is the area of the opening and H is the height of the opening. In the decade or two following this work, a full mathematical description of fully developed fires emerged based on conservation of energy for the compartment, using the air flow model of Kawagoe, heat conduction through the bounding materials, and simple radiative/convective heat transfer modeling (Kawageo and Sekine 1963, Odeen 1963, Magnusson and Thelandersson 1970, Babraukas and Williamson 1978) By the early 1970's, hundreds of tests had been conducted throughout the world and several fire models were being used to predict the outcomes of these tests. The most ambitious experimental program was organized by Phillip Thomas under the auspices of the CIB (Thomas and Heselden 1972). During this time, it was widely recognized that the existing standard time-temperature curve did not represent real fully developed fire conditions. In most cases the standard exposure was less severe than real fires, though the standard exposure was generally longer than real fires.

At the same time, heat transfer and structural analysis methods based on finite difference and finite element methods were emerging, fueled by the ever-growing computational capabilities of computers. By the end of the 1960's, computational methods for predicting the heating and deformation of steel and reinforced concrete building elements were available and in use in research and advanced engineering practice.

Sweden recognized the value of scientifically based structural fire protection design, and undertook the development of a national structural fire protection design method based on the modern science in the 1970's. By 1976 Sweden had a modern structural fire protection infrastructure in place (Pettersson et.al. 1976). Similar methods had evolved worldwide during this period and at least one textbook (Lie 1972) reflected the modern methods.

In the US and elsewhere the old prescriptive methods continued to be used in building code requirements. While the modern analytical methods had been developed, the building code community did not embrace the technology. As a result, the methods never came into general use. Even today, analytical methods in structural fire protection are only used in special circumstances.

The reliance on antiquated methods results in uncertain performance and inefficient design. Many buildings are likely significantly overprotected while others may not be capable of resisting fire threats to the extent generally expected. This represents an opportunity to significantly improve structural fire protection design methods. At the same time, the lack of attention to technology transfer in earlier decades points to potential pitfalls that need to be addressed.

Outstanding Technical Issues

While a significant technical basis for structural fire protection design is available, research in this area has been ignored in the US for decades. As a result, there is work that needs to be done to recreate a technical basis for 21st century design. While the work in the 1960's and 1970's was of high quality in its day, the work does not satisfy current standards of experimental and theoretical research. While structural fire protection has been ignored as a research area, available applicable computational and experimental methods have changed monumentally in the past decades. There is a need to bring the methods of the 1970's up to date with modern methods. In addition, the changes in materials and construction methods over the decades has left holes our basic knowledge base. Finally, research over the past decades has shown that the 1970's scientific knowledge of structural fire protection was incomplete in ways that are significant in engineering practice. These issues are discussed below in the context of the three basic areas involved in structural fire protection: fully developed fire exposure, heat transfer to and through the structural elements, and the structural response of the element and the structural system to the effects of the fire.

Fire Exposure to the Structure

The existing methods for predicting fire exposure assume that a compartment fire can be characterized as a well-stirred reactor with a single compartment temperature. While this is a reasonable characterization for small compartments with small aspect ratios, there are questions about its applicability to many significant situations in practice. Work in recent years by Thomas and Bennetts (1999) has demonstrated that for large aspect ratio compartments, fires first burn vigorously near the vent and the burning region propagates into the compartment as fuel is consumed near the vent. This gives rise to variations in the time-temperature exposure throughout the compartment. These observations indicate that there may be a need to assess fire resistance on the basis of both a global exposure as well as a local exposure. The global exposure is much like the traditional approach, with a local exposure dictated by the proximity to vent openings and the local fuel load. This bears further attention.

In large spaces, like open plan offices, the evidence from real fires like the First Interstate Bank (Nelson 1989) is that fire growth times are a significant fraction of the overall burning duration for an individual floor. Classical methods treat the fire growth time as insignificant. As such, under these circumstances fire exposures predicted tend to be shorter, but more intense than an actual fire. There is very limited understanding of fire spread in large spaces like open plan offices. There are other large spaces such as industrial facilities in which the idea of a fully developed fire throughout a space is simply not realizable. The notion of flashover is simply not an observed phenomenon and the classical methods that assume the entire space to be involved in fire will most often overestimate the actual fire severity. The trend over the decades to larger and larger industrial and commercial spaces makes investigation of large compartment fire phenomena a very relevant issue.

Beyond these new issues, there are lingering problems in the classical methods even within their range of applicability. All the available models use some form of combustion efficiency parameter to reduce the energy output to achieve agreement with experiments. The model by Babrauskas(1979) uses a combustion efficiency directly, but all the other methods have the effect represented in one manner or another. Typically, the combustion efficiency is in the range of 0.5 to 0.9 (Babrauskas, 1981), with 0.7 the most commonly used value. This range of combustion efficiencies can lead to a very wide range of temperatures and even the nominal value of 0.7 represents an empirical factor reducing the energy output by 30% from the theoretical value. The limited available evidence points to several factors that contribute to this value, so that careful experimentation and analysis will be required to develop an understanding of this significant factor.

Heat Transfer

While modern computational methods in heat transfer are generally capable of fulfill the requirements for heat transfer analysis for structural fire protection, there remain issues to be addressed in this area. Most pressing among these are the development of methods for measuring thermal and mechanical properties of materials over the temperature range of significance in fire. Thermal properties of insulating and structural materials are sometimes available, but the temperature range is generally limited and the methods used have not been fully developed and validated. Much of the data is quite old and modern materials replaced better characterized old materials. A notable example of the effect of innovation in materials can give rise to serious structural fire protection effects is the use of high strength concrete that is very prone to severe spalling (See Kodur). The continuing changes in materials and methods requires ongoing attention to fire issues. Some insulating materials like intumescents require additional study to fully characterize their performance. If well validated test methods were available for property measurements, this would facilitate wider characterization of material properties that are needed to support structural fire protection design.

Mechanical properties of insulating materials have been identified as a largely ignored area of concern. Insulating materials need to be sufficiently robust to remain in place through the abuse of construction and the life of the building, so that the insulation will be in place when they are needed to protect the structure from fire. Beyond this, the materials must possess sufficient mechanical strength to remain in place through the course of the fire exposure. The events of 9/11 have highlighted these issues. There has been little study of the mechanical properties of insulating materials needed to resist ordinary insults. The effect of blast and aircraft impact on the mechanical stability of insulating materials has certainly not been studied adequately. During a fire, it is also known that the standard furnace exposure is less severe in terms of mechanical forces and thermal shock than are many realistic fires. This leaves open the possibility that insulating materials may perform well in the standard test, but fail to remain in place during a more severe, but realistic fire exposure. These issues need to be addressed.

Structural Response to Fire

It has long been recognized that non-linear structural analysis is needed to understand the effect of fire on structural elements. Today there is a rich array of commercial codes generally capable of the required analyses for fire applications. These have, to a limited extent, been applied to fire problems and some comparisons with full scale fire exposure data are available in the scientific literature. While these tools are not in wide application in structural engineering design, the challenges in this area are to validate the available methods and to develop high temperature properties for modern materials.

However, there are additional issues that require serious attention. Current testing methods do not consider structural connections. The design, analysis and protection of structural connections is an area in which there is only a modest technical basis. Here again, the events of 9/11 have highlighted these issues. In WTC 5, there was significant evidence of failures at connections during fire exposure. Any 21st century analysis and design methodology will need to treat these issues, and significant research will be required to support this area.

Current fire testing of structural fire protection methods involves the testing of individual structural elements or subassemblies. Failure criteria employed in the tests bear no direct relationship to the structural environment in which that element or subassembly will be used. There are attempts to deal with issues of restraint, but even here there is only a phenomenological link to the actual structural system design. Clearly, routine testing of full structural assemblies is not feasible or necessary. However, it is important to develop and validate methods to integrate the effects of fire on the structural system as a whole, so that failure modes due to fire that cause unacceptable structural collapse can be avoided. While it is unlikely that full non-linear analysis of the structural system is needed, there is a need to develop and validate means of including local non-linear effects into a full system analysis.

Fire Test Methods

As discussed previously, current structural fire protection design depends entirely on test methods, like ASTM E-119, and prescriptive requirements in the building code. In the context of the issues raised above, there is a need to revisit the E-119 test method itself and its role in structural fire protection generally. It is well known that E-119 does not provide a fire environment as severe as is possible in real fire situations. The time-temperature exposure is much less severe in the early portions of the test and the time rate of change of temperature is modest relative to many fires. A more severe test, like UL 1709, is used in some applications to test the performance of structural fire protection systems. In particular, several years ago the US Navy changed from the E-119 to the UL 1709 exposure for qualification of structural fire protection systems for shipboard use. This change eliminated some systems from use due to their inability to remain in place during the more severe fire exposure.

Beyond the particulars of the test methods, the entire role of furnace fire testing in structural fire protection bears review and assessment. A modern approach to structural fire protection would involve the use of small scale tests to measure thermal and mechanical properties for use in models. The models would form the basis for analysis and design. The role of furnace fire testing would, in this approach, serve the role of validation of the combined performance of small scale material characterization tests and the fire/thermal/structural modeling of the fire exposure and response. Such validation might require significant changes in the way tests are performed. Currently, assemblies are not tested to failure. If they pass the failure criteria through the desired duration, the test is stopped without failure. This, of course, would not test the ability of the analytical method to predict the failure mode. Testing to failure may be required in a modern furnace test method.

Potential for Breakthroughs in Structural Fire Protection

While the prior section has identified several areas of required research, it also clearly illustrates that science-based structural fire protection design is definitely technically achievable. As noted previously, the challenges of technology transfer need to be taken seriously.

The environment to make the change to science-based structural fire protection design has never been more favorable. The events of 9/11 have highlighted the issues both in the engineering community and our society at large. There has been wide coverage in newpapers, magazines, and television shows of the role of structural fire protection issues in the 9/11 tragedy. In particular, several months ago an article on the role of the E-119 furnace test in structural fire protection appeared in the N.Y. Times (Glaser et.al. 2002). Prior to 9/11, such an article was unthinkable.

Beyond the broad coverage of the issue in the popular press, the events of 9/11 have motivated organizations like the Amercian Society for Testing and Materials (ASTM), Underwriters Laboratory (UL), American Society of Civil Engineers (ASCE), Society of Fire Protection Engineers (SFPE), and the National Institute for Standards and Technology (NIST) to reexamine the practice of structural fire protection design in the US. The report of the Federal Emergency Management Administration (FEMA) report on the World Trade Center (WTC) tragedy specifically identified the need for study of structural fire protection (FEMA 2002).

This motivation builds upon preexisting commitments in the engineering community to improve the practice of structural fire protection design. ASCE and SFPE had a joint project underway prior to 9/11 to bring together existing knowledge in this area to improve engineering practice. Prior to 9/11 NIST had planned a workshop on structural fire protection with the intention of focusing research in this area. The report of the workshop, held in February 2002, provides a focus of research, education, and technology needs in structural fire protection (Grosshandler 2002).

All these factors point to a general appreciation for the need for change by organizations and institutions that are needed to transfer scientific knowledge to standards and methodologies needed for advancement of the practice of structural fire protection design. NSF has a key role to play in this process.

NSF is the home of academic scientific research funding in this country. Through its role in this research area, NSF will bring scientific credibility to the process, and will attract academic researchers needed for both research and training of the next generation of structural fire protection designers. Beyond this, NSF has experience in other emerging structural engineering areas like earthquake engineering that will facilitate the process of conducting and implementing breakthrough scientifically-based engineering methods.

Not only does NSF have experience in similar emerging areas, but also is a player in multi-hazard and extreme event hazard analysis. There are clear interconnections with these efforts. In fact, fire is a significant factor in damage due to earthquakes and the research in this area of earthquake engineering has been lacking. Direct focus on structural fire protection would also generate technical interest and synergies in other multi-hazard areas of importance to NSF.

Structural fire protection clearly is a clear challenge and opportunity for NSF and the nation. This is a unique time in history to address this challenge. NSF, downstream engineering organizations, and our nation as a whole are motivated and prepared to undertake a coordinated attack on this problem.

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The Fire Problem

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Unwanted fire has always been a problem but the nature of the problem has evolved over the centuries. Since people began living in cities large conflagrations have occurred fairly regularly. A classic example is the Great London Fire of 1666, which combined with the plague made life miserable as well as exceptionally hazardous. Despite the fire Londoners were not benefited by tax-supported fire services until the 1860's. Beginning at about that time in the United States steps began to be taken to reduce the chances of large multi-building fires. By 1900 the first building codes came into play calling for building separations, fire walls, escapes and the like. Water mains had been placed appropriately to give some assurance that fire services had sources of water to pump onto fires. The result: relatively few widespread conflagrations have occurred since. (Those that have include the San Francisco fire (1906) due to earthquake, the Baltimore fire (1904), and two fires at Chelsea, MA.)

Attention then turned to reducing the severity of fires within individual buildings, given ignitions. Test methods and standards began to specify levels of fire resistance for structural members and some interior finishes. By mid-century large, multi-occupancy buildings had columns and beams of a given level of resistance to heating from fires, stairwells are protected by fire doors, standpipes bring water to upper floors, and sprinklers and various detectors stand guard. As a result we rarely lose entire large buildings to fire. (The disaster at the World Trade Center had a cause so severe as to overcome the fire and life safety provisions of the building code.)

And yet in the late 1960's and early 1970's the Congress of the United States became sufficiently concerned about unwanted fire that they enacted several pieces of legislation aimed at reducing the Nation's fire losses. Why?

Some answers are in the Report of the National Commission on Fire Prevention and Control, a Congressionally chartered group to assess the fire problem and recommend remedial actions. The Commission reviewed the loss picture and presented the following figures (ref.1):

12,000 deaths
300,000 injuries
$11.4 costs

In addition, firefighters were being killed at a rate of near 200 a year and suffered injuries at the incredible rate of 39.6 per hundred per year.

The Commission said that the United States led all civilized nations in the world in per capita deaths and injuries: death rates near twice those of Canada the second worst performer and costs one third higher than the Canadians.

The Commission attributed these dreary figures to ignorance, carelessness, and lack of an emphasis on prevention in community governments and the fire services themselves.

The report led to passage of the Federal Fire Prevention and Control Act of 1974. The Act established the Fire Administration, the Fire Academy, and the Fire Research Center at the National Bureau of Standards. This was the first serious attempt at a Federal presence in the fire safety arena.

At the Fire Research Center we set about to analyze the dominant causes of losses due to unwanted fires through analysis of fire scenarios. (ref.2) By studying the available information we concluded that most losses in terms of fatalities and associated injuries occurred in residences. The reasons soon became apparent. Single family residences were not very well controlled by building and fire codes as compared to large multi-occupancy buildings. In the home there were open stairwells, few regulations as to materials used in furnishings, no sprinklers, and in those days few to no detectors. Few people had home fire extinguishers. And there were many different ignition sources also poorly covered by any sort of standards or codes. The initial NBS fire research programs were tailored to provide technology for intervening in the various scenarios. A Fire Research Plan was published (ref.2) to inform the community of the directions we were heading.

Now, over a quarter of a century later, where are we? Are we still the world's worst in terms of per capita losses? Do we have a better handle on the root causes? Let's have a look.

The National Fire Protection Association annually publishes a digest of fire losses in the United States. The most recent figures (ref 3) are for the year 2000:

Deaths	4045 (3445 in residences)
Injuries	22,000
Costs	$11.2 billion

We should note that the figure for deaths in "America Burning" were subsequently revised, in 1977 (ref.4), from 12,000 to 8800, the difference being in the deaths attributed to transportation fires; these were dramatically reduced. The drop since then is over 50%. A lowering of losses by 50% in about 14 years (ref. 1, p8) was the goal enunciated in "America Burning". The goal taken later by the Fire Research Center was 50% fewer deaths by the end of the century. That has been attained.

Note also that the figures for injuries have changed. In America Burning, I believe the injuries were for all burns reported to hospitals or public health officials. When these are restricted to unwanted fire they drop by over half. When fire fighter injuries are removed we find the level of civilian injuries from fire in the range of between 20,000 and 30,000 a year.

The cost figures also have been worked over several times. The total depends on how figures are computed for direct and indirect fire losses. A study funded by the NIST Center for Fire Research in 1991(ref.5) put the total at well over $100 billion. This figure included direct costs, and indirects for insurance, fire services, the extra costs in buildings and materials for complying with fire safety provisions in the codes, and the like. The total is about ten times the direct costs.

The path to lower figures for deaths is shown in Figs. 1 - 3 obtained from John Hall at NFPA. Fires in residences (Fig.1) continue to dominate the fatality data. The international data (Fig.2) show the U.S. and Canada dominating the death rates and declining steadily. The surprise is that Japan's data have risen to match the U.S. in recent years. Fig.3 shows the principal causes of fire and of fire deaths. Whereas cooking causes most fires, smoking causes most deaths. Two fairly recent papers (ref 6. and 7.) present details. Table 1 taken from ref. 6 breaks down losses by equipment involved in fires in the home, reflecting CPSC's interests in products. Table 2 shows the primary cause of fatalities is consistently smoke inhalation. The final NFPA chart from John Hall (Fig.4) I found startling: most fire service responses are now for HazMat incidents and Emergency Medical emergencies. Only 8.3% of calls are for fires.

Various workers have sought detailed explanations for fire losses in different occupancies, in different parts of the country, and in different ethnic populations. NFPA every year discusses some aspect of the fire loss figures. Phil Schaenman, first director of the fire data group at the U.S. Fire Administration, has spent a lot of effort and time over the past twenty five years developing an understanding of the underlying factors. Every study of the differences between the United States data and those of countries in Europe and Asia conclude that the attitude of the state and the public is key. In Japan it has long been a serious social offense to have a fire on one's property; until fairly recently it was a crime. Investments in fire prevention and in the fire services are sufficient to provide superior equipment, education, and training. Schaenman notes that the fire losses for Hispanics in various countries are low - about half that of the U.S. But when they emigrate to the U.S. the rates rise. But is this because of attitudes, or different housing, more flammable furnishings and the like. There is a lot to be learned at this level of detail.

How does one decide if the current loss figures are too high and if so by how much? Back in 1974 we took the first goal of reducing fire deaths by half, but we knew that if we could do that it would not be the end - that we would then have to set a new goal. Since we are still doing poorly compared to most other countries there remains room for more reduction. How much? Will it be good enough to match, say, Great Britain? Japan?

I suspect we would want to keep going. Even one death from a fire that didn't need to happen would be unacceptable. Thousands are certainly so.

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