NIST Special Publication 1130

Reducing the Risk of Fire in Buildings and Communities: A Strategic Roadmap to Guide and Prioritize Research

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Abstract

The burden of fire on the U.S. economy is significant, comprising approximately $310 billion annually, or about 2 percent of the gross domestic product (GDP). Over the last 30 years, the number of reported fires, and the number of civilian fire deaths and injuries have decreased due to the efforts of many organizations. On the other hand, the number of civilian deaths and injuries normalized by the number of reported fires has essentially remained flat, while the number of firefighter injuries and fatalities has significantly increased on a per fire basis. Furthermore, the cost of fire protection has increased, and new and potentially costly threats to fire safety are emerging. Consequently, now is an appropriate time to address this continuing problem and consider how best to impel consistent and significant reductions in overall fire losses and costs. The National Institute of Standards and Technology (NIST) has developed this Roadmap as a response to the national fire problem.

This roadmap was developed to provide a shared vision for communication, bring the limited available resources to bear on the U.S. fire burden in a focused and creative manner for enhanced effectiveness, establish a basis for NIST strategic planning, and identify gaps in knowledge and measurement science that hinder the development of critical enabling technologies.

NIST's long-term vision is that unwanted fire be removed as a limitation to life safety, technical innovation, and economic prosperity in the United States. To realize this vision, the long-term goal of the Reduced Risk of Fire in Buildings and Communities Strategy is to develop and demonstrate the measurement science that enables a one-third reduction in the nation's preventable fire burden, reducing the impact of fire on communities, structures, their occupants, the fire service, and the economy within a generation. The estimated value of the preventable fire burden is about one-third of the total U.S. fire burden.

The preventable fire burden is considered in terms of life safety and societal costs. At the highest level, the problem is analyzed in three parts: fire hazards in buildings, challenges faced by the fire service, and fire spread in wildland-urban interface communities. A series of approaches are proposed to attack problems in each of these three application areas. This roadmap addresses the following questions:

- What are the most pressing fire problems?
- What are the best ways to attack these problems and reduce the overall U.S. fire burden?

In addition, the roadmap addresses more operationally precise questions:

- What measurement science is needed to realize the vision of a fire-safe future?
- What technologies are needed to most quickly reduce the national fire burden?
- What are the metrics to ensure that progress is being achieved?

From the answers to these questions, based on input from NIST staff and stakeholders nationwide, a set of strategic research priorities are developed.

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List of Acronyms and Abbreviations

Acronyms

AFFF	Aqueous firefighting foam
AFST	NIST's Advanced Fire Service Technologies Program
AIA	American Institute of Architects
ASTM	ASTM International (formerly the American Society of Testing and Materials)
ASME	American Society of Mechanical Engineers
ASCE	American Society of Civil Engineers
ASET	Available Safe Egress Time
ATF	Bureau of Alcohol, Tobacco, Firearms, and Explosives
BFRL	NIST Building and Fire Research Laboratory
CDC	Centers for Disease Control
CFR	NBS Center for Fire Research
CNGV	compressed natural gas vehicles
CPSC	Consumer Product Safety Commission
DHS	Department of Homeland Security
DOE	Department of Energy
EHS	environmental health and safety
EL	NIST's Engineering Laboratory
EV	electric vehicle
FEMA	Federal Emergency Management Agency
FF	firefighter
FR	fire retardant
GIS	geographic information system
GPS	global positioning system

GSA	General Services Administration
HEV	hybrid electrical vehicles
HFCV	hydrogen fuel cell vehicles
HRR	heat release rate
HUD	Department of Housing and Urban Development
HVAC	Heating, ventilation, and air conditioning system
IAFC	International Association of Fire Chiefs
IAFF	International Association of Fire Fighters
IBC	International Building Code
IC	incident command
ICC	International Code Council
IRC	International Residential Code
ISO	International Organization for Standardization
JFSP	Joint Fire Sciences Program
LiDAR	Light detection and ranging
LCA	life-cycle analysis
NASFM	National Association of State Fire Marshals
NBS	National Bureau of Standards
NEMA	National Electrical Manufacturers Association
NFPA	National Fire Protection Association
NIOSH	National Institute of Occupational Safety and Health
NIST	National Institute of Standards and Technology
NRC	Nuclear Regulatory Commission
PASS	Personal Alert Safety System
PBD	performance-based design

PPE	personal protective equipment
PHEV	plug-in hybrid electrical vehicles
RSET	Required Safe Egress Time
SCBA	self-contained breathing apparatus
SFPE	Society of Fire Protection Engineers
SRM	Standard reference material
SwRI	Southwest Research Institute
UL	Underwriters Laboratories
UMD	University of Maryland at College Park
USFA	United States Fire Administration
USFS	United States Forest Service
VTT	Technical Research Center of Finland
WPI	Worcester Polytechnic Institute
WUI	wildland-urban interface

Abbreviations

B	billion
°C	degree Celsius
m	meter
M	million
min	minute
s	second
W	watt

Executive Summary

The burden of fire on the U.S. economy is significant, comprising approximately $310 billion annually, or about 2 % of the gross domestic product. Over the last 30 years, the number of reported fires, and the number of civilian fire deaths and injuries have decreased due to the efforts of many organizations and the American public. On the other hand, the number of civilian deaths and injuries normalized by the number of reported fires has essentially remained flat, while the number of firefighter injuries and fatalities has significantly increased on a per fire basis. Furthermore, the cost of fire protection has increased, and new and potentially costly threats to fire safety are emerging. Consequently, now is an appropriate time to address this continuing problem and consider how best to achieve consistent and significant reductions in overall fire losses and costs. The National Institute of Standards and Technology (NIST) has developed this Roadmap, "Reducing the Risk of Fire in Buildings and Communities," as a response to the national fire problem.

This roadmap was developed to provide a shared vision for communication, bring the limited available resources to bear on the U.S. fire burden in a focused and creative manner for enhanced effectiveness, establish a basis for NIST strategic planning, and identify gaps in knowledge and measurement science that hinder the development of critical enabling technologies. Because of the size and nature of the national fire problem, the only hope of achieving the goal is through strong interaction with other organizations in the fire safety, industrial, educational, academic, and standards and code communities. This roadmap sets a path that will position the fire research community firmly on the path to addressing the national fire problem.

NIST's long-term vision is that unwanted fire be removed as a limitation to life safety, technical innovation, and economic prosperity in the United States. To realize this vision, the long-term goal of the Reduced Risk of Fire in Buildings and Communities Strategy is to develop and demonstrate the measurement science that enables a one-third reduction in the nation's preventable fire burden,[*] reducing the impact of fire on communities, structures, their occupants, the fire service, and the economy within a generation.

Based on input from NIST staff and stakeholders nationwide, this roadmap proposes a broad-based set of strategic research priorities, laying the groundwork for advances over the next decade. Building on previous developments, this roadmap incorporates the most viable approaches and ideas, and methods. The document lays a blueprint to address the national fire problem, prioritizing measurement science activities, considering previously defined research needs, and proposing research activities that reconsider the specific issues that contribute to the national fire problem.

* The preventable portion of the national fire burden is defined as the sum of all costs and losses associated with the total fire burden, which could be avoided (reduced) by advancements in measurement science. The estimated value of the preventable fire burden is about $100 billion or one-third of the total U.S. fire burden.

The fire burden is considered in terms of life safety and societal *costs.* In an effort to address the most pressing fire problems, attention is directed towards the burden of fire on communities, structures and their occupants, the fire service, and the economy in three key areas:

- Reducing fire risk in buildings,
- Advancing fire service technologies, and
- Reducing fire risk in wildland-urban interface (WUI) communities.

This roadmap is technology centric and stresses the measurement science needed to enable the most promising technologies that will reduce the preventable burden of fire in the three focus areas.

- To reduce the preventable burden of fire in buildings, the strategic approach taken in this roadmap emphasizes cost-effective prevention and mitigation of the fire and exposure of people. The priority measurement science outcomes focus on the following:
    - Engineered Fire Protection,
    - Safety of Building Occupants,
    - Advanced Flammability Performance of Materials and Products,
    - Next Generation Reliable Detection of Incipient Fires, and
    - Performance-based Design.
- To reduce the preventable fire burden associated with the fire service, the strategic approach taken in this roadmap emphasizes advanced technologies for the community, the fire department, and the firefighter before, during, and after a fire incident. The priority measurement science outcomes focus on the following:
    - Firefighting Equipment,
    - Firefighting Tactics,
    - Firefighter Training and Education,
    - Firefighting Resource Allocation, and
    - Firefighter Situational Awareness.
- To reduce the preventable fire burden associated with fire spread in WUI communities, the strategic approach taken in this roadmap emphasizes advanced fire mitigation technologies for WUI building elements and materials, structures, parcels, communities, and surroundings. The priority measurement science outcomes focus on the following:
    - Prevention of Fire in WUI Buildings and Communities,
    - Fire Protection Engineering in the WUI,

- Response for Improved Fire Fighter Safety and Effectiveness, and People Evacuation, and
- Recovery Guidelines for WUI communities.

For each of the three focus areas, a series of strategic outputs and outcomes are identified. The emphasis is on outputs that advance existing and emerging technologies, and that address significant and preventable portions of the national fire burden. To successfully achieve the technological solutions, a series of measurement science hurdles must be overcome. The timeline for the research priorities is subdivided into three segments, namely short, medium and long term, varying from less than 3 years, 3 years to 8 years, and greater than 8 years, respectively.

A true measure of programmatic success only will be clear over the next two decades as data on the national fire burden becomes available through traceable, third-party fire statistics such as the National Fire Protection Association (NFPA) Annual Summary of the U.S. Fire Problem, including a net decrease in fire-related:

- civilian injuries and fatalities,
- fire fighter injuries and fatalities,
- direct and indirect fire property losses, and
- fire protection costs.

To monitor progress over the short term, a number of constituent metrics are considered including:

- enabling the development or improvement of codes and standards,
- enabling the development or improvement of best-practices, standard operating procedures, or specifications,
- enabling the development or improvement of new technologies,
- enabling the development or improvement of manufacturing processes,
- the development or improvement of standard reference materials, and
- published research or software that is directly used to support the metrics listed above and which reduces the national fire burden.

Emphasizing the importance of standards and codes in reducing the burden of fire, a detailed standards and codes strategy is presented for each of the three fire-related focus areas.

The importance of partner organizations and collaboration is emphasized. As the timeline and strategy have been formulated in terms of the current funding profile, the research priorities reflect a balance of scientific promise and cost. The prioritized research objectives represent a realistic opportunity to reduce the nation's preventable fire burden.

Acknowledgements

We are indebted to the many organizations and people who have supported NIST's work and thinking on the fire problem.   This roadmap would not have been possible without the contributions of the partnering, collaborating, and stakeholder organizations, and the individuals that comprise those organizations, who are working to create a fire-safe future, including ASTM, ATF, BRE, BRI, CALFire, CDC,CFSI, CPSC, DOD, DHS, DOE, DOT, DHS, FEMA, FM Global, FPRF, GSA, HUD, IAA, IAFF, IAFC, ICC, IFF, ISO, NAFTL, NASA, NASFM, NFFF, NFPA, NIOSH, NRC, NVFC, NWCC, SFPE, SP, SWRI, UL, UMD, USDA,USFA,USFS, VA, VTT, WPI, and many others.

1 WHAT THIS ROADMAP IS ABOUT

1.1 WHAT IS A ROADMAP?

A roadmap is a document that starts with a goal and traces the technological paths that lead from the current state of knowledge to that goal.[1] In this case, the paths are centered on the principal contribution from the National Institute of Standards and Technology (NIST), namely measurement science. A roadmap typically indicates the potential contribution of each path to meeting the goal, enabling sorting of (but not rigidly determining) the best chances for success.

1.2 WHY IS NIST DEVELOPING A ROADMAP?

The landscape for providing fire safety has changed markedly in the 35+ years since the establishment of the Center for Fire Research (CFR) within the National Bureau of Standards (NBS, now the National Institute of Standards and Technology, NIST). During these four decades, fire safety in the United States has improved markedly. In partnership with other organizations, CFR contributed in a significant way to the reduction in life loss through conduct of high impact scientific research and shepherding the fruits of that research into standards and building codes. As a result, the profile and magnitude of fire losses have changed. Some prominent fire scenarios have been addressed, while societal changes and commercial advances have led to new fire risks. There have been other contributory changes as well: the evolution of fire safety organizations domestically and worldwide, giant strides in technologies that have been and could yet be applied to fire safety, and considerable turnover in the population of fire scientists. Within the U.S., the demands of both the general public and mission-related agencies have a visage substantially different from those of prior decades.

Fire research within NIST has evolved with these changes. NIST fire research continues to be positioned in areas in which measurement science[*] and fundamental understanding of fire can reduce the risk of fire and the total social cost of fire to the nation. Over the years, the research has broadened in scope from a traditional focus on life safety, to recognition of the importance of overall cost and loss reduction. The combination of attention to more recent fire issues, while maintaining attention to classical, yet still important fire problems, has led to an assemblage of objectives whose overall focus is not readily perceived. It is timely to re-establish a documented strategy and to quantify high-level objectives for a Reduced Risk of Fire in Buildings and Communities Goal and its constituent programs.

This roadmap lays out the logic and structure underlying a strategy to reduce the risk of fire in buildings and communities with the following intended functions:

- This roadmap provides a shared vision for communication among NIST staff, management, external organizations with fire safety needs, and providers of the products and services that

* Measurement science is defined in Section 1.3 of this document.

help meet those needs. The NIST Fire Research Program has a unique role, both within the United States and internationally. It is important that that role be clearly presented to those with whom we interact and those who have expectations for our products. It is beneficial to the fire safety community that everyone has a similar understanding of where NIST is going and how we plan to get there.

- The technological layout in this roadmap will help maximize the impact of the limited available resources to attack the U.S. fire burden.
- This document provides a basis for NIST strategic planning, justifying current and new research activities, and redirecting low-impact efforts.
- The roadmap is explicit in identifying the areas of disciplinary expertise that NIST will maintain and develop as a resource to assisting Federal agencies and commercial organizations with fire issues of concern.
- The roadmap will help to identify gaps in knowledge and measurement science that hinder the development of critical enabling technologies.
- The roadmap will provide stimulation for creative, evolutionary and revolutionary thinking for removing the burden of fire from society.

1.3 WHAT IS MEASUREMENT SCIENCE?

We define measurement science broadly, since history has shown that successful reduction of fire losses involves multiple scientific and technological endeavors, including the following:

- Understanding of the phenomena responsible for an observed effect (e.g., ignition);
- Development of performance metrics, measurement methods, predictive tools, and protocols as well as reference materials, data, and artifacts;
- Conduct of inter-laboratory comparison studies and calibrations;
- Evaluation and/or assessment of technologies, systems, and practices; and
- Development and dissemination of technical guidelines and the basis for standards, codes, and practices—in many instances via testbeds, consortia, or partnerships with the private sector.

1.4 DEFINING ROADMAP COMPONENTS

The Reduced Risk of Fire in Buildings and Communities Strategy is composed of three focus areas presented in Chapter 2. Within each of the focus areas is a hierarchy, which structures the proposed research. This hierarchy is composed of four primary components: problems, approaches, technologies, and measurement science challenges.

The following definitions are terms used in the construction of this roadmap:

- Problem: An identified contributor to the national fire burden. Examples include a prevalent ignition source, lack of a tool for identifying a cost-effective fire safety solution, and inability to establish adequate egress capability for a particular facility.
- Goal: A desired result that addresses a critical national problem, which is strategically targeted through specific, measurable, attainable, realistic and time-targeted objectives.
- Approach: A generic way of addressing a specific problem, such as fire suppression or keeping fire-generated smoke from building occupants.
- Technology: A specific product or tool that addresses a specific problem such as a standardized measurement method for the performance of infrared cameras used in search and rescue operations or on-chip intelligence for fire detectors that are free of nuisance alarms.
- Measurement Science challenge: A specific research hurdle that hinders or prevents a technology from being developed or implemented.
- Output: A tangible result or completion of a specific measurement science activity or a phase of such activity such as publications, reports, and test methods.
- Outcome: An anticipated consequence of the implementation of an output, which has the potential to engender a substantial positive change. Example outcomes include a draft of a new or modified standard or code provision, new tools (software, guidelines, databases) for use in practice, new knowledge for specific end-use applications, or new technical expertise or capabilities such as instrumentation.
- Impact: A realized change in the U.S. fire burden.

This roadmap is organized into several parts. Chapter 2 describes the U.S. fire burden in some detail, including the historical context of fire research at NBS and NIST, the role of the scientific endeavor (referred to herein as measurement science), and key drivers of fire safety progress. Chapter 3 describes the framework for a strategy to address the national fire problem, including a vision statement, a glossary list defining components of the roadmap, a description of the strategic goal and objectives of each of the three component focus areas that comprise the Reduced Risk of Fire in Buildings and Communities strategy, a list of considerations for assessment of research priorities, a description of research considerations to address the objectives for each of the component focus areas. From the landscape of Chapter 3, Chapter 4 lists the priority outputs and anticipated outcomes of the Reduced Risk of Fire in Buildings and Communities strategy. Chapter 5 describes the prioritized implementation plan to address to national fire problem, and achieve the roadmap goals for the measurement science outputs and outcomes outlined in Chapter 4. A standards and codes plan is presented, which is a vital part of the implementation strategy. Chapter 6 summarizes the roadmap and discusses the role of NIST and others in attaining the fire protection goals. Appendix A provides a detailed accounting of the national fire burden. Appendix B provides a detailed accounting of the preventable fire burden and how the roadmap objectives can be realized.

2 THE U.S. FIRE PROBLEM

2.1 THE ROAD TRAVELED: THE HISTORICAL FIRE PROBLEM AND FIRE RESEARCH AT NBS/NIST

Life safety associated with fire in the U.S. has been improving over the last three decades due to the concerted efforts of many organizations and individuals, as seen in Figure 2-1.[2] The decreases are even more significant if the rising U.S. population is considered.[3,*] Nonetheless, new, potentially costly threats to fire safety are emerging. As a prerequisite to presenting how to best impel further and significant reductions in fire losses and costs, it is appropriate first to review previous strategic measurement science plans, which contributed to the historic reduction in life loss, how the concerns for the U.S. fire burden have evolved, and the nature of that burden today.

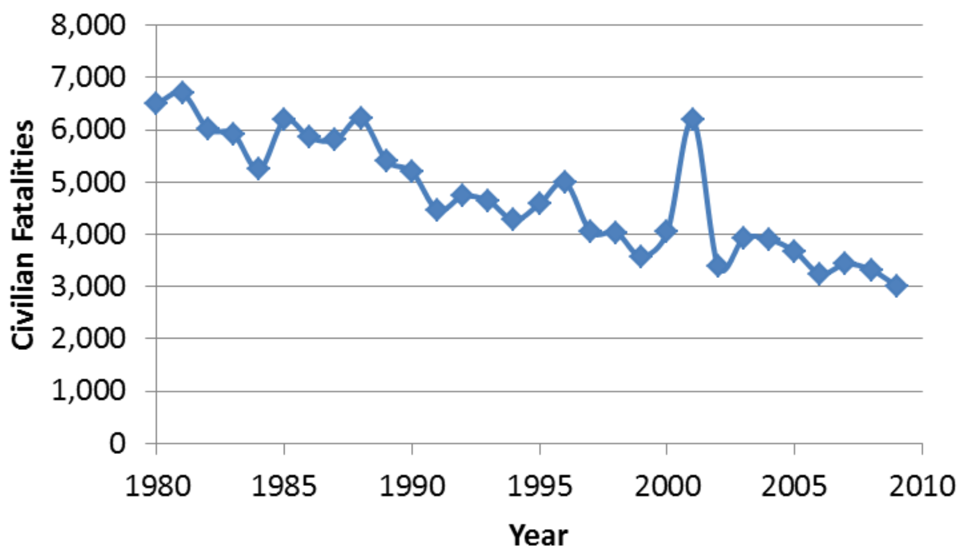

Figure 2-1: Civilian fire deaths (data from NFPA).

In 1974, Congress enacted the *Federal Fire Prevention and Control Act,* in part, as a response to the 1973 report by the National Commission on Fire Prevention and Control entitled *America Burning*.[4] Among other things, this Act created what have become the U.S. Fire Administration and the National Fire Academy. The Act built on existing fire responsibilities at the National Bureau of Standards (NBS) by creating the NBS Center for Fire Research (CFR). The intent of the Act was to attack the national fire

* As the U.S. population grew from 1975 to 2000, the per capita decline in fatalities was larger than indicated in Fig. 2-1 (see Table 2-3).

problem by defining a Federal role for work in tandem with the States and municipalities. The Act authorized research on a broad range of topics, including basic and applied research on the physics and chemistry of combustion processes, flame ignition, flame spread, and flame extinguishment; combustion products, fires in structures, forest fires, fire behavior, oil blowout fires, transportation related fires, industrial fires, fire safety design, biological, physiological, and psychological factors affecting fire victims, fire service performance, toxicity, trauma, cardiac conditions, and other hazards, tests to determine cause of fire death, improved methods of providing first aid to fire victims, characteristics of arsonists and cure of such behavior; reduction of firefighting stress, control or prevention of fires; operation tests, demonstration projects, and fire investigations.

The goals of the CFR were based on the 1973 Commission report, which declared that it should be possible to reduce the Nation's fire losses by half in about 14 years.[5] In the initial strategic document, CFR planners stretched the time line to a generation, taken to be about 20 years, and then sought to define the technical work needed to achieve this goal. While there were reservations that such objectives went beyond the ability of CFR staff to control outcomes, they took it as their responsibility to conduct significant technical work and to push results into practice.[5]

In 1976[*], the U.S. experienced 2.9 million fires and 8,800 fatalities.[6] The CFR approach was based on intervening in the principal fire loss scenarios, which were analyzed using available data.[†] These are illustrated in Figure 2-2, in which loss scenarios were considered in terms of combinations of an ignition source, the first item ignited, and the occupancy type. The Nation met this aggressive life safety goal. Between 1976 and 1995, the total number of fire deaths declined to about 4600 and the number of reported fires declined to 1.8 million,[‡,7] while the U.S. population grew by about 12 %.[8] Since that time, the numbers of reported fires and fatalities have declined to 1.5 million and 3,300,[9] respectively, while the U.S. population grew an additional 12 %.[8]

NBS, NIST, and many other organizations[§] contributed to the fire safety advances through enabling measurement science (defined in Section 1.3) and other means such as education and training.

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* The 1976 data are cited here, since prior compilations overestimated motor vehicle fire deaths.

† Today's National Fire Incident Reporting System (NFIRS) provides detailed information on fire statistics.

‡ This does not take into account the possibility that the severity of reported fires may have evolved over time.

§ Many key results were conducted or funded by important organizations including:

- Governmental organizations such as ATF, CDC, CPSC, DOD, DHHS, DOE, DOT, DHS, FEMA, GSA, HUD, MMS, NIOSH, NRC, USDA, USFA, VA, etc.
- Professional organization such as SFPE, Fire Protection Research Foundation, and others.
- Standards organizations such as ASTM, NFPA, ICC, ISO, and others.
- Industry groups like the North American Fire Testing Laboratories (NAFTL), Underwriters Laboratories (UL) and Southwest Research Institute (SWRI), and FM Global.

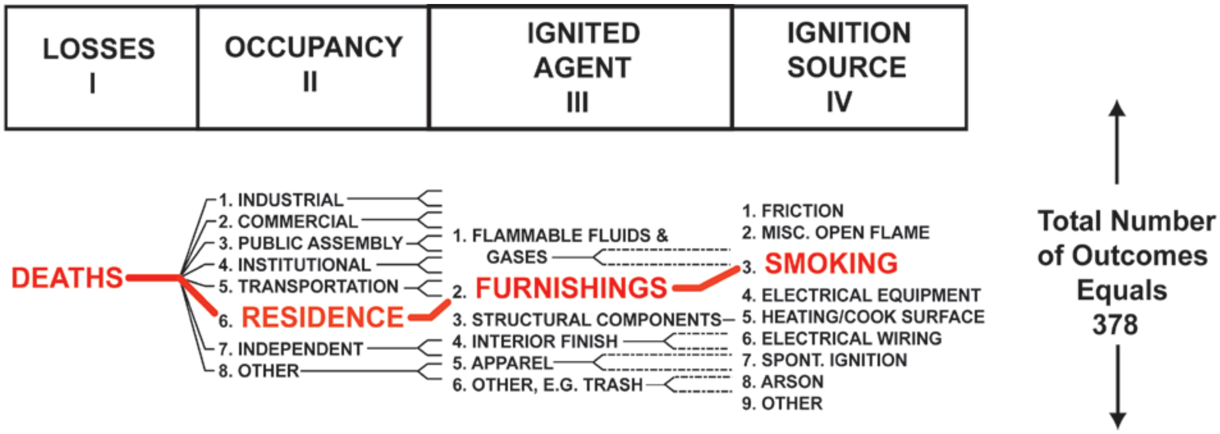

Figure 2-2: Loss scenario methodology, developed as part of the 1976 Center for Fire Research roadmap.

Some key results of the research activities during this period at NBS and elsewhere included the following:

- Smoke Alarm Siting and Sensitivity Standards – supported the development of smoke alarm standards (UL 217, NFPA 74). This led to an increase in sales and decrease in unit cost. By 1998, 95 % of homes in the U.S. had at least one smoke alarm.

- Automatic Fire Sprinkler Standards – (NFPA 13D & 13R) supporting development of the only installation and design standard for residential sprinkler systems and quick response sprinklers.[*]

- Cigarette Ignition Resistance of Upholstered Furniture (ASTM E-1352 and E-1353 and the equivalent NFPA 260 and 261 standards) – developed test methods that have been utilized by the upholstered furniture trade associations.[10]

- Cigarette Ignition Resistance of Mattresses – developed the test method which became the basis for 16 CFR Part 1632, promulgated by the Consumer Product Safety Commission. The impact occurred over the next approximately 20 years to 30 years, as improved mattresses populated U.S. homes.[11]

- Flooring Radiant Panel – flammability test (ASTM E 648) measures the critical radiant flux for flame propagation along floor coverings, simulating an important fire exposure component that can develop in building corridors and exit-ways. This led to the end of certain carpet styles whose burning could enhance the likelihood of room-to-room fire spread.

- Academic research institutions such as Brown University, California Institute of Technology, Harvard University, Pennsylvania State University, University of California at Berkeley, University of Maryland, University of Pittsburgh., Worcester Polytechnic University, and others.
- International fire and building research laboratories like VTT Finland, BRI Japan, and SP Sweden.

* While widespread adoption of residential sprinklers has not been achieved, the 2009 edition of the International Residential Code (IRC) was modified to require residential sprinkler systems for one- and two-family residences.

- Pill test for carpets - became the basis for 16 CFR Parts 1630 & 1631 (promulgated by CPSC), which was implemented to reduce the risk of carpet ignitions.[12]

- Children's sleepwear standard, promulgated by CPSC, which eliminated a particularly heinous fire problem, over 100 deaths and many serious burn injuries annually.

- Installation standards for wood burning stoves, fireplace inserts, and chimneys – NFPA 211. At the height of the energy crisis of the 1970s and 1980s, alternative heating led to a fire fatality rate approaching that of cigarette-initiated fires.[*,13]

Measurement science also led to or supported additional standards that have guided the specification of materials and products, and limited potential fire losses in building and transportation systems:

- Subways, Buses, and Train Fire Safety – NFPA 130, Federal Railroad Regulations requiring use of fire-safe materials.

- Smoke control: stairwell pressurization and zone smoke control technologies pursued by the Veterans Administration. NFPA 92A, B, and the ASHRAE Smoke Control Handbook.

- Cone and Furniture Calorimeters – development of instruments for the scientific characterization of material flammability and fire hazard (ASTM 1354, ASTM E 1537, and ASTM E 2067).

- LIFT – Lateral Ignition and Flame Spread (ASTM E 1321); this test method provides results on ignition and horizontal flame spread over materials.

- Toxicity - ASTM 1678 and the equivalent NFPA 269, the only U.S. method for estimating the lethal toxic potency of smoke from a burning item.

- Fire Hazard - ASTM E 1546, which defines procedures for assessing fire hazards.

- Fire Modeling – ASTM E 1355, ASTM E 1472, ASTM E 1591, and ASTM E 1895, which guide the development, testing, and documentation of predictive tools of fire development.

Advances in fire measurement science led to standards that are beginning to provide the next generation of fire loss reduction:

- Reduced Ignition Propensity Cigarettes – ASTM E 2187 is the basis for regulations in all 50 States, Europe, Australia, and Canada.[14]

* The energy crisis in the late 1970s led to a big increase in the use of wood as an alternate heating source in homes and a surge in the number of heating related fires. NBS led a concentrated research effort to provide new and updated information to develop appropriate codes and standards for installation of the combustors.

- Reduced Mattress Flammability – the basis for 16 CFR 1633, CPSC's regulation which limits the heat release rate of mattresses and thereby, the severity of bedroom fires.

- Improved Firefighter Protective Equipment – enabling safer and more effective firefighting through performance metrics and standards for thermal imagers (NFPA 1801) and personal alert safety systems.

Measurement science at NIST and elsewhere has led the worldwide movement to simulate the spread of fires and their combustion products, enabling the evaluation of a wide range of fire prevention and hazard reduction technologies, etc.

- Fire Models - development and dissemination of fire modeling tools (CFAST, DETACT, CCFM, ELVAC, FIRST, FPEtool, Harvard VI, LAVENT, etc.) to enable the transformation from prescriptive to performance standards through prediction of the behavior of fire, smoke, and toxic products.

- Advanced Fire Models – development and dissemination of advanced fire dynamic models and scientific visualization tools (e.g., the Fire Dynamics Simulator and Smokeview) have revolutionized fire protection engineering.

Recently, significant measurement science has been completed in a number of research areas, some not envisioned by the CFR roadmap (see Figure 2-2), including:

- Heat and Visible Smoke Release Measurements – enabling fundamental heat release rate measurements worldwide via an improved standard test method.

- Halon Replacements – measurement science for identifying and characterizing the performance of environmentally friendly extinguishing methods and alternative agents.

- Building Features – modification of the model building code to include recommendations from studies of disasters and building failures, such as the NIST World Trade Center investigation report, in an effort to improve the safety of building occupants and first responders.

- Positive Pressure Ventilation Firefighting Tactics – development of effective and safe firefighting practices, reducing fire service injuries and fatalities.

- Oil Spill Remediation – development of software to assist decision making on burning oil spills on water.

- Reduced Flammability Materials – development of improvements in environmentally friendly additives for commercial thermoplastics.

These examples show that measurement science has been necessary to make advances in fire safety. The application of measurement science to applied problems has been enabled by supporting fundamental research on fire science including fire dynamics and fire chemistry. As will be seen in the following sections, this paradigm continues to be viable.

2.2 THE U.S. FIRE PROBLEM TODAY

2.2.1 Definitions

Several definitions are used throughout this document to describe the magnitude of the U.S. fire problem. A comparison of the definitions is shown in Table 2-1.

The Core Cost of Fire is the sum of economic losses, cost of career fire departments, net fire insurance (premiums collected minus payouts), and cost of fire protection in building construction.[2]

The Total Fire Burden is the sum of all costs and losses associated with fire. The costs are expenditures used to prevent or mitigate the losses from fire. The losses include economic losses (direct and indirect) and the monetized social value of fatalities and injuries. There are many other costs, which contribute to the total fire burden, including the net insurance costs, fire protection costs, career and volunteer fire department costs, and wildland fire expenditures. Cost estimates of the components of the total fire burden are discussed in the Sections immediately below. More detailed information is given in Appendix A. Some costs or parts of the fire burden are preventable, whereas other costs are not preventable as explained below.

The Preventable Fire Burden is the sum of all costs and losses associated with the total fire burden, which could be avoided (reduced) by implementation of advancements in measurement science. The preventable fire burden can be estimated as the product of the expected fire burden with the avoidable fraction for each component of the fire burden. While some components of the fire burden are largely not preventable, much of the U.S. fire burden, including direct and indirect economic losses and the monetized social value of fatalities and injuries, can be reduced by improving the prevention, control, and response to unwanted fires. Some fire costs are largely not preventable.

The non-preventable fire burden is the difference between the total fire burden and the preventable fire burden. The non-preventable fire burden can be thought of as those fire protection costs, which are required to maintain the current level of life safety and those losses, which are, for example, associated with events beyond control. Examples of non-preventable losses and costs are discussed in Appendix B. The estimated values of the avoidable fraction and preventable fire burden costs for each of the major components of the U.S. fire burden are discussed in Appendix B and given in Table B-1. In aggregate, the estimated value of the preventable fire burden is about 30 % of the total U.S. fire burden. Table 2-1 identifies components of the U.S. fire burden that are estimated as largely[*] preventable (see Table B-1 in Appendix B for the estimated values).

* Greater than 20 %.

Table 2-1: Comparison of the components of various definitions used in the economic assessment of the U.S. fire problem.

	Total Fire Burden	Core Costs	Preventable Fire Burden
Civilian Fatalities	X		X
Civilian Injuries	X		X
Firefighter Fatalities	X		X
Firefighter Injuries	X		X
Direct Economic Losses	X	X	X
Indirect Economic Losses*	X	X	X
Net Insurance Costs	X	X	
Fire Protection Costs	X	X	
Career Fire Department Costs	X	X	
Volunteer Fire Department Value	X		
Wildland Fire Expenditures	X		X

2.2.2 The Cost of the U.S. Fire Problem

In 2008, there were 1.5 million reported fires, 3320 civilian fatalities, 16,705 civilian injuries, 105 firefighter fatalities, and 79,700 firefighter injuries.[2] For 2008, the *Total Fire Burden* was about $314 billion (in 2008 dollars). This represented about 2.2 % of the gross domestic product[†] and was distributed across structure fires ($185 billion), wildland-urban interface (WUI) fires ($14 billion), vehicle and other ($6 billion), and the fire services ($109 billion) (see Appendix A). The Total Fire Burden can be further broken down into the cost of fire protection (44 %), firefighting costs (30 %), monetized social value of fatalities and injuries (13 %), net insurance costs (5 %), and economic losses (8 %) (see Appendix A). Based on the detailed analysis in Appendix A of this report, the U.S. fire burden in 2008 ranged from $231 billion to $461 billion given current measurement techniques, reported data, and fire risks. The preventable fire burden in 2008 was about $102 billion or one-third of the total burden (see Appendix B). The burden of fire significantly detracts from the optimal use of the nation's resources and economic health.

* Indirect losses include the cost of business interruption due to fire; see Appendix A and Ref. 2.

† The GDP in 2008 was $14.3 Trillion (U.S. Census Bureau, 2010 Statistical Abstract, National Data Book, Table 651; http://www.census.gov/compendia/statab/2010/cats/income_expenditures_poverty_wealth/gross_domestic_product_gdp.html)

2.2.3 Trends

In the U.S., the declines in the numbers of reported fires, fire deaths, and fire injuries have slowed considerably not unlike the trends seen in Figure 2-1 and Table 2-2. The advances in fire safety products and human behavior that led to the previous high rates of decline are highly variable and do not exhibit a consistent rate of decline.

Meanwhile, the total burden of fire in the U.S. has been growing and Figure 2-3 shows the rapidly increasing *Core Costs* of fire, which were $138 billion for 2008.[2,*] Over the last 28 years, costs due to property damage, fire protection used in construction, and career fire departments have increased about 35 %, 87 %, and 145 %, respectively, after adjustment for inflation. The U.S. has one of the highest direct fire loss rates among developed nations.[15] Appendix A provides a detailed explanation of the cost of the U.S. fire burden, and discusses details on the major cost areas including an analysis of the uncertainty of the estimates.

Figure 2-1 and Table 2-2 show that in about a quarter century, civilian injuries and fatalities have been reduced by roughly one-half, while the reductions in firefighter injuries and fatalities have been distinctly smaller. At the same time, the core cost of fire has increased steadily. A significant part of this increase has been the increased cost of career firefighting, which has doubled over the last 30 years.[2]

Table 2-3 shows the normalized fire losses in the US during the period from 1980 to 2008. While the number of reported fires has significantly decreased over the last 28 years, the number of civilian deaths and injuries normalized by the number of reported fires has essentially remained flat. For fire fighters, the situation is much worse with injuries and fatalities significantly increasing 68 % and 57 %, respectively, on a per fire basis over the same time period. In addition, the core costs of fire normalized on a per capita basis have risen about 40 % over the last 28 years.

During this period, Table 2-4 shows that most civilian deaths and injuries occurred in home building fires. In 2008, about 84 % and 79 % of civilian deaths and injuries, respectively, occurred in home building fires.[16] This suggests organizing the burden of fire into four components, including costs associated with:

- fires that initiate in buildings,
- firefighting,
- fires that initiate in wildlands and spread into a community, and

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[*] These were distributed across economic losses ($20 billion), which only accounted for property loss, cost of fire departments ($40 billion), cost of net insurance ($15 billion), and the cost of fire protection in building construction ($63 billion). For 2008, the *Direct Impact* of fire was $60 billion. This was composed of direct economic losses ($18 billion), which only accounted for direct property loss, and the monetized social value of fatalities and injuries ($42 billion). See Appendix A for further discussion.

- vehicle, outdoor, and other fires.

The costs for each of these components are discussed next.

Table 2-2: U.S. Fire Losses from 1980 to 2008.[2]

Year	Reported Fires	Civilian Deaths	Civilian Injuries	Firefighter Deaths	Firefighter Injuries	Core Cost of Fire ($ billion In 2008 dollars)
1980	3,000,000	6,505	30,200	138	98,070	$74
1990	2,250,000	5,195	28,600	108	100,300	$86
2000	1,750,000	4,045	22,350	103	84,550	$102
2008	1,451,500	3,320	16,705	105	79,700	$138

Table 2-3: Normalized U.S. Fire Losses from 1980 to 2008.[2]

Year	Reported Fires per Capita	Civilian Deaths per 1000 Fires	Civilian Injuries per 1000 Fires	Firefighter Deaths per 1000 Fires	Firefighter Injuries per 1000 Fires	Core Cost of Fire per Capita (in 2008 dollars)
1980	0.0132	2.2	10.1	0.046	32.7	$326
1990	0.0090	2.3	12.7	0.048	44.6	$344
2000	0.0062	2.3	12.8	0.059	48.3	$362
2008	0.0048	2.3	11.5	0.072	54.9	$454

Table 2-4: U.S. Fire Losses by Type in 2008.[16]

Fire Type	Reported Fires	Deaths	Injuries	Property Loss ($ B)
Building Fires *	515,000	2,900	14,960	14
Wildland Fires	364,000	18	257	3.1
Vehicle & Outside Fires	572,000	402	1,488	1.8
* Buildings and mobile properties used as fixed structures.				

2.2.4 Fire Burden Associated with Fires that Initiate in Buildings.

Table 2-4 provides a summary of fire losses by type in 2008. The numbers of fires in each of the three main fire types in the table are all of the same order of magnitude with building fires associated with the highest number of injuries and fatalities. While life loss in non-residential construction was relatively small, the cost of fire protection in non-residential buildings was about twice as large as that of residential structures.[17]

2.2.5 Fire Burden Associated with Fires that Initiate in Wildlands and Spread into Communities

Fires in the wildland-urban interface (WUI) spread through both vegetative and structural fuels. These fires can originate in either fuel type but usually begin in wildland fuels of natural (e.g., lighting strikes) or manmade (e.g., campfires, runaway prescribed fires, downed or arcing power lines, arson) causes. Documentation of the costs resulting from wildland and WUI fire incidents is less established and comprehensive than for fires within buildings. Figure 2-3 shows that the WUI structural fire problem is an accelerating issue. The total WUI fire burden is expected to double within the next decade (see Appendix A).

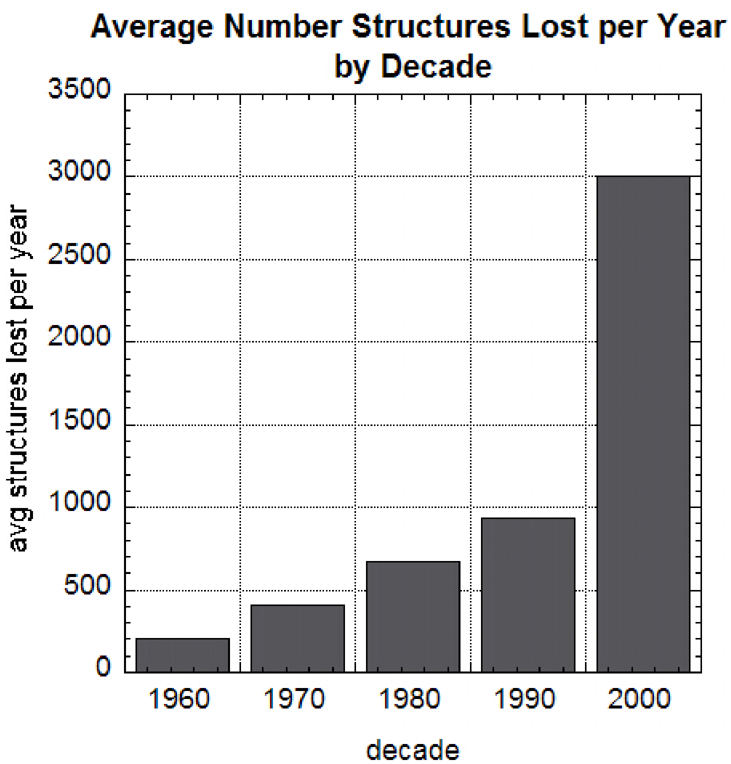

Figure 2-3: Average number of structures destroyed per year in WUI fires by decade from the 1960s to the 2000s.[18]

2.2.6 Fire Burden Associated with Fires that Initiate in Vehicles and the Outside

In 2008, there were about 207,000 reported vehicle fires, 320,000 reported outside fires, and 45,000 reported fires classified as 'other.' These fires accounted for a significant number of life safety losses with vehicle fires comprising 87 % of the civilian fatalities, 57 % of the civilian injuries, and 77 % of the property losses in these categories of fire incidents.

2.2.7 Fire Burden Associated with Fighting Fires

The costs of firefighting associated with maintaining career and volunteer fire departments and the costs associated with fatalities and injuries are estimated as about $110 billion (see Table A-1 in Appendix A). The cost of maintaining career fire departments was $40 billion in 2006, with another $50 billion estimated as the value provided by volunteer departments. These costs support approximately 1.1 million firefighters.[19] In 2008, there were about 105 firefighter fatalities and 79,700 injuries, with 46 % of the injuries occurring on the fire ground.[20]

Fire Departments often have duties beyond firefighting. About three-fourths (77 %) and two-thirds (69 %) of departments say that hazardous material response (Hazmat) and emergency medical service (EMS), respectively, are roles that their department performs.[21] Yet, the primary driver of a career fire department costs are labor, accounting for about 87 % of fire department budgets.[2] In addition, the primary determinant of staffing for fire departments is the need to provide coverage and readiness to respond for a certain geographic area, that is, the ability to provide a safe, effective response in a certain response time.[2] Thus, the primary factor in the cost of the fire service is not workload, but geographical area; the vast majority of fire department costs are not sensitive to marginal changes in fire or non-fire responsibilities. For these reasons, fire service costs here and in Appendices A and B are taken as roughly the same with or without EMS and HAZMAT activities, within the uncertainties in the cost estimates.

2.3 KEY DRIVERS OF FIRE SAFETY PROGRESS

Societal influences and technological changes can support or inhibit fire safety progress and may evolve with time. Some of the key drivers affecting fire safety progress are listed in Table 2-5.

Sustainability, climate change, and environmental and human health considerations are key drivers of fire safety progress.[25] For example, weather conditions, including recent droughts in the western U.S. have exacerbated fire incidents in WUI communities. WUI incidents may become more widespread as the global climate continues to change. Changing building designs and practices as well as the use of advanced materials and technologies in a march towards improved energy efficiency and net zero-energy buildings may present new fire protection challenges and opportunities.

Technology is a key driver of fire safety practice. Faster and less expensive computing power enhances the trend toward routine use of fire models for building design, product evaluation, etc. New sensors may yield earlier and less ambiguous detection of incipient fires. Advanced materials could lead to reduced flammability of products, improved effectiveness of fire suppressants, or improved protective gear for fire fighters.

Regulation can be a key driver. Model code changes recommending the installation of automatic water sprinklers in new residential construction represent a unique fire safety opportunity. Legislation mandating reduced ignition propensity cigarettes will have a large impact on fire safety, provided that enabling measurement science continues to provide support.

Other drivers reflect changes in demographics, which can influence the fire loss profile as the risks of fire death and injury vary by age group, race, region, and community size. For example, children under five and adults 65 or older face the highest risk of fire death, although they do not account for the majority of fire fatalities. According to the NFPA, fire death rates are seen in states with larger than average percentages of people who possess one or more of the following characteristics: poor, smoker, having less formal education, or living in a rural area.[22] New communities in the US are being built near wildlands, with almost 50,000 communities in the U.S. now located in the WUI and particularly vulnerable to WUI fires.

Professional inertia, exemplified by the current system of often archaic and prescriptive fire standards and codes, stifles innovation in fire safety systems, technologies, and building design. From the reverse perspective, constancy in the acceptance and approval processes eases the acceptance of improvements in the current standards and codes system.

Economics have a sharp influence on fire safety progress, especially as the nation emerges from a serious economic downturn. Under such circumstances, first cost may become a larger consideration. Financial constraints on localities can place limits on fire service resource allocation. Provisions to enhance fire endurance comprise a significant fraction of construction costs. The immense bill for repairing aging infrastructure requires new approaches to preserving fire performance while restoring functionality.

Table 2-5: Key Drivers Affecting Fire Safety Progress.

Support Progress	Inhibit Progress	Both Support and Inhibit
• Emergence of new & less expensive technologies and materials • More powerful computing capabilities • New building code requirements • Safety legislation • New fire safety standards • Increased capability for performance-based design • Security concerns • Economic benefits	• measurement science gaps • First cost • Aging and insufficiently maintained infrastructure • Reliance on prescriptive-based rules & improper implementation of performance-based design • Global climate change • Perception of fire as a small problem	• Demand for reduced cost of construction • Sustainability and environmental issues • International harmonization of fire standards • Changing financial support for local fire departments, fire service equipment, and fire research • Changing demographics • Changing building contents components, and configurations

While the solution to many challenging fire related problems continues to be elusive, there are also emerging problems that need attention and the potential or actual re-emergence of previously addressed problems, mainly due to the dynamic nature of the drivers of fire safety progress. For example, newly realized environmental and health risks can threaten hard-won gains in fire safety. Justifiable concerns for stratospheric ozone depletion led to new science to replace the halogenated fire suppressants (Halons) and to identify new refrigerants of low flammability. A combination of extensive measurement science and industrial product expertise resulted in non-carcinogenic replacements for polychlorinated biphenyls (PCBs) in electrical systems. In a similar way, replacements for asbestos were sought and implemented beginning in the 1970s and 1980s. Today, the persistence of brominated fire retardants in the environment is driving the search for alternatives to the current compounds. WUI fires are a prime example of a rapidly emerging fire safety problem. Vigilance is needed to identify and respond to challenges associated with emerging and re-emerging fire challenges.

Whether these drivers represent opportunities or constraints, taking advantage of them will require advances in fire measurement science. The current gaps in understanding (see Section 2.4 below) limit the ability to create new fire safety technologies, to devise efficient ways to make fire safer products without sacrificing other functional requirements, and to demonstrate that proposed innovations are technically feasible, safe, and economically viable.[23] As the factors that affect fire safety progress change, new measurement science hurdles emerge that hinder the implementation of technologies that could successfully address the U.S. fire problem.

2.4 GAPS IN MEASUREMENT SCIENCE

Gaps in measurement science hinder the application of technologies that could address the nation's fire problems. The gaps are both fundamental and applied in nature. To address these gaps, knowledge, standard test methods, methodologies to interpret the test results, and validated predictive methods are needed. The degree of complexity of interacting fire processes involving complex chemistry, radiative and convective heat transfer, combustion mode, fluid dynamics, structural dynamics, fire-structure interaction, and human behavior preclude the use of existing approaches and tests that address only one of these disciplines. Furthermore, insufficient understanding of these interacting fire processes inhibits accurate simulation of fire spread, growth, detection, suppression and egress in a typical building fire. Gaps in modeling capability and appropriate test methods and methodologies, preclude the ability to demonstrate that proposed innovations are technically feasible, safe, and economically viable.

For fire protection in buildings, methodologies are needed to account for uncertainties in the estimate of safety margins for fire performance and to demonstrate that proposed innovations are technically feasible, safe, and economically viable. For fire measurements, advances are difficult to implement due to extremely harsh thermal environments, transient chemical species, soot-laden flows, measurement interference, scaling issues, and turbulent flow fields. There are many other areas that need improved understanding. For fire modeling, for example, knowledge is needed to be able to predict the pyrolysis of and flame spread on heterogeneous building materials, sub-lethal toxicity of fire products, human behavior in fire environments, including egress and ingress in emergency situations, temperature-induced failure of structural elements and load redistribution in fire-weakened structures, and innovative training methods for first responders and code officials. In all of these areas, the lack of a quantitative understanding of uncertainty and system performance precludes the development of rational safety factors for fire protection engineering analysis and design.

There are numerous measurement science gaps that apply to firefighter safety and effectiveness. Firefighters do not usually have in-depth fire science and engineering backgrounds. The challenge is to provide training materials and tools that give firefighters a better understanding of the effects of their strategies and tactics without overwhelming them with physics, chemistry, and mathematics. A measurement science gap for the fire service is the need for an improved understanding of the causal relationship between firefighters and heart attacks. Statistically, about half of the on-duty firefighter deaths are due to heart attacks; however, it is not conclusively known what the relationship is between firefighting and heart disease, or even if there is one.[24] What are the health risk factors which can be used to screen recruits? From the firefighting perspective, building and WUI fires are scenes of "organized chaos" in the sense that there is usually a lot of noise, reduced visibility, and a strong sense of urgency to do the right thing quickly. In this working environment, there is a need for sensors that can provide usable information about fire spread, tenability, the location and physical condition of firefighters and civilians, and the condition of the structures. Post-incident evaluation of the cause and origin of a fire has not traditionally had a solid foundation in fire physics. Lastly, as environmental concerns become more prevalent, measurement science will be needed to understand the consequences of fighting fires in which materials are burning that have different, unusual, or unknown toxicity.

Addressing the full extent of the WUI fire problem will require improving the fire resistance of structures and communities, improving defensive technologies and tactics, and improving the safety and effectiveness of WUI fire fighters. Part of the WUI fire challenge is due to the large range of relevant spatial and temporal scales, environments, and physical processes, all of which present measurement challenges. The scales range from small-scale process of the initial wildfire ignition event to the transport of smoke over thousands of kilometers. The complexity of community evacuation and the negative health impact due to smoke exposure are also important. Advances are needed for a broad range of measurement science issues including laboratory results, field tool development, and modeling methods. Critical to a science based approach to reducing the physical destruction of WUI fires is the proven relevance of laboratory findings to outcomes in real-scale events. Effective standard test methods for building materials and assemblies are needed. Community-scale guidelines are needed to assess and improve WUI community and firefighter safety. This will require field measurements and post-fire data collection of WUI fuels and structure attributes, weather and fire behavior, and first responder and community actions during WUI event. WUI fire modeling tools need field and laboratory measurements to ensure validation.

The strategic objectives for addressing the national fire problem are described below in terms of the approaches and prioritized measurement science activities that can be implemented to reduce the preventable burden of fire on society. Application of measurement science will enable the introduction of technological solutions to the pressing fire issues faced by regulating agencies, product manufacturers, and designers of facilities.

3 THE ROAD AHEAD

3.1 A VISION STATEMENT

The fact that the national fire burden has changed so dramatically in scope and in composition prods us toward a new vision, a new goal, a new set of objectives, and the bringing of new technology to bear.

NIST's long-term vision is that unwanted fire be removed as a limitation to life safety, technical innovation, and economic prosperity in the United States

This vision is founded in the historically validated precept that measurement science can play a pivotal role in:

- saving people's lives from fires,
- helping firefighters do their jobs better and more safely,
- helping save people's homes and communities from structural fires and wildfires,
- promoting U.S. exports by furthering sound international fire safety standards, and
- advancing U.S. commerce by enabling the development, and bringing to market, fire-safe products and the capability to design facilities whose fire protection is performance based (i.e., providing equal or improved fire safety at lower cost, freeing up national resources for other national priorities).

Stamping out the roots of today's fire losses and costs is insufficient to realizing this vision. Large-scale changes within the country and the world can neutralize prior efforts to reduce fire losses, as cited in Section 2.3. These often unanticipated societal and other types of changes require that the understanding of fire phenomena continue to advance in order to be prepared to address new and recurring fire threats in a timely manner.

It is also recognized that, while NIST plays a unique role in furthering fire protection and public safety, its role is primarily supportive or enabling. NIST does not promulgate building codes or product standards, does not do compliance testing, does not test or manufacturer fire protection products, and does not promote the use of such products in the marketplace. NIST's role is to conduct measurement science. In this manner, NIST seeks to work with the greater fire, manufacturing, user, and regulatory communities to enable a fire-safe future.

3.2 THE REDUCED RISK OF FIRE IN BUILDINGS AND COMMUNITIES STRATEGY

The Reduced Risk of Fire in Buildings and Communities Strategy will be accomplished through critical measurement science, which will enable the reduction of the impact of fire on communities, structures, building occupants, firefighters, and the economy.

The goal of this Strategic Roadmap is to reduce the preventable fire burden in the United States by one-third within a generation.

To achieve the goal of reducing the risk of fire spread in buildings and communities, the focus is on outputs and outcomes that are likely to have a major impact on fire costs, losses and benefits to the nation. Selection of paths to the goal involves consideration of:

- cost and loss reduction of the nation's fire burden,
- existence and emergence of beneficial techniques and technologies that can be enabled by measurement science,
- successful delivery of measurement science with a focus on high impact, and
- overcoming barriers to the implementation of critical technologies, including market readiness, which may involve cost and non-financial barriers.

The emphasis is on outputs and outcomes that advance existing and emerging technologies, and that address significant and preventable portions of the national fire burden. To successfully achieve the technological solutions, a series of measurement science hurdles must be overcome. The timeline for the research priorities are broken into three categories, namely short, medium and long term, varying from less than 3 years, 3 to 8 years, and greater than 8 years, respectively. A true measure of programmatic success will only be clear over the next generation as data on the national fire burden become available through traceable, third-party fire statistics such as the NFPA Annual Summary of the U.S. Fire Problem, including a net decrease in fire-related:

- civilian injuries and fatalities,
- fire fighter injuries and fatalities,
- direct and indirect fire property losses, and
- fire protection costs.

In the short term, contribution to the strategic goal can be evaluated based on constituent metrics (see Section 5.6 of this report), which includes a broad list of measurement science outcomes including enabling the development or improvement of codes and standards, best-practices, standard operating procedures, or specifications, technologies, standard reference materials, manufacturing processes, patents, and research publications or software that is used and cited.

It is noted that there may be multiple approaches possible to attack parts of the fire burden. In the past decade, several organizations have performed similar planning exercises and proposed various strategies to attack parts of the current U.S. fire burden.[23,25,26,27,28,29,30,31,32] This roadmap builds on the results of those efforts and considers the critical needs that they cite.

Enabling significant reductions in fire costs and losses will require technical innovation. While there are some important, already available technologies, a number of these will require additional measurement science to achieve their full impact. A strategy to ensure impact requires continued commitment as described in Chapter 5 of this document. And there is a premium on creative advances in the underlying fire science and new concepts for attacking individual fire problems, even if the targets of these innovations have been previously recognized.

The measurement science to enable this goal is organized into three strategic focus areas, addressing fire risk:

Reduced Fire Risk in Buildings:[*] To develop and deploy advances in measurement science to increase the safety of building occupants and the performance of structures and their contents by enabling innovative, cost-effective engineered fire protection technologies .

Advanced Fire Service Technologies: To develop and deploy advances in measurement science to increase the effectiveness and safety of fire fighters by enabling the development of improved equipment, and science-based tactics and training tools for the fire service.

Reduced Fire Risk in Wildland-urban Interface (WUI) Communities: To develop and deploy advances in measurement science to mitigate WUI fires and increase the fire performance of structures and communities in the WUI by enabling development of innovative engineered fire protection technologies, fire resistant designs, standard test methods, and risk assessment tools for use by architects, builders, community decision-makers, homeowners, and fire officials.

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* The Nation's fire problem extends to transportation and industrial settings. Although these applications are not the primary focus of the work considered here, the measurement science and the enabling technologies described in this document are expected to have a favorable impacts on these components of the U.S. fire burden.

3.3 STRATEGIC FOCUS AREA: REDUCED FIRE RISK IN BUILDINGS

This strategic area is focused on reducing the cost of fire protection and fire losses through a combination of approaches involving fire prevention and fire mitigation by reducing the risk of ignition, and improved egress, materials, detection, structural fire resistance, engineered fire protection, and post-fire analysis. The burden of building fires in 2008 was characterized by the 500,000 reported fires, 2,900 civilian fatalities, 14,960 civilian injuries, $14 billion in direct property loss, $63 billion in fire protection in constructed facilities, and $74 billion in fire protection costs for equipment and standards (see Table 2-2, Table 2-4, and Table B-1).

3.3.1 Objective

The long-term objective of this focus area is to develop the measurement science needed to enable a decrease of one-third of the preventable burden of building fires within a generation. * Reduction of the burden of building fires on society is characterized in the long-term by traditional metrics: deaths and injuries to building occupants, direct fire-related property losses, and expenses associated with providing a desired or mandated level of fire protection. Short-term metrics for this strategic focus area are described in detail in Chapters 4 and 5.

Overall, intervention in the fire problem in buildings is easier to assess by dividing buildings into two characteristics:

- Function: commercial or residential
- State: existing or future

The benefits of subdividing the building fire problem in this way are apparent upon examination of the characteristics of life loss due to fire and the feasibility of preventative expenditures. For example, in a typical year, about 90 % of the civilian fatalities and injuries occur in residences, indicating that significant gains in life safety are best targeted at dwellings. Further, within residential construction, an approach such as increasing the number of stairwells is more feasible in new construction than in existing construction, while improved reliability and earlier fire detection applies to both types. Retrofit with automatic sprinklers is more likely to reduce residential fire losses, since these systems are already present in a large fraction of commercial buildings and since life loss from fires is relatively small there. The cost of fire protection in a commercial building is typically higher than for a dwelling, so fire safety technologies that reduce construction cost may be most effective. For the above reasons, the primary emphasis is on residential and commercial buildings rather than other types of structures (bridges, ports, aircraft, subways, trains, etc.). Nonetheless, the measurement science supporting Reduced Risk of Fire in Buildings and Communities is expected to also support advances for fire protection in all structures.

* Appendix B provides a detailed accounting of the preventable fire burden and how the objective can be realized.

3.3.2 Fire Safety Framework

While there are other viable formalisms, the NFPA Guide to the Fire Safety Concepts Tree[33] is a useful framework for deriving strategies to evaluate how fire protection objectives can be achieved. It involves two main parts, including effective strategies for preventing and managing a fire and those exposed to a fire. As a formalism, it addresses both the cost-effectiveness of fire protection and life safety issues, and is generally applicable to both commercial and residential buildings. Systematic consideration of how to intervene in the fire timeline is a key part of the analysis, addressing the incident before and during fire occurrence.

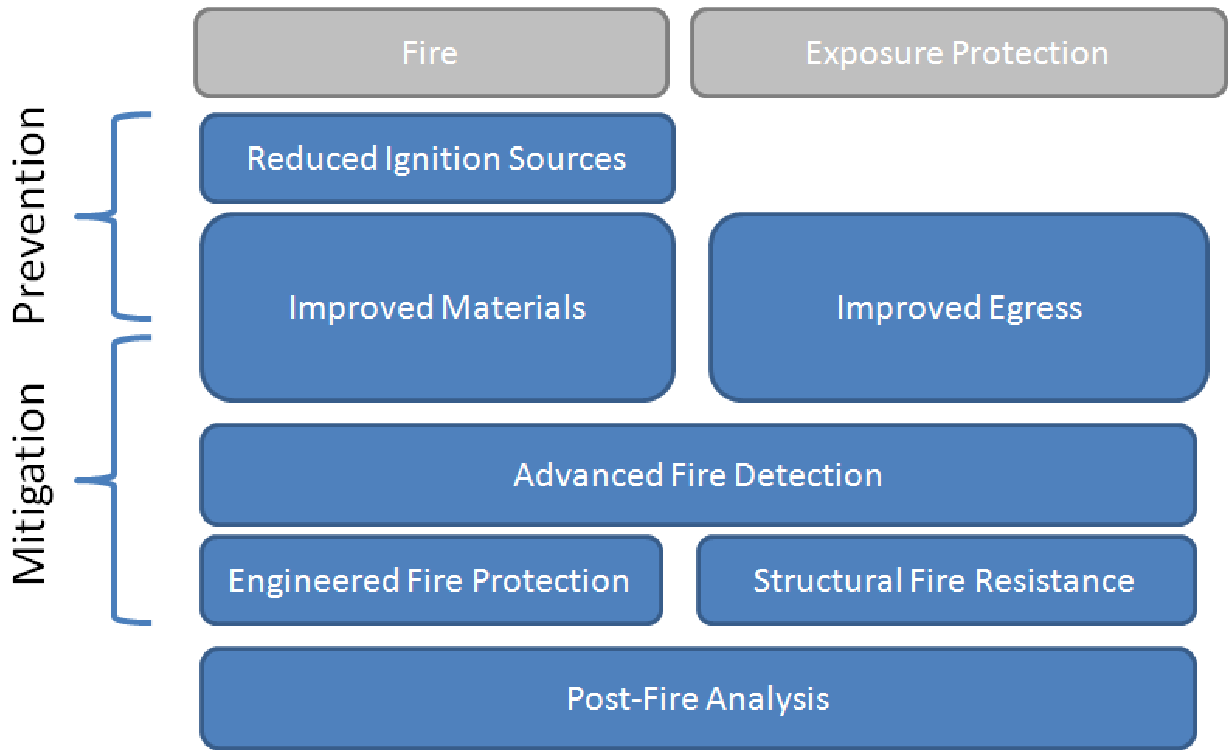

Figure 3-1: Representation of approaches to reduce the fire risk in buildings.

To prevent the fire before a would-be incident and to mitigate the hazard during a fire event, several approaches are important including:

- Reducing ignition at the source and/or nearby items (or preventing secondary ignition),

- Improving detection including the sensitivity and reliability of detection and recognition of fire in its early stages in order to initiate suppression or containment systems,
- Decreasing the fire hazard by controlling the rate of fire growth and the spread of flames and smoke through the use of improved materials and products,
- Mitigating the growth and spread of the fire through use of engineered fire protection systems, and
- Performance-based design methods to maximize design flexibility while minimizing the cost of installed fire protection.

To address the exposure of people and structural assemblies to a fire, several approaches are helpful, including:

- Improving detection including the sensitivity and reliability of detection and recognition of fire in its early stages in order to alert the occupants promptly,
- Assuring adequacy of the egress capacity relative to demand through efficient building design and effective emergency management,
- Performance-based design methods to maximize design flexibility while minimizing the cost of egress and structural systems, and
- Fire resistance of structural systems and assemblies to ensure appropriate design performance during a fire.

The fire problem in buildings is addressed through a hierarchy of approaches as noted above and described below.

3.3.3 Reduced Risk of Ignition

Ideally, the fire problem would be solved through fire prevention. This would eliminate the potential for adverse outcomes and obviate the need to respond and mitigate the impacts of fire. Prevention of unwanted ignitions can be accomplished by weakening or eliminating the ignition sources or by making their "targets" sufficiently resistant to thermal threats. Table 3-1 and Table 3–2 contain National Fire Incident Reporting System (NFIRS) data as analyzed by the NFPA.[34] Most of the fire losses are accounted for by relatively few ignition sources and first items ignited. In Table 3-1, cigarettes ("smoking materials") stand out as the leading ignition source, accounting for approximately one-fourth of the fire deaths and one-tenth of the injuries.[35] Flaming ignitions ("open flame" and "cooking" in the table) account for one-third of the deaths and half of the injuries, suggesting a high potential for improved ignition resistivity of the first items ignited. Heating equipment was a leading ignition source.[36] The leading six ignition sources accounted for approximately 90 % of the total civilian fire deaths and injuries in the US. Residual property loss resulted from a number of causes that may or may not be easily addressed by practical technologies enabled by measurement science. In the table, the first ignited items accounting for approximately one-third or more of the deaths, injuries and property damage are not specified. Most of these are associated with "unclassified" items (e.g., trash, clothing) or multiple items. About half of the losses are associated with ignition sources that are unknown. Improved knowledge and tools to help improve fire investigation and analysis to enable the accurate identification of fire source, cause, and origin would be useful to help plan appropriate solutions and address trends in the national fire loss profile.

Table 3-1: Leading Annual Fire Losses from Home Structure Fires from 2003 - 2006, grouped by Ignition Source.[34]

Leading Ignition Sources	Fires	Civilian Deaths	Civilian Injuries	Property Damage ($ B)
Intentional	17,900	320	870	0.5
Smoking Materials	13,400	710	1,240	0.4
Open flame (candle, lighter, matches)	25,500	440	2,140	0.7
Electrical Distribution/Lighting	21,200	370	840	0.7
Heating Equipment	67,400	620	1,610	1.0
Cooking	150,200	500	4,660	0.8
Subtotal of Above Categories	295,600	2,760	11,400	4.1
Totals [A]	378,600	2,850	13,090	6.1
Percentage of U.S. Fire Burden [B]	23	88	80	50

A. Includes results for all ignition sources (not just those listed here), but does not include unknown sources. Unknown sources account for about one-half of direct property losses and are not listed here. The uncertainty associated with the numbers in the table needs further study.

B. The U.S. totals are listed in Table 2-2.

As shown in Table 3-2, soft furnishings (upholstered furniture and beds) were the first items ignited in fires that led to about one-third of the deaths, one-sixth of the injuries, and one-ninth of the property damage in home structure fires.[34] In addition to the first item ignited, the fire load (including interior furnishings and finishes) and its potential for fire growth and spread are also critical to fully understanding fire hazard.

It is highly likely that new measurement science can enable advanced ignition prevention technologies and substantively reduce the 1+ million remaining fires reported each year. Possible technologies involving innovation advances in materials chemistry of furnishings and construction products are presented in the next section. Possible technologies that address the ignition sources themselves are summarized in Table 3-3 and discussed more fully in Chapter 4. These include kitchen fires and electrical distribution fires, where a number of novel and promising approaches are emerging.

Table 3-2: Leading Annual Losses from Home Structure Fires from 2003 - 2006, grouped by First Item Ignited. [34]

First Item Ignited	Fires	Deaths	Injuries	Property Damage ($ B)
Upholstered furniture	7,400	590	900	0.4
Mattress/bedding	11,200	380	1390	0.4
Thermoplastics [A]	29,400	280	1160	0.7
Structural member, component or insulation	32,500	240	620	1.3
Other furniture or utensils	6,000	170	500	0.2
Confined cooking fire/materials [B]	134,900	130	3670	0.3
Interior wall covering	8,200	120	340	0.3
Subtotal of Above Categories	229,600	1,910	8560	3.6
Totals [C]	378,600	2850	13,090	6.1
Percentage of U.S. Fire Burden [D]	23	88	80	50

A. It is assumed that the overriding reason that the items (in the categories for curtains, wire insulation, carpeting, and appliance housings) first ignited was due to thermoplastic content.

B. Cooking could also lead to ignition of cabinetry and interior wall coverings (not included here).

C. Includes results for all ignition sources (not just those listed here, but does not include unknown sources. Unknown sources account for about one-half of direct property losses and are not listed here. The uncertainty associated with the numbers in the table needs further study.

D. The U.S. totals are listed in Table 2-2.

Cooking fires are the number one cause of home fires and home fire injuries.* According to the NFPA, more than half (55 %) of home cooking fires start with the ignition of food or other cooking materials, and most involve unattended frying on a range top. Recent workshops have identified cooking fire prevention and suppression research needs.[37,38,39] A self-regulating cook-top is a promising emerging technology.[39]

In 2006, electrical distribution or lighting equipment was identified as a significant fraction of the first item ignited in residential fires, accounting for about 120,000 fires, 860 civilian deaths and more than $2.3 billion in property loss. A majority of these electrical fires were the result of wiring and related equipment such as cords and plug failures, possibly due to wiring degradation associated with aging (elevated temperature and temperature cycling, humidity effects, etc.) and/or physical damage associated with the installation or in-situ animal damage. Electrical distribution fires account for about 6 % of the total fires in residential homes, but 12 % of civilian deaths, which indicate that electrical fires are one of the deadliest fire types to occur in homes. CPSC has suggested that arc fault interrupters could address a significant fraction of these fires.[40] Improved flammability behavior of wire and cable insulation could have a big impact on the electrical distribution fire problem. The cost/benefits of possible solutions need consideration.

Table 3-3: Ignition Prevention Technologies.

Existing Technologies	Emerging/Future Technologies
• Less fire-prone cigarettes • Arc-fault circuit interrupters	• Second-generation low ignition propensity cigarettes • Next generation self-monitoring space heaters • Advanced materials and coatings • Self-regulating cook-top units

3.3.4 Improved Materials and Products

As shown in the prior section, soft furnishings (upholstered furniture and beds) are frequently the first items ignited in fires that led to one-third of the deaths, one-sixth of the injuries, and one-ninth of the property damage. Soft furnishings, in addition to being a major contributor to fire losses, are amenable to fire safety improvements due to the fact that they are exchanged within homes on a ten to twenty year time frame. Thus, unlike other items such as building materials or wire and cables, a change in soft furnishing product performance can have widespread impact in less than twenty years. Beyond soft furnishings, thermoplastic polymers (curtains, wiring cable insulation, carpeting and electronic appliance

* Homes are defined as dwellings, duplexes, manufactured homes, apartments, townhouses, rowhouses and condominiums.

housings) appear to play a large role in the first item ignited in over 29,000 fires per year, resulting in 280 deaths, over 1,100 injuries, and almost $1 billion in property damage. In addition, thermoplastic-based fabrics used in upholstered furniture and bedding are a significant contributor to annual fire losses from these two classes of products.

Should a combustible item become ignited, controlling the severity of the ensuing fire begins with limiting the item's mass burning rate and the related heat release rate. This improves life safety outcomes in multiple ways. Low burning rates delay or even prevent the generation of untenable thermal conditions and harmful levels of toxic smoke, which is the principal cause of deaths in fires. Keeping the burning rate small also reduces the potential for igniting successive items in the room, either by direct flame spread or as a result of room flashover. In the extreme, the initial burning generates insufficient heat to continue the combustion, and the product appears as ignition-resistant.

Missing from the U.S. fire statistics is the role of the second (or sequential) items ignited. In many cases, there is evidence that some secondary combustible took a small fire to the level that resulted in death, injury, or extensive property damage. The role in the U.S. fire burden of high heat content, high heat release rate items (e.g., upholstered furniture) is probably significantly underestimated. Resolving the fire data issue and addressing the challenge of resisting larger ignition sources (from the first ignited item) are roles for NIST measurement science. With the exception of the U.S. mattress standard (16 CFR 1633), resistance to ignition by a previously burning item has not been considered.

There are a number of small-scale tests that are used to screen individual materials for ease of ignition and potential for fire spread. These include UL 94, Limiting Oxygen Index, ASTM E 1352 and ASTM E 1353. However, these cannot capture the effect of the other components in, for example, a mattress or an upholstered chair.

Thus, a number of prescriptive fire regulations for furniture, mattresses and other furnishings require testing of the full product. While more accurate for estimating contribution to fire hazard, these tests can be an impediment to the development of improved fire-safe products by U.S. industry. A requirement that each new material be formulated and fabricated into a final product to evaluate its flammability performance is prohibitively costly for industry.

The solution lies in small-specimen tests that enable the accurate prediction of a component material's flammability contribution at real scale. This is an undertaking that is supremely challenging and has not been successful over the past decades. However, it is a challenge the NIST fire program must accept, since such metrics are critical to the commercial development of less fire-prone products in an environment where the societal constraints continue to increase. Specific examples include ignition and flame spread contribution from upholstered furniture components, spark ignition resistance in thermoplastic wire and cable insulation, and thermal protection provided by fire barrier materials.

In addition to flammability behavior, it may be important to know when the smoke from a burning product is of high or unusual toxic potency. This affects the time over which spaces and egress paths in a burning building remain tenable as occupants and responders are exposed to cumulative doses of the smoke. Thus, bench-scale (small specimen) methods to enable accurate prediction of the full-scale toxic potency of materials and furnishings is critical to both the screening of materials prior to approval for use in buildings, as well as computational prediction of the performance of candidate building designs. Successful scaling requires knowledge of combustion conditions and material composition, proportion, orientation, and geometry.

In recent years, the demand has been increasing for products that are sustainable, as characterized using life cycle assessment (LCA). While the formulations for these methods are well along and sometimes standardized, they require input data which do not exist for many new materials, especially for fire performance. Indeed, the National Research Council reports that lack of appropriate data is a significant barrier to sustainability analyses and the resulting decision making for U.S. industry in general.[41] Examples pertinent to this focus area are toxicity data for replacement fire retardants (especially nanomaterials) and data on the retention/diminution of fire performance over the life of use of a product. Such areas require extensive research to gather this complex information. In this daunting environment are a number of existing and emerging technologies for burning rate reduction that could lead to significant decreases in the U.S. fire burden. These are summarized in Table 3-4 and discussed more fully in Chapter 4.

There are potential barriers to implementation of less flammable materials and products, especially if their first cost is higher than the products they would replace. First, without regulations requiring their sale, higher cost home furnishings, appliances, etc. are less likely to be purchased and thus less likely to penetrate the market. Second, there are emerging concerns regarding the environmental safety of certain fire retardant additives that could expand to encompass many other fire-resistive materials.

Table 3-4: Improved Materials and Products.

Existing Technologies	Emerging/Future Technologies
• Fire barrier materials for mattresses • Fire retardant additives for materials and products	• Fire barrier materials for furniture • Next generation sustainable fire retardants and coatings • Ignition resistant upholstery fabrics • Padding materials that are both smolder resistant and low heat release rate when flaming • bench-scale tests and computational methods to predict the flammability contribution of furniture component materials at real scale

3.3.5 Advanced Fire Detection

An analysis of US fire statistics by NFPA shows that about 22 % of civilian deaths occurred in homes with smoke alarms present, but that failed to operate, and 43 % of civilian deaths occurred in homes with no smoke alarms.[42] Nearly 1,000 additional lives could be saved annually if all homes had working smoke detectors.[43] About half of the homes without working alarms have units that were installed but did not properly operate, often because batteries are missing. Research points to two main reasons for non-working smoke alarms: missing or dead batteries and intentional power source interruption.[44] Unreliable detection that leads to false alarms due to nuisance sources is thought to be the main contributor to this situation. A public/private Fire Safety Council white paper on reducing residential fire deaths identified quicker detector response to a range of fires while reducing nuisance alarms as a key component.[45] The white paper also stated the need for continued research to improve performance measurement of smoke alarms.

Early and reliable alarming has been shown to improve survivability and likely reduce property losses. An analysis by Hall indicates that roughly one-half of the deaths and two-thirds of fire-related injuries could be prevented if the time to incapacitating exposures was lengthened sufficiently, if alarms were successful in waking sleeping victims, and if victims in close proximity to a fire were able to escape.[46] Hall suggests that sufficient extra time alone would likely help reduce about one-quarter of the fatalities and injuries. In this regard, highly sensitive and reliable (false alarm free) alarms would have a significant beneficial effect on the fire problem. Some enabling technologies are listed in Table 3-5.

There is an additional gain to be derived from nuisance-free fire detection. Fully reliable detection is a necessary condition to enable direct transmission of alarm information from a residence to a local fire department. The resulting reduction in fire department response time would improve chances of survival for victims unable to escape a fire without assistance. It would also reduce property losses.

The technology to detect fire smoke components and airborne, non-fire species has been around for decades. Experiments in which multiple fire signatures have been analyzed to explore early and fault-free identification of the presence of a fire have also been accomplished. This work, in concert with flow modeling and well controlled experiments, could form the basis for a new generation of fire detectors.

The potential impediments to realizing the benefits of such new capability continue to center around the issues of how to get working detectors into the homes that need them most and how to keep them working. While public education may be an important approach, there may also be technical solutions such as long-life, sealed batteries.

Table 3-5: Detection Technologies.

Existing Technologies	Emerging/Future Technologies
• Smoke, heat, CO, hydrocarbon detectors, multi-signature detection	• Next generation detectors (early, reliable, nuisance resistant, video, self-diagnose malfunctions) • Automatic Fire Department notification

3.3.6 Engineered Fire Protection

Engineered fire protection systems constitute a significant component of the cost of installed fire protection. Engineered systems utilize three primary means to reduce the threat of fire: containing the fire, suppressing the fire, and controlling the heat and smoke. These engineered fire protection features are more frequently deployed in commercial and high-value projects, relative to residential construction.

3.3.6.1 Enhanced Compartmentalization

Fire- and smoke-rated partitions are an effective means to control the spread of fire and smoke in a structure. Therefore, standard test methods are needed to ensure the performance of fire and smoke rated doors and partitions. Successful containment requires (a) that the wall, floor, and ceiling assembly be designed to resist an appropriate fire load (currently expressed as duration of exposure in minutes or hours according to the ASTM E119 standard fire test), (b) that the doors or windows incorporated into the assembly also resist the fire load, and (c) that all penetrations of the assembly (pipes or wires, e.g.) be completely sealed.

3.3.6.2 Enhanced Automatic Fire Suppression

The complementary approach to controlling the burning rate is the use of a fire suppression system. A variety of suppression technologies currently exist, including wet- and dry-pipe sprinklers (residential and commercial), water mist systems, carbon dioxide and other gaseous suppression systems, and foam systems (including AFFF). The effectiveness of manual suppression during structural firefighting operations is considered below in the Advanced Firefighting Technologies area.

Automatic sprinklers have demonstrably reduced losses in residential fires. Scottsdale, AZ required all new residential construction to have sprinkler system protection in 1985/1986. After ten years, a study found that fires in homes with residential sprinkler systems were controlled by activation of one or two sprinkler heads in over 90 % of the incidents. In homes with sprinklers, the average amount of water per fire was 357 gal versus an estimated 4,800 gal from fire service suppression. Further, a study fifteen years after the sprinkler requirement found that the average property loss in a residence protected by a sprinkler system was about $2,200, compared to $45,000 in homes not protected by residential sprinklers.[47] Widespread adoption of residential sprinkler has not been achieved; however, the

International Residential Code (IRC) was recently modified to require a residential sprinkler system for one and two-family dwellings.[48]

While recent code changes to the IRC will improve fire safety in new construction (once the provisions are locally adopted and enforced), the majority of residential building stock in this country will not be retroactively required to install automatic residential sprinklers. Therefore, novel methods to suppress a fire during the initial growth phase could have significant impact. These methods may be targeted to specific products (cooking / stovetop fire suppression, for example, in the form of a non-plumbed fire suppression system) or may be holistic, such as robotic fire suppression which can detect and actively move through a residence to deliver suppression water or chemicals.

3.3.6.3 Control of Heat and Smoke

Most building fire fatalities result from smoke exposure, rather than exposure to heat or trauma. As noted in the previous section, reducing the exposure to smoke could prevent roughly one-half of the deaths and two-thirds of the injuries. Roughly 310,000 to 670,000 people per year are exposed to fire smoke in reported U.S. home fires.[49] Thus, for fires that are not prevented or kept very small, as discussed in the previous two sections, management of the fire's combustion products has the potential to significantly reduce life loss and injuries. Of key importance is quantifying the role of smoke toxic potency in the determination of the performance requirements for building smoke control systems. In addition, provisions need to be made for combustibles whose smoke is of unusually high toxic potency.

Design costs for a building’s fire protection features (including smoke control and compartmentalization) are a significant component of total constructed fire protection costs. Validated fire models, including sub-models and algorithms which efficiently and accurately account for the impact of fire protection systems such as smoke control and fire-rated partitions, are a critical tool for the fire protection community in order to provide assured fire safety in a timely and cost effective manner.

Current fire protection design calculations of Available Safe Egress Time (ASET) and the Required Safe Egress Time (RSET) either neglect the effects of smoke on the ability to escape and the rate of escape progress or include a single point of incapacitation. The incapacitation is typically based on an average value of smoke toxic potency, whereas published data indicate at least an order of magnitude spread among the lethal and incapacitating smoke toxic potencies of materials commonly used in buildings.[50] This database is quite small and needs to be expanded to include a wider range of construction and furnishing materials and products. A validated bench-scale measurement method is needed to generate these data. Principles for recognizing materials whose smoke could be of unusual toxic potency could reduce expensive research and development costs.

3.3.7 Advanced Building Sensors

Primarily driven by efforts to reduce energy costs, the leading edge of current-generation commercial buildings already incorporate massive amounts of sensor information feeding several “smart systems” throughout the building. Occupant sensors in rooms allow for customization of the air conditioning, heating and automated lighting. Smoke detectors are individually addressable with a known location within the building which enhances the utility of the fire alarm system.

Analysis of sensor data is already leading to active signage to guide occupants away from high-hazard environments in real-time during building evacuation. Advanced cyber-physical systems will exploit existing sensors, analyzing sensor data and integrating the information, allowing automated containment or suppression of the fire by opening / closing dampers or doors, activating suppression systems to pre-wet combustibles in areas ahead of the fire spread, or minimizing the risk to evacuees by optimizing the load of people on various exit components and steering them away from hazardous areas, including firefighting operations. Existing and emerging engineered fire protection technologies are summarized in Table 3-6 and discussed more fully in Chapter 4.

Table 3-6: Engineered Fire Protection Technologies.

Existing Technologies	Emerging/Future Technologies
• Automatic sprinklers • Water mist systems • Appliance-based suppression systems • Improved standard test method for fire- and smoke-rated partitions	• Building sensor system which integrates sensor information to automate fire protection systems • Non-plumbed fire suppression systems • Robotic fire suppression systems • Security systems

3.3.8 Improved Egress

Hall indicates that one-fourth of fire victims perish during evacuation,[46] which suggests that as many as 700 persons could be saved by egress design improvements. However, making significant improvements in evacuation time in single-family residences through design changes (with the possible exception of requiring a second means of escape from basements and upper stories) would not address the root causes[51] of residential fire deaths and injuries. Further, improvements in signage, markings, stair width, and emergency lighting would not be likely to save many lives in residences where occupants tend to be familiar with the egress routes and where occupant crowding along those routes is not significant. Residential fire fatalities would be better addressed by reducing the number of fires and the resulting fire growth and spread, and by advances in detection to provide very early and reliable warning. Existing and emerging/future technologies to enable performance-based design are listed in Table 3-7.

Egress design technologies could impact the life loss in the first two classes of buildings. Improvements in signage, markings, and lighting led to great reductions in egress time from One World Trade Center on September 11, 2001 compared to the 1993 bombing and subsequent evacuation of the same building. On September 11, 2001, self-evacuation and the use of elevators in World Trade Center Building Two (before it was struck by an airplane) led to several thousand saved lives.[52] Advanced egress design can also mitigate the growing costs of fire protection features in building construction, which are now approximately $10 billion annually. A key technology for enhanced egress capability is an elevator that can, in the event of a fire, be used by occupants to escape. This is especially valuable for people with conditions that make egress more difficult, a group which was estimated as 6 % of the occupants of the World Trade Center towers.[52] The elevators would need to know the locations of fire-threatened areas, information that would be obtained by connection to the building information system. Once elevator usage during emergencies is determined to be reliable and effective, some fraction of the existing stairwells might be eliminated, reducing up-front costs, maintenance costs, and allowing a greater percentage of the floor area to be used as tenant space. The vehicle for realizing these economies in engineered buildings is performance-based design as discussed below. Tools to accurately predict the evacuation time of building occupants are needed to assess the effectiveness of egress-enhancing cost-effective building improvements. While many evacuation models exist, little data is available to validate the predictive capabilities of these models.

Effective management of an emergency situation, including the ability to deliver evacuation information to occupants and responders in a timely manner, is an important aspect of building evacuation. Emergency management has two primary stakeholders in leadership positions: personnel working in the building who may have part-time or full-time emergency responsibilities and personnel who respond to an incident from outside the building (such as the fire department). Either or both emergency management groups may use mass notification devices (public address systems, mass email or cellular announcements, radio or television statements, or other technologies). While mass notification technologies are proliferating among buildings and organizations (such as universities) engaged in emergency preparedness planning, the technology lacks performance standards and there is little guidance available for users about how, what, and to whom emergency information should be directed. The absence of performance standards may lead to inefficient spending on emergency preparedness and the absence of message content guidelines may lead to ineffective (or harmful) messages.

While it is recognized that improved situational awareness by incident wardens and managers, and improved real-time communication with building occupants and first responders, would certainly be useful, the value of possible incremental life safety gains associated with implementation of particular technologies may be difficult to assess.

Table 3-7: Technologies for Improved Building Egress.

Existing Technologies	Emerging/Future Technologies
• Stairs • Occupant-use and firefighter-use elevators • Improved signage • Emergency lighting	• Active signage for improved way-finding • Mass notification technologies • Reliable egress prediction technologies

3.3.9 Structural Fire Resistance

During the years from 1970 to 2002, a total of 22 fire-induced tall building collapses occurred world-wide. Although this number may appear low, these fire events are of high consequence with respect to economic costs and potential life safety losses, including collapses at the New York World Trade Center, One New York Plaza, Boston Venodome Hotel, and Sao Paulo's CESP 2 building.[53] In addition, a number of burning buildings of all types have suffered collapsed roofs, walls, and floors. These have resulted in significant injuries and deaths, especially for firefighters, as well as significant business interruption. Between the years 1979 and 2002, there were over 180 firefighter fatalities due to structural collapse, not including those firefighters lost in 2001 in the collapse of the World Trade Center.[54] There is a lack of validated engineering-based computational tools to predict fire growth and spread, and the performance of large-scale structural connections, components, subassemblies, and systems under realistic fire and structural load.[28, 55]

Tools are needed to serve the design community that would assure full building burn-out without collapse (partial[*] or total), to predict building performance from small-scale tests, and to enable the use of innovative materials or designs. Standard test methods are needed to evaluate fire resistance of structural components, connections, assemblies, and systems at elevated temperatures for improved fire resistance design and retrofit of buildings. Finally, validated predictive tools are needed to help designers understand the trade-offs between active fire and passive fire protection performance, and to help community planners understand issues associated with resilience in the context of multi-hazards, both natural and man-made.[†] NIST's National Fire Research Laboratory scheduled to open in late 2012 will provide advanced capabilities to test the performance of real-scale structures under realistic fire and structural loading, and will enable the development of the next generation of performance-based standards for fire resistance design of structures. Existing and emerging engineered fire protection technologies are summarized in Table 3-8 and discussed more fully in Chapter 4.

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* Including fire fighter safety during response to a fire in wood frame construction.

† Including, for example, post-earthquake fires or a terrorist incident.

Table 3-8: Technologies for Improved Structural Fire Resistance.

Existing Technologies	Emerging/Future Technologies
• test methods (e.g., E119) to ensure structural fire resistance of building elements; • computational tools of structural response to mechanical loads.	• full-scale experimental methods to determine the response of structural members to full building burn-out; • next generation computational tools to predict building performance from small-scale tests; • validated tools to predict the performance of large-scale structural connections, components, subassemblies, and systems under realistic fire and mechanical loading; • innovative use of materials and engineering design to improve building fire performance; • test methods that enable performance based design of buildings.

3.3.10 Performance Based Design

Engineering or performance based design (PBD) utilizes all of the approaches mentioned above and is important for the development of appropriate structures, communities, products, and technologies. For buildings, design approaches can be either prescriptive or performance based. Prescriptive code changes can be thought of as inflexible solutions to building design. To develop improvements for a prescriptive code, a long series of steps must be taken including doing the science, writing the code, integrating the code, testing the code, documenting the code, getting the code used, and checking the effects of a revised code. PBD methods provide a framework for increased design flexibility and implementation of novel technologies. Both of these can promote the incorporation of building features that limit fire hazard while controlling construction cost. As most fire safety requirements currently are prescriptive, rather than performance-based, the $1.2 trillion in annual construction and building costs[*] may be inflated as suggested by the Australian Building Codes Board, which estimated that reliance on prescriptive codes rather than performance-based codes inflates construction costs by more than 0.5 %.[56]

While infrequently used compared to the prescriptive codes, the International Code Council (ICC) has published a performance-based alternative (International Performance Code),[57] NFPA has included a performance-based option in the *Life Safety Code*,[58] and the Society of Fire Protection Engineers has

* Construction statistics for 2006 are from the U.S. Census Bureau website: www.census.gov/mcd/

published engineering design guides to facilitate implementation and best practices in the use of performance-based fire protection techniques.[59] Performance-based design of buildings requires verified and validated tools to justify equivalent safety when compared to prescriptive code requirements. Without the necessary tools to develop and quantify the effectiveness and cost of possible design options, architects and engineers are constrained from realizing efficient solutions. Examples of applications of PBD principles include assessment of low-probability, high-consequence building threat (for which prescriptive solutions do not generally exist) or highly unusual designs (such as extreme high-rise buildings which exceed the assumptions implicit in the prescriptive codes). Currently, however, PBD methods are used only in a small minority of building designs due to several technical and administrative roadblocks. NIST measurement science can help overcome present barriers to the full implementation of PBD methods.

Computational fire modeling methods to predict the growth and spread of fire and smoke are quite advanced. However, numerous technical challenges remain in order to ensure accurate predictions which run on affordable systems in a reasonable period of time. Alternatives for a building design should deliver a level of occupant life safety performance equivalent to or better than the level which would otherwise be required by the prescriptive code. Work to define this equivalence is just beginning.

During a fire in a building, the interaction between the combustion of the interior finishes, furnishings, and the installed fire protection systems primarily determines the resultant tenability of a specific space. The metric for determining the time to untenable conditions is typically determined by calculation of a fractional effective dose (FED).[60,61] Measurement science is needed to reduce the significant level of uncertainty in the calculation of both sub-lethal and incapacitating toxic exposure, along with bench-scale methods to identify toxic potency of materials included in buildings (furnishings and building components).

The technology to predict the impact of active fire protection systems on fire growth requires the development of (a) a fundamental understanding of the extinction mechanisms of various suppression agents (water, gas, or foam, for example), (b) computational techniques to predict suppression effectiveness, and (c) computational techniques to predict the changes in smoke and gas species produced by the fire after suppression has initiated.

The key to understanding the uncertainty of predictions from software tools is comprehensive procedures for verification (standard testing of the tools to insure calculations are being done as intended) and validation (defining the accuracy of the calculations by comparison with other validated tools or more commonly experimental data). While considerable validation efforts have been performed,[62] these efforts have focused on only a small fraction of the predictive ranges of the models largely due to a lack of real-scale experimental data for important physical phenomena. The lack of a quantitative understanding of uncertainty and system performance precludes the development of rational safety factors in fire protection engineering analysis and design. Through uncertainty analysis,[63] the most significant components of uncertainty can be identified.[64] Once the principal components are identified, measurement science can be applied to systematically reduce the combined uncertainty.

Reducing the combined uncertainty in hazard and risk analyses will improve reliability of outcomes for engineered systems and enhance confidence that the performance-based design will function as intended. Existing and emerging/future technologies to enable performance-based design are listed in Table 3-9.

Table 3-9: Technologies to Enable Performance Based Design.[65]

Existing Technologies	Emerging/Future Technologies
• integrate stochastic model inputs and outputs for risk-informed computational analyses;	• predict the impact of active fire protection systems on fire growth; • software tools that include stochastic methods and uncertainty for hazard and risk analyses; • software tools to predict the relationship between building design and people movement; • software tools to predict the effect of fire effluent on people movement and behavior; • bench-scale tests and computational methods to predict the impact of material and geometry changes of interior furnishings on fire growth; • computational models of fire spread and growth; • predict the effect of combustion products on building occupants.

3.3.11 Post-Fire Incident Analysis

Post-fire incident analysis may involve one or all of three types of analysis as described in Table 3-10: brief incident overview, a criminal or civil dispute investigation, or a generalizable study to determine root cause. NIST does not work on Type II investigations involving matters of civil or criminal proceedings directly, yet measurement science may have direct benefits to law enforcement or other investigative agencies. Measurement science needs for Type I and Type III post-fire investigations are described below.

3.3.11.1 Aggregate Incident Data to Track the Fire Problem

The U.S. fire service is generally tasked with conducting type I investigations. This allows analysis of national fire trends, which informs efforts to attack the national fire problem. NFIRS data is reported to the U.S. Fire Administration, while subsequent analysis is performed yearly by USFA, as well as third parties such as NFPA. Advancements in measurement science are needed to accurately measure, characterize the uncertainty, and track the U.S. fire problem. Currently, measures of uncertainty surrounding the national fire statistics are limited. Without improved accuracy and estimates of the uncertainty and its variation with time, it is difficult to assess year-to-year variations (e.g., trends) in key fire statistics, and to evaluate the impact new technologies or fire mitigation strategies have on fire losses, injuries, and fatalities.

Table 3-10: Types of Post-fire Investigations.

	Type of Post-Fire Incident Study	Purpose of Study
I	A brief incident overview using a standardized reporting system such as the National Fire Incident Reporting System (NFIRS)	Aggregate the reporting of many fire incidents to support generalization and trend identification
II	A more detailed criminal or civil dispute investigation to determine incident-specific root causes	Support of civil or criminal justice proceedings
III	An analysis of the incident to determine root causes	Promote the implementation of recommendations from disaster studies for improvements to codes, standards, and practices, and fill gaps in current knowledge about buildings, infrastructure, emergency response, and human behavior.

3.3.11.2 Incident Analysis and Fire Forensics

NIST has statutory authority to conduct post-fire analysis and studies, which focus on type III outcomes (see Table 3-10).[*] Those organizations with law enforcement objectives, like ATF, are involved with type II activities. Post-fire studies help understand and quantify the technical reasons for the incident and any issues associated with evacuation and emergency response procedures. While the primary

* Congress has conferred authority for NIST to conduct post-fire studies through the Fire Prevention and Control Act (1974) and the National Construction Safety Team Act (2002). Over the years, NBS and NIST have been involved in many post-fire studies, including the DuPont Plaza Hotel, San Juan, PR (1986); First Interstate Bank Building, Los Angeles, CA (1988); Loma Prieta Earthquake, CA (1989); Hillhaven Nursing Home (1989); Pulaski Building, Washington, D.C. (1990); Happyland Social Club, Bronx, NY (1990); Oakland Hills, CA (1991); Hokkaido, Japan (1993); Watts St, New York City (1994); Northridge Earthquake, CA (1994); Kobe, Japan (1995); Vandaila St, New York City (1998); Cherry Road, Washington, D.C. (1999); Keokuk, IA (1999); Houston, TX (2000); Phoenix, AZ (2001); World Trade Center Towers and Building 7 (2001); Cook County Administration Building Fire (2003); The Station Nightclub, RI (2003); Charleston, S.C., Sofa Superstore Fire (2007); Witch and Guejito Fires, CA (2007); Amarillo WUI fires, TX (2010).

objective of a post-incident study is to identify technical factors which contributed to significant loss of life or property, advancement of the measurement science of post-fire incident studies is often needed. The investigation of the collapse of the World Trade Center towers, for example, required innovative techniques to model the interaction between the thermal environment and the structural response. The National Research Council has amplified the need for additional measurement science by calling for a fundamental strengthening of the underlying principles and methods for forensic science, including "fire and explosive analysis." [66] In the event of a fire or fire-induced structural event, a post-incident study can inform building codes and standards, and engineering best practices to avert future losses. Historically, fire investigations have resulted in profound changes in fire safety in the United States. Significant loss of life or property due to fire is generally followed by one or more formal investigations to identify root causes and contributory factors, along with a list of potential solutions to ensure that the magnitude of loss will not reoccur. These solutions are often reflected in changes to state laws, national model codes, fire safety practices, consensus standards, or other appropriate regulatory documents.

Deriving lessons learned from fire disasters enables improved engineering design and retrofit and recommended changes to practices, standards, and codes to reduce the potential for similar incidents in the future. A comprehensive approach to this would include development of improved data collection, analysis and archiving systems as well as creation of a national resource database to store and broadly disseminate findings from studies of fire incidents. The development of improved methods and technologies including validated computational fire, structure, and people movement models, eyewitness or survivor interview methods, material testing apparatus, and evidence collection and preservation techniques will improve fire investigation practice.

3.3.12 Summary

To reduce the nation's fire problem, measurement science must be applied to reduce the risk of fire hazards in buildings. Research is needed to enable the groups of key technologies to impact the fire problem. Using the framework of the NFPA Fire Safety Concepts Tree, the objective of this chapter was to examine the many potential mechanisms for mitigating the national fire burden. Technologies listed in Tables 3-1 to 3-10 with significant potential to contribute to this effort are highlighted in Table 3-11 and include both existing and emerging technologies. While Table 3-11 lists many technologies, some are more likely than others to have significant impact, therefore, a prioritized research investment will be necessary to maximize the impact of limited resources. The priorities, which are presented in the beginning of Chapter 4, emphasize two key areas:

- Mitigate residential fire losses through the reduction of upholstered furniture and foam flammability and early and reliable smoke alarms, and
- Enable performance-based design through validated computer fire and evacuation predictions, product toxicity assessment, and fire-resistant structural design.

Table 3-11: Summary of Technologies to Reduce the Risk of Fire Hazard in Buildings.

Existing Technologies	Emerging/Future Technologies
• Smoke, heat, CO detectors • Barrier materials for mattresses • Fire retardant additives • Automatic sprinklers • Water mist systems • Reduced ignition propensity cigarettes • Occupant-use elevators for evacuation during fire • Arc-fault circuit interrupters • Integrated stochastic model inputs and outputs for risk-informed computational analyses	• Next generation detectors (early, reliable, nuisance resistant, video, self-diagnose malfunctions) • Automatic fire department notification • Fire barrier materials for soft furnishings • Ignition resistant upholstery fabrics • Second-generation low ignition propensity cigarettes • Non-plumbed fire suppression systems • Robotic fire suppression systems • Next generation sustainable fire retardants • Self-regulating cooking units • Next generation self-monitoring space heaters • Advanced materials • Prediction of the impact of active fire protection systems on fire growth • Software tools that include stochastic methods and uncertainty for hazard and risk analyses • Software tools to predict the relationship between building design and movement and behavior of building occupants • Software tools to predict the effect of fire effluent on movement and behavior of occupants • Bench-scale tests and computational methods to predict the impact of material and geometry changes of interior furnishings on fire growth • Full-scale and computational methods to determine the response of structural members to full building burn-out • Computational models to predict the growth and spread of fire and smoke • Software tools to predict the effect of combustion products on building occupants combustion products on building occupants

3.4 STRATEGIC FOCUS AREA: ADVANCED FIRE SERVICE TECHNOLOGIES

3.4.1 Objective

This strategic area is focused on improving the safety and effectiveness of emergency response to fires by enabling the development of improved protective equipment, situational awareness, and science-based tactics and training tools for the fire service. In recent history, firefighter safety has been characterized by the nearly 100 on-duty deaths and 100,000 on-duty injuries suffered annually. These numbers are affected not only by the quality and condition of the firefighters, their training, their equipment, and their fireground procedures, but also by the number and nature of the fires they attend.

The long-term objective of this focus area is to develop the measurement science needed to enable a decrease of one-quarter of the preventable burden associated with the fire service within a generation.[*] The reduction in the burden of the fire service on society is characterized in the long-term by metrics related to the safety of firefighters (injuries and fatalities), the cost-effectiveness of the fire service, and fire service operational effectiveness associated with reduction of preventable life and property fire losses. Short-term metrics for this strategic focus area are described in detail in Chapters 4 and 5.

While firefighter safety is naturally characterized by deaths and injuries, firefighter effectiveness is more complex. Firefighter safety is linked to firefighter effectiveness, as improved technologies, tactics, and strategies are used by firefighters, it would be expected that firefighter safety should improve. The primary metrics for evaluating programmatic progress and prioritizing research investments in firefighter safety and effectiveness research are published annual estimates[†] of firefighter injuries and deaths and property loss due to fire. While these metrics are subject to fluctuations due to macro-scale factors beyond the scope of our programs such as the national and local economy, building maintenance, or terrorist attacks, these metrics ensure that the research program is focused on achieving real-world impacts.

3.4.2 Fire Safety Framework

While the majority of firefighter (and civilian) injuries and fatalities occur in residential buildings, a significant number of firefighter deaths and injuries occur in commercial buildings. It is useful to examine the cause and nature of firefighter deaths and injuries when considering approaches toward improving firefighter safety and effectiveness. In Table 3-12, firefighter deaths that occurred in 2006 are presented by cause, nature of fatal injury, and by type of duty.[67] More recent numbers from 2008 show a similar distribution of cause of death.[68] There were 106 reported on-duty deaths in 2006 and a majority were attributed to stress and overexertion, which includes all deaths that are cardiac or

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* Appendix B provides a detailed accounting of the preventable fire burden and how the objective can be realized.

† Several agencies or institutions produce annual estimates of firefighter injuries and deaths, including the U.S. Fire Administration, the National Fire Protection Association, the National Institute of Occupational Safety and Health, and the National Fallen Firefighter Foundation. Annual property loss estimates are produced by the U.S. Fire Administration and the National Fire Protection Association.

cerebrovascular (stroke) in nature. The Caught or Trapped category refers to firefighters that were unable to escape rapid fire progression and were overcome by flames, heat, smoke, toxic gases, or were drowned or crushed. For the Type of Duty category, the “Other On-Duty” grouping refers to deaths resulting from activities that were not associated with the response to any particular emergency.[*] While the number of fires are decreasing with time (see Table 2-2), the trends in the line of duty deaths are rather irregular.[69,†]

Table 3-12: Examination of On-Duty Firefighter Deaths in 2006.

Cause of Death	Percentage	Nature of Fatality	Percentage	Type of Duty	Percentage
Stress/Overexertion	51	Heart Attack	47	Fire ground Operations	34
Vehicle Collision	18	Internal Trauma	23	Other On-Duty	20
Caught/Trapped	12	Asphyxiation	11	Responding/Returning	14
Collapse	7	Burns	7	Training	8
Struck By Object	6	Crushed	5	Non-fire Emergencies	5
Lost	3	Stroke	4	After an Incident	19
Contact/Exposure	2	Electrocution	1		
Other	1	Other	2		

As shown in Table 3-12 and Table 3-13, NFPA categorizes injuries and fatalities by the type of duty, such as responding to or returning from an alarm, and the nature of an injury, such as burns or cardiac death. The nature of firefighter injuries is captured in Table 3-13. These statistics for Type of Duty Injuries are not well aligned with the Type of Duty Deaths (Table 3-12),[70] except for the top two most prevalent categories. There were a total of 83,400 reported on-duty injuries in 2006. Strains, sprains, and muscular pain were the most frequently reported injury category for every type of duty. Wounds were also a significant fraction of the injuries.

The problems facing the fire service are addressed here in terms of firefighter safety and effectiveness by enabling effective use of existing and new technologies, tactics, and strategies. Stakeholders that

* For example, nine firefighters suffered heart attacks that were not attributed to training or incident response activities.

† While the number of fatalities in 2010 was 72, in 2008 there were 105 line of duty fatalities.

specialize in other aspects of fire service safety and effectiveness, such as human physiology and physical conditioning, are better suited to address those areas.

Table 3-13: Firefighter Injuries by Nature of Injury and Type of Duty in 2006.

Nature of Injury	Responding / Returning % / Number	Fireground % / Number	Non-Fire % / Number	Training % / Number	Other % / Number	Total % / Number
Burns (Fire or Chemical	3.3 / 155	6.9 / 3070	0.8 / 100	3.2 / 245	1.3 / 180	4.5 / 3750
Smoke or Gas Inhalation	2.3 / 110	5.6 / 2475	0.9 / 120	0.5 / 40	0.6 / 80	3.4 / 2825
Other Respiratory Distress	0.8 / 40	2.9 / 1280	1.0 / 125	0.8 / 60	0.9 / 120	2.0 / 1625
Burns/Smoke Inhalation	0.8 / 40	1.3 / 575	0.1 / 10	0.4 / 30	0.6 / 75	0.9 / 730
Wound, cut, Bleeding, Bruise	18.9 / 895	17.3 / 7640	16.4 / 2140	17.9 / 1375	18.8 / 2575	17.5 / 14625
Dislocation, Fracture	3.7 / 175	2.4 / 1065	1.6 / 210	3.9 / 300	3.0 / 410	2.6 / 2160
Heart Attack/ Stroke	0.7 / 35	0.8 / 350	1.2 / 155	1.3 / 100	2.6 / 360	1.2 / 1000
Strain, Sprain, Muscular Pain	55.9 / 2650	46.7 / 20655	60.0 / 7855	62.1 / 4760	51.0 / 6975	51.4 / 42895
Thermal Stress (frostbite, heat)	5.0/235	5.1 / 2280	1.5 / 190	2.7 / 205	1.4 / 190	3.7 / 3100
Other	8.6 / 410	10.9 / 4820	16.7 / 2185	7.2 / 550	19.9 / 2725	12.8 / 10690
Totals	4745	44210	13090	7665	13690	83400

Finally, there is a synergistic effect between firefighter and fire safety engineering research programs. Improving the safety and effectiveness of firefighters will lead to a beneficial collateral effect on building occupant safety and property loss when firefighters can size-up, search, rescue, and suppress or extinguish fires more efficiently. Likewise, firefighters can be more effective and operate more safely when they are called to fires more quickly and/or confront smaller fires as a result of positive impacts of fire safety engineering research.

While there are many approaches to address fire safety and effectiveness, a matrix was chosen that captures the natural progression of a fire incident (before, during, and after), as well as an increasing scale and level of complexity in the fire service operational approaches (firefighter, fire department, community). Figure 3-2 represents this matrix and illustrates the relationship in the overlapping approaches considered here.

Improvements in firefighter training, health, and conditioning, both from the perspective of the individual firefighter and the policies of the fire department, along with community education programs, contribute to the preparedness of the fire service and the community for emergency events. Enhanced training would prepare firefighters to deal with hazards in a cost effective way, helping to increase operational effectiveness and reduce the risk of injury. Educating the public about basic fire safety principles and actions can mitigate the number and magnitude of fires, as well as minimize the consequences.

Prior to an incident, appropriate resources should be made available to respond to emergency events. Cost effective resource decisions require detailed information on the cost/benefit profile of possible resource investments, including number and location of fire stations, number, type, and location of fire apparatus, firefighter staffing levels, and pre-planned alarm assignments.[*] Resource allocation may also address community infrastructure such as fire hydrants and building inspections. Situational awareness may also be developed by effective fire department pre-planning for the incident location.

Due to the operational challenges occurring during a fire incident, many avenues are possible for improving firefighter safety and effectiveness. For the firefighter, improved personal protective equipment and knowledge of the fire environment (situational awareness) allow firefighters to make informed decisions about how to safely perform tasks. The type, number of resources available and deployed to the event, along with the arrival time of the resources will influence the safety and effectiveness of the firefighters. Operational and tactical decisions made by the Incident Commander (IC) may be improved by innovative technology and/or better use of existing decision-making technology.

All aspects of firefighter safety and effectiveness can be evaluated during the post-incident timeframe. This is often achieved through incident investigations. Better understanding of the fire conditions to

* A pre-planned alarm assignment is the standard number of apparatus and personnel deployed to an incident. For example, a working residential structure fire may have an initial alarm assignment of 20 firefighters, arriving in three fire engines, one fire truck, one battalion chief, and one ambulance. These assignments may vary by jurisdiction, though the NFPA 1710 standard provides minimum assignment levels.

which firefighters and structures are exposed during an incident and during overhaul could lead to improved training, situational awareness equipment, tactics, incident command, or resource allocation.

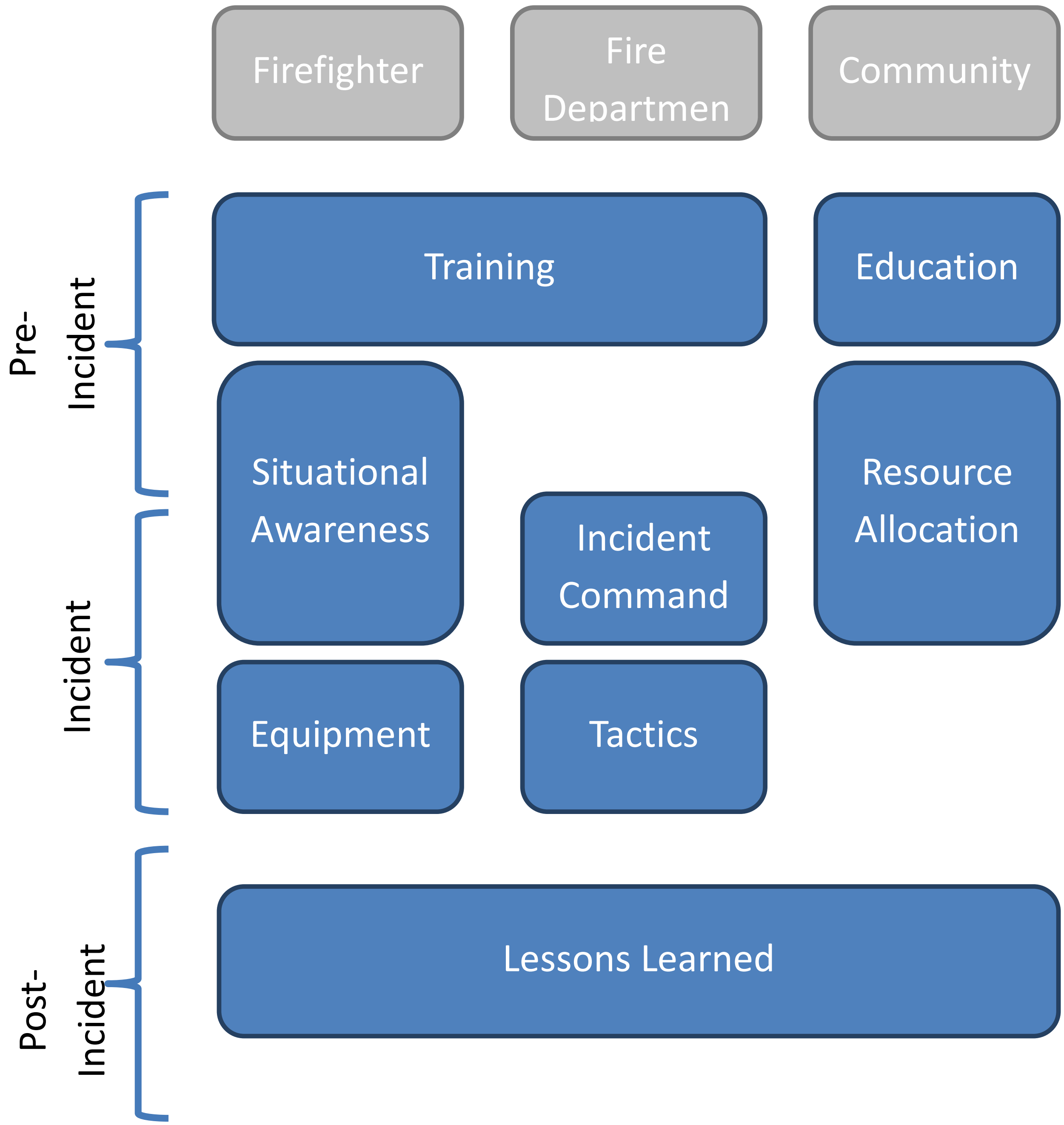

Figure 3-2: Approaches to enable advanced firefighting technologies.

Improvements in the flow and accessibility of information about the detailed impact of fire incidents can be used to shape the future of the fire service and the communities they serve. This information may include examination of certain fire conditions that were tracked over time, fire origin and cause, the interactions between or effectiveness of various tactics and/or strategies used, knowledge of potential hazards encountered in the cleanup process, etc.

Each of the approaches broadly outlined above make use of supporting technologies that factor prominently in their successful implementation. These technologies may be unique to a particular approach or they may have application across several approaches, varying in either scope or nuance. An overview of the technologies and the required measurement science is provided below and has been grouped in a manner that highlights the relationship between approaches.

3.4.3 Training and Education

A better understanding of operational procedures, fire dynamics and the influence of ventilation, suppression, and other tactical operations will lead to safer and more effective firefighters. The types of technologies that facilitate the training and education of firefighters, fire officers, and communities range from relatively simple reports of experimental results to highly complex interactive models of virtual fire environments.

There are two main categories that address the physical well-being of firefighters: technologies and fire department training and education policies that support improved firefighter health, fitness, and injury prevention; and technologies that enable monitoring of firefighter biometrics during and after incident response. Emerging cyber physical systems will combine sensors with computational resources to track fire ground conditions and warn fire fighters of hazardous exposures. Since cardiac arrest accounts for about half of firefighter line-of-duty deaths, technologies that provide insight into the risk factors for heart health are of particular importance.[*]

Similar to firefighter training and education, technologies that support the education and fire safety awareness of civilians may be cost-effective prevention measures. Community scale fire prevention programs have not been rigorously evaluated for cost / benefits. Technologies to improve fire service education, training, health, conditioning, and community education are summarized in Table 3-14.

* On-going work at DHS and NIOSH are addressing this issue.

Table 3-14: Summary of Training and Education Technologies.

Existing Technologies	Emerging/Future Technologies
• Theatrical virtual trainers • Classroom training • Tabletop exercises • Hands-on training (including fire academy burn buildings or flashover simulators) • Driving simulators • Training & education materials (CDs, DVDs, literature) • Health and fitness programs, including education materials • Community education programs, such as Learn Not to Burn	• Physics-based virtual training tools • Advanced fire reconstruction • Biometric monitors and guidelines for use • Environmental sensors linked to exposure warning systems • Health screening tests for risk factors • Prevention programs targeted to high-risk populations

3.4.4 Strategic Resource Utilization

The Incident Command (IC) at an emergency event must make strategic decisions immediately upon arrival at the scene and would benefit from access to crucial information about the event en route. The strategies employed depend on the particular characteristics of the incident and resource availability. In cases in which prior knowledge is unavailable or unreliable, technologies that permit quick, efficient evaluation (size-up) of the situation would be of great utility. Emerging cyber physical systems will combine personnel and equipment tracking sensors with computational resources to track fire ground resources and enable intelligent deployment of fire apparatus and fire fighters.

On a community scale, GIS-based technologies would provide information that would enable the fire service to optimize the use of personnel, apparatus, and fire stations, and to maintain an acceptable level of coverage for the areas they serve. These and other types of technologies may work across many boundaries, for example in coordinating traffic signals such that the most direct route from the responding fire station(s) to the emergency scene is readily available or may be used to identify closest responding units based upon actual apparatus location rather than station locations. Existing and emerging technologies to improve strategic resource utilization, incident command and resource allocation are shown in Table 3-15.

Table 3-15: Summary of Strategic Resource Utilization Technologies.

Existing Technologies	Emerging/Future Technologies
• GIS-based station location/resource coverage models • National Incident Command Structure • Traffic signal routing • Real-time apparatus location / tracking	• Science-based guidelines and risk analysis tools for crew size and station location relative to the location and frequency of hazards in the community • Wireless building/contents, access points, staging areas, and hydrant locations available to IC • Pre-planning/crew size guidelines and decision tools

3.4.5 Situational Awareness

Situational awareness is key to the safety and effectiveness of firefighters and is closely tied to training, tactics, and communication. Prior knowledge of critical incident site information through department-level pre-planning of the structure layout, contents (occupants, chemicals or other unusual fire hazards, construction materials), access points, water availability, adjacent structures, and suppression options would contribute to the quality of firefighting operations, which could be enhanced by new or improved technology. Emerging cyber-physical technologies that enable a firefighter to quickly monitor and analyze fire conditions will inform his/her tactical decisions. The ability of new cyber-physical systems to communicate fire conditions, the location of emergency responders, and changing egress routes would improve operational safety and effectiveness. Improving communication for the fire service has numerous avenues and levels of complexity. Firefighters working inside and/or outside one or more burning structures need to communicate among themselves as well as with their IC, who is typically located beyond the event epicenter. Firefighter PPE may interfere with effective communication as hoods, helmets and respirators make it difficult for firefighters to clearly hear. Depending on the severity of an event, the IC may need to communicate with other emergency responders, including the police, emergency medical personnel, and possibly other local, state, and federal responders. In these cases, the communication technology must allow multiple parties to speak within an established hierarchy. When communication is needed with other organizations, the communication technologies must be compatible and the command structure adequate to affect timely, appropriate, and coordinated actions. Transmitted signals are extremely dependent on both the physical and electromagnetic conditions at the site. The construction materials, size, and relative location of structures play an important role in determining which communication technology will perform well. Likewise, the presence of electrical machinery and other transmitters may interfere with emergency communications. In most cases, the particular electromagnetic environment of an emergency site is not known prior to an incident, therefore, the communication technology employed must be adaptable to provide reliable performance.

One of the most important technologies supporting situational awareness is firefighter location and tracking systems, which are beginning to become commercially available. There are many different types of location and tracking systems, some of which stand alone and some that use combinations of technologies to increase reliability in challenging environments. As with any technology that depends on transmitted signals, the operational environment has a strong influence on signal quality. Standard test methods and benchmarks are needed to ensure that tracking is of acceptable accuracy.

Monitors, sensors, and controls for fire detection, suppression, and strategic and tactical decision-making may be integrated into the design of new buildings, worn by the firefighter, or, in the case of robots, sent into the burning structure to monitor the fire environment. Advanced sensing technologies capable of artificial intelligence may automatically respond to harmful conditions and send information directly to the fire department. The information collected by these devices may potentially be processed in near real-time to provide insight into the stability of the structure and the risk of performing certain tasks, and to provide an evacuation alarm.

While training on fire dynamics is effective in teaching firefighters about how a fire spreads, there are situations in which conditions deteriorate unexpectedly for reasons that may not be readily apparent without advanced sensing technology. Technologies to improve situational awareness, communication, and sensors are summarized in Table 3-16.

Table 3-16: Summary of Situational Awareness Technologies.

Existing Technologies	Emerging/Future Technologies
• Building sensors (flux, gases, temperature, smoke) • Digital & analog communication devices, including ultra-wide band, cell phones, and other advanced devices • Interoperability technology • Thermal imagers	• Building sensors (fire control, real-time fire modeling and forecasting, wireless information to IC) • Structural collapse monitors that track building integrity and warn fire fighters to evacuate • Body worn sensors (biometrics and fire environment monitors) • Personnel locator and tracking systems • Flashover predictor that track conditions, analyze, and alarm when pre-flashover conditions occur • Communication devices that function in high rise buildings and under adverse conditions

3.4.6 Equipment

The urgency associated with locating and rescuing fire victims, locating and attacking a fire, and accounting for the safety of other firefighters requires adequate protection from the harsh environment in which firefighters typically operate. Confidence in the performance of personal protective equipment (PPE) is therefore of vital importance. Technologies and test methods that measure the performance of turnout gear, personal alert safety systems (PASS), and self-contained breathing apparatus (SCBA), which are considered "life-critical" personal protective equipment, must be reliable. Ideally, turnout gear would allow firefighters to safely operate with ease in fire or hazmat environments. Technologies that bring the current state of the art closer to this ideal through improvements in materials and design, such as integrated passive/active cooling systems, are sought. Personal Alert Safety Systems (PASS) are currently transitioning from independent devices to integration with Self Contained Breathing Apparatus (SCBA) and new technology is driving optimization of alarm sounds and PPE heat resistance. Emerging cyber-physical systems are desired in the SCBA functionality, for example, integration of formerly independent equipment such as PASS devices, wireless crew-to-crew or crew-to-IC communication systems, or a heads-up display that includes thermal imaging and provides information on gas and surface temperatures and biometrics. In short, embedded intelligence and linked technologies that support improvements in functionality, heat resistance, size, shape, and weight of firefighting equipment are very important to firefighter safety and effectiveness.

End of service life indicators for PPE and sensors that monitor exposures of both PPE and firefighters to harmful conditions will provide useful information for retirement planning and budgeting of new equipment. As with personal protective equipment, advances in operational equipment (such as apparatus, nozzles, hoses, pumps, ladders, extraction equipment, robotics, cooling stations or kiosks, etc...) will require methods to evaluate their usefulness, particularly in cases where a considerable investment is necessary. Technologies to improve PPE and operational equipment are listed in Table 3-17. Finally, buildings may provide equipment critical to fire service success. For example, a fire command center may improve situation awareness and fire service access elevators in high-rise buildings ensure firefighters are able to rapidly and safely access upper portions of high-rise buildings without exerting significant energy carrying equipment up stairwells.[*]

* Advanced PPE is needed for special operations including multi-hazard applications such as hazardous materials or possible chemical/biological exposure, but this is beyond the scope of this roadmap, which is exclusively focused on fire-related fire service activities.

Table 3-17: Existing and Emerging Equipment Technologies.

Existing Technologies	Emerging/Future Technologies
• Turnout gear • PASS • SCBA • Radios • Fire equipment: includes nozzles, hoses, pumps, ladders, extraction equipment, irons, cooling stations, etc... • Thermal imagers • End of service life indicators • Fire apparatus, including fire engines, rescue trucks, ambulance, and other specialized mobile equipment • Fire service access elevators	• Advanced/integrated SCBA: includes improved materials, design and integration of PASS, communication, heads-up display, fire and biometric monitors, etc... • Improved equipment characteristics: lightweight, thermally durable, and robust • Smart fire fighting equipment combining sensors, computational resources, and/or communication • Robust fireground communications that work in high challenge RF and high-temperature environments • Robotics for high-risk fire operations • Remote sensor packages including unmanned drones and robots • Collapse monitors / predictors • Smart hose deployment/delivery systems • Passive/active cooling turnout gear • Ergonomic design of equipment and apparatus

3.4.7 Tactics

During an emergency incident firefighters are expected to carry out the strategy of the IC to the best of their ability. Given adequate training and equipment, firefighters may engage in tactical operations such as search and rescue, fire suppression, hazmat operations, ventilation or compartmentalization, and rapid intervention procedures. Tactics may include overhaul (ensuring complete fire extinguishment), clean-up of the structure and neighborhood as appropriate, and fire source identification (cause and origin). Post-incident tactics may include analysis of the lessons learned. Measurement science can evaluate the efficacy of different tactics for a range of different fire scenarios. For example, tactics during wind-driven fire events may be different than tactics during a fire response in the absence of wind. Technologies that support improved tactics may include equipment that allows better and faster tactical decisions to be made, such as robotics, and research that provides a better understanding of the benefits or consequences of new or existing tactical operations.

Additionally, new tactics may need to be developed as new construction techniques, construction materials, environmental regulations, and energy systems are implemented in communities and affect buildings (such as photovoltaics), vehicles (hydrogen fuel cells, new battery technologies, etc.), storage and transportation systems. The environmental impact of different tactics may change over time as well, due to evolving construction and suppression materials and environmental regulations. In cases involving mutual aid among fire departments or multiple responses from federal, state, or local emergency response organizations, technology is needed to ensure that all parties are capable of coordinating tactics during joint operations.

Fire service fire control tactics fall into two general categories: those that relate to the application of a suppression agent such as water, gas, or foam, and those that encompass other types of strategies such as compartmentalization and control of ventilation. Emerging cyber physical systems will combine sensors with computational resources to identify fire location and direct suppression resources, either robotic or fire fighter based systems to enable more effective suppression. Table 3-18 lists existing and emerging tactics and technologies that support advanced tactics. The table also lists technologies that address new fire types and environmental impact.

Table 3-18: Existing and Emerging Tactics and Technologies that Support Tactics.

Existing Technologies	Emerging/Future Technologies
• Ventilation/compartmentalization • Search and rescue • Suppression (internal/external hose streams, tactics, agents, building systems) • Hazmat and chemical/biological exposure • Overhaul • Rapid intervention procedures • Fire source identification • Clean-up/environmental impact •	• Physics-based advanced tactical decision aids • Post-fire analysis tools (evaluation of tactics, lessons learned, fire behavior) • New suppression agents • Optimized use of forced and natural ventilation • Alternative/advanced suppression methods • Remote fire detection and intelligent suppression systems • Deployable sensor packages with communication links

3.4.8 Summary

Applying measurement science to the areas of training and education, resource allocation, situational awareness, equipment, and tactics will lead to an increase in *the effectiveness and safety of firefighters*. Emerging cyber physical technologies will combine remote sensors with other mechanical systems or computational resources to assist future fire fighters in monitoring the fire ground environment, maintain communication, and deploy necessary resources in order to improve the effectiveness while maintaining the safety of fire fighters. Research is needed to enable the groups of key technologies (listed in Table 3-18) that can have an impact on the fire problem. While Table 3-18 lists many different technologies, some technologies are more likely than others to have significant impact. Therefore, a prioritized research investment in advanced fire service technologies will be necessary to maximize impact with finite resources. The priorities, presented in the beginning of Chapter 4, emphasize several key areas. At the conclusion of Chapter 4, additional research needs are discussed and prioritized (provided that additional resources become available).

Technologies listed in Tables 3-12 to 3-18 with significant potential to contribute to this effort are highlighted in Table 3-19 and include both existing and emerging technologies. While Table 3-18 lists many different approaches, some are more likely than others to have significant impact, therefore, a prioritized research investment will be necessary to maximize the impact of limited resources. The priorities, are presented in the beginning of Chapter 4, and emphasize firefighting equipment and tactics. At the conclusion of Chapter 4, additional research needs are discussed, and would be useful provided additional resources become available.

Table 3-19: Summary of Technologies to Improve the Safety and Effectiveness of Firefighters.

Existing Technologies	Emerging/Future Technologies
• Theatrical virtual trainers • Virtual training tools • Training & education materials (CDs, DVDs, literature) • Health and fitness education materials • Pre-planning/crew size decision tools • GIS-based station location/resource coverage models • Community outreach programs • Traffic signal routing • Building sensors (flux, gases, temperature, smoke) • Digital & analog communication devices, including ultra-wide band, cell phones, and other advanced devices • Interoperability technology • Turnout gear • PASS • SCBA • Fire apparatus: includes nozzles, hoses, pumps, ladders, extraction equipment, vehicles, cooling stations, etc... • Thermal imagers • End of service life indicators • Interoperability • Ventilation/compartmentalization • Search and rescue • Hose streams (including internal vs external attack) • Suppression (tactics, agents, building systems) • Hazmat • Overhaul • Rapid intervention procedures • Fire source identification • Clean-up/environmental impact	• Physics-based virtual training tools • Computational fire reconstructions • Biometric monitors and guidelines for use • Environmental sensors linked to exposure warning systems • Health screening tests for risk factors • Guidelines and risk analysis tools for crew size and station location • Wireless building/contents data to IC • Fuel efficient, multi-use apparatus • Building sensors (fire control, real-time modeling, wireless information to IC) • Structural collapse monitors that track building integrity and warn fire fighters • Body worn sensors (biometrics and fire environment monitors) • Flashover predictor that tracks conditions, analyzes and alarms • Personnel locator and tracking systems • Advanced/integrated SCBA: includes PASS, communication, heads-up display, fire and biometrics monitors, etc... • Improved equipment characteristics: lightweight, thermal durable, and robust • Smart fire fighting equipment combining sensors, processors, and/or communication • Robust fireground communications (RF challenged and high-temp. environments) • Robotics for high-risk fire operations • Smart hose deployment/delivery systems • Passive/active cooling turnout gear • Ergonomic design of equipment/apparatus • Physics-based tactical decision aids • Smart tactical decision tools based on fireground sensor data and computation • Smart fire detection/ suppression systems • Deployable sensors with communication links

3.5 STRATEGIC FOCUS AREA: REDUCED FIRE RISK IN WILDLAND-URBAN INTERFACE (WUI) COMMUNITIES

This strategic area is focused on fire mitigation and the improvement of the fire performance of structures and communities in the wildland-urban interface (WUI) through the development of engineered fire protection technologies, standard test methods for building materials, risk assessment tools and risk mitigation design for use by architects, builders, community decision-makers, homeowners, and fire officials.

3.5.1 Objectives

The long-term objective of this focus area is to develop the measurement science needed to enable a decrease of one-half of the preventable burden associated with Wildland-urban interface fires within a generation.[*][†] The reduction in the burden of WUI fires on society is characterized in the long-term by a metric related to the fraction of houses at the wildland-urban interface that are ignited by exposure to wildland fires. Short-term metrics for this strategic focus area are described in detail in Chapters 4 and 5.

3.5.2 Fire Safety Framework

Damaging WUI and wildland fires have many negative impacts on society and the built and natural environments. This section first provides a general discussion of the WUI problem. This is followed by a discussion of specific approaches to reducing the impact of WUI fires.

The total burden of WUI fires are estimated as about $14 billion annually (see Table A-1 in Appendix A). There are few life losses associated with the WUI. The dominant costs are associated with the costs of suppression, property loss, and other types of economics losses (e.g., business interruption). Unlike the structure fire problem, the WUI fire problem appears to rapidly be getting worse in terms of structures lost and acres burned. Using forecast methods, estimates of the WUI fire problem were conducted and are shown in Figure A1-1 in Appendix 1. The analysis suggests that the WUI fire burden, if unchecked, will likely double over the next decade and become a more significant portion of the national fire burden. In this respect, slowing the growth of WUI losses over time could be considered a substantial achievement.

While there are many approaches to address fire safety and effectiveness, a matrix was chosen that juxtaposes the natural progression of a fire incident (the timeline) with increasing level of complexity in the fire service operational environment (firefighter, fire department, community). Figure 3-3 represents this matrix and illustrates the relationship in the overlapping approaches considered here. Improvements in firefighter training, health, and conditioning, both from the perspective of the

* Appendix B provides a detailed accounting of the preventable fire burden and how the objective can be realized.

† Outdoor fires are defined as fires that burn beyond the confines of a structure. WUI fires are fires that involve fire spread through an intermix of vegetative and structure fuels distributed in a community or on the landscape.

individual firefighter and the policies of the fire department, along with community education programs, contribute to the preparedness of the fire service and the community for emergency events. Enhanced training would prepare firefighters to deal with hazards in a cost effective way, helping to increase operational effectiveness and reduce the risk of injury. Ensuring that appropriate resources are available to respond to emergency events requires careful allocation of community funds, which can be very difficult without detailed information on the cost/benefit profile of resource investments.

While costs have been high, suppression of wildfires in the U.S. has been effective: about 98 % of wildfires on U.S. Forest Service lands are suppressed during initial attack by firefighters.[71,72] However, the remaining 2 % of escaped wildfires occur in extreme conditions (e.g., high winds, dry fuels). In about 87 % of large wildfires during 2003 and 2004, protecting private property was a major component of the fire suppression effort and represented from 50 % to 95 % of suppression costs.[72] Because damaging WUI fires (in terms of both property loss and suppression cost) predominantly occur in extreme weather and wildland fuel conditions, they result in multiple, extensive, rapidly spreading wildland fires that overwhelm the resources of both wildland and structural firefighters.[72,73] These conditions present extreme challenges for effective fire suppression techniques and the supporting infrastructure (e.g., roads and water delivery systems). Some estimate the cost of improving the existing infrastructure to be in the hundreds of billions of dollars.[*,72] While complete suppression of wildland fires would solve the WUI fire problem, it would take a major breakthrough in suppressant technology and/or delivery effectiveness to provide anything but an incremental reduction in the WUI fire problem through suppression efforts in the wildlands. Measurement science research focused on defensive technologies and tactics (including suppression), however, could have value, given that it can be an effective means to safeguard property under certain conditions.[74]

Most civilian deaths and injuries associated with WUI fires in the US occur during evacuation. Firefighters are also at risk and suffer injuries keeping evacuation routes clear. The costs associated with evacuation (firefighters, police, National Guard) are not well documented, but are significant (for example, over 500,000 people in the 2007 California firestorm). Improved predictions of smoke obscuration over evacuations routes are needed.

Reducing the likelihood of structure ignition is the best course of action to reduce the negative impact of the WUI problem.[75] If WUI communities and homes were designed to withstand WUI fire exposure and support efficient evacuation, then the escalating costs of fire suppression and damages to homes and

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* For example, the simultaneous use of water by numerous residential sprinkler systems and firefighter's hose applications can result in a drop in municipal water pressure to the point where both measures become ineffective. Aircraft delivery of fire suppressant to assure sufficient quenching of a large wildfire would require a larger fleet of aircraft and a larger supply of nearby suppressant than is generally feasible. In addition, the hazardous conditions caused by high winds can preclude the use of air attack.

community infrastructure would be significantly reduced. This is consistent with the conclusions reached by the Quadrennial Fire Review,[76] which promotes the creation of Fire Adapted Communities.

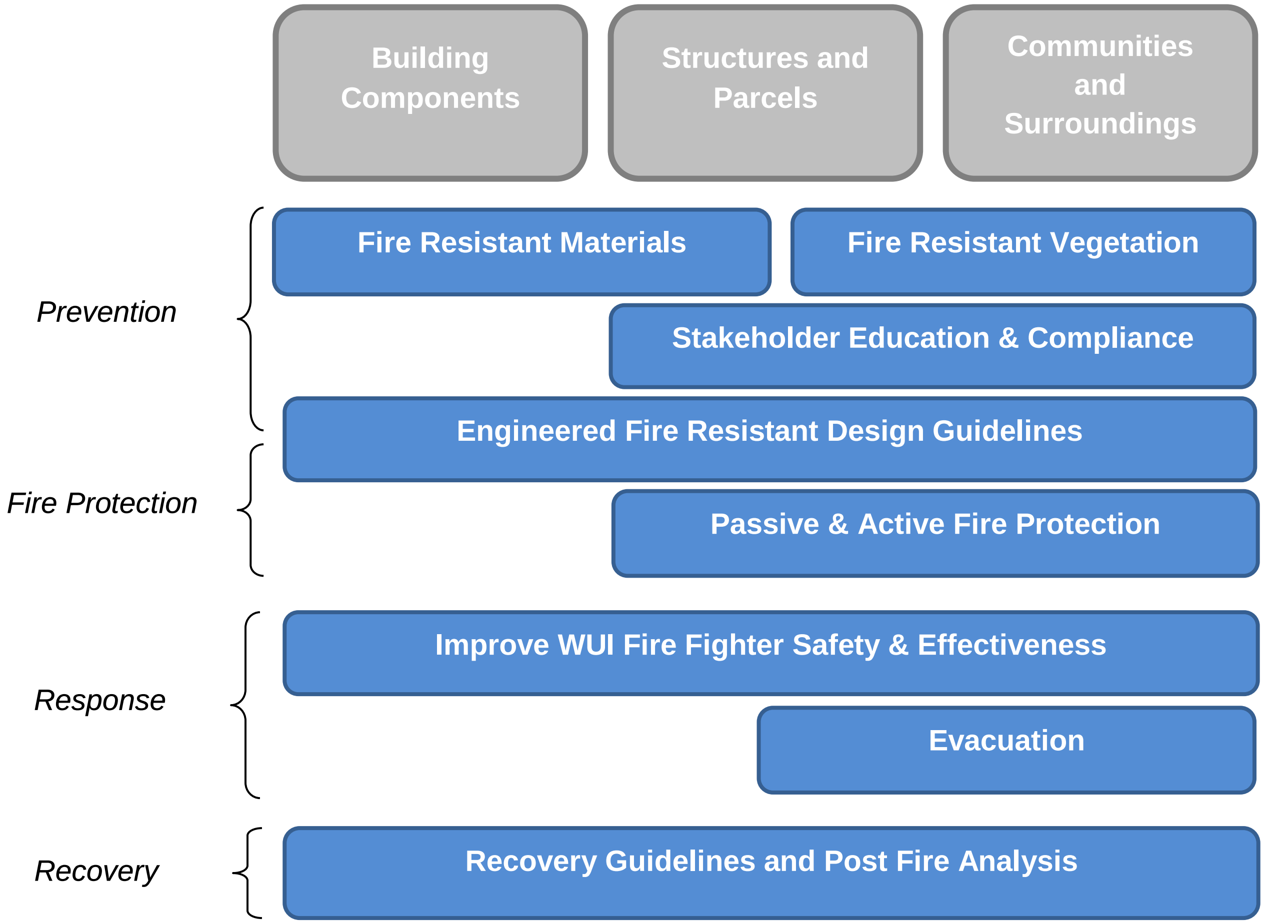

Figure 3-3: Approaches to reduce the risk of ignition and fire spread in WUI communities.

Guidance is available for WUI homeowners and communities to assess and mitigate their risk of structure ignition.[77,78,79] This guidance, which is focused on the homeowner's structure and residential vegetation, is limited in a number of ways. First, it is not the result of scientific study or based on measured or modeled exposure conditions across a range of WUI fire environments (i.e., wildland fuel types, terrain, and weather). Second, it has not been evaluated for effectiveness through post-fire analysis. Third, most current practices are designed for structures on large parcels of land (greater than 1.5 acres), which are, in general, larger than parcels characteristic of the high-loss WUI fire events, such as the recent damaging fires in southern California (2007), Texas (2011), and Australia (2011). Finally, little guidance is available to communities to reduce structure ignition via firebrands, even though previous[80] and ongoing[81] post-fire studies find that firebrands account for over 60 % of structure ignitions.

Research focused on reducing structure ignitions begins with furthering the understanding of the mechanisms and conditions leading to structure ignition by a WUI fire.[82] This would form the basis for improved building materials, construction, risk assessment tools and risk mitigation design (for architects, builders, homeowners, communities, and fire and land use officials) leading to reduced structure ignitions. These tools would take into account the different implementation opportunities and challenges due to existing construction versus new construction. Public education is critical to the success of any effort to reduce WUI fire structural ignition, and several organizations are actively working this issue.[83]

In Figure 3.3, approaches to reducing structure ignition, and other negative impacts of WUI fires, are categorized according to physical scale (across the figure) and the stage in the evolution of a WUI fire event (down the figure). This categorization is used to organize the needs assessment discussion in the following sections. The physical scales of interest are, from fine to coarse, denoted by: Building Components, Structures and Parcels, and Communities and Surroundings. The stages of WUI fire risk reduction are denoted by: Prevention, Fire Protection, Response, and Recovery. This framework was developed after input from two workshops on the WUI fire problem, which were held in June 2009.[84,85] Findings from these workshops and other literature[72,81,82,86,87] were used to develop the strategy outlines in the following sections.

3.5.3 Prevention

From a WUI community and fire official's point of view, prevention focuses on fire resistant materials and vegetation (fuels management), stakeholder education and compliance, and engineered fire resistant design. A fundamental component of effective and efficient fuels management practice is reliable risk assessment, knowledge and tools applicable to a range of scales, from building components, to buildings, to communities. These tools would include mapping of potential fire exposure zones. Within a WUI community these zones would be associated with codes for building materials and assemblies, residential vegetation choices, and landscaping practices. These all would contribute to lowering the likelihood of structure ignition. Continuous maintenance of fuel conditions is essential.

Some states have wildfire hazard risk maps based on vegetation, terrain, weather, firebrands, historical and/or predicted fire behavior (e.g., California[88]). In California these Hazard Maps are used to enforce building standards for new construction. A website containing links to similar activities in other states exists.[89] This hazard mapping is based solely on the potential for severe wildfire activity over landscape-scales. Also, the fire behavior models used cannot directly provide exposure conditions (heat and firebrand flux) or capture fire spread through complex, heterogeneous fuels. The characteristics and conditions the of the WUI fuel system (structures and vegetation) at the community or sub-community scale are not considered. Thus, while this hazard mapping approach is a good first step, the technology exists and is being developed to include WUI fire behavior predictions and fuels at the community to sub-community scales. Emerging cyber physical systems will combine data collected by distributed sensor networks with computational resources to provide insight on how fire might spread before an incident and during an actual incident. This will lead to an improved understanding of exposure conditions and, therefore, hazard mapping, building standards, and landscaping guidelines.

The wildland vegetation surrounding a community can play a critical role as to how a fire may spread into a community. Adjacent tree vegetation may ignite structures through intense thermal radiation or through embers. Incorporating non-combustible zones or fire breaks between nearby forest and communities aids in the prevention of radiative ignition. Adjacent grass vegetation may ignite structures through direct flame contact or thermal radiation. Non-combustible zones around structures would aid in the prevention of ignition from either flame contact or thermal radiation. Wildland fires, however, generate embers which can be lofted into the air and carried by the wind for distances as large as 20 km. Incorporating fire breaks sufficiently wide to prevent ember ignition are difficult to implement due to terrain, ownership, and jurisdictional issues. Fuels management or wildland fuel treatments are designed to reduce the amount of fuel available to the fire in wildland areas adjacent to communities.

A significant amount of field research on wildland fuel treatments has been, and continues to be, funded by the Joint Fire Sciences Program.[90] However, the large majority of these studies are focused on the ecological effects of the wildland fire, rather than how wildland fuel treatments would change the exposure conditions (e.g., heat and firebrand fluxes, or smoke production) of proximate WUI communities. Even for purely wildland fires, there is a lack of systematic, science-based, field research to characterize how wildland fuel treatments alter fire behavior and firebrand and smoke generation.[91] Some, largely anecdotally based, studies have found wildland fuel treatments can aid firefighter actions through improved access and visibility. Field studies that seek to understand the influence of wildland fuel treatments, in WUI settings, on overall fire behavior (e.g., spread rates, crowning potential, firebrand and smoke production) are needed. Current wildland fuel mapping for the U.S. is at 30 m resolution (LANDFIRE[92]). This is too coarse for use at most WUI settings. However, the technology exists now to map (at sub-structure scales) the fuels, terrain, and fire behavior using airborne infrared and LiDAR measurements. Such measurements during prescribed fires, along with ground based measurements of wind, fuels, and fire behavior would provide a much needed dataset to improve the understating of the fire exposure conditions experienced by WUI communities. These measurements would also support the development of WUI fire computer models for risk assessment at the structure to community scale. Currently, WUI fire behavior models, which account for complex fuel loading and wind patterns in a WUI community, are in their first steps of development. WUI fire models can be used to better understand the exposure conditions present in severe conditions under which most damaging WUI fires occur but are beyond the scope of prescribed fire studies.

Relevant laboratory-scale standard test methods for building materials and structure design also require an improved understanding of the exposure conditions faced by WUI structures. Effective WUI building materials (e.g., siding) or assemblies (e.g., vented eaves) require standard test methods that simulate exposure conditions that are as, or more, severe than those in an actual WUI fire. Currently, standards development organizations (such as ASTM and others) are active advancing WUI related building and construction standards by compiling, organizing and harmonizing the understanding of WUI fire exposure conditions for structures and communities. Work is needed to advance standard guidelines for landscaping on residential parcels, community-scale landscaping, and wildland fuel treatments. The NFPA and ICC have relevant standards documents[93,94] for residential and (to a lesser degree) community landscaping. How well structure and community scale risk assessment/mitigation tools actually help reduce structure ignition is best tested through post-fire studies (discussed below).

Education and effective information delivery is essential to the implementation of homeowner and community guidelines. There are a number of existing web-based resources that can be used to promulgate improved guidelines. The four most heavily used are ICC,[95] Firesafe,[78] Firefree,[77] and Firewise.[79] These guidelines are focused on building materials, structure attributes, and parcel landscaping. Expansion of these approaches is needed to include risk factors based on the attributes of adjacent structures and the surrounding vegetation. In addition, a benefit versus cost analysis tool that considers a range of recommended homeowner or community risk reduction actions is required. Communities differ in the amount of financial resources available for landscape and residential fuel treatments. An economic based tool that can account for this would be an attractive and effective component of an overall risk assessment/mitigation toolkit.

Table 3-20: Prevention: Existing and Emerging Technologies.

Existing Technologies	Emerging / Future Technologies
• Landscape-scale hazard mapping • Fire Retardant Chemical Treatment • Fire resistant glazing and ember resistant ventilation portals • Simple landscape-scale wildland fire behavior models • Non-standardized WUI community data collection and risk assessment tools • Fire resistant house wraps	• Community to sub-community hazard mapping • Ignition resistant building materials and vegetation • Fire resistant component assemblies • Physics based , laboratory to landscape scale, WUI and wildland fire behavior models • Standardized, GIS-based, WUI data collection and risk assessment tools • Sensor networks linked to computational models of fire behavior to predict/track fire spread

3.5.4 Fire Protection

Engineering Fire Resistant design for building components, structures and communities is the focus of a mitigation approach, which begins with improving risk assessment tools and using engineered fire protection to mitigate or limit the impact of a WUI fire. A key component to improving risk assessment and mitigation tools (such as guidelines and standard test methods) is a well-founded and sufficiently broad database of structure and community attributes after damage due to a WUI fire. The objective is to learn lessons from WUI fire losses and to be able to provide science-based rehabilitation guidance for buildings and communities after a WUI fire event. The kind of information needed would include, for example, an accounting of roofing and siding materials, terrain, structure locations, and residential vegetation for all structures (destroyed, damaged, and undamaged) that were exposed to the WUI fire. Ideally, pre-fire community attributes would also be known. In addition, essential components to the database are defensive actions taken by firefighters, homeowners, and police. These include, for example, suppression of vegetative fires near a structure, closing of garage doors, or the use of a fire engine hose to suppress a roof fire.

Engineered fire resistant design is also an essential component the mitigation approach and can reduce exposure to the fire, decrease the likelihood of ignition, and/or reduce fire spread. The geometry of the building may play a role. If a corner or seam allows embers to accumulate, a group of embers may transfer enough energy to cause ignition. A fire resistant design strategy would prevent the accumulation of embers through designs that reduce or eliminate geometries with internal corners, for example, which allow thermal radiation to be re-radiated from one surface to another. For communities, exposure to thermal radiation can be reduced by designing non-combustible zones between adjacent structures or vegetation. Implementation of effective fire resistant designs for building components, structures, and communities are a critical component of mitigating WUI fires.

Standardized post-fire data collection methods do not currently exist. This includes hardware, software, field procedures and protocols, and training of field crews. Emerging cyber physical systems will combine personnel and equipment tracking sensors with computational resources to track fire ground resources and enable intelligent deployment of fire apparatus and fire fighters.

LiDAR, both ground and aerial based, and other remote sensing data can be a very valuable addition to ground based data. Both standardized reporting methods and a data repository system will support effective post-fire analysis. The data repository needs to be compatible with Geographic Information System (GIS) software in order to take advantage of GIS based analysis and visualization tools. The database and analysis tools would provide a means to track, with time, the effectiveness of existing and new risk assessment and mitigation techniques across a range of WUI community types and WUI fire exposure conditions.

Post-fire (and pre-fire) WUI community data collection could also identify shortcomings in recommended mitigation actions in terms of ease of implementation or clarity. This would help determine what improvements are needed in terms of community education and incentives. Analysis of post-fire data and sufficiently accurate WUI fire behavior and economic models would also support the development of rehabilitation guidelines (e.g., landscaping, vegetation choice and maintenance, building placement and construction choices and prioritization) for damaged communities.

Table 3-21: Fire Protection Activities: Existing and Emerging Technologies.

Existing Technologies	Emerging / Future Technologies
• Fire shutters for windows • Non-standardized field data collection methods • Non-combustible zones • Pre-Fire Foam Application • Structure protection technologies deployed for special cases (e.g., historic buildings)	• Architectural designs to minimize re-radiation zones • Component and structure design to minimize ember accumulation • Standardized, GIS-based, field data collection methods • Risk Assessment of WUI fire hazard • Community design tools using science based fire exposure mapping, and fire behavior and economic models • Remote activated suppressant application-foam & water • Advanced structural protection technologies for relatively general application

3.5.5 Response

Destructive WUI fire events usually occur in severe conditions (e.g., high winds, dry fuels) resulting in large, rapidly spreading, fire perimeters. As a result, firefighter suppression resources are overwhelmed. Large WUI fire events can involve thousand s of firefighters for days, or even weeks. Satellites are used for detection but in severe conditions the turn-around time of satellite information is too long for tactical use. Overall operational command and control is centered at an Incident Command Post. Firefighter safety and communication are of primary importance. In complex terrain, communications can be spotty. In extreme fires, cell phone towers and power lines may be destroyed. There is a need for improved rugged, portable communication systems and firefighter location technologies to improve firefighter safety, situational awareness, and command and control decision support. Emerging cyber-physical technologies that enable a firefighter to quickly monitor and analyze fire conditions will inform his/her tactical decisions. The ability of new cyber-physical systems to communicate fire conditions, the location of emergency responders, and changing egress routes would improve operational safety and effectiveness. Firefighter personal protection equipment, tools, and resources can also be improved. This includes, for example, clothing, goggles, head lamps, fire shelters, fire weather information quality and use, respirators, and carbon monoxide detectors.[96,97]

WUI fires differ from structural fires. They are more complex and require different equipment and operating procedures. Since there are no WUI specific standard equipment and operating procedures, these things need to be developed to effectively fight fires in the wildland-urban interface.

The WUI fire environment needs to be characterized to develop measurement capability to evaluate personal protective equipment. Limited data are available on the chemical and thermal environment of WUI fires. Structural fire fighters have safety equipment (SCBA & turnout gear) designed for interior attack but are too heavy and bulky for WUI fire fighting. Wildland fire fighters have minimal safety equipment (nomex uniforms and red bandanas) that is insufficient for wildland fires as well as WUI fires. Addressing this need would characterize the environment generated by a WUI fire and develop measurement science necessary to evaluate the effectiveness of safety equipment.

There is a need to develop the measurement science to characterize the effectiveness of existing and new passive defense technologies. Community response to WUI fires is typically limited to deployment of fire engines and fire fighters. There are a number of potential technologies which could harden structures and communities to be more fire resistive. For structures, these include metal shutters over openings (windows, doors, vents), water sprinklers for the exterior of structures, ember-resistant fences, foams or fire resistant wraps applied to the entire exterior of a structure. For communities, these include the strategic placement of non-combustible zones to either prevent fire spread or channel fire spread to specific defensible zones within a community. Several of these technologies are beginning to be offered to communities without any clear technical basis if the technologies are effective. Underlying measurements are needed to evaluate whether any of these technologies are effective in improving the fire resistance of communities.

Currently, there are no proven computer models capable of simulating fire spread through the complex fuels in the WUI. Current operational wildland fire behavior modeling tools used in the U.S. are based on the Rothermel fire spread model developed in the early 1970s.[98] This fire spread model has a number of shortcomings.[99] The U.S. Forest Service (USFS) has recently begun an effort to improve their operational wildland fire predictions by improving wind prediction.[100] The National Oceanic and Atmospheric Administration (NOAA) provide fire weather forecasts over the US. These forecasts can also be used by fire officials to strategically pre-position resources. Fire weather forecasts use the atmospheric variables of wind, humidity, and temperature forecasts to rate fire risk. No accounting of fire/atmosphere interaction or smoke transport is made. There is a need for WUI fire behavior models for operational use. Especially important are the influence of terrain, varying, fuels, and fire/atmosphere interaction on the development of extreme fire behavior.[101,102,103]

Smoke transport predictions would aid implementation of community evacuation and aerial suppression. The Department of Homeland Security is funding research on structure protection such as wrapping homes with a protective blanket.[104] Presumably, with accurate fire spread predictions, sufficient lead-time, and a system capable of deployment in strong winds, a number of homes could be protected. It is unclear how such a system would be used to protect 100s or 1000s of threatened homes, which is not uncommon in extreme fires. As mentioned in the previous section and discussed more fully in the next section, it is essential to build a database of communities burned by WUI fires. This will often require data collection in burned communities while the main fire is still active. For safe and effective deployment, teams must be fully trained, firefighter certified, and integrated in the incident command systems. There is a need for a standardized and rapid data collection methodology. The resulting dataset would guide subsequent, more in-depth, data collection efforts which also need to be standardized.

Table 3-22: Response: Existing and Emerging Technologies.

Existing	Emerging / Future Technologies
• Piloted reconnaissance of fireline • Coarse resolution tactical fire weather models based on atmospheric variables or simple fire behavior models	• Distributed Suppression Tactics • WUI specific training and tactics • Reliable and standard communication equipment in rugged terrain • Respirator and other personal protective equipment suitable for wildland firefighting • High resolution tactical fire weather models that capture terrain influence on wind and fire/atmosphere interaction • Strategic placement of non-combustible zones to break-up fire line • Evacuation Models for Communities • Body worn sensors (biometrics and fire environment monitors) • Smart hose deployment/delivery systems • Remote sensor packages and robots

3.5.6 Recovery

Standardized post-fire data collection methods do not currently exist. This includes hardware, software, field procedures and protocols, and training of field crews. LiDAR, both ground and aerial based, and other remote sensing data can be a very valuable addition to ground based data. Both standardized reporting methods and a data repository system will support effective post-fire analysis. The data repository needs to be compatible with Geographic Information System (GIS) software in order to take advantage of GIS based analysis and visualization tools. The database and analysis tools would provide a means to track, with time, the effectiveness of existing and new risk assessment and mitigation techniques across a range of WUI community types and WUI fire exposure conditions.

Post-fire (and pre-fire) WUI community data collection could also identify shortcomings in recommended mitigation actions in terms of ease of implementation or clarity. This would help determine what improvements are needed in terms of community education and incentives. Analysis of post-fire data and sufficiently accurate WUI fire behavior and economic models would also support the development of rehabilitation guidelines (e.g., landscaping, vegetation choice and maintenance, building placement and construction choices and prioritization) for damaged communities.

3.5.7 Summary

To reduce the fraction of houses at the wildland-urban interface that are ignited by exposure to outdoor fires, measurement science must be applied to improve prevention, fire protection, response and recovery. Emerging cyber physical technologies will combine remote sensors with other mechanical systems or computational resources to assist homeowners and fire fighters in monitoring the fire ground environment, maintain communication, and deploy necessary resources in order to improve the effectiveness while maintaining the safety of fire fighters and homeowners. Research is needed to enable the groups of key technologies (listed in Table 3-23) that can have an impact on the fire problem. While Table 3-23 lists many different technologies, some technologies are more likely than others to have high impact. A prioritized investment in WUI technologies will maximize the impact with finite resources. The priorities are presented in Chapter 4.

Table 3-23: Summary of WUI Technologies.

Existing Technologies	Emerging / Future Technologies
• Landscape-scale hazard mapping • Fire Retardant Chemical Treatment • Fire resistant glazing and ember resistant ventilation portals • Simple landscape-scale wildland fire behavior models • Non-standardized WUI community data collection and risk assessment tools • Fire Resistant House Wraps • Radiation Reflective Coatings for Windows • Coarse resolution tactical fire weather models based on atmospheric variables or simple fire behavior models • Structure protection technologies deployed for special cases (e.g., historic buildings) • Pre-Fire Foam Application • Fire Shutters • Non-standardized field data collection methods	• Community/ sub-community hazard maps • Community design tools using science based fire exposure mapping, and fire behavior and economic models • Ignition resistant building materials and vegetation • Fire resistant component assemblies • Physics based , laboratory to landscape scale, WUI and wildland fire behavior models • Standardized, GIS-based, WUI field data collection and risk assessment tools • Sensor networks linked to computational models of fire behavior to predict/track fire spread • Body worn sensors (biometrics and fire environment monitors) • Smart hose deployment/delivery systems • Remote sensor packages and robots • Distributed suppression tactics • WUI specific training and tactics • Reliable communication equipment for rugged terrain • Wildland firefighting respirator • High resolution tactical fire weather models that capture terrain influence on wind and fire/atmosphere interaction • New structure protection technologies for relatively general application • Remote activated suppressant application-foam & water • Strategic placement of non-combustible zones to break-up fire line • Evacuation models for communities • Architectural designs to minimize re-radiation zones • Component and structure design to minimize ember accumulation • Risk assessment of WUI fire hazard

3.6 OTHER FIRE TYPES

Fires associated with means of transportation, manufacturing and industrial fires all contribute to the U.S. fire burden. While these areas are not the direct focus of this roadmap, the measurement science developed to mitigate fire losses in buildings and communities are also applicable to these sectors.

The transportation sector is particularly worthy of further discussion. This sector includes vehicles themselves (road vehicles, aircraft, trains, subway cars), as well as the supporting infrastructure, including underground subway stations, airports, ships, and ports. Of these, motor vehicles are the most substantive contributors to the U.S. fire burden, in terms of life safety, property loss and intervention cost (see Appendix A). About 10 % of U.S. fire fatalities are attributed to post-collision vehicle fires,[2] almost exclusively associated with post-collision entrapment. About 16 % of emergency fire responses are to highway vehicle fires.[105]

Additional challenges may come from the next generation vehicles, which will likely be powered by alternative fuels and energy sources. These vehicles may include plug-in hybrid electrical vehicles (PHEV), electrical vehicles (EV), hydrogen fuel cell vehicles (HFCV), and biofuel vehicles. Already on the market are compressed natural gas vehicles (CNGV) and hybrid electrical vehicles (HEV). Due to the differences in the technologies employed in these vehicles, a number of fire safety challenges unique to these vehicles may emerge and ought to be addressed before the vehicles are fully commercialized. Although some of the fire safety issues are similar for some of the alternative fuels (e.g., CNG vs. GH2), the combination of different technologies in these vehicles, together with new and untested technology warrant special attention.

The areas of fire safety concern involve the vehicle itself (design, operation, accident, fueling, parking, and maintenance) and problems specific to alternative fuels (e.g., flammability, storage, and fuel leakage). Both active and passive fire protection strategies can play a role.

Post-collision battery-induced shorts are a common mechanism for initiation of car fires. Preventing ignition by hardening battery storage and considering material issues would be useful. Fire safety issues associated with Li-ion batteries become more important as battery cell sizes increase to meet the driving requirements for HEVs, PHEVs, and EVs.

Improving material flammability performance would slow fire spread within vehicles. In addition, in alternatively fueled vehicles, these materials will be subjected to different potential ignition sources or other thermal exposures (e.g., flammable electrolytes, hydrogen flames). A new set of material flammability test methods will likely need to be developed.

Advances have been made on active suppression of car fires.[106] The challenge is to find cost-effective solutions with an emphasis on reliable low-weight solutions.

3.7 CROSS-CUTTING STRATEGIC FOCUS AREAS

3.7.1 Introduction

While Sections 3.2 to 3.5 describe strategic focus areas in building fires, WUI fires, and firefighting, research is often conducted in areas where the potential impacts can apply broadly. These cross-cutting research areas represent an opportunity to simultaneously attack several aspects of the national fire problem, therefore representing a potential economy of scale.

Fundamental fire science is a prime example of the benefits of cross-cutting research. Through measurement science to improve the fundamental understanding of fire phenomena, novel insights are often developed which may enable technology development in one or more seemingly disparate thrusts. For example, fundamental investigations of basic fluid mechanics at NIST, including the formulation of the low Mach number form of the Navier-Stokes equations, led to the development of the basic numerical algorithm for modern computational fluid dynamic (CFD) fire modeling. NIST's Fire Dynamic Simulator (FDS) computational fire model has become a common engineering tool used by the fire protection engineering community, the fire service, and wildland fire modeling (WFDS). [*] Basic research areas include advanced fire phenomenology, theory, measurements, and materials. Other examples include development of computational models and advanced sensors. Without advances in fundamental fire science, gaps in understanding will hinder progress on applied fire safety.

3.7.2 Fire Physics and Chemistry

Improved understanding of the physical science of fire is essential to enable innovation and progress at all scales in applied fire protection. Fundamental fire physics includes the processes of non-ideal mass and heat transfer, gas phase fluid flow about objects in boundary layers, as well as turbulent fire flow, and radiative exchange including its blockage by smoke. Fire chemistry includes gas phase flame reactions including flame inhibition and the formation of smoke, and solid phase chemistry including detailed mechanisms associated with charring, pyrolysis, bubbling, vaporization, intumescence, and melt-drip phenomena. Each of these topics involves in-depth knowledge of the processes and the instrumentation used to characterize them. Facilitating fire protection solutions mandates collaborations between those who have experience with fire phenomena and those with scientific disciplinary expertise.

3.7.3 Fire Measurements and Data

Improved measurements are needed to fully characterize fire phenomena, validate models, and support code and standards development, and fire investigations. Innovative and inexpensive (low hardware and labor costs) instrumentation and measurement techniques are needed to fully characterize real scale and reduced scale fire phenomena. Advanced sensors (see section below) and instrumentation will enable the next generation of fire measurements. New or improved techniques are needed to improve

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* The history and future development plans of the FDS model can be found at "FDS/Smokeview Research Plan " (http://code.google.com/p/fds-smv/wiki/FDS_Road_Map)

the measurement of important fire phenomena to improve basic understanding of heat release rate, toxic gases, particulates, temperatures and heat fluxes. Improved temporal resolution, spatial resolution and accuracy in the measurement of these properties would facilitate fire science. Other examples of measurement challenges include:

- Continuous real-time field measurements of fire structure, including the time/temperature/gas composition history with in-situ soot particle and toxic gases in the upper layer of underventilated compartment fires,
- Highly dynamic heat release rate measurements (fast fire growth or extinguishment),
- Structural performance measurements in a fire environment,
- Community-scale wildfire measurements, and
- Solid phase material properties relevant to pyrolysis and material flammability, and fire behavior.

Prediction of soot, hydrocarbons and toxic species is limited. Measurements are needed to provide input for existing models, guide future model development, and support model validation. Fire measurements for benchmark problems are important for the validation of theory and models. A multimedia web searchable fire measurement database with well documented data fields, images, videos, schematics, scaled drawings, and reports would greatly enhance the investment in fire research. Integration of measurements and models would enable appropriate interpretation of measurements. Advances in the use and interpretation of results from appropriate standard test methods would expand their utility.[*]

3.7.4 Advanced Fire Sensors

New sensor technologies have the potential to significantly improve fire safety and even fundamentally change the way humans behave and interact with un-wanted fires. Sensors that can detect the very early stages of fire, or even pre-fire conditions could facilitate the earliest possible intervention (e.g. automatic de-energizing of systems or localized automatic suppression). Sensors provide the trigger to alert occupants of a fire hazard. Sensors that do not false alarm would improve evacuation time. They could also be used to locate, track, and direct occupants during a fire event. Fire environment sensors could be used in a tactical manner in situations ranging from structure fires to WUI fires, to determine where the active fire is located and how it is spreading in order to more effectively fight the fire. In addition, autonomic, robotic firefighting opens up a new domain in fire safety. The right sensors (thermal, radiative, chemical species, video, etc.) and automatic information processing are necessary for success. The health and safety of the fire service can be much improved with advanced sensing to determine exposure threats experienced in a myriad of on-scene activities.

The keys to applying sensor technologies are:

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* The cone calorimeter and the LIFT device are two of the standard test apparatus needed as part of a measurement science fire protection instrument arsenal.

- Clear identification of the types of signals that would provide productive information to people and the various information systems,
- Requisite expertise in the particular sensor platform,
- Experimental characterization of sensor response associated with its expected use,
- Signal processing, and
- Modeling and data fusion techniques.

3.7.5 Advanced Materials

New innovative approaches to developing advanced fire-safe materials are critical to preventing fires, protecting civilians and fire service personnel from injury and death, and enabling the US industry to be competitive in the global marketplace. These innovative approaches enable materials and fire-safe products to comply with fire resistance and service life performance requirements defined by global standards, regulations, and markets while also enabling compliance with environmental and health regulations, and the manufacturer's requirements for fabricating and consumer's aesthetic requirements for the purchasing of end-products. Critical to successfully developing and transferring these approaches and materials to US industry is developing the characterization tools and methods to understanding the structure property relationships that dictates the performance changes. Equally critical is developing tools and methods to simulate and measure the impact of end-use stressing on the performance, health safety, and service life of these fire-safe products. The cross-cutting fundamental mechanistic understanding obtained from these measurements will enable US industry to use these approaches and materials to develop cost-effective and long service life fire-safe products.

Examples of cross cutting innovative approaches to develop advanced materials are:

- Layer-by-layer coatings
- nanotechnologies
- polymer covalently linked flame retardants
- bio-derived flame retardants and fire resistant polymers
- non-leachable flame retardants
- combinations of approaches

Many of these approaches show sufficient potential to deserve complete evaluation and characterization in all relevant applications and fire-safe products. Examples of potential fire-safe products that will use advanced materials for manufacturing, and in-service use, burning, and disposal of:

- protective clothing
- soft furnishings
- wall and floor coverings
- insulation
- wire/cable
- electronic and component housings
- building roof and siding products

Examples of cross-cutting characterization tools are:

- measuring the characteristics at the flame retardant and nanotechnology interface with substrates (e.g., Forster resonance energy transfer spectroscopy)
- highly sensitive and accurate measurements of the amount and surface area of nanomaterials released from manufacturing and materials use (e.g., Scanning Mobility Size Counter)

The keys to US industry and standards/regulation committees using these innovative approaches, advanced materials, and testing tools and protocols are:

- systematic and detailed evaluation and characterization of innovative approaches and advanced materials intended for fire-safe products
- clear identification of the current and emerging global performance and environmental health and safety (EH&S) requirements for manufacturing, in-service use, and service life for fire-safe products and the containing materials
- developing tools and methodologies that enable characterizing and testing the fire resistance, physical, mechanical, EH&S properties of the innovative approaches and advanced materials
- guidelines for using, testing, selecting, and restricting the use of innovative approaches and advanced materials based on state of the art knowledge

3.7.6 Advanced Computational Models

Models can be a testbed for the conversion of theory into practice. For example, models can form the basis of the engineering tools used by practitioners for design calculations. Performance based design, for example, relies primarily on the designers ability to numerically predict the growth, spread, and mitigation of the fire and the movement of the occupants. Regional emergency management officials may issue evacuation orders or devise specific mitigation strategies based upon the prediction of numerical WUI fire models. Additionally, numerical models may assist in the planning for experiments, replace or reduce the need (and cost) of full-scale experiments, or allow for the extrapolation of experimental findings and interpretation of experimental results.

Models facilitate the understanding of fire phenomena and allow one to ask questions that support the development of Reduced Risk of Fire in Buildings and Communities technologies. Due to limitations of the current generation of computers, computational models are not able to provide fundamental solutions across the many orders of magnitude in length scale that are relevant for realistic fire phenomena. Multi-scale modeling and the use of engineering approximations is needed to represent processes, properties, and relationships. There are many types of modeling relevant to the fire problem, representing a variety of applications over different time and length scales. They include fire modeling, molecular dynamics modeling, and modeling at intermediate scales. These models can be linked to human behavior through egress modeling and to building and infrastructure behavior through structural modeling.

Fire modeling addresses both fires within structures and in the wildlands. Fire modeling is commonly used by fire protection engineers for building safety system design and is being developed for use by incident commanders (WUI and structural) and community planners. The current generation of fire models is accurate to varying degrees depending on the specific application. In general, fire models are adequate for predicting the far field thermal and chemical environment for overventilated fire conditions in buildings, but are less accurate for the prediction of near-field effects, underventilated fire conditions (such as flashover), and phenomena such as fire suppression, fire toxicity, fire spread and growth, and ultimately fire hazard. The 2006 workshop of The International Forum of Fire Research Directors identified two issues as the most important research topics of the fire research community – these included models of active fire protection systems on fire growth, and the fate of combustion products.[65] A slew of submodels are needed to address these issues including better approximations of solid-phase pyrolysis, gas-phase fire chemistry and more accurate descriptions of the suppression systems. For example, the simultaneous discharge from several sprinkler or water mist nozzles have effects on the pressure of the pipe system, and therefore on the mass flow of suppressant. In terms of pyrolysis, there have been numerous models developed over the past 30 years. Insights into specific material configurations and phenomena have been gained; there is a further need to develop comprehensive condensed phase models for practical, general-purpose applications. Computational fire models have only been around about a decade. Much work is needed to increase their value in addressing fire protection engineering problems. Models of fire spread from the wildlands into and through a WUI community would help in the planning of different landscaping options, land use options, fuels management requirements and use of community resources. Fires on large scales need completely different ways to handle engineering approximations over course grid sizes, fire weather interaction, and burning of vegetative fuels, etc.

Fire Modeling: With important phenomena acting at many scales, a multi-scale approach to fire modeling enables calculation of material properties and system behavior from molecular to regional levels. Models at intermediate scales between molecular and macroscopic models are needed to improve understanding of fundamental fire physics including mechanisms of charring, pyrolysis, bubbling, vaporization, and melt-drip phenomena, and to fill the gap between small-scale testing and real scale contributions to flammability. Model development must go hand-in-hand with experimental testing, both to identify the relevant/critical physics at any given scale and to provide necessary material properties that are not (yet) available from lower scale models.

Egress modeling: While numerous numerical models are available for egress analysis, the dearth of usable input or validation data renders model output highly uncertain. The need for validated models and data is seen as a significant measurement need for technological innovation in building construction in the NIST Assessment of the United States Measurement System and in recent international workshops on evacuation.[107,108,109,110,111] The current approach adopted by the evacuation community focuses on deterministic solutions using physics-based modeling analogues (such as fluid or electron flows). While appealing from a computational and theoretical perspective, evacuation is more stochastic than deterministic and there are no models that approach the complexity of human behavior. More and better data are needed to form the basis of these models.

Structural modeling: The state of the art in measurement science to predict structural performance to failure under extreme loading conditions such as in an uncontrolled fire is lacking, which can lead to significant safety concerns. Thus, there is an urgent and critical need to develop and implement improved standards, methodologies, and tools that explicitly consider realistic building fire loads, both in the design of new structures and in the rehabilitation of existing structures. Development of accurate models to predict complex structural system behavior resulting from the effects of thermal expansion and diminished mechanical properties at elevated temperatures requires the availability of robust computational models, validated against large-scale tests under real fire exposures. At the present time, experimental data on the behavior of connections, members, and systems under realistic building fire conditions are lacking. Conducting real-scale structural/fire experiments poses significant challenges with respect to structural loading, instrumentation, protection of the facility, hydraulic components, and reaction frames from fire exposure, and ensuring that tests can be conducted safely and effectively to support the validation of predictive models. Better predictive capability in the performance of structures in realistic fires supports the development of performance-based design tools.

3.7.7 Cyber-Physical Systems

A whole new generation of smart systems are achievable through the convergence of networking and information technology with manufactured products, engineered systems of products, and associated services. The boundary between advanced sensor networks and advanced models yields advanced cyber-physical systems and enables Smart Fire Protection with the possibility of enhanced safety and functional performance. Access to specific and reliable information regarding fire location, history and projected growth, building geometry and contents, the location of occupants and firefighting personnel, fire suppression activities and their consequences, and the status of fire protection assets would enable optimization of fire service response and transform fire protection from one based on experiential judgment to one that fully exploits available information and knowledge.

Smart fire response would be the result of the integration of smart fire apparatus, fire-smart buildings, and smart firefighter equipment. The technologies for many of these components exist; their effective integration is lacking. Situational awareness for the firefighter and incident commander is critical and would form the basis of smart firefighting equipment, transmitting information about fire environment, the status of firefighter and equipment, and firefighter location to the firefighter and incident commander. In addition, the incident commander would be able to communicate and transmit information to the firefighter. Smart fire apparatus would employ sensing and communications technology which, when combined with a smart fire fighting operating system, would enhance the safety and effectiveness of the modern firefighter. A Fire Smart Building would aggregate sensor and performance data from various building systems – including HVAC, elevator, security, fire alarm, sprinkler, occupancy/energy management systems to enable capabilities to visualize the present severity of the incident, forecast future conditions (e.g., significant hazards such as pending collapse or flashover conditions) and monitor and track emergency responders within and around a structure.

Other advanced mobile and stationary cyber-physical systems such as ground-based and flying robots would support fire fighting activities before fire fighter arrival or as fire fighting tools, providing mapping reconnaissance of a building or physical tasks such as pulling hose line up stairs. Cyber physical systems have the potential to enable a transformation from traditional to next-generation structural and WUI fire protection and fire fighting response.

3.7.8 Green Fire Protection: Ensuring Sustainability and Safety

Societal concern for sustainability[112,*] presents emerging challenges and opportunities for many fields including fire safety. The range of issues is broad and includes many facets of building and community design. Changes are happening rapidly and include the use of new designs and green materials in products and construction in the built environment, restricted use of water for testing and maintenance of fire control systems, alternative power systems for buildings and vehicles, and new materials and products that consider life cycle implications. Innovative technical solutions are needed to ensure that sustainable solutions do not negatively impact fire safety.

Many new residential and non-residential buildings are being designed and constructed to meet “green” standards. This is a world-wide phenomenon. The International Code Council and others are endorsing green building codes. In the US, LEED is a common certification fostered by the U.S. Green Building Council. Green designs may promote a tight building envelope with low leakage, novel insulation materials or assemblies, double and triple pane windows, and other energy-efficient construction methods, which may affect fire conditions and dynamics as well as fire fighting operations. Fire safety performance associated with emerging green building products and technologies (e.g., LED lights, solar panels and other on-site power generation) presents numerous questions and challenges. The development of “green” or sustainable chemicals used in the manufacture of products and the proposed bans on halogenated flame retardants in several states and Europe, suggest that new test methods are needed to assess green materials, products and practices in terms of fire safety performance. New test methods and standards may be needed to ensure that new green materials and technologies are fire-safe. New materials, products, technologies, and building design will likely have ramifications in terms of the effectiveness of fire fighting operations. New performance metrics, new fire fighting tactics, and new technologies may be needed to deal with the human and environmental health, sustainable site development, water savings, energy efficiency, materials selection and indoor environmental quality issues. To better understand the effects of the changing landscape, the impact of green materials and technologies on fire safety needs to be assessed to ensure that green technologies don’t compromise established levels of fire protection.

[*] Sustainability: meeting the needs of the present without compromising the ability of future generations to meet their needs.

4 PRIORITIZED OUTPUTS AND OUTCOMES FOR THE REDUCED RISK OF FIRE IN BUILDINGS AND COMMUNITIES GOAL

4.1 PHILOSOPHY

Within the construct of three major focus areas associated with reducing the risk of fire in buildings and communities, Chapter 3 systematically analyzed the universe of possible technical approaches to reduce the national fire burden. However, finite resources only are available[*] to pursue the overall Reduced Risk of Fire in Buildings and Communities Goal. Therefore, some prioritization is necessary to ensure that the available resources are applied with a high return on investment.

Strategic priorities for research programs are determined by identifying research areas which reduce one or more significant component of the national fire problem and are amenable to application of measurement science and technological solutions. In addition to extensive internal discussion of research priorities, assessment of future research investment was provided by experts from industry, state and federal agencies, and academia during a recent workshop[85] and on-going discussions. Additional insight will be garnered from response to this roadmap and its periodic reevaluation.

In the first section below, using the aforementioned criteria, the highest priority research areas are identified given the current resources available within the Innovative NIST Fire Protection Goal. This necessitates focus on a limited number of high-impact projects in each strategic area, each with a phased schedule for delivery of outputs and outcomes.[†] Identification of specific measurement science outputs and outcomes ensures that critical technologies are adequately supported. The outcomes are framed in terms of the outputs or measurement science results that are needed to enable its realization. Thus, the output/outcome pairs are categorized in terms of a timeline broken into three durations: short-term (immediate to three years), medium-term (three to eight years), and long-term (greater than eight years) based on current resource limitations. This strategic plan and the outcomes will be reviewed and refined over the years to better achieve the Reduced Risk of Fire in Buildings and Communities Goal, depending on a number of factors including the identification of new technological opportunities, emerging and evolving fire safety issues, information that becomes available, or redirection recommended by major reconnaissance and investigative studies in the aftermath of disaster and failure events, or changes in major fire loss trends.

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* Resources include federal appropriation, staffing level and expertise, and equipment and facilities.

† Outputs and outcomes are defined in Chapter 1 of this document.

4.2 STRATEGIC PRIORITIES GIVEN CURRENT RESOURCES

4.2.1 Reduced Fire Risk in Buildings

As described in Chapter 3, the emphasis of this work is to develop and deploy advances in measurement science to increase the safety of building occupants and the performance of structures and their contents by enabling science-based standards and codes, software tools, and best practice guides. The key technical ideas fall into two major categories:

- to reduce residential fire losses, through measurement science that emphasizes:
    - Improved Flammability Performance of Materials and Products, and
    - Advanced Fire Detection.
- to enable cost-effective fire safety solutions by enabling performance-based design, which emphasizes:
    - Improved Egress Performance,
    - Improved Structural Fire Resistance,
    - Advanced Engineered Fire Protection, and
    - Lessons Learned from Post-Fire Analysis.

The highest priority research products for these areas are listed below.

4.2.1.1 Residential Fire Safety

4.2.1.1.1 Improved Flammability Performance of Materials and Products

- Standard cigarette (NIST Standard Reference Material) for testing new mattresses and upholstered furniture for their resistance to ignition by cigarettes, the single largest cause of U.S. fire deaths – since the conventional test cigarette is no longer being manufactured, this will protect homeowners against a resurgence of fatal furnishing fires. ***Short Term***

- Novel nanoparticle fire retardants using Layer-by-Layer (nano-FR/LbL) coatings - advanced technology to reduce the heat release rate (HRR) of foam by 30 % and thereby reduce the fire hazard of polyurethane foam. ***Short Term***

- A technically sound furniture design tool based on characterized physical and combustion properties of the furniture components that will be used by furniture manufacturers to produce residential upholstered furniture (RUF) with improved flammability behavior.* The design tool would enable RUF manufacturers to identify the materials and configurations necessary to produce RUF with desired levels of fire performance. ***Short Term***

- Bench-scale methods to identify effective non-brominated gas-phase fire retardant compounds with superior environmental, health, and safety (EH&S) characteristics – a new generation of sustainable and effective fire retardants will enhance public safety. ***Short Term***

- Guidelines for quantifying the performance of fire blocking barrier fabrics which are employed to provide fire-safe mattresses and upholstered furniture – these guidelines will provide a competitive advantage for U.S. industry, by enabling development of superior fire blocking fabrics that are critical to complying with full-scale fire regulations for mattresses and upholstered furniture. ***Short Term***

- Database on the environmental fate of polymer nanoparticle flame retardants after the material is involved in a fire – This will provide the basis for consensus test methods and standards for nanoparticle emissions enabling industry to develop products with environmentally safe nanoparticle flame retardants. ***Short Term***

- Sustainable materials which demonstrate improved material flammability performance and acceptable Environmental Health & Safety characteristics – these materials (including high char yield, low smoldering fabrics and batting fibers, novel fiber blends, and nanocomposite coatings on fabrics and foams, as well as bio-based, sustainable thermoplastics such as polylactide using high char yield, anti-drip nano-additives) will maintain or improve the ignition and burning characteristics of interior furnishings (upholstered furniture, bedding, mattresses, etc.), ensure long-term societal use, and reduce the risk of hidden societal costs. ***Medium Term***

- Database of room test results and small-scale test data that characterize fire spread within furnished residential rooms – identification and incorporation into standards of the appropriate fire properties of room furnishings and interior finish will stimulate the manufacture of low flammability household products. ***Medium Term***

- Guidelines and NIST standard reference materials (NIST SRMs) for understanding the parameters and properties of polymeric materials which control material flammability – guidelines and SRMs will aid industry in developing new sustainable flame retarded polymers, and contribute to standard procedures for quantifying the fire safety of foam, fabric and composites. ***Medium Term***

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* Much like the existing mattress standard, a hazard analysis will guide the development of an upholstered furniture standard or regulation which will ensure that compliant products produce significantly better outcomes in residential fire events.

- Guidelines for processing nano-additives in polymer nano-composites to improve fire performance when used in plastics, fiber, fabrics and foam – this knowledge will enable U.S. industry utilize nano-additives to develop a sustainable competitive advantage in international markets associated with consumer electronics, wire and cable, mattresses and upholstered furniture products ***Medium Term***

- Measurement science toolkit for characterizing innovative approaches (e.g., bio-nano-materials and flame retardant additives) to reduce material flammability while accounting for sustainability – this capability will enable reduced flammability furnishings, building materials, and consumer products and will lead to substantial reduction in the societal cost of fire. ***Long Term***

4.2.1.1.2 Advanced Fire Detection

- Data on the characteristics of very early combustion signatures – this information along with novel real-time analytical methods will enable a reduction in sensing time and nuisance alarms.

- Standard test method for residential smoke alarms that accounts for nuisance signal sources – a disproportionate number of fire deaths occur in residences without working smoke detectors, many purposely disabled due to the annoyance of frequent false alarms; reliable smoke alarms will reduce the number of residential fatalities. ***Short Term***

- Next-generation detectors – development of low-cost, multi-criteria micro-sensors will improve reliability and robustness for early and accurate fire detection. ***Medium Term***

4.2.1.2 Performance-based Design

4.2.1.2.1 Advanced Engineered Fire Protection

- The next generation of predictive fire models with demonstrated accuracy and robustness combined with development based on user needs – advanced fire models will enable performance-based design engineering. Recent progress in verification and validation (V&V) standards has enabled V&V for field and zone models, such as FDS and CFAST, respectively, to be conducted in a consistent manner. Additionally, new algorithms will improve predictive accuracy.[*] ***Short Term***

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* Implementation of novel algorithms such as Immersed Boundary Method will improve and expand the predictive capability of current fire models using sub-models that better describe critical physical and chemical processes in fires and can be validated using advanced fire measurement techniques. FDS is the Fire Dynamics Simulator and CFAST is the Consolidated Fire and Smoke Transport model. NIST intends to support the continued development and maintenance of CFAST and FDS, advancing these advanced engineering design tools.

- Verified and validated software tools, including field and zone models, to enable practicing engineers to predict fire spread and growth, and the emission of smoke and toxic gases during a building fire – the ability to quickly and accurately model fire growth and spread in rooms with realistic furnishings and fire protection systems will support advanced design methods and cost-effective fire protection of engineered buildings. ***Medium Term***

- The first computational software tools that predict the fire performance of engineered buildings, their fire safety systems, and the hazards to occupants and emergency responders during a fire – the ability to compare alternative fire protection capabilities for a variety of fire and building types will significantly reduce design and construction costs, life and property losses, and business interruption in both new construction and buildings undergoing retrofit. ***Long Term***

4.2.1.2.2 Improved Structural Fire Resistance

- New measurement capabilities to evaluate predictive calculations on the response of multi-story structural frames to fire and other imposed loads, which will enable more cost-effective structural installations. ***Short Term***

- Database on the fire resistance performance of large-scale structural connections, components, subassemblies, and systems under realistic fire and loading conditions – the database will facilitate validation of predictive models and enable the development of performance-based design methodologies. ***Medium Term***

- Validated software tools to enable performance prediction of a structure as a complete system of components and connections exposed to fire and mechanical loads – these tools will enable the transition to performance-based methods for design of the fire resistance of structures. ***Long Term***

4.2.1.2.3 Improved Egress Performance

- Database of information for use by practicing engineers that characterizes occupant movement during fire drill evacuations for a suite of buildings types – the database will provide the basis for engineering design of safe and cost-effective emergency egress systems in buildings. ***Short Term***

- Standard test method for estimating the toxic potency of smoke and gases from burning interior furnishing products (chairs, electrical cables, etc.) – smoke inhalation kills more people than burn injuries and smoke obscuration is a principal factor in the escape time from a fire; *knowing ho*w long it takes for a fire to produce life-threatening conditions within a structure will enable cost-effective fire safety design practices. ***Medium Term***

- Validated egress models that include behavioral characteristics affecting people movement and emerging movement technologies – development of fundamental theory of human behavior (e.g., wayfinding, collective behavior, interpretation of environmental cues, and ris*k perception*) during a structure fire will his will enable performance based design tools for practitioners. Models will incorporate emerging movement methods, such as occupant evacuation elevators. ***Long Term***

4.2.1.2.4 Post-Fire Analysis

- Lessons learned from analysis of fire incidents- Disaster and failure studies will inform changes to fire standards and building codes and will significantly reduce life and property losses in both new construction and buildings undergoing retrofit. ***Long Term***

4.2.2 Advanced Fire Service Technologies

As described in Chapter 3, the emphasis of this work is to enable the implementation of cost-effective advanced fire service technologies through the development of science-based standards and codes, software tools, and best practice guides. The new technical ideas fall into a matrix of categories, before, during and after a fire incident, and within the context of the following three major categories, involving:

- The Community
- The Department
- The firefighter

A number of key approaches within these categories (see Fig. 3.2 and discussion) represent the highest priority measurement science activities, including:

- Equipment,
- Tactics,
- Training and Education,
- Strategic Resource Allocation, and
- Situational Awareness.

The highest priority research activities for each of these areas are listed below.

4.2.2.1 Equipment

- Performance standards for improving protection provided by firefighter respiratory masks, and self-contained breathing apparatus. This will ensure adequate respiratory protection is maintained during harsh firefighting conditions. ***Short Term***

- Performance standards for predicting the service life of firefighter protective clothing – this evaluation tool will ensure performance of existing gear and provide a method to retire gear that has reached the end of its useful life; improved test methods will also facilitate the development of new fabrics and materials for U.S. and international markets. ***Medium Term***

- Performance standards and test methods for evaluating critical electronic equipment used by first responders – performance-based testing of safety equipment including radios and locator/tracking systems, will ensure that firefighters can depend on equipment to work under actual firefighting conditions; realistic test scenarios and standards will enable U.S. manufacturers to develop additional technologies that will reduce injuries to and fatalities of firefighters and building occupants. ***Medium Term***

4.2.2.2 Tactics

- New tactical guidelines for fire departments to control and extinguish wind-driven fires in buildings – incorporating science-based guidelines for fighting these especially hazardous fires into fire department training programs will save lives and reduce property losses. ***Short Term***

- Guidelines for improved fire ground operations and tactics developed from understanding of fire phenomena – while many current operations and tactics, such as hose stream and smoke venting are based on prior fire experience, science-based principles and computer modeling will enable better approaches to put the fire out more quickly with less water, control the spread of fire and smoke, and reduce the loss of property, all while exposing fewer firefighters to potential hazards. ***Medium Term***

4.2.2.3 Training and Education

- Guidance from the study of current fire fighting tactics to develop an understanding of the fire behavior in the structure and interactions with fuels in the structure and that compose the structure. This information will also be used to examine new tactics or technologies to improve safety and effectiveness. ***Medium Term***

- Guidance from the study of significant fire incidents – computerized simulations of such incidents will provide comprehensive "lessons learned" from actual fires, resulting in more realistic training of new firefighters, improved fire ground tactics, and reduced injuries, deaths and property damage. ***Medium Term***

- Comprehensive computer-based firefighter training tool to teach firefighting strategies and tactics – a firefighter trainer—similar to a flight simulator—will incorporate a wide variety of building and fire scenarios including multi-family residential and large commercial structures; advanced training via simulators will increase firefighter effectiveness, while reducing trainee exposure to hazardous fire conditions that historically has led to training injuries, and on occasion, fatalities. ***Long Term***

4.2.2.4 Strategic Resource Utilization

- Metrics, developed with the input of fire service experts, to characterize fire service effectiveness and safety – validated metrics will enable focused measurement science activities and lead to focused project selection. ***Short Term***

- Validated computer models to quantify the impact of various fire service deployment configurations within a community - community risk models will allow fire departments to optimize deployment. **Medium *Term***

4.2.2.5 Situational Awareness

- Evaluation metrics for collapse prediction technologies for firefighting operations in residential applications – this will reduce firefighter injuries and fatalities. ***Medium Term***

- Real-time situational awareness systems that will provide firefighters with information and a warning prior to the onset of hazardous conditions such as structure failure or flashover* – these systems will provide both incident commander and firefighter *with physi*ological† and fire environment data. Monitoring the exposure of each firefighter in real time, using integrated smart sensors, will enable an incident commander to fight the fire more effectively, while maximizing the safety level for all tasks. ***Long Term***

4.2.3 Reduced Risk of Fire Spread at the Wildland-urban Interface

In Chapter 3, an overview of the negative impacts of WUI fires on the built and natural environments was given. The focus here is on mitigation of WUI fires in the built environment. This can be achieved through a number of approaches (in particular, refer to Figure 3-3):

- Fire Prevention in WUI Buildings and Communities
- Fire Protection Engineering in the WUI
- Response for Improved Fire Fighter Safety and Effectiveness, and People Evacuation
- Recovery Guidelines for WUI communities.

The highest priority research activities for these areas are listed below.

4.2.3.1 WUI Fire Prevention

- Data to characterize WUI fire exposure conditions for building components, structures, and communities via data collection from WUI fire events – lessons learned will enable identification of designs that help structures survive fire exposure. ***Short Term***

- A well-characterized and model standard ember source for exposing building components and vegetation to ignition and fire spread from embers - this will support development of standard exposure test for ignition and fire spread resistance. ***Short Term***

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* ***Flashover*** is a condition in which temperatures throughout a fire room exceed about 600 ºC (110 ºF) and the fire transitions from a single item burning to all combustibles in the room burning.

† ***Physiological data*** for a firefighter include heart rate, blood pressure, and core and skin temperatures.

- Database (from laboratory experiments and field measurements) using standard test methods on the performance of materials, products and technologies to reduce the flammability of building elements – the database will provide information to homeowners, community planners and regulators, and builders on the ignition resistance of traditional and emerging materials, products and technologies to improve ignition resistance of buildings, critical information for the specification of standards and the design of fire resistant buildings. ***Medium Term***

- Standard test methods for characterizing the resistance of building components (vents, roofing assemblies, glazing, etc.) and building materials when exposed to WUI fires – these will promote use of ignition resistant building products for WUI communities. ***Medium Term***

- Database from laboratory experiments and field measurements on the ability of firebrands to ignite building components – flaming brands (or embers) are a principal way buildings are ignited; knowing ho*w brands cause* ignition is the key to the use of firebrand resistant building design in WUI communities. ***Short Term***

- Validated computer models to simulate burning trees, shrubs, grass – these models provide predictions of characteristic heat fluxes on buildings to support the design of laboratory tests of fire resistant building materials. ***Long Term***

- Benefit versus cost analysis tool that incorporates a range of recommended homeowner or community risk reduction actions – an economic tool will help communities optimize WUI fire prevention plans. ***Long Term***

4.2.3.2 WUI Fire Protection

- Standard test method for ember ignition and fire spread. ***Short Term***

- Passive fire protection technologies including development and implementation of advanced coatings; fire retardant additives; advanced design to harden vulnerable building elements such as windows and doors; fire resistant vegetation. ***Medium Term***

- Active fire protection technologies including improved advanced fire control and suppression technologies for structures in WUI; next generation agents and technologies for WUI building fire protection including chemically advanced foams, gels, powders to reduce the flammability of landscaping, vegetation, and buildings. ***Medium Term***

- The first computational tools that predict fire spread through WUI communities and surrounding vegetation – use of these tools for new and retrofitted WUI buildings and landscapes will significantly reduce design and construction costs to minimize fire losses. ***Medium Term***

- Best practices guidelines for construction and landscaping from the residential to community scales—for homeowners, community planners, and emergency responders—to assess and mitigate WUI fire risk – science-based guidelines will decrease the risk of structure ignition and ensuing damage, increase public safety, and preserve community infrastructure and the environment. ***Long Term***

4.2.3.3 WUI Fire Response

- Database of vegetation and structure damages, and heat flux and firebrand exposure conditions from post-fire field studies and computer modeling of fire behavior in communities affected by WUI fires – the development of standard test methods and fire exposure severity mapping tools are needed to develop a technical basis for model codes intent to reduce structure losses; this database also forms the technical basis for more informed and effective decision making when preparing for and responding to WUI fires. ***Medium Term***

- Develop equipment standards and standard operating procedures to address WUI fires. There are no WUI specific equipment and operating standards. ***Medium Term***

- Characterize the WUI fire environment and develop measurement capability to evaluate personal protective equipment. ***Medium Term***

4.2.3.4 WUI Fire Recovery

- Standardized, GIS-based, field data collection methods including hardware, software, field procedures and protocols, and training of field crews. ***Short Term***

- A framework for a WUI fire exposure severity risk rating system – such a framework will provide standards organizations a way to develop technically-based standards for WUI communities, parcels and buildings.* ***Short Term***

- Guidelines and field data collection methods for mapping the characteristics of structures and vegetation in WUI communities – Having the right information in a consistent and usable form enables state and local officials to more effectively prepare WUI communities. ***Short term***

- Database of WUI fire disasters and failures - the database will serve as a public archival repository on hazard characteristics, the performance of WUI buildings and infrastructure, associated

* A fire exposure severity zoning system would be similar to flood plain mapping and would drive building codes and standards requirements for construction in WUI areas. Established communities in each fire exposure zone would need to consider building retrofit, and community and parcel landscaping guidance to address fire hazards.

emergency response and evacuation procedures, and social and economic factors that affect pre-disaster mitigation activities and post-disaster response. ***Medium Term***

4.3 NEXT PRIORITY AREAS GIVEN ADDITIONAL RESOURCES

The scope and depth of the national fire problem is immense as outlined in Chapter 2. The measurement science outcomes listed in Section 4.2 above are designed to optimize impact on the national fire problem by attacking dominant aspects of the problem that are ripe for solution. Given the current funding profile for measurement science research, prioritization of activities is necessary. At the same time, if additional resources were available, the strategy outlined in this document would be accelerated, allowing realization of critical outputs and outcomes for the Reduced Risk of Fire in Buildings and Communities Goal, as prioritized within each of the sections below.

4.3.1 Reduced Fire Risk in Buildings

4.3.1.1 Next-generation Performance of Materials and Products

- Test methods and risk guidelines to ensure fire safety of a new generation of sustainable materials, products, and systems (e.g., refrigerants, appliances, energy-efficient buildings, etc.) – test methods and guidance is needed to ensure understanding of risk associated with commercialization of new technologies.

4.3.1.2 Safety of Building Occupants

- Technology to support rapid mass notification –broad base technology-neutral communication with individualized escape guidance helping occupants to avoid hazardous areas

4.3.1.3 Infrastructure Protection

- Guidelines and test methods to ensure cost-effective fire protection of the telecommunications and datacenter infrastructure – guidelines will improve fire protection of electronic communications facilities which are of vital importance during emergencies.

- Guidelines and test methods to ensure cost-effective fire protection of the transportation infrastructure – guidelines will improve fire protection of ports, tunnels, bridges and above-ground and underground train stations vulnerable to fire.

- Guidelines and test methods to ensure fire safety in buildings and infrastructure using alternative fuel types such as batteries, hydrogen fuel cells, biofuels, natural gas, and other hydrocarbon based fuels - guidelines and standard test methods will prevent safety from being an impediment to innovation and sustainability.

4.3.1.4 Next-generation Detection and Communications

- Incipient detection and automated apparatus dispatch - reducing the time from the initiation of a fire to the dispatch of fire apparatus and personnel to a total of 90 seconds to be achieved by faster and more reliable sensing and automated call routing and dispatch.

4.3.1.5 Engineered Fire Protection

- Guidelines to reduce the probability of compartment flashover by 90 % - this will be accomplished through systematic engineered fire protection combining (a) improved material and furnishing performance, (b) incipient fire detection and suppression, and (c) advanced fire service response. The impact will be a 50 % reduction in the overall fire burden.

- A systematic software tool for estimating the costs and benefits of installation of arc fault interrupters in residences for state and local community planners – this tool will facilitate informed decision making on the regulatory adoption of arc fault interrupters, which address electrical fire safety issues.

- Guidelines and knowledge on the effectiveness of advanced and sustainable fire suppressants – guidance on new suppressant technologies will ensure suppressant effectiveness.

- Standard test methods for robotic fire suppression: early and reliable sensing of incipient fires provides a means to suppress incipient fires before they become deadly.

4.3.1.6 Performance-based Design

- Stochastic risk methods to support performance based design calculations – PBD will reduce the cost of fire protection with understood levels of risk, while maintaining public safety.

4.3.1.7 Post-Incident Investigation

- Measurement science tools to improve determination of fire origin causality, patterns of fire growth and spread, and movement of occupants and firefighters – will ensure lessons learned from fire incidents are used as best practices for building design and firefighter response and inform building codes and standards development.

4.3.2 Advanced Fire Service Technology

4.3.2.1 Equipment

- Advanced end of service life indicators - monitoring exposures of both PPE and firefighters to harmful conditions will provide useful information for retirement planning and budgeting of new equipment.

- Performance evaluation methods for improved fire apparatus and other large equipment - nozzles, hoses, pumps, ladders, extraction equipment, vehicles, cooling stations, etc... are all subject to technological advancements that may need supporting measurement science to ensure a safer and more effective fire service. This may include advanced sensors which automate fireground data collection and then optimize and evaluate tactics and operations.

- Evaluation metrics for fire ground communication equipment – there are no performance standards for radios and other equipment that transmit signals, and the signal quality of existing equipment is unreliable. Better signal quality and ruggedness tests for communication equipment will result in a safer and more efficient fire service.

- Performance evaluation methods for robotic equipment – robots are emerging as useful firefighting tools on several fronts. They can be sent into structures to analyze the fire environment and to conduct fire suppression, search and rescue, and other tactics in situations that would be unsafe for humans.

- En route size-up technologies – fire service operations can be more effective if information needed for initial actions is sent to the IC and first out when the fire alarm is activated.

4.3.2.2 Tactics

- New and improved ventilation and compartmentalization tactics – understanding the effects of various ventilation tactics in different scenarios will help firefighters make stronger decisions that are safer and deliver expected results.

- New and improved fire suppression tactics - fire suppression tactics, both internal and external to the structure, have a significant impact on property loss. Understanding the benefits of different types of suppression agents and different means of applying them will contribute to firefighter effectiveness.

- Guidelines for identification of building construction type and potentially hazardous fire conditions – new construction techniques and materials may affect the strategic and tactical options available to the IC. Pre-planning tools will facilitate decision making at an incident.

- New tactics for new construction – over time, the nature of structure fires is changing as new construction techniques and materials come into use, which may also affect the strategic and tactical options available to the fire service.

- New and improved overhaul tactics - technologies that enable firefighters to ensure that the fire has been completely extinguished and hazards have been removed will contribute to the reduction of the number of re-ignitions and will ensure that the post-incident fire ground no longer poses a threat to the community.

- Provide science-based methods of identifying fire origin and cause – technology that enables consistent, physics-based analysis of fire origin and cause will give more credibility to future findings.

- Develop and improve rapid intervention procedures – when firefighters are in trouble and need help, better methods and technologies for rescue are needed.

- Develop new methods of search and rescue - technologies that support more accurate, thorough, and faster search and rescue operations will enable firefighters to save more civilians.

- Development of post-incident analysis tools – tools that enable examination of certain fire conditions that were tracked over time, fire cause and origin, the interactions between or effectiveness of various tactics and/or strategies used, and knowledge of potential hazards encountered in the cleanup process will contribute to the safety and effectiveness of the fire service and provide a database that can be used for future planning.

- Guidelines for tactical interoperability during mutual aid incidents- technology is needed to ensure that all parties are capable of operating together effectively.

- Guidelines for post-incident clean-up – new measurement science will be needed to understand the consequences of fighting fires in which materials are burning that have different, unusual, or unknown toxicity and fate. Also, new environmental regulations may require different tactics.

- Development of physics-based tactical decision aids – intelligent systems that can monitor the fire environment and predict the optimum combination of tactical operations and timing will be of great importance to firefighter safety and effectiveness.

- Guidelines for post-incident analysis tools - Improvements in the quality of information about the detailed impact of fire incidents can be used to shape the future of the fire service and the communities in which it operates. This information may include examination of certain fire conditions that were tracked over time, fire cause and origin, the interactions between or effectiveness of various tactics and/or strategies used, knowledge of potential hazards encountered in the cleanup process, lessons learned, etc.

4.3.2.3 Training and Education

- Guidelines for fire behavior, ventilation and fire control knowledge and skills needed by fire fighters to perform their mission in the safest and most effective manner.

- Guidelines for community education programs – science-based information that helps communities understand the important role the fire service plays in fire loss protection/prevention will improve the political viability of, and flow of resources to, fire departments.

- Guidelines for fire investigators on fire dynamics, fire testing, and fire modeling knowledge needed to enable scientific assessment of fire patterns in a structure.

4.3.2.4 Strategic Resource Utilization

- Development of community-scale resource allocation tools – GIS-based technologies that optimize coverage while conserving valuable resources will help the fire service and communities maintain an acceptable level of fire protection.

- Guidelines for risk analysis tools for crew size – crew size and other strategic decisions depend on the nature of the risks involved, tools that enable risk to be assessed for potential incidents will streamline the response and target essential tactics.

- National Fire Service Response Database – While national fire statistics such as NFIRS aggregate fire incident data, the fire service lacks standardized response-based data elements to evaluate response effectiveness. A national database will enable comparative analysis for development of best practices, early identification of trends, and performance metrics.

4.3.2.5 Situational Awareness

- Performance evaluation methods for firefighter location/tracking systems – enabling the IC to know the location of firefighters at an incident will improve the strategic and tactical decision making, and the ability to rescue firefighters and civilians.

- Guidelines for operability and interoperability of communication equipment – there are two components of this outcome: determination of the communication hierarchy at incidents in which multiple responder organizations are participating, and the physical ability of the communication equipment to function reliably. Both components are necessary for effective, coordinated response to large incidents.

- Database on the thermal environment for body-worn sensors – sensors that are worn on the outside of fire fighter turn-out gear must be designed to function properly in adverse fire ground environments for improvements in personal protective equipment and situational awareness technologies to be implemented.

- Database on the thermal environment for building sensors – sensors that inform firefighters of the condition of the fire ground (including the structure itself) must be designed to function properly in adverse fire ground environments in order for improvements in situational awareness technologies and post-incident analysis to be implemented.

- Database on the thermal environment for biometric sensors – biometrics sensors for firefighters are in the development stage. These sensors, and other equipment that might be worn under turn out gear, must be designed to function properly in adverse fire ground environments in order for improvements in personal protective equipment and situational awareness technologies to be implemented.

4.3.3 Wildland Urban Interface

4.3.3.1 WUI Fire Prevention

- Innovative building materials, products, and designs that resist ignition and limit fire spread in the WUI - advanced materials for new construction and retrofit of structures and communities would reduce WUI fire losses.
- Database of fuels and landscape characteristics across a range of WUI community types[*] - such a database would support the post-fire analysis of similar communities (since it is unlikely that burned communities will have been pre-fire surveyed) and provide inputs for fire behavior modeling for testing of risk reduction practices in realistic settings.
- A database of large-scale laboratory measurements of fire behavior in vegetation with an imposed wind of characteristic wind speeds and gusts - key information on firebrand production (from structures and vegetation), surface to crown fire transitions, the influence of vegetative fuel treatments on fire transitions and firebrand production would support the development, and verify the effectiveness of, laboratory-scale standard test methods and structure scale fuel treatments.[†]

4.3.3.2 WUI Fire Protection

- Advanced fire protection technologies for building exteriors such as fire resistant building wraps and "smart" vents – such technologies would prevent ignition, reduce fire exposure, firebrand penetration, and structural ignition.
- Smart passive fire protection design of building elements that exploits intumescent materials – such designs would exploit the unusual expansion properties of intumescing materials upon exposure to heating.
- A portable WUI vegetation calorimeter - efficient measurement of flammability and, potentially, firebrand characteristics of vegetation (both wildland and ornamental) commonly found in WUI communities would support the development of laboratory test methods, input for fire behavior

* It is anticipated that a trained and fully equipped field crew dedicated to data collection in high risk, characteristic, WUI communities that have not been burned would be needed to accomplish this output.

† The recently constructed Institute of Building and Home Safety (IBHS) wind tunnel appears to have the required capabilities to perform these experiments.

models, and the development of simple checklist type homeowner guidance regarding ornamental vegetation choices.

- Database of field-scale fire behavior and fuels using ground based and airborne measurement methods* - the resulting database would support development fire behavior and fuel modeling tools and GIS-based risk assessment tools for use in community planning and incident response.

4.3.3.3 WUI Fire Response

- Advanced fire service safety equipment and training for WUI fire fighting including advanced respirators, fire fighter locators, carbon monoxide warning systems, and advanced (breathable) protective clothing - advanced equipment would enhance the safety and effectiveness of WUI fire fighting.
- Advanced fire service response tactics for WUI fires – advanced tactics would enhance the safety and effectiveness of WUI fire fighting.
- Computer-based models to guide evacuation of communities threatened by WUI fires - computer-based modeling would enable effective evacuations.
- A database of field-scale wind measurements over a range of terrain and vegetation cover types using ground based and airborne measurements - strong ambient winds are a major driver of wildland and WUI fire behavior and large fires have potential to create winds that significantly alter the behavior of the fire; the database would directly support WUI fire model developme***n***t for use in community planning and as an incident response tool.†
- Advanced WUI firefighter communication technologies including robust, reliable, standardized communication systems that function in complex terrain – advanced communication technologies would enable communication among fire fighters on the ground and with incident commanders.
- A suite of GIS based software tools including the ability to ingest various WUI community data from ground crew field collection and remote sensing, perform risk assessment, and provide input files for a range of fire behavior models – such tools would enable effective fire fighting response and prevention activities.
- Ground based unmanned vehicles – unmanned vehicles would enable safe and effective WUI firefighting.

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* including measures of the fireline progression and intensity, terrain and fuel vegetation and structures maps, and firebrand characteristics and production rates for characteristic vegetative and structural fuels over a range of environmental conditions.

† complete datasets of wind fields over terrain do not exist. Especially useful would be wind measurements over a volume rather than at point locations from towers. Airborne platforms such as unmanned aerial vehicles may be particularly well suited for this.

- A significantly enhanced NOAA Fire Weather Prediction System, that captures with high resolution the winds and fire-atmosphere interactions – this will provide on-the-ground, real-time look-ahead predictions of the local weather and fire behavior to support fire suppression planning, community evacuation, and firefighter safety. ***Long Term***

4.3.3.4 WUI Fire Recovery

- Rebuilding structures and communities with advanced new materials that provided improved fire resistance.
- Advanced fire resistant designs for rebuilding structures and communities.
- Post-fire analysis of actual WUI fire events - actual events provide a testbed for the determination of what worked and what did not work, providing lessons learned on WUI fire prevention and protection technologies, as well as WUI fire response.

5 IMPACT PLAN

5.1 CHANGES TO PRACTICE

There are many ways to impact the national fire problem. Some of them include the following: engineering tools, changes in tactics, best practices for community managers, guidelines or best practices for engineers and architects, procurement specifications, new or improved SRMs, industry practice or manufacturing process, standards of care, and decision support tools.

5.2 STANDARDS AND CODES STRATEGY

Staff activism in domestic and international standards and codes development has been an effective means to translate NIST measurement science outputs into tangible and long-lasting impacts on the national fire problem. Historically, the spectrum of staff participation in these activities has varied between being highly organized and being based on individual initiative. Looking ahead, the intent is to integrate the best features of these two models, taking advantage of the enthusiasm of skilled individuals in a planned, targeted program. This section provides an overview of the codes and standards strategy for the Reduced Risk of Fire in Buildings and Communities Goal.

For clarity, there are three types of arenas for these activities.

- *Building Codes*. These are laws which govern the construction, alteration, movement, enlargement, replacement, repair, equipment, use and occupancy, location, maintenance, removal and demolition of buildings or structures. Building codes typically address permanent components of the building, such as the structural members, architectural features or installed fire protection systems.
- *Fire Codes*. These are laws which govern matters affecting or relating to structures, processes and premises from the hazard of fire and explosion arising from the storage, handling or use of structures, materials or devices; from conditions hazardous to life, property or welfare and the fire protection of buildings once the buildings are occupied.
- *Standards*. These are documents which prescribe requirements for performance or design of a material, methods for conducting tests, or procedures for installing or maintaining equipment. Standards become required when cited within a building code, fire code, or other state law.

In short, codes tell you what you must do; standards tell you how you must do it. Since the U.S. Constitution does not explicitly assign the authority to regulate building construction and maintenance to the federal government, under the 10th Amendment, this authority resides with the states. As a result, the U.S. building codes and standards system is a complex combination of state and local regulations, each of which derives from a *model code*.

While there have been multiple model building codes in the past, today the dominant model code for new construction or major building modification is the International Code Council's International Building Code. Each state or local jurisdiction may elect to adopt the model code in full or to modify the model code to reflect local priorities or special hazards. Local modifications may differ substantially from one jurisdiction to another.

Hundreds of standards are typically referenced within the model code and are not usually modified during the local adoption process. Standards Developing Organizations (SDOs) include ASTM International, Underwriters Laboratories (UL), American Society of Mechanical Engineers (ASME), National Fire Protection Association (NFPA), the Society of fire Protection Engineers (SFPE), Federal , state and local government, and industry associations, such as the National Electrical Manufacturers Association (NEMA) and the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). Standards must be referenced by text in a code and only the section or topic that is referenced by specific code language is enforceable, not the entire standard.

There are also numerous product-specific standards that are not cited in building codes. Most of these address fire performance of items not attached to structures, such as furnishings and clothing. Sometimes these standards are used, because a code sets forth a requirement that a product or equipment must be listed or approved.

To reduce the costs of and losses from unwanted fires, the scientific basis for technically sound codes and standards are needed through the following venues:

- Domestic fire safety standards and code provisions. These promote protection for people where they live, work, travel, and visit. Fire codes and standards also provide the basis for an orderly U.S. marketplace for manufacturers and consumers of goods.
- International standards.* These documents are important as they have a direct influence on international business competition. Standards that are technically sound and that address the proper fire behavior properties are (1) less likely to restrict exports of U.S. products unfairly and (2) more likely to ensure that imported products actually measure up to U.S. safety requirements.
- Regulatory rulemaking by key states and other Federal agencies. These include the Nuclear Regulatory Commission, Consumer Product Safety Commission, the Department of Housing and Urban Development, and others. Key states, such as California, Texas, and others, have significant influence in regulatory rulemaking conducted by other states.

The process of achieving fire safety progress requires three stages of organizational commitment:

Stage 1. Developing the measurement science to initiate or support a particular fire safety improvement and translating this into usable code or standard format.

* Often referred to as standards from ISO and IEC but also any standard that is accepted globally.

Stage 2. Performing additional research to address issues arising during standardization technology development, and code implementation phases. Examples of these include difficulties in reproducing the test apparatus, and simplifications of t he test procedure to enhance the reproducibility of the test results.

Stage 3. Following implementation of the standards and code provisions, identifying external changes that have the potential to negate the safety gains. Examples of these include conflicts with environmental concerns over the means for products to meet the standard, new products entering the marketplace, and manufacturers identifying ways to circumvent the standard, i.e. less fire-safe ways to "pass the test." This stage often occurs distinctly later than the implementation of the original standard or code provision.

Figure 5-1 is a qualitative timeline for this three-stage commitment, which takes place over years and requires various amounts of resources and follow-up activities. The timing and the relative size of the efforts involved in the various stages will vary from case to case.

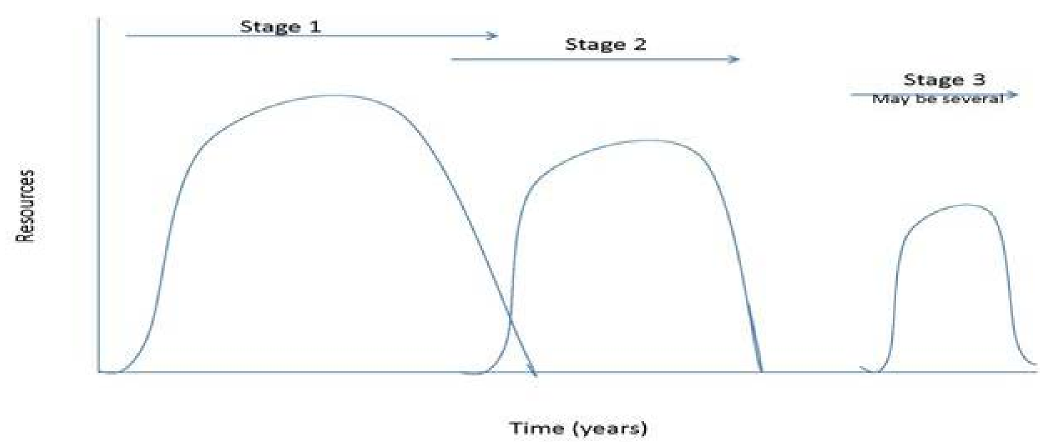

Figure 5-1: Qualitative timeline of the three stages of codes and standards implementation.

A further consideration in technology implementation commitment involves the collaboration and partnership of organizations involved in approval of a code or standard and those who will be involved in its implementation into practice and/or enforcement. The NIST Reduced Risk of Fire in Buildings and Communities Strategy relies on forging and strengthening these relationships. Such classes of partners include:

- Product manufacturers and their trade associations;

- Leading architects and engineers in the fire safety industries, such as those represented by SFPE and AIA;*
- Standards and model code development organizations in the U.S. and internationally, such as ICC, NFPA, and ISO; ASME, ASTM, ASCE, NEMA;
- Non-NIST researchers and practitioners in building materials, fire protection, risk analysis, and structural performance;
- Emergency responders;
- Code officials;
- Federal regulators, such as NRC, CPSC, EPA, GSA, HUD, and DOE;
- Insurers;
- Product testing and certification organizations, including members of the North American Fire Testing Laboratories Consortium such as FM Global, Underwriter's Laboratory, Intertek, and Southwest Research Institute;
- Government planners; and
- Facility owners and managers.

Measurement science is critical in the development of codes, standards, and regulations and historically occurs through the aforementioned three stage approach. Participation in these development processes also ensures ongoing technical dialogue directly with key stakeholders. Oftentimes, the discussions and debate conducted in committee meetings, hearings, or during preparations for meetings identify emerging problems, new technologies, or regulatory gaps which are oriented towards measurement science solutions. As a consequence, consortia and partnerships may be formed during codes, standards, or rulemaking which support measurement science in direct (monetary) or indirect (assistance-in-kind) modes. This critical two-way dialogue serves to increase the likelihood that research conducted in the Reduced Risk of Fire in Buildings and Communities Goal will solve problems of direct interest to stakeholders, while mitigating the U.S. fire burden.

In summary, efforts comparable to that devoted to measurement science are needed to translate NIST research into tangible fire protection improvements. The process for evaluating choices of fire safety initiatives necessitates comprehensive discussion of such efforts prior to reaching a decision as well as periodically during the three stages of organizational commitment. Key inputs to this process are a comprehensive project plan and performance metrics. Participation in the various development processes will evolve as the needs for codes and standards change. And the level of participation will vary in scope, depending on the urgency and importance for a standard or code, from monitoring

* A list of acronyms and their definitions is provided in the preface of this document.

progress in the development of a standard committee, to participating in a committee as a member, as a task leader, as a chair or as a convener.[*] The level of participation must be considered strategically. The standards strategy for the Reduced Risk of Fire in Buildings and Communities Goals are outlined below in terms of the three focus areas and sub-areas.

5.3 STRATEGY FOR REDUCED FIRE RISK IN BUILDINGS

As discussed in the previous section, the implementation strategy for codes and standards involves numerous partnerships. The Reduced Fire Risk in Buildings strategy will leverage numerous implementation partners, including: (a) building and fire code developers, (b) regulators, (c) standards developers, and (d) industry in the two thrust areas:

- To reduce residential fire losses, and
- To enable cost-effective fire safety solutions by enabling performance-based design.

5.3.1 Building and Fire Codes

National model codes are a primary means to leverage the results of NIST measurement science. There are several ways to translate research results to the model codes:

- Service on model code[†] technical,[‡] administrative,[§] or ad-hoc committees,[**]
- Presentation of measurement science to committees or assemblies for consideration in support or opposition to specific code change proposals

5.3.2 Standards

Standards on the following technologies are critical to successful implementation of this roadmap:

- It is expected that the following standards will be developed or improved to reduce residential fire losses: ASTM E 2187 (Standard Test Method for Measuring the Ignition Strength of Cigarettes) and ISO 12863 (Standard test method for assessing the ignition propensity of cigarettes)
- ASTM E5.15 (Subcommittee on Fire and Interior Furnishings and Contents) and the Consumer Product Safety Commission to develop upholstered furniture flammability standards

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* Proper training must be provided to participants in particular those in leadership positions.

† Model building codes include the International Building Code (International Code Council) and NFPA 5000.

‡ An example of service to a standing committee would include an appointment to the ICC Means of Egress Committee, which has jurisdiction for the egress and accessibility requirements in the International Building Code.

§ An example of an administrative committee would be appointment to NFPA Standards Council, which oversees NFPA codes/standards development activities, administers rules/regulations, and acts as an appeals body.

** An example of an ad-hoc committee would be an appointment to the ICC Code Technology Committee.

- UL 0217 (Smoke Detectors and Alarms) and NFPA 72 (National Fire Alarm and Signaling Code) will be updated to enable early and accurate sensing of unwanted combustion products

It is expected that the following standards will be developed or improved to enable full implementation of performance-based design:

- comprehensive suite* of International Organization for Standardization (ISO) combustion product toxicity standards,
- ASTM International (ASTM) E1355 (Standard Guide for Evaluating the Predictive Capability of Deterministic Fire Models) and a companion standard for egress models for ASTM E05-33 Committee on Fire Safety Engineering,
- International Code Council (ICC) International Building Code and National Fire Protection Association (NFPA) 101 (Life Safety Code) will reflect changes in the national elevator code American Society of Mechanical Engineers (ASME A17.1) .
- Develop performance guidance considering fire as a structural design load ASCE 7.

5.4 STRATEGY FOR ADVANCED FIRE SERVICE TECHNOLOGIES

For the fire service, strategic priorities for consensus standards and code activities are focused on standards to improve the safety and effectiveness of firefighters and include work on the selection, care, and maintenance of key firefighting equipment as well as fire ground tactics and operations. More specifically, high priority standards activities include thermal exposure test methods for existing self-contained breathing apparatus (SCBA), standardized alarm sounds for Personal Alert Safety System (PASS) devices, durability test standards for firefighter protective turn-out gear, standard tactics for non-mechanical ventilation of structures during fires, and test methods for the high temperature performance of portable radios.

Stakeholders play a large role in standards developing organizations such as NFPA and ASTM. Some of the key stakeholders, which have significant influence on the development of standards and codes for the fire service, include fire service professional organizations (IAFC, NVFC, NFFF, ISFSI, FDSOA, etc), firefighter unions, government organizations such as DHS, USFA, NIST, DOL/OSHA, and NIOSH, manufacturing interests, military/defense, university researchers, and certification organizations.

5.4.1 Firefighting Equipment

The NFPA 1900 series of standards, guides, and best practices includes 30 documents that cover a very wide range of firefighter equipment and protective clothing, from automotive fire apparatus to

* Five documents are in various stages of development, including: ISO/DIS 12828-1 Method validation for fire gas analysis – Part 1: Limits of detection and quantification; ISO/CD 29903 Comparison of toxic gas data from different tests; ISO/DIS 29904 Aerosols generation and measurement in fire; WD 26367-2 Assessing the adverse environmental impact of fire effluents– Part 2: Environmental Toxic Effect; and ISO/TR 26368 Mitigation and containment of fire-fighting water run-off.

electronic safety equipment to protective clothing for emergency medical operations. NFPA 1221 is a standard on emergency services communications systems. ASTM provides specifications, guidance, and test methods for specific fire testing activities. For example, ASTM F1060-01 is a test method for thermal protective performance of materials for protective clothing for hot surface contact. The highest priority standards work in this area includes:

- Convective oven and radiant panel lens test procedures for SCBAs are needed for National Fire Protection Association's (NFPA) 1981 Standard for Open-Circuit SCBA for Emergency Services.
- Alarm sound standards for PASS devices need to be incorporated into NFPA 1982 Personal Alert Safety Systems.
- Protective turn-out gear durability standards are included in NFPA 1971 Standard for Protective Ensembles for Structural Firefighting and Proximity Firefighting.
- Protective ensembles for structural firefighting and proximity firefighting (NFPA 1971). Measurement science for stored thermal energy of turnout gear garments is under stage 1 development.
- Ventilation tactics to be included in NFPA 1410 Initial Emergency Scene Operations

Other important standards work is needed in the firefighting equipment area to ensure fire service safety and effectiveness, including:

- Personal protective equipment (ASTM E54-04). Test methods for firefighter respirators, protective clothing using reactive cooling, and firefighter locator technologies using radio frequency identification (RFID) are in stage 1 development.
- Protective clothing and equipment (ASTM F23). Ongoing stage 2 input is needed on existing heat and thermal test methods.
- Open-circuit self-contained breathing apparatus (SCBA) for emergency services (NFPA 1981). Stage 1 measurement science is needed for face piece performance in rough-duty environments.
- Personal alert safety systems (NFPA 1982). Stage 1 measurement science is needed for optimization of alarm sound characteristics and also for PASS devices that transmit RF signals. Stage 2 research has been completed for device performance in high heat environments, and this work has now moved into a stage 3 phase.
- Umbrella standard on all fire ground electronic safety equipment (Draft NFPA 1800). Stage 1 measurement science is needed for minimum performance metrics and test methods.
- Thermal imaging cameras (NFPA 1801). Stage 3 work is needed to support running routine test methods at commercial testing labs.
- Radios (NFPA 1801). This standard when it is time to begin document development.
- Firefighter location/tracking systems (NFPA 1801). Stage 1 work is needed to support the development of appropriate test methods.
- Operational equipment (ASTM E54-08). Stage 1 development of test methods is needed to evaluate the performance of radio communication links used in urban search and rescue robots.

5.4.2 Safe Staffing and Fire Ground Operations

The highest priority work in this area is to enable ventilation tactics which are part of NFPA 1410, Initial Emergency Scene Operations. The possibility of convening standards activities in firefighting tactics needs to be explored as there is a gap in this area.

Other important work is needed in this topic area. For example, work is needed in NFPA 1710 and 1720, standards on organization and deployment of fire suppression operations and special operations by career and volunteer fire departments, respectively, addresses the challenges and hazards faced by today's firefighters and special operations professionals. NFPA 1620 is a standard on pre-incident planning, while NFPA 1670 is a standard on operations and training for technical search and rescue incidents.

In addition to the high priority standards topics identified above, there are other important standards activities in the fire service area. These include firefighter training procedures and guidelines, fitness, performance metrics, test methods, and incident command, which are discussed below.

5.4.3 Training Procedures and Guidelines

The NFPA 1400 series of standards, guides, and best practices includes: recording and reporting of fire incidents; training center design and construction; live fire training; respiratory protection training; marine vessel fires for land-based firefighters; rapid intervention crews; initial emergency scene operations; vehicle operations; and dwelling safety survey procedures. Research is needed to support Live Fire Training (NFPA 1403). Stage 2 measurement science is needed, which derives information from real-scale fire experiments and computer-based fire models to ongoing standard development activities.

5.4.4 Fitness

The NFPA 1500 series of standards, guides, and best practices includes: occupational safety and health; infection control program; comprehensive occupational medical program for fire departments; health-related fitness programs; and rehabilitation process for members during emergency operations and training exercises.

- Measurement science is needed to support fire service training organizations that provide training manuals, model standard operating guidelines, conferences and web-based training to transfer science based technology and fire dynamics information to the fire service and the fire investigation community.
- Fire and Explosion Investigation (NFPA 921). The process and methodologies of investigation have been in development for more than 20 years, however the science based support for many components of the fire investigation process are in still in early stage 1 research. Further real scale fire experiments and continued development of predictive methods are needed.

5.4.5 Incident Command

The NFPA 1000 series of standards covers professional qualifications for a number of firefighter positions, including incident management personnel. NFPA 1201 is a standard on providing emergency services to the public. ASTM F1422-08 provides a standard guide for using the Incident Command System (ICS) framework in managing search and rescue operations. NIST is not currently involved in incident command research.

5.5 STRATEGY FOR REDUCED RISK OF FIRE SPREAD AT THE WILDLAND-URBAN INTERFACE

Work on standards and codes can be divided into three categories: building materials, the residential structure and parcel, and the community. These correspond to increasing physical scale. Standards for building materials focus on preventing ignition (i.e., limiting the response of the material to a given exposure); at the residential and community scales standards focus on reducing the exposure (i.e., magnitude and duration of heat and firebrand fluxes). The objective of the codes and standards is to reduce the likelihood of structure ignition due to firebrand and heat flux exposure from burning vegetation and by rapidly developing a test for structural fire resistance during WUI fires. Support of targeted local code activities (in California, for example) is used as a model to inform national standards and codes efforts. The highest priority standards and code activities are listed below in terms of building materials, residential structures and parcels, and WUI communities.

5.5.1 Standards and Codes for Building Materials

These standards and codes are focused on the ignition response of a given building material (e.g., wall) and/or the ignition prevention capability of a given building component (e.g., screen to block firebrand penetration through a vent) when subjected to heat and/or firebrand fluxes. Development of codes and standards in this area requires laboratory facilities that recreate realistic exposure conditions due to heat and firebrand fluxes under different wind conditions. An understanding of what constitutes realistic exposure conditions requires field measurements during prescribed fires and wildfires, post-fire studies of communities burned by WUI fires, and predictions from computer models – all of these are in the initial stages of development. An ASTM E05 subcommittee has recently been established to assess the state of knowledge of WUI exposure conditions.

High priority standards and codes for reducing the risk of fire in the WUI include:

1. ASTM E5.14.03 committee: new standards on firebrand penetration of vents; firebrand ignition of roofing, siding, window glazing, and decks; window vulnerability to firebrand assault. Stage 1 measurement science support is needed on this topic.
2. ICC WUI Building Code: science-based performance test methods are needed to replace/improve existing test methods for building materials exposed to WUI fires, which currently cite ASTM E119, UL263, ASTM E1354, and FM4470. Stage 1 measurement science support is needed on this topic.

3. California State Building Code Chapter 7A: Improved standards for materials and construction methods for building exteriors exposed to wildfire. Stage 1 measurement science support is needed on this topic.

5.5.2 Standards and Codes for Residential Structure and Parcel

These standards and codes are focused on reducing the exposure of a structure to heat and firebrand fluxes (e.g., proven landscaping practices) and improving structure design to reduce ignitions (e.g., deck placement and design). This requires a database, at the parcel-scale, of fire behavior (exposure conditions) and structure response. No such database exists. Such a database could be constructed from pre-fire measurements of parcel and structure attributes, post-fire fire measurements of fire behavior and structure response, laboratory experiments, and computer predictions. Reliable data collection requires proven field worthy software and hardware and standardized field protocols. Findings from the field can guide targeted laboratory experiments to investigate structure vulnerabilities. Examples of high priority standards and codes activities in this area are:

1. NFPA Forest and Rural Fire Protection and ICC WUI committees: new standards for field data collection; improved standards for residential landscaping and building placement and design (NFPA 1144; ICC International Wildland Urban Interface Code). Stage 1 measurement science support is needed on this topic.
2. California State Fire Code (Chapter 86B): Improvements to existing standard 86B (Material and construction methods for exterior wildfire exposure). Stage 1 measurement science support is needed on this topic.
3. Office of the State Fire Marshall (OFCM), California: Improvements to guidelines for residential setback and defensible space management. Stage 1 measurement science support is needed on this topic.
4. Community outreach programs are in need of Stage 1 research. Here, support and improvements are needed to FIREWISE (consortium of wildland fire organizations and federal agencies), FireSafe (Fire Safe Council of California), Firesmart (Canadian fire officials), and Firefree (Safeco Insurance, industry, fire agencies, private citizens) are needed.

5.5.3 Standards and Codes for Wildland–Urban Interface Communities

These standards and codes are focused on reducing the exposure of a community to heat and firebrand fluxes from WUI fires spreading through both vegetation (wildland and residential) and structures at the community scale. This requires an understanding of how fire behavior is affected due to fuel management (e.g., modification of wildland vegetation bordering a community) and community design (e.g., open space size and location). Reduction of structure ignitions, improved community evacuation, and appropriate placement of safety zones are examples of desired objectives. Achieving this requires significant advancement in standardized community data collection hardware, software, and field protocols for post-fire study; fire behavior measurements in prescribed fire and wildfire settings; and computer models capable of predicting firebrand and smoke transport and fire spread through the complex WUI fuel structure. High priority standards and codes activities in this area are:

1. NFPA Forest and Rural Fire Protection and ICC WUI committees: improved standards for field data collection and community design (NFPA 1141; ICC International Wildland Urban Interface Code). Stage 1 measurement science support is needed on this topic.

2. California State Fire Code (Chapter 86A): Improvements to existing standard 86A (Requirements for wildland-urban interface fire areas). Stage 1 measurement science support is needed on this topic.

5.6 METRICS TO MEASURE PROGRESS

Here, an attempt is made to answer the question, "How do we know if we're making progress?" There are two types of metrics: constituent metrics and global metrics. Constituent metrics are specific measurement science outcomes which affect a significant part of the overall U.S. fire burden. For example, advanced smoke alarms can have a constituent metric to reduce time to detection of an unwanted fire by one order-of-magnitude. The constituent metric focuses the project on a component of the overall problem and is generally one step removed from impact on the U.S. fire problem. Global metrics measure the total U.S. fire burden and are used by NIST to assess large-scale trends and programmatic progress. The metrics used in this report are derived from NFPA's annual report *Total Cost of Fire in the United States.*

The first step to being able to recognize progress is a comprehensive project plan that begins with the Stage 1 measurement science and proceeds through to realization of impact. While the three focus area objectives are linked, progress will be independently measured for each of these areas. During Stage 1 research, progress is monitored as completion of, e.g., construction of a computational model, completion of a set of experiments, completion of significant research results in reports or archival journals. Progress in measurement science takes many forms, including:

- Enabling the development or improvement of codes and standards,
- Enabling the development or improvement of best-practices, standard operating procedures, or specifications,
- Enabling the development or improvement of new technologies,
- Developing or improving new standard reference materials,
- Enabling the development or improvement of manufacturing processes, and
- Published research or software that is used and cited.

In the short-term, contributions to reduce the risk of fire spread in buildings and communities can be evaluated based on the constituent metrics given above, which are seen as a stepping stone to achieving the Reduced Fire Risk in Buildings and Communities goal. In the long term, however, the most tangible and objective marker of success is an observable improvement in the national fire statistics. If a direct connection can be shown between measurement science results (constituent metrics) and real-world impact (global metrics), then the following ought to occur:

- Reduced civilian and firefighter fatalities,
- Reduced civilian or firefighter injuries,
- Improved cost-effectiveness of building fire protection systems, and
- Reduced property loss and other costs enumerated in the NFPA core costs of fire analysis.

It is widely recognized, however, that real-world impact may take decades to discern, as the results of measurement science are implemented as best practices, standards and codes, and new products pervade U.S. residences, commercial buildings, transportation vehicles, etc.

6 SUMMARY

6.1 NIST'S ROLE

This roadmap was developed to provide a shared vision for communication, bring the limited available resources to bear on the U.S. fire burden in a focused manner for enhanced effectiveness, provide a basis for strategic planning, and identify gaps in knowledge and measurement science that hinder the development of critical enabling technologies. History has shown that the field of fire safety has demanded and spawned technological advances. Tens of thousands of lives have been prolonged because of such classic inventions as the automatic sprinkler, halogenated fire suppressants, fire retardants, the rollable fire hose, and the smoke detector. Today, the cultural and technological climate in which fire safety is provided is experiencing change as never before. New products, materials, technologies, advances in computing, advanced information analysis and availability, and environmental constraints are driving new concepts for preventing and mitigating fires as prevalent approaches are strained. This changing landscape requires constant observation and re-assessment of the most critical measurement science research needs. By necessity, this roadmap will need to evolve as technical progress continues, as new problems emerge, and as the world of fire safety progress changes. This document ought to be periodically reviewed to ensure that it is current.

Based on input from NIST staff and stakeholders nationwide, this roadmap identifies a set of strategic research priorities in the year 2012. The priorities provide a blueprint to attain the *long-term vision that unwanted fire be removed as a limitation to life safety, technical innovation, and economic prosperity in the United States.* In this roadmap, a systems approach to fire protection is implicit. Problems are broken down to root causes and multiple approaches are proposed to attack specific issues.

In an effort to address the most pressing fire problems, the strategic plan outlined here emphasizes three focus areas:

- Reducing the risk of fire hazard in buildings,
- Advancing firefighter technologies, and
- Reducing the risk of fire spread in wildland-urban interface communities.

This roadmap is technology centric and focuses on the measurement science needed to enable the most promising technologies to reduce the preventable burden of fire in these three focus areas:

- To reduce the risk of fire hazard in structures, strategic approaches focus on preventing and mitigating the fire and mitigating exposure of people. The priority measurement science outcomes focus on the following approaches:
    - Engineered Fire Protection,
    - Safety of Building Occupants,

- Advanced Flammability Performance of Materials and Products,
- Next Generation Reliable Detection of Incipient Fires, and
- Performance-based Design.

- To advance firefighter technologies, strategic approaches focus on issues for the community, the fire department, and the firefighter before, during, and after a fire incident. The priority measurement science outcomes focus on the following approaches:
  - Firefighting Equipment,
  - Firefighting Tactics,
  - Firefighter Training and Education, Firefighter Situational Awareness, and

  Firefighting Resource Allocation.

- To reduce the risk of fire spread in WUI communities, strategic approaches emphasize WUI fire mitigation technologies through consideration of structural fire prevention, structural fire protection, advanced fire service response, and post-fire recovery with a focus is on WUI communities and surroundings, structures, and parcels in the WUI, and WUI building materials. The priority measurement science outcomes focus on the following approaches:
  - Prevention of Fire in WUI Buildings and Communities,
  - Fire Protection Engineering of WUI Buildings and Communities,
  - Response for Improved Fire Fighter Safety and Effectiveness, and People Evacuation, and
  - Recovery Guidelines for WUI communities.

For each of these approaches, a series of strategic outputs and outcomes are identified. The emphasis is on outputs that advance existing and emerging technologies, which address significant and preventable parts of the national fire burden. To successfully achieve the outputs and implementation of the technological solutions, a series of measurement science hurdles must be overcome. Research activities are prioritized for each of the fire protection focus areas in terms of this needed measurement science. The timeline for the research priorities are broken into three categories, namely short, medium and long term, varying from less than 3 years, 3 to 8 years, and greater than 8 years, respectively. The prioritized outcomes stretched over the next two decades represent a realistic opportunity to significantly impact the national fire burden. As the timeline and strategy have been formulated in terms of the current funding profile, the research priorities reflect a balance of scientific promise and cost.

6.2 COLLABORATION

While measurement science research has a distinct function in furthering fire protection and public safety, it is a supporting role. Measurement science does not promulgate building codes or establish product standards, does not encompass compliance testing, does not include testing or manufacturing fire protection products, and does not provide education or promote the use of such products in the marketplace. Measurement science enables the technical basis for these functions, which are critical endeavors of the greater fire protection community.

There are many players in the fire protection community, including industry, academia, non-profits, government agencies, and professional, educational and standards organizations, each with their own roles, responsibilities, and authorities. NIST's role is to conduct and support fire-related measurement science. The entire community of fire safety organizations needs to work together if the vision of a fire-safe future is to be realized. Working together, the greater fire, manufacturing, and user communities will be able to ensure that research results have meaning, are implemented, and ultimately enable a fire-safe future. The full impact of measurement science results cannot be achieved without the important activities of partner organizations, including:

- Public education (e.g., Fire Safety Council),
- Professional education and training (e.g., SFPE),
- Standards development (e.g., ASTM, ICC, ISO, NFPA, SFPE),
- Code development (e.g., ICC),
- Regulation (e.g., CPSC, GSA, NRC, state governments),
- Product testing and certification (e.g., NAFTL),
- Product and material manufacturers and suppliers,
- Fire service (e.g., IAFF, IAFC, IFF, NVFC, IAA, NASFM, NFFF, CFSI, Vision 20-20, CALFire),
- Government organizations (e.g., CALFire, ATF, CDC, CPSC, DHS, DOE, GSA, NASA, NIOSH, NIST[*], NRC, NWCC, USFA, and USFS),
- Academia (e.g., WPI, UMd, University of Edinburgh, Lund, etc.), and
- Technology research and development organizations (e.g., FM Global, Underwriters Laboratories, United Technologies, IBHS, Sandia National Labs, IAFSS, FORUM, SP, BRE, BRI, NRC-Canada, materials industry).

6.3 INNOVATIVE AND EXPLORATORY RESEARCH

Measurement science in the area of fundamental and applied fire research has a record of innovation over the last three decades that has facilitated a safer world (as described in Chapter 2.1). Some of the most innovative work has revolutionized fire safety:

- The concept of oxygen consumption calorimetry, and the ensuing invention of the cone calorimeter;

* Including the many experts within NIST beyond the Engineering Laboratory, who provide expertise in chemistry, electronics, metallurgy, polymers, information technology, physics, economics, and law enforcement standards.

- Nanoparticle fire retardancy, the first truly new approach to less fire-prone products in half a century;
- Science-based analysis of fire incidents, providing lessons learned for the fire service and code officials;
- The low Mach number formulation of the Navier Stokes equations and their implementation in the form of efficient and validated fire field models for engineering analysis; and
- Smokeview, a revolutionary visualization tool of the output of ever more complex fire models;

To continue to impact the national fire problem, NIST's Reduced Risk of Fire in Buildings and Communities strategy is committed to exploring new measurement science approaches, measurement methods, and technologies. Innovation is not just complementary to the role of measurement science, it is an essential ingredient.

APPENDIX A THE U.S. FIRE BURDEN

A.1 EXPLANATION OF THE VALUE OF THE U.S. FIRE BURDEN

The total value (cost plus loss) of U.S. fire burden in 2008 is estimated at about $310 billion (in 2008 dollars)[*] with fires in structures accounting for $185 B, wildland-urban interface fires accounting for $14 B, vehicle and outdoor (e.g., trash fires) and other fires accounting for $6 B, and the fire service accounting for $109 billion with the component costs presented in Table A-1. The estimation method employed here is primarily based on analysis by Hall.[2] A scaling procedure[114] is used to adjust NFIRS incident data[113] to be consistent with NFPA survey statistics, with a few deviations and additions made here. An uncertainty analysis is also provided with the range of the U.S. fire burden estimated to vary from $231 billion to $461 billion given current measurement techniques, reported data, and fire risks. The details of these analyses are documented below.

Missing are those unknown or currently unquantifiable costs and losses. This is, perhaps, of greatest concern with wildland-urban interface fires. Thus, the values presented are only for those known and quantifiable values based on current measurement techniques. All dollar values shown are in 2008 dollars, unless otherwise noted.

A.1.1 Structure Fires

Structure fires are defined in NFIRS 5.0 as those with an incident type 111 through 123. In 2008, an estimated 515,000 structure fires occurred (including fixed mobile homes, apartments and single family dwellings) using a scaling procedure detailed by Hall and Harwood.[114] Associated with those fires were 2900 civilian fatalities and 14 960 injuries. Hall assumed another 6.4 % civilian fatalities and 9.2 % civilian injuries were unreported.[2] Given the value of a statistical life of $5 M and injury of about $238,000 (the per injury value of $166,000 was inflated using the Bureau of Labor Statistics Consumer Price Index from 1993 dollars to 2008), as used by Hall,[2] the estimated loss of life and limb is valued at $15.4 billion for civilian fatalities and $3.9 billion for civilian injuries.

For structures, property losses are estimated at $14.1 B. This figure was also produced using 2008 NFIRS data and the scaling procedure detailed in Hall and Harwood.[114] Hall assumed that 5.3 % of property losses go unreported.[2] In addition, the $2.5 billion in indirect losses reported in Hall[2] has been added to structure fires. Hall[2] breaks out indirect losses based on the following property classes: 65 % manufacturing and industrial properties; 25 % public assembly, educational, institutional, store, and office properties; 10 % residential, storage, and special-structure property; and 0 % for vehicle and outdoor fires. Thus, all of the indirect costs were assumed to apply to structures.

* This differs somewhat from the value provided by Hall (2009), primarily due to detailed accounting associated with the cost of volunteer firefighters and WUI costs. Details are given below.

The insurance estimate presented by Hall has been distributed between fire incident types based on their relative property losses reported in NFIRS.[2] Insurance related to structure fire is estimated at $12.2 B. The building construction for fire protection presented by Hall is attributed to structures.[2] This cost is estimated at $62.7 B.

Hall[2] reports on five categories of costs that are not considered "core" costs. These categories consist of the costs of meeting fire grade standards for manufactured equipment ($28.5 B), fire maintenance ($10.3 B), retardants and product testing associated with fire safety ($4.0 B), disaster recovery plans ($0.9 B), and preparing and maintaining standards ($0.3 B). These figures are estimated by inflating Meade's original estimates into current dollars.[115] In Meade's analysis, the two biggest cost factors, the costs of meeting fire grade standards for manufactured equipment and cost of fire maintenance, are computed as a function of statistics published by the Census Bureau[*] and the Bureau of Economic Analysis.[†] For both these inputs, figures for 2008 are available,[‡,§] so these costs deviate from those reported by Hall.[2] Based on the 2008 data, the cost of fire protection of equipment and standards is estimated at $73.8 B, with $53.0 billion attributed to the costs of meeting fire grade standards for manufactured equipment, and with $15.6 billion attributed to the cost of fire maintenance. The $29.8 billion increase over Hall's estimate[2] suggests that in 2011, 68 % more fire grade equipment and fire maintenance in structures than was observed than in 1990.

A.1.2 Outdoor Fires or Natural Vegetation Fires

Natural vegetation fires are defined in NFIRS 5.0 as those with an incident type of 140 through 143. In 2008, an estimated 364,000 natural vegetation fires occurred using a scaling procedure detailed by Hall and Harwood.[114] Associated with those fires were 18 civilian fatalities and 257 civilian injuries. The loss of life and limb are valued at $0.1 billion for civilian fatalities and $0.1 billion for civilian injuries. Property losses are estimated to have been $3.1 B. (These include $1.4 B, the losses associated with the 2008 California wildfires,[116,**] added to the scaled loss estimate.) No indirect losses are included.

Assuming 13 % of the insurance costs reported in Hall[2] occurred due to wildland-urban interface (WUI) fires (the percentage of property and content losses from natural vegetation fires reported in NFIRS), natural vegetation fires accounted for $1.5 billion of the net insurance cost for fire protection costs. [††]

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* Quarterly Financial Report for Manufacturing, Mining and Trade Corporations—First Quarter 1990.

† Survey of Current Business, July 1990 (reported private purchases of producer durable equipment by type).

‡ U.S. Census Bureau, Fourth Quarter 2008 Data from the Quarterly Financial Report U.S. Manufacturing, Mining, and Wholesale Trade Corporations.

§ Bureau of Economic Analysis, National Economic Accounts, National Income and Product Accounts, Private Fixed Investment in Equipment and Software by Type.

** The 2008 California wildfires resulted in damages significantly higher than the 5-year average (about double). Wildfire damages appear to vary greatly from year-to-year.

†† While Hall's insurance cost estimates are based on fire policy, multi-peril homeowner, and commercial and fire-owner policy premiums (e.g., automobile policies are not considered), a method was used to allocate these costs

While the $62.7 billion spent on fire protection of building construction, it may limit structure damage resulting from a WUI fire—meaning some portion of this amount should accrue to this incident category. However, this is not well understood. Communities do invest in fire protection technologies to reduce their risk to wildland fires. This includes, for instance, investments into fuel treatments around WUI communities. The cost of fire protection around constructed facilities is estimated at $1.7 B. This estimate is based on the assumptions that 10 % of the at-risk WUI communities[*] invest in risk mitigation strategies, whether formally through programs such as Firewise Communities, or informally on their own initiative, and that the average household spends about $1200 in time, labor, or direct expenditures each year. This estimate is expected to grow each year as more at-risk communities participate and as the number of households in the at-risk area of the WUI increases.

According to the Blue Ribbon Panel Report on WUI Fire, average annual federal ($1.9 B), state ($0.9 B) and local firefighting costs ($0.5 B) from 2000 to 2006 was $3.3 billion (ICC 2008), an increase from a $1.4 billion annual average in 1990 to 2000.[29] In 2006, $2.7 billion was appropriated to the U.S. Forest Service and Department of Interior for wildfire management activities.[†] These activities included fuel reductions, restoration projects, and fire preparedness. These activities are estimated at $0.8 B.[‡] The 2006 dollar estimates are inflated to 2008 dollars.

The economic impacts of WUI and wildland fires are not well understood. These can include losses related to business interruptions, tourism and sales affects, as well as impacts to utility and infrastructure losses. Based on data from two recent studies evaluating the costs and losses of large wildfires, a multiplier was developed to scale property losses into total economic impacts.[§,117,118] Thus, the economic impact of WUI fires is estimated at $3.5 billion.

A.1.3 Vehicle, Outside, and Other Fires

This category includes all other fires not already classified as structure or natural vegetation. This includes NFIRS' major incident categories such as fire in "mobile property (vehicle) fires," "outside rubbish fires," "special outside fires," "cultivated vegetation," "crop fires," "fires," and "other." In 2008, an estimated 570,000 other fires occurred using a scaling procedure detailed in Hall and Harwood.[114]

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across the different fire (ignition) types (structure, outdoor and natural fires, vehicle and other fires) to recognize that some structure fires result because of other fires.

* At-risk WUI communities are defined as those with an estimated mean fire return interval of 20 years or less. See Thomas and Butry, 2010.

† Up to 95 % of the U.S. Forest Service's large wildfire suppression expenditures are used to protect WUI areas (USDA 2006).

‡ The difference between $2.7 B spent for all federal wildfire management and $1.9 B spent on federal firefighting.

§ The ratio of total loss to property loss was developed and used as the multiplier. Based on the data, the ratio ranged from 2.1 to 3.0, meaning total losses ranged from 2.1 times to 3.0 times known property losses. The pairwise correlation between total losses and property losses was 0.93, which demonstrates a high degree correlation between the two values.

Associated with those fires were 402 civilian fatalities and about 1500 civilian injuries. Using the same procedure detailed above produces cost estimates due to loss of life and limb at $2.1 billion for civilian fatalities and $0.4 billion for civilian injuries. Property losses are estimated to have been $1.8 B. No indirect losses are included. Assuming 10 % of the insurance costs reported by Hall[2] occurred due to vehicle, outside, and other fires (the percentage of property and content losses from these fires reported in NFIRS) , these fires accounted for $1.5 billion of the net insurance cost for fire protection costs. The cost of building construction for fire protection has not been estimated for these fires.

A.1.4 Fire Service

Hall estimated that 105 firefighter fatalities and 79 700 firefighter injuries occurred in 2008. Based on the value of a statistical life and injury used for civilians, firefighter fatalities cost society $0.5 billion and injuries cost $19.0 billion in 2006. Hall estimates the cost of career fire departments at $39.7 B. Because there are considerably more volunteer firefighters than career, the value of their donated time is a significant cost to society. Hall estimates this value at $138 B, which is based on a 4-to-1 ratio between volunteer and career firefighters.[119,*] This analysis uses a more conservative estimate based on the 2.6-to-1 ratio implied in Karter,[7] which uses a different methodology than that found in Hall, and a range of values related to the worth of donated time.[†] Based on the range of two estimates, the cost of volunteer fire department time is estimated as $50.0 B.

A.2 UNCERTAINTY AND MEASUREMENT PRECISION

Table A-1 provides point estimates for each of the cost and loss items. All of the estimates are subject, to varying degrees, to uncertainty and measurement error. In addition, Table A-1 only provides estimates for known costs and losses, and for those where a value can be estimated in a defensible manner. Missing are those costs and losses that are not well understood or that are difficult to measure (e.g., WUI fires and ecosystem service degradation). The known and well-defined statistics are based on survey sample data that has been used to compute population estimates. For these, measures of uncertainty or sample variation are not well known. This section attempts to evaluate the degree of uncertainty underlying these estimate, where possible, to provide an indication of the potential size of the fire burden (i.e., evaluate the order of magnitude of particular estimates).

A.2.1 Structure Fires

Previously discussed were two methods for estimating the cost of fire protection of equipment (inflating and re-calculating Meade's estimates).[115] The two methods differed in assumptions related to the portion of fire grade equipment found in constructed facilities. Perhaps the more important issue regarding Meade's first pass estimates is that they rely on a small survey of experts from 20 years ago. How well these estimates reflect the true costs is unknown. Costs related to fire protection in

[*] The 4-to-1 ratio is the result when determining the number of non-metropolitan firefighters needed to create the same level of fire protection coverage in metropolitan areas.

† See the discussion below in Section A.2 on *Uncertainty and Measurement Precision*.

constructed facilities also falls into this category. The science-base for these estimates is over 30 years old. Assuming the costs of fire protection in equipment *and in* building construction are 68 % larger (see Section A.1.1) than as derived by the inflation method used in Hall,[119] in which the fire burden resulting from structure fires may range from $130 billion to $230 B.

Table A-1. Value of the U.S. Fire Burden (2008).

Category	Item	$ Billion
Structure Fire		
	Civilian Fatalities	15.
	Civilian Injuries	3.9
	Property Losses	16.
	Net Insurance Cost	12.
	Fire Protection in Constructed Facilities	62.
	Fire Protection (Equipment & Standards)	73.
	Sub-Total	**184**
Wildland-Urban Interface Fire		
	Civilian Fatalities	0.1
	Civilian Injuries	0.1
	Property Losses	3.1
	Net Insurance Cost	1.5
	Fire Protection around Constructed	1.7
	Suppression	3.5
	Fuel Treatments, Preparedness,	0.9
	Economic Impacts	3.5
	Sub-Total	**14.**
Vehicle, Outside & Other Fire		
	Civilian Fatalities	2.1
	Civilian Injuries	0.4
	Property Losses	1.8
	Net Insurance Cost	1.5
	Sub-Total	**5.9**
Fire Service		
	Firefighter Fatalities	0.5
	Firefighter Injuries	19.
	Career Fire Department Costs	39.
	Volunteer Fire Department Costs	50.
	Sub-Total	**109**
	Total	**314**

A.2.2 Natural Vegetation Fires

Given the recent emergence of wildland-urban interface fires, these estimates are likely the most affected by uncertainty and measurement error. A Monte Carlo simulation was developed to assess the uncertainty. Suppression costs, amount of suppression resources used to protection WUI areas, property losses, and the property loss/total loss multiplier were varied to produce a range of fire burden estimates related to natural vegetation fires. Simulated distributions and input parameters were derived from a number of sources.

Suppression costs follow a uniform distribution, with a minimum of $0.5 billion and a maximum of $4.3 B. The range was derived by varying the $3.3 billion in baseline suppression costs (see above) proportionally with the variation demonstrated by U.S. Forest Service's suppression expenditures from 1994 to 2009.[120] The amount of suppression resources used to protect WUI areas follows a triangular distribution, with a minimum of 33 %, most likely of 50 %, and a maximum of 95 %.[121] Property losses follows a maximum extreme distribution (with truncation at zero), with a likeliest value of $0.8 billion and the 90 % percentile of $2.5 billion with the distribution taken from Ref. 122. Consistent with the property loss to total loss multiplier described above, this multiplier follows a lognormal distribution with the 50 % of 2.1 and a 90 % of 3.0.

A total of 10,000 simulations were completed. The mean WUI-based portion of the U.S. fire burden is estimated at $6.9 B, with a median value of $6.5 B. The minimum value is $2.7 billion and the maximum value is $28.4 B. The 2006 dollar estimates are inflated to 2008 dollars for the range shown below.

A.2.3 Fire Service

As discussed in the above Fire Service cost and loss section, two methods were used to estimate the donated value of volunteer firefighter time (in addition to the method used in Ref. 119). The first was based on a computed annual cost of career firefighter time multiplied by the number of volunteer firefighters. Hall reports that 87 % of the total career costs is for personnel cost ($34.5 B).[2] Karter estimated that 321,700 firefighters in the U.S. are career firefighters.[7] Thus, on average a career firefighter costs about $92,500 per year. Karter also reported the number of volunteer firefighters in the U.S., at about 827,000.[7] Based on these numbers, total volunteer personnel cost is $76.5 B, i.e., the cost society would bear should career departments replace volunteer departments. The second method multiplies total firefighting volunteer hours (assuming all volunteer are full-time [2080 hour/year]) by the average value of volunteer time ($20.25/hour).[123] This method yields an estimate of $34.8 B. Thus, the Fire Service portion of the fire burden ranges from $94.0 billion ($39.7 B + $34.8 B + $19.5 B) to $197.2 B ($39.7 B + $138 B + $19.5 B), with $135.7 B ($39.7 B + $76.5 B + $19.5 B) as an additional data point.

A.2.4 Total Range of U.S. Fire Burden

Based on the ranges provided above, plus the baseline for vehicle, outside, and other fires (no uncertainty analysis was performed), the U.S. fire burden ranges from $231 B to $461 billion given current measurement techniques, reported data, and fire risks.

A.3 WUI FIRES: AN EMERGING PROBLEM

Unlike the structure fire problem, the wildland-urban interface fire problem appears to be getting worse, in terms of structures lost and acres burned.[95] Using forecast methods, estimates of the WUI fire problem are shown in Figure A-1. The baseline analysis (i.e., the medium forecast) demonstrates that the WUI fire burden will likely double over the next decade.

Low-, medium-, and high-range forecasts were made by estimating the annual growth in structure losses and annual growth in fire protection costs around WUI communities (i.e., firewise[79] and other types of guidance). Economic losses (indirect losses), societal losses from fatalities and injuries, insurance costs were all assumed to grow proportionally with structure losses. The at-risk WUI housing stock was assumed to grow at a 2 % annual rate.[124]

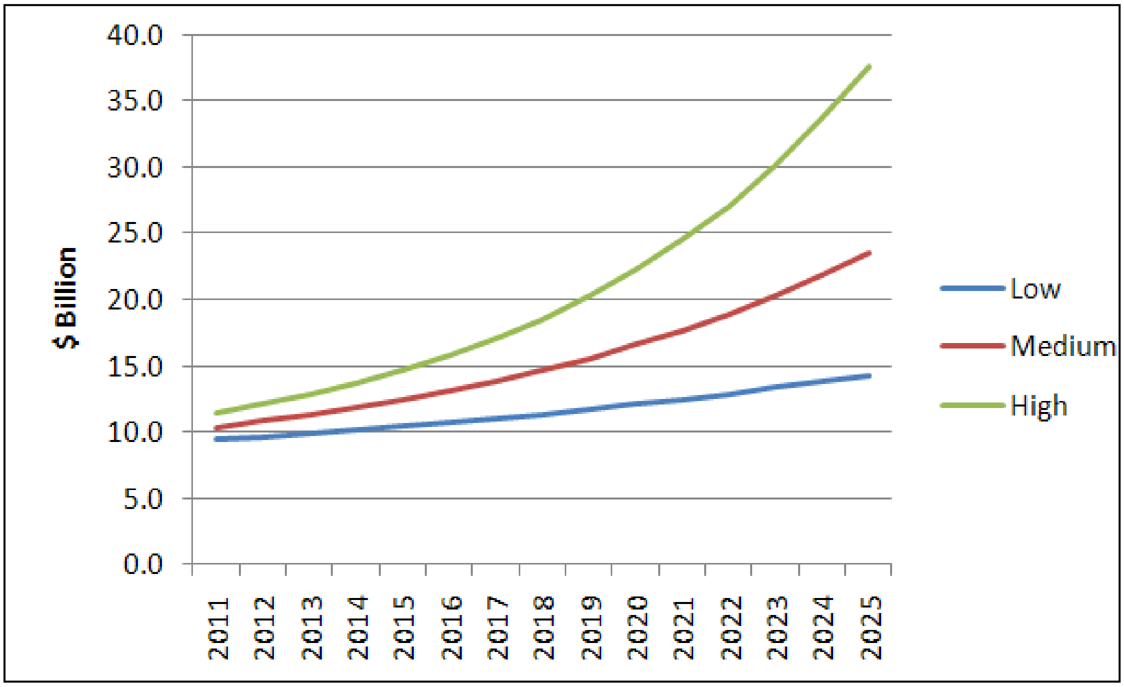

Figure A-1: Forecasted WUI Fire Burden (2011-2025).

Baseline values (2011) were derived as follows. Total losses were based on average property and crop damages reported in the National Climate Data Center's *Summary of Natural Hazard Statistics* from 1998-2005, and adjusted by the economic multiplier described in Section A.1.2. Spending on fire suppression and fire protection of constructed facilities were set to the values shown in Table A-1. Costs related to fuels management were not included. Net insurance costs were set to $0.4 billion to more accurately reflect WUI fire damage levels from a more representative year (non-2008).

The medium-range (baseline) structure loss forecast used a 7 % annual growth rate, a value that was derived from fitting an exponential trend-line to the decadal ICC data (1960 to 2000; R^2 = 0.97). The low-range annual growth was set to 5 %. The high-range annual growth rate was set to 10 %.

The medium-range forecast fire protection costs around WUI communities used a 10 % annual growth rate. While an exponential model fitting Firewise expenditures (2003 to 2009) fit well (R^2 = 0.97), the annual growth rate was 46 %, which was determined as unsustainable over the long-term. To be conservative, 10 % was used. The low-range annual growth was set to 5 %. A high-range annual growth rate was set to 15 %.

Federal, state, and local wildfire expenditures (suppression, fuels management, preparedness, restoration) were set to their forecasted 2011 combined estimate (ranging from $5.2 billion to $6.9 B). Thus, the forecasted WUI fire burden, shown in Table A-1, is conservative, as the loss estimates assumed a relatively small increase in wildfire expenditures.

APPENDIX B REDUCING THE U.S. FIRE BURDEN

The total value (cost plus loss) of the U.S. fire burden is the main focus of Appendix A. In 2008, it is estimated that the U.S. fire burden was about $310 billion (in 2008 dollars) with fires in structures accounting for $185 B, wildland-urban interface fires accounting for $14 B, vehicle and outdoor (e.g., trash fires) and other fires accounting for $6 B, and the fire service accounting for $109 B. The component costs are presented in the text of Appendix A and in Table A-1. An uncertainty analysis is also provided with the range of the U.S. fire burden estimated to vary from $231 billion to $461 billion given current measurement techniques and reported data. All dollar values shown are in 2008 dollars, unless otherwise noted.

The goal of this Roadmap is to provide a pathway to reduce the U.S. fire burden. In order to understand the impact that measurement science could play in reducing the fire burden, it is useful to estimate the portion of the U.S. fire burden which is preventable. That is the focus of this Appendix.

The Total Fire Burden is the sum of all costs and losses associated with fire. The costs are expenditures used to prevent or mitigate the losses from fire. The losses include economic losses (direct and indirect) and the monetized social value of fatalities and injuries. There are many other costs, which contribute to the total fire burden, including the net insurance costs, fire protection costs, career and volunteer fire department costs and wildland fire expenditures. The total fire burden is estimated as $314 B. The components of the total fire burden tabulated in Table A-1 (Appendix A) are reproduced in Table B-1 below. Some parts of the fire burden are preventable, whereas other parts are not preventable as explained below.

The Preventable Fire Burden is the sum of all costs and losses associated with the total fire burden, which could be avoided (reduced) by advancements in measurement science. The preventable fire burden can be estimated as the product of the expected fire burden with the avoidable fraction for each component of the fire burden. While some components of the fire burden are largely not preventable, much of the U.S. fire burden, including direct and indirect economic losses and the monetized social value of fatalities and injuries, can be reduced by improving the prevention, control, and response to unwanted fires. This roadmap highlights the measurement science approaches and technologies needed (see Chapters 3 and 4 above) to reduce the preventable fire burden. The total preventable fire burden is estimated as $102 billion or about one-third of the total fire burden.

The Non-Preventable Fire Burden is the difference between the total fire burden and the Preventable Fire Burden. The non-preventable fire burden can be thought of as those fire protection costs, which are required to maintain the current level of life safety and those losses, which are, for example, associated with events beyond control. Measurement science cannot immediately enable elimination of 100 % of the preventable national fire burden. Historical precedent suggests that the impact of strategically planned measurement science can be significant, but is finite and depends on many factors including the multiplicity and complexity of specific components of the fire problem, the effects of economic, social, political, and technical drivers of various parts of the fire problem, and the appearance of new and emerging fire problems. The total non-preventable fire burden is estimated as $212 billion or about two-thirds of the total fire burden. Examples of non-preventable losses and costs are described in this appendix.

The estimated values of the avoidable fraction and preventable fire burden costs for each of the major components of the U.S. fire burden are estimated in Table B-1 and discussed below. Estimates of the avoidable fraction for components of the U.S. fire burden are estimated to take on values ranging from 0 to 1. Table B-1 shows that in aggregate, the estimated value of the preventable fire burden is about one-third of the total U.S. fire burden.

There is a distinction between preventable fires and preventable burden. Building on past successes, this roadmap emphasizes measurement science that improves life safety and reduces losses. While total societal costs are a central consideration in this roadmap, the emphasis is on improved measurement science that

- leads to improved life safety (reduced injuries and fatalities) at reduced societal spending associated with fire prevention and protection,
- leads to improved fire safety for flat or unchanged societal spending, or
- leads to a flat or unchanged level of fire safety at reduced societal spending.

Assuming that the measurement science conceived in this roadmap is successfully completed, this Appendix provides a rough estimate of its anticipated impact, enabling technological solutions that address each of the components of the preventable fire burden associated with structure fires, wildland-urban interface fires, the fire service, and other or outdoor fires.

For each component of the U.S. fire burden, estimates in the sections below quantify how the preventable burden of fires could be reduced. The values are not based on reference documents as no such documents exist. Instead, the values are estimates based on engineering judgement, which includes an understanding of the fire problem and possible technological solutions. Subtleties such as coupling and interaction among the various problems and solutions are not addressed, as such as analysis would add little value and could obscure the fact that the results are inexact.

Table B-1: Value of the US Fire Burden, Avoidable Fraction and Preventable Fire Burden (2008).

Category	Item	Total Fire Burden ($ Billion)	Avoidable Fraction	Preventable Fire Burden ($ Billion)
Structure Fire				
	Civilian Fatalities	15.4	1	15.4
	Civilian Injuries	3.9	1	3.9
	Property Losses	16.6	1	16.6
	Net Insurance Cost	12.2	0	0
	Fire Protection in Constructed Facilities	62.7	0.2	12.5
	Fire Protection (Equipment & Standards)	73.8	0.2	14.8
	Sub-Total	**184.6**		**63.2**
Wildland-Urban Interface Fire				
	Civilian Fatalities	0.1	0.9	0.1
	Civilian Injuries	0.1	0.9	0.1
	Property Losses	3.1	0.9	2.8
	Net Insurance Cost	1.5	0	0
	Fire Protection in Constructed Facilities	1.7	0.5	0.9
	Suppression	3.5	0.1	0.4
	Fuel Treatments, Preparedness, Restoration	0.9	0.25	0.2
	Economic Impacts	3.5	0.9	3.2
	Sub-Total	**14.4**		**7.7**
Vehicle, Outside & Other Fire				
	Civilian Fatalities	2.1	1	2.1
	Civilian Injuries	0.4	1	0.4
	Property Losses	1.8	1	1.8
	Net Insurance Cost	1.5	0	0
	Sub-Total	**5.8**		**4.3**
Fire Service				
	Firefighter Fatalities	0.5	0.9	0.5
	Firefighter Injuries	19.0	0.9	17.1
	Career Fire Department Costs	39.7	0.1	4.0
	Volunteer Fire Department Costs	50.0	0.1	5.0
	Sub-Total	**109.2**	**-**	**26.6**
	Total	**314.0**	**-**	**101.8**

B.1 REDUCING THE PREVENTABLE BURDEN OF STRUCTURE FIRES

In this section, an accounting is made to quantify how the preventable burden of structural fires could be reduced by about one-third, emphasizing the application of promising measurement science as discussed in Chapters 3 and 4 to address key aspects of the structural fire problem. Referring to Table B-1, a reduction in the value of the structural fire burden will require significant reductions in the number and severity of structural fires. A detailed accounting of the avoidable fraction, the preventable fire burden, and the anticipated impact of this roadmap is described below in terms of the most fruitful measurement science areas to enable the reduction of the structural fire burden.

B.1.1 Avoidable Fraction

The estimated avoidable fraction for each of the major components of the U.S. fire burden are estimated in Table B-1 and discussed immediately below.

B.1.1.1 Civilian Fatalities and Injuries

Within the context of current social expectations, measurement science is needed to eliminate ignition sources, reduce the ignition propensity of furnishings and building contents, limit the flammability of post-ignition items, and effect advanced suppression and control of the fire. To do this, the severity of all fires must be reduced. It is assumed that this strategy will reduce losses from all types of fires, including child-playing fires and intentional structure fires, which account for a significant number of civilian fire fatalities and injuries.[125,126]

B.1.1.2 Property Losses

Given that structure fires are generally preventable through the methods described above. There are some property losses that may not be avoidable, but they are relatively small in terms of the fire loss profile. Sprinklers, for example, while effective in achieving positive life safety outcomes, can induce fire-related water damage in structures.

B.1.1.3 Net Insurance Cost

The net cost of insurance is another component of the total fire burden that is not preventable. The net cost only includes the operating expenses and profit associated with an insurance company providing the insurance. The assumption is that even as the number of fires decrease with a subsequent decrease in insurance claims, the total insurance premiums may decrease, but the net cost of insurance companies provide will not decline. The cost of the property loss is included as a separate line item listed as the cost of property losses. The property loss includes not only the insured property loss, but also the uninsured property losses. Therefore, the net insurance costs are not considered a preventable cost.

B.1.1.4 Fire Protection in Constructed Facilities

Fire protection in constructed facilities is a major contributor to the fire burden. It is critical to fulfilling the public expectations for basic life safety outcomes. Costs involve a long list of important fire protection items, including the cost of fire protection equipment such as sprinklers, fire alarm systems, testing of commercial products to specific fire safety standards, business opportunity costs such as lost use of building floor space to stairwells, sprayed on fire resistant materials for protection of steel building elements, installation and maintenance costs of fire extinguishers, and so on. Total fire protection expenditures can be reduced by technological innovation, redundancy elimination, and performance-based design methods which tailor fire protection resources to match risks, all while improving life safety outcomes. Presuming that the current level of life safety must be ensured, only a fraction of these costs are avoidable. Based on engineering judgement and an analysis of the magnitude and types of costs involved, a value of 0.2 is assigned as the avoidable fraction for this item as shown in Table B-1.

B.1.1.5 Fire Protection (Equipment & Standards)

Furnishings, building elements, and infrastructure generally require compliance with one or more standard test method or certification process. These test methods are specific to components or assemblies. They are developed by numerous standards developing organizations (NFPA, ICC, ASTM, ISO, UL, FM, for example) as well as voluntary industry standards or practices. Infrastructure needed to conduct standardized tests include equipment, personnel, and materials to be tested. Developing and maintaining consensus standards consumes time and resources. Based on engineering judgement, it is estimated that about 20 % of total invested costs could be achieved through improved measurement science to eliminate redundant or poor-performing standards or tests, improve the efficiency of the testing protocols, or improving the scientific basis for the standards.

B.1.2 Reducing the Preventable Burden of Building Fires

The total fire burden associated with structure fires in the U.S. is nearly $185 billion annually. Table B-1 shows that roughly $60 billion or one-third of the structure fire burden is preventable. To address this problem, there would have to be significant measurement science advances in two areas, as described in Chapter 3, including effective strategies for (1) preventing and managing a fire and (2) managing those exposed to a fire. The cost-effectiveness of fire protection and life safety issues are a concern in both commercial and residential buildings. Systematic consideration of how to intervene in the fire timeline is a key part of the analysis.

To prevent the fire before a would-be incident and to mitigate the hazard during a fire event, several approaches are important as discussed in Chapter 3, including:

- Reducing ignition at the source and/or nearby items (or preventing secondary ignition),Improving detection including the sensitivity and reliability of detection and recognition of fire in its early stages in order to initiate suppression or containment systems,
- Decreasing the fire hazard by controlling the rate of fire growth and the spread of flames and smoke through the use of improved materials and products,
- Mitigating the growth and spread of the fire through use of engineered fire protection systems, and

- Performance-based design methods to maximize design flexibility while minimizing the cost of installed fire protection.

To address the exposure of people and structural assemblies to a fire, several approaches may be helpful, including:

- Improving detection including the sensitivity and reliability of detection and recognition of fire in its early stages in order to alert the occupants promptly,
- Assuring adequacy of the egress capacity relative to demand through efficient building design and effective emergency management,
- Performance-based design methods to maximize design flexibility while minimizing the cost of egress and structural systems, and
- Fire resistance of structural systems and assemblies to ensure appropriate design performance during a fire.

B.1.2.1 Prevention and Mitigation

Below, an accounting is made to quantify how the preventable burden of fire in buildings could be reduced, emphasizing the application of promising measurement science as discussed in Chapters 3 and 4 to address key aspects of the US fire problem:

- Cigarette Ignitions: Reduced-ignition-propensity (RIP) cigarettes may reduce cigarette-related ignitions and consequent fires, injuries, deaths, and property loss by 50 % (NFPA Fact Sheet[*]). As discussed in Section 3.3.3, cigarettes ("smoking materials") stand out as a leading fire ignition source in the US, accounting for approximately one-fourth of the fire deaths and one-tenth of the injuries.[35] Advances in this technology through measurement science could result in savings of approximately:
    - 50 % of the approximately 700 annual cigarette-related fire deaths,
    - 50 % of the roughly 3,500 annual cigarette-related fire injuries, and
    - 50 % of the roughly $800 M of direct property loss.
- Residential Upholstered Furniture: Improved ignition resistance and reduced flammability of residential upholstered furniture may reduce injuries and deaths by 25 % through improved barrier material performance, reduced flammability foam, and/or improved fire standards. This could result in savings of approximately:
    - 25 % of the roughly 500 annual residential upholstered furniture related fire deaths,
    - 25 % of the roughly 1400 annual residential upholstered furniture fire-related injuries, and
    - 25 % of the roughly $4000 M of direct property loss.

* http://www.nfpa.org/assets/files//PDF/smokingfactsheet.pdf

- Cooking: Improved safety performance of cooking appliances (such as automatic heat source cut-off switches or over-the-range suppression devices) may reduce injuries and deaths by 10 % (NFPA Fact Sheet*). This could result in saving approximately:
  - o 50 of the 500 annual cooking related fire deaths,
  - o 50 of the 500 annual cooking fire injuries, and
  - o $8 M of the $76 M direct property loss.
- Space Heaters: Improved safety performance of portable space heaters may reduce injuries and deaths by 10 % (NFPA Fact Sheet*). This could result in saving approximately:
  - o 49 of the roughly 490 annual space heater related fire deaths,
  - o 225 annual space heater fire injuries, and
  - o $46 M of direct property loss averted.
- Mattress and Bedding: Improved ignition resistance and reduced flammability of mattresses and bedding may reduce injuries and deaths by 10 % through improved barrier material performance, reduced flammability foam, and/or improved fire standards. This could result in savings of approximately:
  - o 40 of the 400 annual mattress and bedding related fire deaths,
  - o 90 of the roughly 900 annual mattress and bedding -related fire injuries, and
  - o $40 M of direct property loss averted.
- Open Flame and Intentional Fires: Improved ignition resistance and reduced flammability residential upholstered furniture may reduce injuries and deaths by 25 % through improved barrier material performance, reduced flammability foam, and/or improved fire standards. This could result in saving approximately:
  - o 43 of the 430 annual open flame fire deaths,
  - o 200 annual mattress and bedding related fire injuries, and
  - o $90 M of direct property loss averted.
- Once a fire has ignited and begins to spread, fire safety may be improved by limiting the growth and spread of fire by design of material properties which limit the peak HRR of burning objects or through improved suppression, including widespread implementation of residential sprinkler systems and novel suppression technologies. This could result in saving approximately:
  - o 240 of the 2,400 annual fire deaths not prevented through reduced ignitions,
  - o 1,100 annual fire injuries, and
  - o $1,300 M of direct property loss averted.
  - o $700 M of reduced cost of installed fire protection through performance-based design methods which creates safety-equivalent solutions at reduced cost.
- Early detection of fires may improve fire safety by providing more timely notification to occupants and fire department responders. More reliable detection will reduce the likelihood of the detector being removed due to false alarms and reduce the number of unnecessary

* Hall 2009, page i.

emergency responses. This could result in saving approximately:
    - 240 of the 2,400 annual fire deaths not prevented through reduced ignitions,
    - 1,100 annual fire injuries, and
    - $300 M of direct property loss averted.
    - $500 M of reduced cost of installed fire protection through performance-based design methods which creates safety-equivalent solutions at reduced cost.
- Mitigating combustion products or controlling the flow or accumulation of smoke and other combustion products may reduce occupant exposure to toxic gases and limit damages due to smoke spread. This could result in saving approximately:
    - 240 of the 2,400 annual fire deaths not prevented through reduced ignitions,
    - 1,100 annual fire injuries, and
    - $660 M of direct property loss averted.
    - $100 M of reduced cost of installed fire protection through performance-based design methods which creates safety-equivalent solutions at reduced cost.

B.1.2.2 Addressing Exposure of People and Structural Assemblies to Fire

There are three primary societal burdens associated with structure fires: civilian injuries and deaths,[*] the direct cost of property losses, and reducing the cost of installed fire protection.[†] Each is considered separately below:

- Tools and best practices to better manage large incidents may reduce losses during large fire incidents through improved situation awareness and knowledge. This could result in saving approximately:
    - 29 of the 570 annual fire deaths which result from non-residential fires,
    - 135 annual fire injuries, and
    - $100 M of reduced cost of installed fire protection through performance-based design methods which creates safety-equivalent solutions at reduced cost.
- Adequate egress provisions which incorporate emerging technologies for people movement and development of technical basis for existing egress technologies can improve fire safety through more rapid, available, and cost-effective building evacuation. This could result in saving approximately:
    - 20 of the 570 annual fire deaths which result from non-residential fires,
    - 100 annual fire injuries, and

* Injury statistics are not always as available as fatality statistics. It is assumed for simplicity that there are 4.6 injuries per fire death and that the relationship between injuries and deaths is constant across the fire threat profile. This assumption, while limited, should be correct to first-order.

† A civilian injury or death should be attributed to a single cause. An effort was made to limit “double-counting” the statistics (in other words, this is an analysis which “couples” the fire problem, allowing victims to be saved through a hierarchy: first through fire prevention, then by detection and suppression or reduced fire spread, and then through evacuation).

  - $3,000 M of reduced cost of installed fire protection through performance-based design methods which creates safety-equivalent solutions at reduced cost.
- Development of novel performance-based fire safety design solutions can reduce the total cost of construction by 0.5 % of the total cost of construction. This could result in saving approximately:
  - $5,000 M of reduced cost of installed fire protection through performance-based design methods which creates safety-equivalent solutions at reduced cost.
- Developing a technical basis for structural response to fire conditions can reduce the cost of construction through more cost-effective design and construction methods. This could result in saving approximately:
  - $100 M of reduced cost of installed fire protection through performance-based design methods which creates safety-equivalent solutions at reduced cost.

B.1.3 Summary of the Strategy to Reduce the Preventable Burden of Structural Fires

The total fire burden associated with structure fires in the U.S. is nearly $185 billion annually, and roughly $63 billion or one-third of the structural fire burden is preventable. Through the targeted measurement science plan described above, there would be a significant decrease in the number and severity of building fires. Table B-2 below summarizes this section and the accounting how fatalities and injuries could be reduced by about 40 %, and how the preventable burden of structural fires could be reduced by about $21 billion or about one-third in a generation, through an emphasis on the application of targeted measurement science. In addition, a proportionately smaller number and severity of fire service injuries would be expected as the number and severity of reported fires decreased.

Table B-2: Anticipated Reductions in the Preventable Burden of Structural Fires.

Lives ($M)	Injuries ($M)	Direct Loss ($M)	Fire Protection ($M)	Total Savings ($M)	Technology	
$1,950	$438	$303	$0	**$2,691**	Prevent Ignition	Cigarettes
$243	$55	$46	$0	**$343**		Space Heaters
$215	$48	$92	$0	**$355**		Open Flame and Intentional Fires
$250	$56	$76	$0	**$382**		Cooking
$220	$49	$0	$0	**$269**		Ignition of Thermoplastics
$375	$84	$57	$0	**$516**		Upholstered Furniture
$295	$66	$20	$0	**$381**	Reduced HHR of Mattress and Bedding	
$190	$43	$381	$0	**$614**	Reduced HRR of furniture, thermoplastics and mattresses	
$1,211	$272	$1,006	$650	**$3,139**	Improved fire protection, materials	
$1,211	$272	$303	$500	**$2,286**	Improving the sensitivity/reliability of detection	
$1,211	$272	$660	$100	**$2,243**	The ability to mitigate or control the combustion products.	
$143	$32	$0	$100	**$274**	Ability to effectively manage an emergency evacuation	
$86	$19	$1	$3,000	**$3,106**	Adequacy of the egress capacity relative to demand	
$0	$0	$0	$100	**$100**	Preventing structural failure/ maintaining structural integrity.	
$0	$0	$0	$5,000	**$5,000**	Performance Based Design	
				$21,700	**Total Potential Savings**	

B.2 REDUCING THE PREVENTABLE BURDEN OF WILDLAND-URBAN INTERFACE FIRES

In this section, an accounting is made to quantify how the preventable burden of fire in the WUI could be reduced by one-half, emphasizing the application of promising measurement science as discussed in Chapters 3 and 4 to address key aspects of the WUI fire problem. Referring to Table B-1, a reduction in the value of the WUI fire burden will require significant reductions in the number and intensity of WUI fires, efficiencies through more cost-effective infrastructure investments, a significant impact on fire fighter response (injury reduction and increased effectiveness), and improved fire resistance of WUI structures. A detailed accounting of the avoidable fraction, the preventable fire burden, and the anticipated impact is described below. The most fruitful measurement science areas to enable the reduction of the WUI fire burden are described below.

B.2.1 Civilian Fatalities and Injuries

Today, life safety losses in WUI fires are very low for both civilians and fire fighters as compared to building fires, and the avoidable fraction is considered to take a value between 0.9 and 1 (see Table B-1). Through a range of approaches, progress will be made to reduce life safety losses and ensure that this number does not increase as wildland fires continue to increase in severity and frequency. The targeted approaches are discussed in Chapters 3 and 4, and include engineered fire resistant design of structures, use of fire resistant materials and vegetation, and passive and active fire protection technologies. This is a new field and each of these approaches will require time to develop. Each specific technology will first be incorporated into new construction and over time, existing communities will be retrofitted with the technology. Improved evacuation models and procedures will also reduce civilian fatalities and injuries by providing more timely warning to community residents that a wildland fire threatens their community. Again, a better understanding of the evacuation dynamics will be developed and then incorporated into evacuation models. Once verified and validated, the models would be used by incident commanders to evacuate communities. Stakeholder education and compliance can be incorporated into existing outreach programs such as Firewise and FireSmart.[79] The anticipated reductions in preventable fire burden enabled by measurement science are tabulated in Tables B-3 and B-4.

Table B-3: Anticipated Reductions in Civilian Fire Injuries by Approach.

Civilian Fire Injuries - Preventable Fire Burden of $ 0.1 B		
Approach	Fraction of Reduced Injuries	Net Reduction in Preventable Fire Burden $ Million
Fire Resistant Materials [a]	0.05	5
Fire Resistant Vegetation [a]	0.05	5
Stakeholder Education and Compliance	0.075	7.5
Eng. Fire Resistant Design Guidelines [a]	0.2	20
Passive and Active Fire Protection [b]	0.025	2.5
Evacuation [c]	0.1	10
Total	0.50	50
For a list of applicable technologies, see: a. Table 3-20. b. Table 3-21. c. Table 3-22.		

Table B-4: Anticipated reductions in Civilian Fire Fatalities by Approach.

Civilian Fire Fatalities - Preventable Fire Burden of $ 0.1 B		
Approach	Fraction of Reduced Fatalities	Net Reduction in Preventable Fire Burden $ Million
Fire Resistant Materials [a]	0.05	5
Fire Resistant Vegetation [a]	0.05	5
Stakeholder Education and Compliance	0.075	7.5
Eng. Fire Resistant Design Guidelines [a]	0.2	20
Passive and Active Fire Protection [b]	0.025	2.5
Evacuation [c]	0.1	10
Total	0.50	50
For a list of applicable technologies, see: a. Table 3-20. b. Table 3-21. c. Table 3-22		

B.2.2 Property Losses

Property losses that result from wildland-urban interface fires could be reduced through the same approaches mentioned for life safety (see above). The anticipated reduction enabled by measurement science in the preventable fire burden associated with property loss is tabulated in Table B-5.

Table B-5: Anticipated Reduction in Property Loss by Approach.

Property Loss - Preventable Fire Burden of $ 2.8 B		
Approach	Fraction of Reduced Property Loss	Net Reduction in Preventable Fire Burden $ Million
Fire Resistant Materials [a]	0.05	155
Fire Resistant Vegetation [a]	0.05	155
Stakeholder Education and Compliance	0.15	465
Eng. Fire Resistant Design Guidelines [a]	0.1	310
Improved WUI Fire Fighter Safety and Eff. [c]	0.1	310
Recovery Guidelines and Post Fire Analysis	.05	155
Total	0.50	1550
For a list of applicable technologies, see: a. Table 3-20. c. Table 3-22.		

B.2.3 Fire Protection in Constructed Facilities

The cost of fire protection in WUI buildings (constructed facilities) could be reduced through three main approaches and corresponding technologies: engineered fire resistant design of structures, passive and active fire protection, and recovery guidelines and post fire analysis. Each of these approaches will require time to develop, test and refine applicable technologies. Technologies will first be incorporated into new construction and over time existing communities will be retrofitted with the technology. The majority of cost reduction will be realized through science-based designs that harden the communities against WUI fires. Currently, most passive and active fire protection technologies are unproven and lack standardized performance metrics. The anticipated reduction in preventable fire burden enabled by measurement science is tabulated in Table B-6.

Table B-6: Anticipated Reduction in the Cost of Fire Protection in Constructed Facilities by Approach.

Fire Protection in Constructed Facilities - Preventable Fire Burden of $ 0.9 B		
Approach	Fraction of Reduced Costs	Net Reduction in Preventable Fire Burden $ Million
Eng. Fire Resistant Design Guidelines [a]	0.4	380
Passive and Active Fire Protection [b]	0.05	40
Recovery Guidelines and Post Fire Analysis	.05	40
Total	0.50	460
For a list of applicable technologies, see: a. Table 3-20. b. Table 3-21.		

B.2.4 Suppression

The suppression activities covered by this component of the total fire burden are mostly the costs trying to extinguish fire in the wildlands, before they threaten a WUI community. This includes the cost of smoke jumpers, wildland fire fighters, and aerial water drops. Whereas most of these costs are not considered preventable, there is a small fraction, about 10 %, of suppression costs, which are estimated as preventable and are related to improved efficiency of suppression activities defending WUI communities. The preventable costs of suppression will be reduced through a range of approaches and technologies: use of improved fire resistant materials and vegetation, passive and active fire protection, improved fire fighter safety and effectiveness, and recovery guidelines and post fire analysis. The anticipated reductions in preventable fire burden enabled by measurement science are tabulated in Table B-7.

Table B-7: Anticipated Reductions in the Cost of Suppression by Approach.

Suppression - Preventable Fire Burden of $ 0.35 B		
Approach	Fraction of Reduced Cost	Net Reduction in Preventable Fire Burden $ Million
Fire Resistant Materials [a]	0.05	18
Fire Resistant Vegetation [a]	0.05	18
Passive and Active Fire Protection [b]	0.05	18
Improved WUI Fire Fighter Safety and Eff. [c]	0.05	18
Recovery Guidelines and Post Fire Analysis	0.05	18
Total	0.25	90
For a list of applicable technologies, see: a. Table 3-20. b. Table 3-21. c. Table 3-22.		

B.2.5 Fuel Treatments, Preparedness, and Restoration

The fuel treatments, preparedness, and restoration activities covered by this component of the total fire burden are mostly the costs of trying to prepare and prevent WUI fires and to restore the wildlands after a wildland fire. There are more human-caused ignitions than those due to natural (lightning) causes.[127] All of these fires are very difficult to prevent. A significant amount of the cost is due to fuel treatments such as cutting and removing excess fuels from the wildland areas and the preparation of WUI community buffer zones and fire breaks. After a fire, water control devices, ground cover, and new trees may be used near WUI communities to minimize soil erosion and mudslides. Because most wildland fires are started by natural causes, typically lightning strikes, most of these costs are not considered preventable. However, there is a fraction, about 25 %, of treatment, preparedness, and restoration costs which are estimated as preventable. The preventable costs of fuel treatments, preparedness, and restoration could be reduced through a range of approaches: use of improved fire resistant materials and vegetation, engineered fire resistant design, passive and active fire protection, and recovery guidelines and post fire analysis. The anticipated reductions in preventable fire burden are tabulated in Table B-8.

Table B-8: Anticipated Reduction in the Cost of Fuel Treatments, Preparedness, and Restoration by Approach.

Fuel Treatments, Preparedness, and Restoration - Preventable Fire Burden of $ 0.23 B		
Approach	Fraction of Reduced Cost	Net Reduction in Preventable Fire Burden $ Million
Fire Resistant Materials [a]	0.025	6
Fire Resistant Vegetation [a]	0.025	6
Eng. Fire Resistant Design Guidelines [a]	0.075	17
Passive and Active Fire Protection [b]	0.1	23
Recovery Guidelines and Post Fire Analysis	0.025	6
Total	0.25	56
For a list of applicable technologies, see: a. Table 3-20. b. Table 3-21. c. Table 3-22.		

B.2.6 Economic Impact

The economic impacts covered by this component of the total fire burden include displacement, loss of public services, business and rental income loss, and loss of transportation and utility services. Displacement costs include temporary quarters for displaced occupants of residential, commercial and public buildings. Loss of public service includes the cost of functional downtimes for police, fire, and medical facilities as well as emergency shelters. Loss of transportation and utility services includes cost of traffic delays and detours due to road and bridge closures as well as the loss of electric power, potable water, and waste water systems. Reducing the ignition and fire spread within a community will result in decreased need of temporary shelters and will prevent loss of public service and business income. About 90 % of the economic impact is estimated as avoidable. Preventable costs will be reduced through a range of approaches/technologies: use of improved fire resistant materials and vegetation, stakeholder education and compliance, engineered fire resistant design, passive and active fire protection, recovery guidelines and post fire analysis. The cost reductions will be realized by stake-holder education & compliance, engineered fire resistant design, and recovery guidelines. The anticipated reductions in preventable fire burden enabled by measurement science are in Table B-9.

Table B-9: Anticipated Reduction in Economic Impact by Approach.

Economic Impact - Preventable Fire Burden of $ 3.2 B		
Approach	Fraction of Reduced Costs	Net Reduction in Preventable Fire Burden $ Million
Fire Resistant Materials [a]	0.05	160
Fire Resistant Vegetation [a]	0.05	160
Stakeholder Education and Compliance	0.15	480
Eng. Fire Resistant Design Guidelines [a]	0.05	160
Passive and Active Fire Protection [b]	0.1	320
Recovery Guidelines and Post Fire Analysis	0.01	160
Total	0.5	1580
For a list of applicable technologies, see: a. Table 3-20. b. Table 3-21.		

B.2.7 Summary of the Strategy to Reduce the Preventable Burden of WUI Fires

The total amount of preventable WUI fire burden is about $ 7.5 billion or about one-half of the total WUI fire burden. Over the next generation, the research described by this roadmap is estimated to reduce the preventable WUI burden by about $3.6 billion or about one-half. Figures B-1 and B-2 show the anticipated cost reductions enabled by targeted measurement science in components of the WUI fire burden and in the contributions to technical approaches to reduce the WUI fire burden, respectively.

Figure B-1: Estimated cost reductions in components of the WUI fire burden.

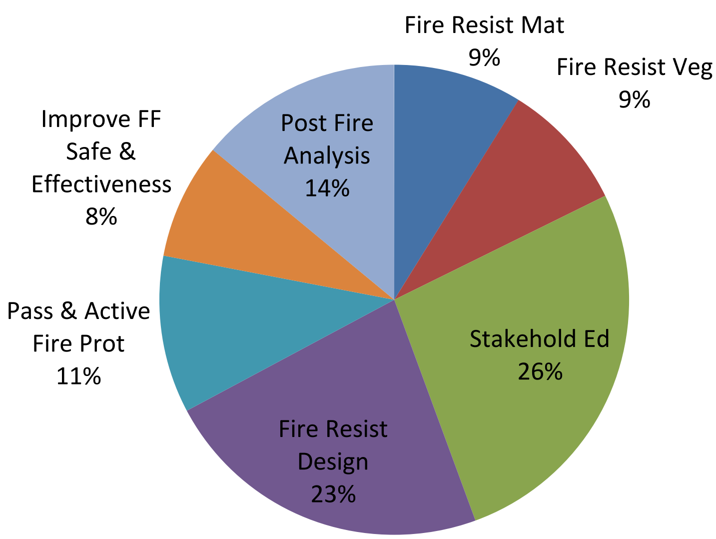

Figure B-2: Contributions of technical approaches to reduce the WUI fire burden.

B.3 REDUCING THE PREVENTABLE BURDEN OF THE FIRE SERVICE

In this section, an accounting is made to quantify how the preventable burden associated with the Fire Service could be reduced by about one-third, emphasizing the application of promising measurement science as discussed in Chapters 3 and 4 to address key aspects of the problem. A reduction in the value of the Fire Service burden will require significant improvements to fire fighter safety and effectiveness. A detailed accounting of the avoidable fraction, the preventable fire burden, and the anticipated impact of this roadmap is described below in terms of the most fruitful measurement science areas to reduce the fire service burden.

B.3.1 Fire Fighter Safety: Fatalities and Injuries

The monetized social cost of fire fighter injuries (79,700) and fatalities (105) in 2008 was $19 billion and $0.4 B, respectively, as seen in Table B-1. The avoidable portion of fire fighter injuries and fatalities was estimated as 90 %. The unavoidable fraction is associated with events outside of human control. Fatalities and injuries are being reduced through a range of approaches: situational awareness, incident command, tactics, equipment, training, and lessons learned from incident investigation.

Injuries and fatalities can be classified according to the type of duty the fire fighter was involved when an incident occurred, including fire ground operations, other on-duty, responding to or returning from an incident, training, non-fire emergency, and after an incident. The number and cost of injuries and fatalities for calendar year 2006 are tabulated according to type of duty in Table B-10. For the purposes of estimating the impact of these approaches and technologies, only injuries and fatalities that resulted from fire ground operations and training were considered. All (100 %) heart injuries that result from heart attack/stroke and most (50 %) of the strains, sprains, and muscle pains were judged as not likely to be impacted by the measurement science and technologies addressed by this roadmap. These issues could be addressed by the medical and kinesiology community. This reduces the number of fatalities (fire ground and training) being targeted (about 45) and the number of injuries (fire ground minus 100 % heart/stroke and 40 % of strains, sprains, and muscle pain) being considered (about 38,700).

The injuries and fatalities covered by this component of the total fire burden are the costs of fire ground and training activities. For the fatalities, these activities include being caught or trapped in the structure, collapse of the structure, being lost in the structure, and contact/exposure to flames or gases. For injuries, these activities include burns (fire or chemical), smoke or gas inhalation, respiratory distress, burns and smoke inhalation, wounds, dislocations, strains, sprains, muscle pain, and thermal stress, frostbite, or heat exhaustion.

The anticipated reductions in the cost of preventable fire fighter fatalities and injuries are tabulated in Tables B-11 and B-12. For both fatalities and injuries, the largest reductions in preventable cost burden were estimated to be realized through situational awareness, equipment, tactics, and training. Smaller reductions were estimated to result from improved incident command and post-fire lessons learned.

Each specific technology will be incorporated into fire department training, fire ground operations, and personal protective equipment. Urban fire departments may incorporate these technologies through their municipal training programs or academies. Rural fire departments may incorporate these technologies through state fire training academies. Additional training on incident command may be provided at the National Fire Academy (US Fire Administration) in Emmitsburg, MD. Equipment performance metrics will be incorporated into existing or new standards such as first responder standards developed by the National Fire Protection Association (NFPA) or American Society for Testing Methods (ASTM).

Table B-10: Number and Cost of Fire Fighter Fatalities and Injuries by Type of Duty (2006).

Type of Duty	Number of Fatalities	Cost of Fatalities $ Millions	Number of Injuries	Cost of Injuries $ Millions
Fire Group Operations	36	170	44,210	1,007
Other On-Duty	21	100	13,690	3,118
Responding / Returning	15	70	4,745	1,081
Training	8	40	7,665	1,746
Non-Fire Emergency	5	25	13,090	2,982
After an Incident	20	95	0	0
Total	106	500	83,400	9,934

B.3.2 Fire Fighter Effectiveness

Enhanced fire fighter effectiveness is expected to reduce direct property loss in both residential and non-residential structural fires by about 10 % due to improved fire fighting tactics, incident command, situational awareness, training, and post-fire lessons learned.[*] Improved tactics would prevent fire spread and reduce property loss. Enhanced incident command and situational awareness would allow better utilization of resources, limit fire spread, and facilitate rapid suppression that would result in reduced property loss. Incorporating lessons learned and better understanding of fire dynamics into fire service training would allow more efficient fire ground operations and reduce both residential and commercial property losses.

* The impact of enhanced fire fighter effectiveness for fighting WUI fires was credited in Appendix B.2.

Table B-11: Anticipated reductions in Fire Fighter Fatality by Approach.

Fire Fighter Fatalities - Preventable Fire Burden of $ 0.2 B		
Approach	Fraction of Reduced Fatalities	Net Reduction in Preventable Fire Burden $ Million
Training [a]	0.1	21
Situational Awareness [b]	0.1	21
Incident Command [c]	0.05	11
Equipment [d]	0.1	21
Tactics [e]	0.1	21
Lessons Learned	0.05	11
Total	0.50	105
For a list of applicable technologies, see: a. Table 3-14. b. Table 3-16. c. Table 3-15. d. Table 3-17. e. Table 3-18.		

The anticipated reductions in the cost of preventable property losses are tabulated in Table B-12. For improved fire fighter effectiveness, the largest reductions in preventable cost burden were estimated to be realized through incident command, training, and post fire lessons learned. Each specific technology will be incorporated into fire department training, fire ground operations, and personal protective equipment. Urban fire departments may incorporate these technologies through their municipal training programs or academies. Rural fire departments may incorporate these technologies through state fire training academies. Additional training on incident command may be provided at the National Fire Academy (US Fire Administration) in Emmitsburg, MD. Equipment performance metrics will be incorporated into existing or new standards such as first responder standards developed by the National Fire Protection Association (NFPA) or American Society for Testing Methods (ASTM).

Table B- 12: Anticipated reductions in Fire Fighter Injuries by Approach.

Fire Fighter Injuries - Preventable Fire Burden of $ 8.8 B		
Approach	Fraction of Reduced Injuries	Net Reduction in Preventable Fire Burden $ Million
Training [a]	0.1	880
Situational Awareness [b]	0.1	880
Incident Command [c]	0.05	440
Equipment [d]	0.1	880
Tactics [e]	0.1	880
Lessons Learned	0.05	441
Total	0.50	4,410
For a list of applicable technologies, see: a. Table 3-14. b. Table 3-16. c. Table 3-15. d. Table 3-17. e. Table 3-18.		

B.3.3 Fire Department Costs

Career and volunteer fire department costs are significant ($89.7 billion in 2007), and are mostly not avoidable. A significant fraction of fire department costs are spent on emergency medical and disaster services, neither of which are addressed in this roadmap. Even if fire calls were reduced to 25 % of the current value, there would still be a need for local fire departments, which would be needed to respond to infrequent fires to ensure the safety of building occupants and communities. In this sense, the cost of fire departments providing fire response as well as medical and disaster services would not be considered avoidable. Based on the ratio of EMS to fire service response calls and assuming that the fire service will be needed even as fire calls continue to drop, the avoidable fraction of career and volunteer fire department costs is estimated as 10 %, leading to an estimate of about $9 billion of preventable burden associated with fire department costs.

In addition to reducing the fatalities and injuries, and property losses, improved technologies can be used to provide the same level of community fire protection at lower fire department costs. More cost efficient fire protection would reduce both career and volunteer fire department costs through a range of approaches: better resource allocation and community education. Better allocation of fire department resources allows a community to characterize its needs and provide the resources, both in terms of equipment and personnel. Educating the community on how to prevent fires will result in fewer responses and decreased equipment maintenance and operating expenses such as vehicle fuels. Because each of these approaches requires time to develop better understanding of the technologies, it may require time to implement these approaches. The anticipated reductions in the cost of preventable property losses are tabulated in Table B-13.

Table B-13: Anticipated reductions in Property Loss Costs by Approach.

Property Losses - Preventable Fire Burden of \$ 1.3 B		
Approach	Fraction of Reduced Property Loss	Net Reduction in Preventable Fire Burden \$ Million
Training [a]	0.2	257
Situational Awareness [b]	0.05	65
Incident Command [c]	0.1	128
Equipment [d]	0.1	128
Tactics [e]	0.05	65
Total	0.50	642
For a list of applicable technologies, see: a. Table 3-14. b. Table 3-16. c. Table 3-15. d. Table 3-17. e. Table 3-18.		

Table B-14: Anticipated reductions in the Cost of Fire Departments by Approach.

Fire Departments - Preventable Fire Burden of $ 9 B		
Approach	Fraction of Reduced Costs	Net Reduction in Preventable Fire Burden $ Million
Education [a]	0.075	670
Resource Allocation [b]	0.1	900
Total	0.175	1570
For a list of applicable technologies, see: a. Table 3-14. b. Table 3-15.		

B.3.4 Summary of Strategy to Reduce the Preventable Burden of Fire Fighting

The total preventable fire service burden is almost $ 27 billion or about one-quarter of the total fire service burden. Within the next generation, the research described by this roadmap is estimated to reduce the preventable fire service burden by about $7 billion or about one-quarter. Figures B-3 and B-4 show the estimated cost reductions in components of the Fire Service burden, and the contributions of technical approaches to reduce the WUI fire burden, respectively.

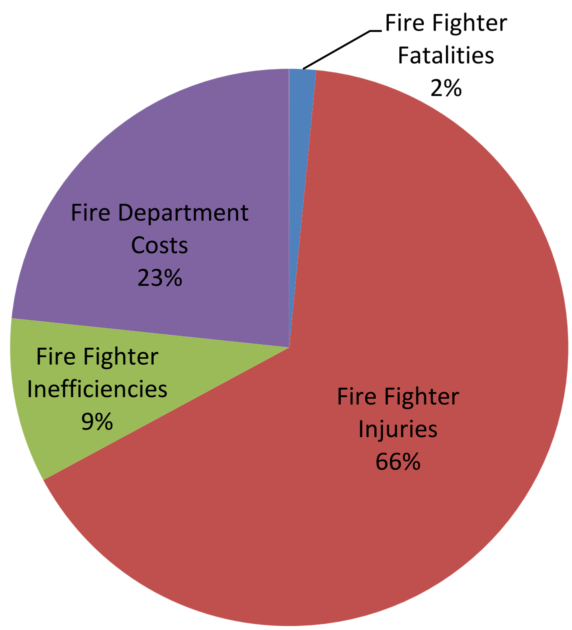

Figure B-3: Estimated cost reductions in components of the Fire Service burden.

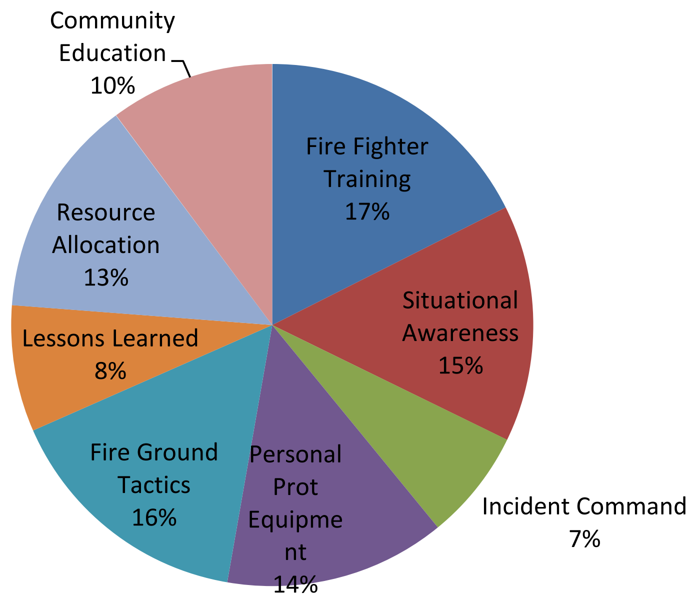

Figure B-4: Contributions of technical approaches to reduce the WUI fire burden.

B.4 REDUCING THE PREVENTABLE BURDEN OF VEHICLE, OUTDOOR AND OTHER FIRES

As described in Appendix A, this category includes all other fires not already classified as structure or natural vegetation. This includes NFIRS' major incident categories such as fire in "mobile property (vehicle) fires," "outside rubbish fires," "special outside fires," "cultivated vegetation," "crop fires," "fires," and "other." In 2008, an estimated 572,000 fires of this type occurred according to the NFRIS database. The loss profile is dominated by vehicle fires both in terms of direct property loss and life safety.

About 20 % of the total number of reported fires was related to vehicles accounting for a significant number of civilian deaths and injuries.[128] About 10 % of fire related fatalities in the US involve post-collision vehicle fires in which the victim is trapped inside the vehicle and unable to effect timely escape; while these fatalities represent just about 1 % of all of vehicle fatalities.[129] The motor vehicle industry is working on advanced collision avoidance technologies to prevent vehicle collisions. Some of these are already commercially available on modern vehicles (including anti-lock brakes and Forward collision warning and mitigation systems), and other technologies are being developed. This approach is seen as a cost effective way to deal with the complexities of fire related fatalities associated with post-collision gasoline powered vehicles.

B.5 SUMMARY OF THE STRATEGY TO REDUCE THE PREVENTABLE FIRE BURDEN

Table B-1 shows that the total preventable fire burden is about $102 billion or about one-third of the total U.S. fire burden of $314 B. Table B-1 also shows that the contributors to the preventable fire burden are due to structure fires ($63 B), WUI fires ($7.7 B), vehicle and outside fires ($4.3 B), and the fire service ($26.6 B). Of the total preventable fire burden, it is anticipated that the measurement science described in this roadmap will contribute to the reduction of about $31 billion or about one-third of the preventable fire service burden through combined reductions in structure fires ($21 B), WUI fires ($3.7 B), and the fire service ($6.7 B). This represents reductions in the cost and loss associated with structure fires, WUI fires, and fire service by fractional amounts equal to about 1/3, ½, and ¼, respectively.

REFERENCES

1. Garcia, M.L, and Olin, H.B., Fundamentals of Technology Roadmapping, Sandia National Laboratories, Report # SAND97-0665 , Albuquerque, NM 87185, April 1997.

2. Hall, J.R., Jr, The Total Cost of Fire in the United States National Fire Protection Association. Quincy, MA, 2011.

3. Ahrens, M., Trends and Patterns of U.S. Fire Losses in 2009, National Fire Protection Association, Quincy, MA, Sept. 2010.

4. National Commission on Fire Prevention and Control, “America Burning”, U.S. Government Printing Office, 1973.

5 . Wright, R.N., Building and Fire Research at NBS/NIST 1975-2000, NIST BSS 179, pp. 332, Dec. 2003.

6. Derry, L., A *Study of the U.S. Fire Experience, 1976*, Fire Journal, November 1977, pp 50-53.

7. Karter, M.J., Jr, *NFPA's Latest Fire Loss Figures*, NFPA Journal, September/October 1996, pp. 52-59.

8. *Statistical Abstract of the United States: 2010*, U.S Government Printing Office, Washington, DC, 2010.

9. *U.S. Fire Loss for 2008*, NFPA Journal, September/October 2009, pp. 72-77.

10. ASTM E 1352, Standard Test Method for Cigarette Ignition Resistance of Mock-up Upholstered Furniture Assemblies, ASTM International, West Conshohocken, PA.

11. ASTM E 1353, Standard Test Method for Cigarette Ignition Resistance of Components of Upholstered Furniture, ASTM International, West Conshohocken, PA.

12. Standard for the Surface Flammability of Carpets and Rugs, 16 CFR Part 1630 (DoC FF-1-70), 1970.

13. Peacock, R.D., *Wood Heating Safety Research: An Update*, Fire Technology 23, 292-312, 1987.

14. ASTM E 2187, Standard Test Method for the Ignition Strength of Cigarettes, ASTM International, West Conshohocken, PA, 2009.

15. International Association for the Study of Insurance Economics, World fire statistics: information bulletin of the world fire statistics. Geneva (Switzerland): The Geneva Association, No. 23, October 2007.

16. Karter, M.J. Jr., Fire Loss in the United States in 2007, Report No. FLX07-01, National Fire Protection Association, Quincy, MA, August 2008.

17. Chapman, R.E., D.T. Butry, A.L. Huang, and D.S. Thomas, *Economics of Egress and Life-Safety Costs*. NIST Special Publication 1109, Gaithersburg, MD, National Institute of Standards and Technology. 2010.

18. Bailey, D., Director of Wildland Fire, Natural Hazard & Natural Resource Programs, ICC. Personal Communication to Alexander Maranghides, 2011.

19. Karter, M.J., U.S. Fire Department Profile through 2008, NFPA. Quincy, MA, 2009.

20. U.S. Fire Administration. Firefighter Casualties 1999-2009, http://www.usfa.dhs.gov/fireservice/fatalities/statistics/casualties.shtm (accessed 03/15/2011).

21. Third Needs Assessment of the U.S. Fire Service Conducted in 2010 and including Comparisons to the 2001 and 2005 Needs Assessment Surveys, National Fire Protection Association, June 2011.

22. Hall, Jr., J.R., U.S. Unintentional Fire Death by State. Report No. USS15, National Fire Protection Association, Quincy, MA, May 2010.

23. Committee to Identify Innovative Research Needs to Foster Improved Fire Safety in the United States, National Research Council, Making the Nation Safe from Fire: A Path Forward in Research, The National Academies Press, Washington, D.C., 2003.

24. NIOSH Alert: Preventing Firefighter Fatalities Due to Heart Attacks and Other Sudden Cardiovascular Events, [DHHS (NIOSH) Publication No. 2007-133]

25. The Fire Protection Research Foundation. Fire Protection and Safety: The Next 25 Years, Quincy, MA, December 2008.

26. Institute of Fire Engineers US Branch. "National Strategies for Fire Loss Prevention: Washington DC 2008 Forum Results and Report," Washington, D.C., October 2008.

27. Underwriters Laboratories Inc. Research Program for Improved Fire Safety of Upholstered Furniture, Northbrook, IL, September 2008.

28. Kodur, V., M. Garlock, and N. Iwankiw. National Workshop on Structures in Fire: State-of-the-Art, Research, and Training Needs (prepared for National Science Foundation), NIST-GCR-07-915, December 2007.

29. International Code Council. The Blue Ribbon Panel on Wildland/Urban Interface Fire. Washington, D.C., February 2008.

30. National Fallen Firefighters Foundation, Report of the National Fire Service Research Agenda Symposium, Emmitsburg, MD, June 2005.

31. The Society of Fire Protection Engineers. A Research Agenda for Fire Protection Engineering, Bethesda, MD, February 2000.

32. Cox, G (Ed.), “The Technical Basis for Performance-Based Fire Regulations: A discussion of capabilities, needs, and benefits of fire safety engineering,” United Engineering Foundation, New York, NY, January 2001.

33. NFPA 550, Guide to the Fire Safety Concepts Tree, National Fire Protection Association, Quincy, MA, 2007.

34. Ahrens, M., Home Structure Fires, National Fire Protection Association, Quincy, MA, Jan. 2009.

35. Hall, J.R. Jr., U.S. Smoking-Material Fire Problem, National Fire Protection Association, Quincy, MA, Nov. 2008.

36 . Hall, J.R. Jr., Homes Fires Involving Heating Equipment, National Fire Protection Association, Quincy, MA, Jan. 2009.

37. Madrzykowski, D., Hamins, A., and Mehta, S., *Residential Fire Suppression Research Needs: Workshop Proceedings,* NIST SP 1066, National Institute of Standards and Technology, Gaithersburg, MD, March 2007. http://www.fire.nist.gov/bfrlpubs/fire07/PDF/f07079.pdf

38. Vision 20/20, Kitchen Fire Prevention Technologies Workshop Report, Nov, 2010. http://www.strategicfire.org/ckfinder/userfiles/files/kitchen%20Final%20Report.pdf

39. NFPA Conference on Technology Assessment: Home Cooking Fire Mitigation, Development of an Action Plan, July 14, 2011, BWI Airport Marriott.

40. Consumer Product Safety Commission, Publication: Preventing Home Fires: Arc Fault Circuit Interrupters (AFCIs).
http://webcache.googleusercontent.com/search?q=cache:8r6t6tz2HWkJ:www.cpsc.gov/cpscpub/pubs/afci.html+cpsc+arc+fault+interupter&cd=1&hl=en&ct=clnk&gl=us

41. National Research Council, “Sustainability in the Chemical Industry,” 2005.

42. Ahrens, M. “Home Structure Fires,” NFPA, Quincy, MA, February, 2007.

43. Ahrens, M., “U.S. Experience with Smoke Alarms and Other Fire Detection/Alarm Equipment,” NFPA, Quincy, MA, Nov. 2004.

44. Smith, C.L., “Smoke Detector Operability Survey – Report on Findings,” U.S. Consumer Product Safety Commission, Bethesda, MD, Nov. 1993.

45. Home Smoke Alarms and Other Fire Detection and Alarm Equipment, Public/Private Fire Safety Council, April 2006. http://www.firesafety.gov/programs/

46. Hall, J.R. Jr., "How Many People Can Be Saved from Home Fires if Given More Time to Escape?," Fire Technology, 40, 117–126, 2004.

47. Madrzykowski, D. and Fleming, R., "Residential Sprinkler Systems." Volume 2; Chapter 6 - Section 16; NFPA FPH2008; Fire Protection Handbook, 20th Ed., Vol. 2, Chapter 6, Section 16, National Fire Protection Assoc., Quincy, MA, Cote, A. E.; Grant, C. C.; Hall, J. R., Jr.; Solomon, R. E., Editors, 16/91-107, 2008.

48. International Residential Code for One- and Two-Family Dwellings, International Code Source, Country Club Hills, IL., 2009.

49. Hall, J.R., Jr, "How Many People are Exposed to Sublethal Fire Smoke?," Fire Technology, 40, 101–116, 2004.

50. Neviaser, J.L., and Gann, R.G., "Evaluation of Toxic Potency Values for Smoke from Products and Materials," *Fire Technology*, 40, 177-200 (2004).

51. One-Stop Data Shop, Socioeconomic Factors and Fire, National Fire Protection Association, Quincy, MA, December 2008.

52. NIST NCSTAR 1: Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Final Report of the National Construction Safety Team on the Collapses of the World Trade Center Tower, September 2005.

53. Beitel, J., and Iwankiw, N., Analysis of Needs and Existing Capabilities for Full-Scale Fire Resistance Testing, NIST GCR 02-843, 2002; available at: http://www.bfrl.nist.gov/866/pubs/NISTGCR02-843.pdf

54. Brassell, L.D., and Evans, D. D., Trends in Firefighter Fatalities Due to Structural Collapse, 1979-2002, NISTIR 7069; 37 pp., November 2003.

55. Almand, K., Phan, L.T., McAllister, T.P., Starnes, M.A., Gross, J.L., NIST-SFPE Workshop for Development of a National R&D Roadmap for Structural Fire Safety Design and Retrofit of Structures: Proceedings, NISTIR 7133, April 2004.

56. Impact Assessment of Major Reform Initiatives, Australian Building Codes Board, Feb. 24, 2000.

57. ICC Performance Code. International Code Council, Washington, DC, 2006.

58. NFPA 101, *Life Safety Code*, (Ron Cote, Gregory Harrington, Eds.), 10th edition, National Fire Protection Association, Quincy, MA, 2006.

59. The SFPE Code Official's Guide to Performance-Based Design Review, Society of Fire Protection Engineering, 2004.

60. Levin, B. C., Braun, E., Navarro, M., and Paabo, M. "Further Development of the N-Gas Mathematical Model: An Approach for Predicting the Toxic Potency of Complex Combustion Mixtures." In: Proceedings of the American Chemical Society. Fire and Polymers II: Materials and Tests for Hazard Prevention. National Meeting, 208th. Chapter 20. ACS Symposium Series No. 599. August 21-26, 1994, Washington, DC, American Chemical Society, Washington, DC, Nelson, G. L., Editor, 293-311, 1995.

61. ISO 13571: Life-threatening Components of Fire – Guidelines for the Estimation of Time to Compromised Tenability in Fires, International Standards Organization, Geneva, 2012.

62. U.S. Nuclear Regulatory Commission, Verification and Validation of Selected Fire Models for Nuclear Power Plant Applications (NUREG-1824), Volumes 1-7, May 2007. (http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1824/).

63. Taylor, B.N. and Kuyatt, C.E. Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results. NIST Technical Note 1297. September 1994.

64. Bryant, R. A.; Mulholland, G. W. Guide to Characterizing Heat Release Rate Measurement Uncertainty for Full-Scale Fire Tests. Fire and Materials, Vol. 32, No. 3, 121-139, April/May 2008.

65. Grosshandler, W. (Editor). *Forum Workshop on Establishing the Scientific Foundation for Performance-Based Codes: Proceedings.* NIST SP 1061, December 2006.

66. Committee on Identifying the Needs of the Forensic Sciences Community, National Research Council. "Strengthening Forensic Science in the United States: A Path Forward," The National Academies Press, Washington, D.C., 2003.

67. U.S. Fire Administration, Firefighter Fatalities in the United States in 2006, July 2007.

68. Fahy, R.F., LeBlanc, P.R., Molis, J.L., Firefighter Fatalities in the United States - 2008, NFPA, July 2009.

69. Fahy, R.F., LeBlanc, P.R., Molis, J.L., Firefighter Fatalities in the United States -2010, National Fire Protection Association, Quincy, MA, June 2011 (Revised July 2011).

70. Karter, M. J., Molis, J. L., U.S. Firefighter Injuries – 2006, National Fire Protection Association, pp. 9, Nov. 2007.

71. Stephens S.L., Ruth, L.W., (2005) Federal forest-fire policy in the United States, *Ecological Applications*, 15(2): 532-542.

72. Bailey, D.W., The wildland/urban interface crisis, is there a solution?, *Wildfire 2007*, 4th International Wildland Fire Conference, 13-17 May, 2007, Seville, Spain http://www.fire.uni-freiburg.de/sevilla-2007/contributions/doc/cd/SESIONES_TEMATICAS/ST5/Bailey_2_USA.pdf

73. Cohen J.D. The Wildland-Urban Interface Problem - A Consequence of the Fire Exclusion Paradigm, Forest History Today, Fall 2008, pp. 20-26.

74. Maranghides, A., Mell, W., A Case Study of a Community Affected by the Witch and Guejito Fires, *NIST Technical Note 1635,* April 2009.

75. Cohen, J.D., The Wildland-Urban Interface Problem - A Consequence of the Fire Exclusion Paradigm, Forest History Today, Fall 2008, pp. 20-26.

76. Quadrennial Fire Review Final Report, January 2009; http://www.nifc.gov/QFR/index.htm

77. Firefree (2010) http://www.firefree.org/

78. Firesafe (2010) The Fire Safe Council, http://www.firesafecouncil.org/

79. Firewise (2010) Homeowner guidance http://www.firewise.org/resources/homeowner.htm

80. Blanchi, R. Leonard, J. 2005, "Investigation of Bushfire Attack Mechanisms Resulting in House Loss in the ACT Bushfire 2003," Bushfire CRC Report CMIT Technical Report - 2005-4778, April 2005.

81. Maranghides, A, Mell, W.E., A Case Study of a Community Affected by the Witch and Guejito Wildland Fires, Fire Technology, 47, 379-420, 2011.

82. Mell, W.E., Manzello, S.L., Maranghides, A., Butry, D., Rehm, R.G., The wildland-urban interface fire problem – current approaches and research needs, Int J. Wildland Fire, 19: 238-251, 2010.

83. Firewise (2010) Information portal for WUI community resources http://www.firewise.org/usa/

84. Wildland Urban Interface (WUI) Fire Colloquium, California Polytechnic State University, San Luis Obispo, CA, June 17 & 18, 2009.

85. Hamins et al. (2010) Proceedings of the 2009 Workshop on Innovative Fire Protection, NIST Technical Note 1662, April 2010.

86. Cohen JD (2008) The Wildland-Urban Interface Problem - A Consequence of the Fire Exclusion Paradigm, Forest History Today, Fall 2008, pp. 20-26.

87.Quadrennial Fire Review Final Report, January 2009, http://www.nifc.gov/QFR/index.htm

88. California (2010) California Fire Hazard Severity Zone Maps, California Department of Forestry and Fire Protection, http://www.fire.ca.gov/fire_prevention/fire_prevention_wildland_zones.php

89. USDA (2010) National Database of State and Local Wildfire Hazard Mitigation Programs, http://www.wildfireprograms.usda.gov/index.html

90. Joint Fire Sciences (JFSP) Program, 2010, webpage http://www.firescience.gov/

91. Carey, H., Schumann, M. (2003) Modifying wildfire behavior – the effectiveness of fuel treatments, the status of our knowledge. National Community Forestry Center, Southwest Region Working Paper2. Available at http://maps.wildrockies.org/ecosystem_defense/Science_Documents/Carey_Schumann_2003.pdf

92. LANDFIRE (2010) Landscape Fire and Resource Management Planning Tools Project, http://www.landfire.gov

93. NFPA (2008) NFPA Standard for fire protection infrastructure for land development in suburban and rural areas, National Fire Protection Association, http://www.nfpa.org/aboutthecodes/AboutTheCodes.asp?DocNum=1141

94. International wildland urban interface code, *International Code Council*, 2009, http://www.iccsafe.org

95. International Code Council, ICC, The Blue Ribbon report on wildland urban interface fire, 2008, International Code Council, Washington, D.C., available at: http://www.iccsafe.org/government/blueribbon

96. Driessen, J., Mangan, D., (2000) Wildfire equipment development priority needs: A comparison 1994 to 1998, TE02P16 – Tech Services, F & AM Residues, November 2000, USDA Forest Service, Technology & Development Program, Missoula, MT

97. Department of Homeland Security, DHS (2009) website, What the blazes in going on? http://www.dhs.gov/files/programs/gc_1255701313051.shtm

98. Rothermel, R.C. (1972) A mathematical model for predicting fire spread in wildland fuels. USDA Forest Service, Intermountain Forest and Range Experiment Station General Technical Report INT-11. (Ogden, UT)

99. Cruz, M.G., Alexander, M.E. (2010) Assessing crown fire potential in coniferous forests of western North America: a critique of current approaches and recent simulation studies, Int. J. Wildland Fire, 19: 377-398.

100. Forthofer, J., Butler, B. (2007) Differences in fire spread over Askervein Hill using two advanced wind models and a traditional uniform wind field, USDA Forest Service Proceedings RMRS-P-46CD.

101. Western Governors' Association Policy Resolution 05-04, June 14, 2005, (www.westgov.org/wga/policy/05/fire-weather.pdf)

102. OFCM (2007) National Wildland Fire Weather: A Summary of User Needs and Issues, Office of the Federal Coordinator for Meteorological Service and Supporting Research, July 3, 2007.

103. NOAA (2008) Fire Weather Research: A Burning Agenda for NOAA, A report from the NOAA science advisory board, October 2008, http://www.sab.noaa.gov/Reports/2008/FWRWGreportFINALfromSABtoNOAA_11_03_08.pdf

104. Takahashi, F., Abbott, A., Hsu, S-Y, T'ien J.S., Olson, S.L., Characterization of fire blanket materials for structure protection in wildland-urban interface fires, *Spring Technical Meeting of the Western States Section of the Combustion Institute*, Univ. of Colorado Boulder, March 22-23, 2010.

105. "Highway Vehicle Fires," FEMA Topical Fire Report Series, Volume 9, Issue 1, September 2008.

106. Hutchinson, H., "Fighting Fire, Saving Cops," ASME Mechanical Engineering, September 2005.

107. NIST Assessment of the United States Measurement System, NIST Special Publication SP 1048, 2010.

108. Averill, J.D., Peacock, R.D. and Keeney, R.L. "Rethinking Egress: A Vision for the Future, Workshop Proceedings," NIST Technical Note TN 1647, Nov. 2009.

109. Pedestrian and Evacuation Dynamics Conference, Wuppertal, Germany, February 2008.

110. Human Behavior in Fire Conference, Cambridge, UK, July 2009.

111. Pedestrian and Evacuation Dynamics Conference, Gaithersburg, MD, March 2010.

112. Brundtland, G.H., "Our Common Future: Report of the UN Commission on Environment and Development," Oxford University Press, Oxford, England, 1987.

113. U.S. Fire Administration National Fire Data Center, National Fire Incident Reporting System 5.0. (NFIRS), FEMA, Washington, DC, 2010.

114. Hall, J.R. Jr. and Harwood, B., "The National Estimates Approach to U. S. Fire Statistics," Fire Technology, pp. 99-113 (1989).

115. Meade, W.P., "A First Pass at Computing the Cost of Fire in a Modern Society," The Herndon Group, Chapel Hill, NC, March 1991.

116. “The U.S. Fire Problem,” National Fire Protection Association, http://www.nfpa.org/itemDetail.asp?categoryID=953&itemID=23033&URL=Research/Fire%20statistics/The%20U.S.%20fire%20problem.

117. Rahn, M., Wildfire Impact Analysis. San Diego State University, San Diego, CA: 15 pp., 2009.

118. Dale, L., The True Cost of Wildfire in the Western U.S. Western Forestry Leadership Coalition, Lakewood, CO: 16 pp., 2009.

119. Hall, J.R., The Total Cost of Fire in the United States National Fire Protection Association. Quincy, MA, 2009.

120. Prestemon, J.P., U.S. Forest Service, personal communication on wildfire expenditures, 15 June 2010.

121. U.S. Department of Agriculture, Audit Report, Forest Service Large Fire Suppression Costs, November 2008.

122. *Summary of Natural Hazard Statistics for 2005 in the United States* for the period 1998-2005, National Weather Service Report.

123. “History of the Dollar Value of a Volunteer Hour: 1980-2009,” Independent Sector, http://www.independentsector.org/volunteer_time, last accessed 03/16/2011.

124. Hammer, R.B., Radeloff, V.C., Fried, J.S., Stewart, S.I., *International Journal of Wildland Fire,* 16: 255-265, 2007.

125. Everts, B., Children Playing with Fire, November 2011, National Fire Protection Association (NFPA), Battery Park, MA.

126. Everts, B., Intentional Fires, January 2010, National Fire Protection Association (NFPA), Battery Park, MA.

127. National Interagency Fire Center Database, last accessed 03/16/2012, http://www.nifc.gov/fireInfo/fireInfo_stats_lightng.html

128. Hamins, A., Evaluation of Active Suppression in Simulated Post-Collision Vehicle Fires, National Institute of Standards and Technology, NIST IR 6379, Nov. 2000.

129. Ahrens, M., U.S. Vehicle Fire Trends and Patterns, June 2010, National Fire Protection Association (NFPA), Battery Park, MA.