MAKING THE NATION SAFE FROM FIRE

A PATH FORWARD IN RESEARCH

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

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

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

THE NATIONAL ACADEMIES PRESS 500 Fifth Street, N.W. Washington, DC 20001

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This study was supported by Grant No. 0135915 between the National Academy of Sciences and the National Science Foundation. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the authors and do not necessarily reflect the view of the organizations or agencies that provide support for this project.

International Standard Book Number: 0-309-08970-0 (paperback)
International Standard Book Number: 0-309-52581-0 (PDF)

Available from:

Board on Infrastructure and the Constructed Environment
National Research Council
Keck Center
500 5th Street, N.W.
Washington, DC 20001

Additional copies of this report are available from the National Academies Press, 500 Fifth Street, N.W., Lockbox 285, Washington, DC 20055; (800) 624-6242 or (202) 334-3313 in the Washington metropolitan area; Internet, <http://www.nap.edu>.

Printed in the United States of America

THE NATIONAL ACADEMIES

Advisers to the Nation on Science, Engineering, and Medicine

The National Academy of Sciences is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Bruce M. Alberts is president of the National Academy of Sciences.

The National Academy of Engineering was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. Wm. A. Wulf is president of the National Academy of Engineering.

The Institute of Medicine was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Harvey V. Fineberg is president of the Institute of Medicine.

The National Research Council was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Bruce M. Alberts and Dr. Wm. A. Wulf are chairman and vice chairman, respectively, of the National Research Council.

www.national-academies.org

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

DAVID LUCHT, *Chair*, Worcester Polytechnic Institute, Worcester, Massachusetts
CRAIG BEYLER, Hughes Associates, Inc., Baltimore
DAVID COLLINS, American Institute of Architects, Cincinnati
FRED DRYER, Princeton University, Princeton, New Jersey
KEN DUNGAN, Risk Technologies, LLC, Knoxville, Tennessee
OFODIKE "DK" A. EZEKOYE, University of Texas at Austin
WILLIAM FEINBERG, University of Cincinnati, Cincinnati
CHARLES KIME, Arizona State University East, Mesa
JOHN LYONS, U.S. Army Research Lab (retired), Mt. Airy, Maryland
FRED MOWRER, University of Maryland, College Park
ELI PEARCE, Polytechnic University, Brooklyn
JUDY RIFFLE, Virginia Polytechnic Institute and State University, Blacksburg
JAMES T'IEN, Case Western Reserve University, Cleveland
BETH TUBBS, International Conference of Building Officials, Northbridge, Massachusetts
FORMAN WILLIAMS, University of California at San Diego, La Jolla
TOM WOODFORD, Oklahoma State University, Stillwater

Staff

RICHARD G. LITTLE, Director, Board on Infrastructure and the Constructed Environment
JASON DREISBACH, Research Associate
DANA CAINES, Financial Associate
PAT WILLIAMS, Senior Project Assistant

BOARD ON INFRASTRUCTURE AND THE CONSTRUCTED ENVIRONMENT

PAUL GILBERT, *Chair*, Parsons, Brinckerhoff, Quade, and Douglas, Seattle
MASSOUD AMIN, University of Minnesota, Minneapolis
RACHEL DAVIDSON, Cornell University, Ithaca, New York
REGINALD DESROCHES, Georgia Institute of Technology, Atlanta
DENNIS DUNNE, California Department of General Services, Sacramento
PAUL FISETTE, University of Massachusetts, Amherst
YACOV HAIMES, University of Virginia, Charlottesville
HENRY HATCH, U.S. Army Corps of Engineers (retired), Oakton, Virginia
AMY HELLING, Georgia State University, Atlanta
SUE McNEIL, University of Illinois, Chicago
DEREK PARKER, Anshen+Allen, San Francisco
DOUGLAS SARNO, The Perspectives Group, Inc., Alexandria, Virginia
WILL SECRE, Masterbuilders, Inc., Cleveland
DAVID SKIVEN, General Motors Corporation, Detroit
MICHAEL STEGMAN, University of North Carolina, Chapel Hill
DEAN STEPHAN, Charles Pankow Builders (retired), Laguna Beach, California
ZOFIA ZAGER, County of Fairfax, Virginia
CRAIG ZIMRING, Georgia Institute of Technology, Atlanta

Staff

RICHARD G. LITTLE, Director, Board on Infrastructure and the Constructed Environment
LYNDA L. STANLEY, Executive Director, Federal Facilities Council
MICHAEL COHN, Project Officer
DANA CAINES, Administrative Associate
JASON DREISBACH, Research Associate
PAT WILLIAMS, Senior Project Assistant

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 contributes 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, 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 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.

REFERENCES

International Code Council (ICC). 2001. ICC Performance Code for Buildings and Facilities, December. Falls Church, Va.: International Code Council.

National Fire Protection Association (NFPA). 2003. Building Construction and Safety Code, NFPA 5000, 2003 edition. Quincy, Mass.: National Fire Protection Association.

Society of Fire Protection Engineers (SFPE). 2000. SFPE Engineering Guide to Performance-Based Fire Protection. Bethesda, Md.: Society of Fire Protection Engineers.

1

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, the 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, and
- 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.

REFERENCES

The Geneva Association. 2002. *World Fire Statistics*. Information Bulletin No. 18.

Hall, J. 1999. *The Total Cost of Fire in the United States Through 1996*. Quincy, Mass.: National Fire Protection Association.

Lyons, J.W. 2002. The Fire Problem. Paper prepared for the Workshop to Identify Innovative Research Needs to Foster Improved Fire Safety in the United States. April 15-16. Washington, D.C.: National Research Council.

National Commission on Fire Prevention and Control (NCFPC). 1973. *America Burning.* Washington, D.C.

Quintiere, J.G. 2002. Deterministic Models for Fire Protection Engineering: The Thermal and Fluid Mechanics of Fire. Paper prepared for the Workshop to Identify Innovative Research Needs to Foster Improved Fire Safety in the United States. April 15-16. Washington, D.C.: National Research Council.

Society of Fire Protection Engineers (SFPE). 2000. *A Research Agenda for Fire Protection Engineering.* Bethesda, Md.: Society of Fire Protection Engineers.

SFPE. 2002. *Federal R&D for Fire Protection Engineering: A Baseline Report*, March. Bethesda, Md.: Society of Fire Protection Engineers.

2

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 (including formal fire safety programs) can be viable.

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).
- 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).

---

[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.

- 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 on which 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 11 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 and 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 approach 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.

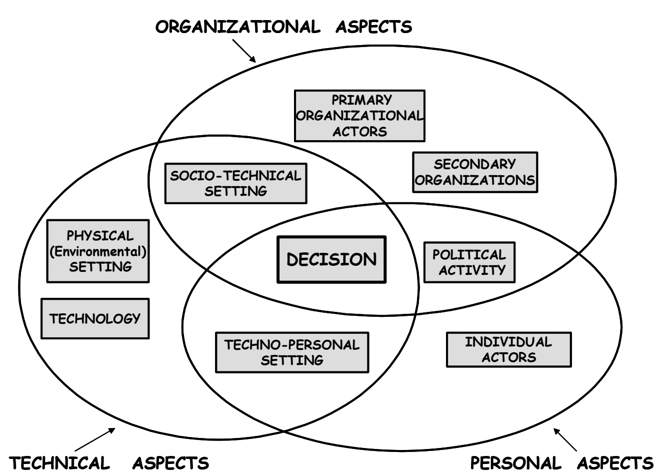

FIGURE 2.1 A sociotechnical system view for decision making (Linstone, 1984).

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).

REFERENCES

Applied Technology Council (ATC). 2002. ATC-58 Project: Development of Performance-Based Seismic Design Guidance. Available at http://www.atcouncil.org/pdfs/WorkPlanP1-073102.pdf [April 3, 2002].

Arnold, C. 1998. Reducing Earthquake Risk: NEHRP at the End of the 20th Century. Testimony to the United States House of Representatives, Committee on Science Subcommittee on Basic Research: Hearings on the National Earthquake Hazards Reduction Program. Washington, D.C. Available at http://www.wsspc.org/publicpolicy/nehrp/arnold_022399.htm [April 3, 2003].

Cutter, S. 2001. *American Hazardscapes: The Regionalization of Hazards and Disasters.* S. Cutter, ed. Washington, D.C.: Joseph Henry Press.

Federal Emergency Management Agency (FEMA). 2002. *World Trade Center Performance Study: Data Collection, Preliminary Observations, and Recommendations*. FEMA 403. Washington, D.C.: Federal Emergency Management Agency.

Hall, J. 1999. *The Total Cost of Fire in the United States Through 1996*. Quincy, Mass.: National Fire Protection Association.

International Code Council (ICC). 2001. ICC Performance Code for Buildings and Facilities, December. Falls Church, Va.

Joint Fire Science Program (JFSP). 2002. 2002 Business Summary. Available at http://jfsp.nifc.gov/2003business_summary.pdf. [April 7, 2003].

Linstone, H. 1984. *Multiple Perspectives for Decision Making: Bridging the Gap Between Analysis and Action.* New York, N.Y.: Elsevier Science Publications.

National Research Council (NRC). 2002. *Living on an Active Earth: Perspectives on Earthquake Science*. Washington, D.C.: National Academy Press.

Petak, W.J. 2003. Earthquake Mitigation Implementation: A Sociotechnical System Approach. 2003 Distinguished Lecture, 55th Annual Meeting of the Earthquake Engineering Research Institute, February 5-8, 2003, Portland, Oreg.

United States Fire Administration (USFA). 2001. United States Fire Administration's Fire Research Agenda. Submitted to the Committee on Commerce, Science, and Transportation of the United States Senate and the Committee on Science of the United States House of Representatives. Available at http://www.usfa.fema.gov/downloads/doc/agenda.doc. [April 7, 2003].

USFA. 2003. 102 Firefighter Deaths in 2002. Available at http://www.usfa.fema.gov/inside-usfa/media/03-005.cfm [April 25, 2003].

United States Geological Survey (USGS). 2002. Deaths from Earthquakes in the United States. Available at http://neic.usgs.gov/neis/eqlists/us_deaths.html [December 9, 2002].

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 the 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 p.m. **Materials and Retardant Issues**

Moderator: 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

Kathleen Almand
Executive Director
Society of Fire Protection Engineers
7315 Wisconsin Avenue
Suite 1225W
Bethesda, MD 20814
Phone: (301) 718-2910
Fax: (301) 718-2242
kalmand@sfpe.org

Arvind Atreya
Professor
University of Michigan
2158 G.G. Brown Building
Department of Mechanical Engineering
Ann Arbor, MI 48109-2125
Phone: (734) 647-4790
Fax: (734) 647-3170
Aatreya@engin.umich.edu

Howard Baum
NIST Fellow
NIST
100 Bureau Drive, Stop 8663
Gaithersburg, MD 20899-8663
Phone: (301) 975-6668
howard.baum@nist.gov

Craig Beyler
Technical Director
Hughes Associates, Inc.
3610 Commerce Drive, Suite 817
Baltimore, MD 21227-1652
Phone: (410) 737-8677
Fax: (410) 737-8688
cbeyler@haifire.com

David Collins
Manager, Codes Advocacy Program
AIA
316 W. Fourth St.
Cincinnati, OH 45202
Phone: (513) 621-2109
Fax: (513) 621-7297
pregrp@aol.com

Paul Croce
Vice President and Manager of Research
FM Global Research
1151 Boston-Providence Turnpike
Norwood, MA 02062
Phone: (781) 255-4910
Fax: (781) 255-4028
paul.croce@fmglobal.com

Fred Dryer
Professor, Mechanical and Aerospace Engineering
Princeton University
D-329-D Engineering Quadrangle
Princeton, NJ 08544-5263
Phone: (609) 258-5206
Lab: (609) 258-0316
Fax: (609) 258-1939
fldryer@phoenix.princeton.edu

Ken Dungan
President
Risk Technologies, LLC
1310 Centerpoint Blvd.
Knoxville, TN 37932
Phone: (865) 531-1700
Fax: (865) 531-0428
kwdungan@risktek.com

Ofodike "DK" A. Ezekoye
Associate Professor
General Motors Foundation Centennial Teaching Fellow in Mechanical Engineering
Department of Mechanical Engineering
University of Texas at Austin
Austin, TX 78712
Phone: (512) 471-3085
Fax: (512) 471-1045
dezekoye@mail.utexas.edu

Rita Fahy
Fire Analysis and Research Division
NFPA
1 Batterymarch Park
Quincy, MA 02269-9101
rfahy@nfpa.org

William Feinberg
Professor Emeritus of Sociology
University of Cincinnati
5300 Hamilton Ave #1704
Cincinnati, OH 45224-3165
Phone: (513) 542-8328
billfeinberg@prodigy.net

Masoud Ghandehari
Assistant Professor
Polytechnic University
6 Metrotech Center
Brooklyn, NY 11201
Phone: (718) 260-3441
Fax: (718) 260-3433
masoud@poly.edu

Dan Gottuk
Senior Engineer
Hughes Associates, Inc.
3610 Commerce Dr., Suite 817
Baltimore, MD 21227
Phone: (410) 737-8677
Fax: (410) 737-8688
dgottuk@haifire.com

Norman Groner
Independent Consultant
P.O. Box 488
Santa Cruz, CA 95061
Phone: (831) 457-2972
Fax: (831) 457-2071
ngroner@cs.com

William Grosshandler
Chief, Fire Research Division
Building and Fire Research Lab
NIST
Gaithersburg, MD 20899
Phone: (301) 975-2310
Fax: (301) 975-4052
William.grosshandler@nist.gov

Anthony Hamins
Leader, Analysis and Prediction Group
NIST
100 Bureau Drive, Stop 8663
Gaithersburg, MD 20899-8663
Phone: (301) 975-6598
anthony.hamins@nist.gov

Bob Iding
Wiss, Janney, Elstner Associates, Inc.
Engineers, Architects, Material Scientists
2200 Powell Street, Suite 925
Emeryville, CA 94608
Phone: (510) 450-5530
Fax: (510) 428-0456

Marc Janssens
Associate Professor
University of North Carolina, Charlotte
Department of Engineering Technology
320 Smith
9201 University City Boulevard
Charlotte, NC 28223-001
Phone: (704) 687-2930
Fax: (704) 687-6499
mljansse@uncc.edu

Edwina Juillet
Consultant
Fire and Life Safety for People with Disabilities
637 Riverside Drive
Luray, VA 22835-2910
Phone: (540) 743-4601
Edwina@shentel.net

Takashi Kashiwagi
NIST
100 Bureau Drive, Stop 8665
Gaithersburg, MD 20899-8665
Phone: (301) 975-6699
takashi.kashiwagi@nist.gov

Charles Kime
Associate Professor
Fire Programs Coordinator
Arizona State University East
7001 E. Williams Field Road
Technology Center, Bldg. 50, Rm. 143
Mesa, AZ 85212
Phone: (480) 727-1321
Fax: (480) 727-1684
chuck.kime@asu.edu

Michael Klassen
Principal Research Engineer
Combustion Science & Engineering, Inc.
8940 Old Annapolis Road, Suite L
Columbia, MD 21045
Phone: (410) 884-3266
Fax: (410) 884-3267
mklassen@csefire.com

Venkatesh Kodur
Research Officer
Fire Risk Management Program
Institute for Research in Construction
National Research Council of Canada
Bldg. M59, 1500 Montreal Road
Ottawa, ON, K1A 0R6
Canada
Phone: (613) 993-9729
Fax: (613) 954-0483
venkatesh.kodur@nrc.ca

Erika Kuligowski
Graduate Student, Fire Protection Engineering
University of Maryland
0151 G.L. Martin Hall
College Park MD 20742-3031
Phone: (301) 405-3999
kuligows@wam.umd.edu

Jack Lesko
Visiting Scholar
Department of Materials Science
University of Southern California
3651 Watt Way, VHE-602
Los Angeles, CA 90089-0241
Phone: (213) 740-7281
lesko@usc.edu
jlesko@vt.edu

Richard Thomas Long, Jr.
Managing Engineer
Exponent Failure Analysis Associates
770 Ritchie Highway
Suite W15
Severna Park, MD 21146
Phone: (410) 975-9141
Fax: (410) 975-9143
longrt@exponent.com

David Lucht, *Chair*
Professor and Director, Center for Firesafety Studies
Worcester Polytechnic Institute
100 Institute Road
Worcester, MA 01609
Phone: (508) 831-5104
Fax: (508) 831-5680
dalucht@wpi.edu

Richard Lyon
Manager, Fire Research Program
Federal Aviation Administration
Fire Safety Section, AAR-422
W.J. Hughes Technical Center
Atlantic City Airport, NJ 08405
Phone: (609) 485-6076
Fax: (609) 485-6909
Richard.e.lyon@tc.faa.gov

John Lyons
Director, U.S. Army Research Lab (retired)
7430 Woodville Road
Mt. Airy, MD 21771
Phone: (301) 829-1175
jlyons@frederickmd.com

Kevin McGrattan
Mathematician
NIST
100 Bureau Drive, Stop 8663
Gaithersburg, MD 20899-8663
Phone: (301) 975-2712
kevin.mcgrattan@nist.gov

Brian Meacham
Principal Risk and Fire Consultant
ARUP
160 East Main Street
Westborough, MA 01581 USA
Phone: (508) 616-9990
Fax: (508) 616-9991
brian.meacham@arup.com

Jim Milke
Associate Professor
Fire Protection Engineering
0151 G.L. Martin Hall
University of Maryland
College Park, MD 20742-3031
Phone: (301) 405-3995
milke@eng.umd.edu

Vahid Motevalli
Director, Aviation Safety and Security Program
GW Transportation Research Institute
George Washington University
20101 Academic Way
Ashburn, VA 20147-2604
Phone: (202) 994-7152
Fax: (202) 994-0127
vahid@seas.gwu.edu

Fred Mowrer
Associate Professor of Fire Protection Engineering
University of Maryland
0151 Glenn Martin Hall
College Park, MD 20742-3031
Phone: (301) 405-3994
fmowrer@eng.umd.edu

Vern Nicollette
Member of the Technical Staff
Sandia National Laboratories
P.O. Box 455
Baldwinsville, NY 13027
Phone: (315) 678-2990
vfnicol@sandia.gov

Kathy Notarianni
Leader, Integrated Performance Assessment Group
NIST
Mailstop 8664, Bldg. 224
100 Bureau Drive
Gaithersburg, MD 20899
Phone: (301) 975-6883
Fax: (301) 975-4052
kathy.notarianni@nist.gov

Jake Pauls
Consultant
12507 Winexburg Manor Drive, Suite 201
Silver Spring, MD 20906-3442
Phone: (301) 933-5275
Fax: (301) 933-5541
bldguse@aol.com

Eli Pearce
President elect, American Chemical Society
University Research Professor
Polytechnic University
6 Metrotech Center
Brooklyn, NY 11201
(718) 260-3030
epearce@poly.edu

Guylène Proulx
Fire Risk Management
Institute for Research in Construction
National Research Council Canada
Ottawa, Ontario K1A 0R6
Phone: (613) 993-9634
Fax: (613) 954-0483
guylene.proulx@nrc.ca

Jim Quintiere
John L. Bryan Professor of Fire Protection Engineering
0151 G L Martin Hall
University of Maryland
College Park, MD 20742-3031
Phone: (301) 405-3993
jimq@eng.umd.edu

Judy Riffle
Professor of Organic Chemistry
Virginia Polytechnic Institute and State University
Mail Code 0212
Blacksburg, VA 24061
Phone: (540) 231-6717
Fax: (540) 231-8517
judyriffle@aol.com

Susan Rose-Pehrsson
Environmental and Chemical Sensing Section
Code 6116
Chemical Dynamics and Diagnostics Branch
Naval Research Laboratory
Washington, DC 20375-5342
Phone: (202) 767-3138
Fax: (202) 404-8119

Nathan Siu
Senior Technical Adviser
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001
Phone: (301) 415-6925
nos@nrc.gov

James T'ien
Professor
Case Western Reserve University
Glennan Building, Room 415
10900 Euclid Avenue
Cleveland, OH 44106-7222
Phone: (216) 368-4581
Fax: (216) 368-6445
jst2@mae.cwru.edu

Rick Tontarski
Chief, Fire Research Laboratory
ATF
National Laboratory Center
1401 Research Blvd.
Rockville, MD 20853
Phone: (301) 217-5732
Fax: (301) 413-0649
retontarsk@atfhq.atf.treas.gov

Beth Tubbs
Senior Staff Engineer
International Conference of Building Officials
244 Brookway Drive
Northbridge, MA 01534
Phone: (508) 234-8762
Fax: (419) 730-6531
tubbs@icbo.org

Ed Weil
Polymer Research Institute
Polytechnic University
6 Metrotech Center
Brooklyn, NY 11201
Phone: (718) 260-3715
eweil@poly.edu
http://www.edweil.com

Dennis Wenger
Program Director
Infrastructure Systems Management and Hazard Response Program
Division of Civil and Mechanical Systems
National Science Foundation
4201 Wilson Boulevard
Arlington, VA 22230
Phone: (703) 292-7014
Fax: (703) 292-9053
dwenger@nsf.gov

Alex Wenzel
Director, Fire Technology Department
Southwest Research Institute
6220 Culebra Road
San Antonio, TX 78238
Phone: (210) 522-2311
Fax: (210) 522-3377
awenzel@swri.org

Forman Williams
Professor
University of California, San Diego
Director, Center for Energy Research
9500 Gilman Drive
La Jolla, CA 92093-0411
Phone: (858) 534-5492
Fax: (858) 534-5354
faw@mae.ucsd.edu

Tom Woodford
Associate Professor and Head
Department of Fire Protection and Safety Engineering Technology
Oklahoma State University
303 Campus Fire Station
Stillwater, OK 74078-4082
Phone: (405) 744-5721
Fax: (405) 744-6758
woodfor@okstate.edu

Bob Zalosh
Professor
Worcester Polytechnic Institute
100 Institute Road
Worcester, MA 01609
Phone: (508) 831-5562
bzalosh@wpi.edu

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, Guylène. 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 and Their Effects on Flame Durability and 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.