A Legacy of Fire Safety:

NIST Marks 50 Years of the Federal Fire Prevention and Control Act of 1974

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Cover Photo
Photograph of a flame plume from a shed filled with wood cribs, impacting a mock residential structure in the Wildland-Urban Interface. This image was captured during the Structure Separation Experiments at the NIST National Fire Research Laboratory. (Credit: NIST)

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Abstract

Over the past 50 years, the National Institute of Standards and Technology (NIST) has effectively fulfilled its responsibilities under the Federal Fire Prevention and Control Act of 1974. For 70 years prior to that, the National Bureau of Standards (NBS), renamed NIST in 1988, was a pioneer in fire safety and fire science. The highlights described in this publication were selected to showcase technically diverse areas of NIST fire research that have advanced fire science and have led to or are in the process of leading to substantial improvements in fire safety in the United States.

Acknowledgements

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We gratefully acknowledge the contributions of the organizations named in this report, whose efforts were instrumental in achieving the results documented here. We also extend our thanks to the countless individuals who have contributed to advancements in fire safety and share our vision of a future where unwanted fires no longer impede life safety, technological innovation, or economic prosperity.

Key words: fire, Federal Fire Prevention and Control Act of 1974, fire research, fire safety, NBS, NIST

Author Contributions

Richard G. Gann: Conceptualization, Data Curation, Methodology, Writing- Original draft, Writing – review & editing. **Robin Materese**: Conceptualization, Methodology, Supervision. **Brandon Hayes**: Timeline graphic design. **Natasha Hanacek**: Timeline graphic design. **Matthew S. Hoehler**: Conceptualization, Methodology, Supervision, Writing – review & editing.

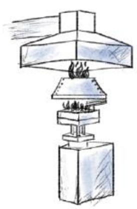
50 Years of Fire Safety Advances

Since the **Federal Fire Prevention and Control Act of 1974** was passed, annual U.S. fire fatalities have decreased by more than 50 percent. NIST's fire research has played a crucial role in saving thousands of lives annually.

1970s

Cigarette resistant furnishings
Tests for cigarette ignition resistance made mattresses and upholstered furniture safer

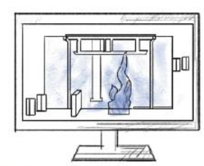
Smoke alarm effectiveness
Guidance on performance and location for the first home smoke alarms



1980s

Measuring fire size
Oxygen consumption calorimetry theory and invention of the cone calorimeter

Cost-effective fire safety
Fire Safety Evaluation System for cost-effective design and retrofit incorporated into the Life Safety Code



1990s

Computer fire models
Model development and support for research and practical applications

Quantified smoke toxicity
Measurement standard for estimating the toxic potency of fire smoke

2000s

World Trade Center investigation
Reconstruction of the 9/11 fires and building collapses

Mattress flammability
Test method for reducing life loss from burning beds

Standard reference cigarettes
Standardized test cigarettes for assuring fewer furniture and bed fires

2010s

Firefighter gear and tactics
Practical solutions to improve firefighter equipment and tactics

Low nuisance smoke alarms
Performance data for a new, low nuisance rate smoke alarm standard

2020s

Wildland-Urban Interface fire loss mitigation
Science to reduce fire spread and community losses from wildfire

Fire behavior of structures
Fire performance of new and enhanced construction materials and designs

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INTRODUCTION

Societal Priorities Regarding Fire

The relationship between humankind and fire evolved through a succession of societal priorities. The first of these priorities was, ironically, to *preserve fire*. The first hominids saw the destructive power of fires started by lightning and volcanic activity. They also realized that the flames provided warmth, trapped animals, and made food easier to chew. However, they didn't yet know how to start a fire, so sustaining a glowing ember was critical to survival.

The next priority was to *preserve the town*. Using fire for clearing land for agriculture engendered the rise of permanent settlements. *Natural* fires were still a threat and were now joined by *intentional* fires for cooking and fabricating metal and ceramic objects. Concern about great life loss and the loss of large parts of the town increased as the settlements grew and became more crowded. The city of Rome had the first fire "code," with required spacing between buildings, a bucket of water in each dwelling, and delivery of firefighting water from the city's superb aqueduct system. This wasn't enough, and ancient Rome experienced over forty devastating fires. Moreover, no such fire protection existed outside of Rome, and major urban conflagrations continued in pre-industrial Europe and later in North America.

By the mid-20th century, the frequency of building-to-building fire spread had diminished in urban areas where there were improvements in roads for bringing water and equipment to the fire, a general adoption of improved firefighting technology and procedures, and the rise of concrete and steel for *commercial* construction. However, fires would continue to decimate the wood-framed buildings in *residential* neighborhoods.

Humankind was about to embark on its third fire priority: *control the fire within a building*. In the United States, the technical spearhead for this effort was a little-known federal agency based in Washington DC and whose name had nothing to do with fire.

The National Bureau of Standards' Impact on Fire Safety 1904 – 1974

Established in 1901 as the nation's agency for the development and custody of measurement standards, the National Bureau of Standards (NBS) dealt with practical matters of daily commerce, such as ensuring that the area of a parcel of land was measured in a uniform way and that a pound of flour meant the same thing to the grocer and the consumer.

The NBS had first become involved in fire safety in response to a 1904 complaint about the incompatibility of different shipboard fire hose couplings. The extent of this problem was highlighted during the 1904 Baltimore fire. The hose couplings on fire trucks arriving from surrounding communities had different threads and could not connect to the Baltimore fire hydrants. The trucks were sidelined and the fire destroyed about one-fourth of the city. Staff at the NBS surveyed the coupling threads nationwide and in 1905 the fledgling National Fire Protection Association (NFPA) adopted its first standard for fire hose couplings and adapters (now NFPA 1963) based on the NBS data.

This result gave rise to the realization that, whether an idea for providing fire safety might arise from science, engineering, or intuition, turning that idea into a practical tool might well involve a standard method of measurement. This was NBS's bread and butter.

In 1913, responding to the heavy loss of life and property in the United States, which was ten times that of any country in Europe, NBS investigated the fire-resistant properties of building materials. The findings showed that poor measurement of building materials properties was at the heart of the high domestic fire losses. As a result, in 1914 NBS established a **Fire Resistance Section (FRS)**, collaborating with NFPA, Underwriters Laboratories (UL), the Associated Factory Mutual Fire Insurance Companies (now FM Global), and the National Board of Fire Underwriters to address the measurement problems associated with building construction. NBS conducted room-scale tests of floors, ceilings, walls, and structural elements (e.g., columns and beams) constructed of concrete, wood, and metal. Based on newly developed measurement methods, the products of this program included:

- Quantitative criteria for determining a desired degree of resistance to room-to-room fire spread,
- A standard test method that became the American Society of Testing and Materials (ASTM), now ASTM International, standard E119 for characterizing the duration over which building components could withstand a standard fire, and
- A compilation of performance data for numerous partitions and structural elements.

These products became the cornerstones of building codes in the United States. By the 1960s, nearly all conflagrations were attributed to large natural disasters or buildings that had not been built and maintained according to code. As buildings and their contents evolved, research on fire resistance in the re-named **Fire Technology Division (FTD)** extended into the 21st century.

Following World War II, Americans increasingly moved into suburban housing and filled their new homes with furnishings and clothes that were often made of new synthetic materials. Many of these products were easier to ignite and burned faster than those made of wood, cotton, and other traditionally used natural materials. Thus, a new priority was to *reduce the casualties and property damage from the burning contents of a building*, and the Congress funded additional fire safety research at NBS.

The first such legislative action was the Flammable Fabrics Act of 1953. The fabrics in some clothing (notably brushed sweaters, children's cowboy chaps, and children's sleepwear) ignited easily and burned rapidly, resulting in deaths and disfiguring burn injuries. As this research progressed, the Congress passed a second Flammable Fabrics Act in 1967. This directed the Department of Commerce (DoC) to establish material and product flammability tests and regulatory criteria, the Department of Health, Education, and Welfare (HEW) (now the U.S. Department of Health and Human Services) to investigate fires leading to deaths and injuries, and the Federal Trade Commission (FTC) to enforce the regulations. In 1968, the DoC delegated its responsibility to the NBS, which established an **Office of Flammable Fabrics (OFF)**.

By 1974, the OFF had made substantial progress in controlling fires involving fabrics, including:

- A 1972 DoC standard for children's sleepwear for ages nine months to six years old (16 Code of Federal Regulations Part 1615). Each year, hundreds of children died, and a substantially larger number suffered disfiguring burn injuries when their pajamas caught fire. NBS staff developed a test method for upward flame spread on a strip of a sleepwear fabric. The fabric specimen was first washed fifty times, ensuring that the low flame spread would continue well into the garment's lifetime. Responsibility for maintaining and enforcing this regulation was transferred to the new Consumer Product Safety Commission (CPSC). By the time the National Fire Incident Reporting System (NFIRS) had been established in the mid-1970s, deaths and serious injuries due to children's sleepwear fires had all but ended.
- Prototype test methods for the resistance of mattresses and upholstered furniture to ignition by cigarettes, along with recommended pass/fail criteria. (See Page 12.)
- Research on limiting the flaming behavior of textile floor coverings. Some flooring materials were rapidly spreading flames to adjacent rooms and increasing the smoke obscuration along building evacuation paths. This was especially problematic in schools and medical facilities. In 1970, NBS began developing a test method (now ASTM E 648) for critical radiant flux (CRF), the minimum level of thermal radiation from an existing fire that will spread flames over a

carpeted surface. NFPA 101, the Life Safety Code, soon added minimum CRF values for the flooring in various categories of buildings, and carpeting is now seldom the primary carrier of fire from one room to another.

With the Fire Research and Safety Act of 1968, Congress took two significant steps forward in addressing the nation's growing fire loss problem, through:

1. Authorization of a broad fire research and engineering program at the NBS. The NBS created an **Office of Fire Technology (OFT)** to unify the NBS fire expertise into a single, expanded program. This would combine the technical threads of fire research and engineering that would soon be re-authorized under the Federal Fire Prevention and Control Act of 1974.
2. Authorization of a National Commission on Fire Prevention and Control to undertake "a comprehensive study and investigation to determine practicable and effective measures for reducing the destructive effects of fire throughout the country." The Commissioners were appointed in June 1971 and completed their two-year task on May 4, 1973.

The Commission's report, entitled *America Burning*, depicted a dismal U.S. annual fire loss record: 12,000 deaths (later updated to 6,200), 300,000 injuries (later updated to 100,000), 10.4 billion worth of destroyed property, and a total cost to the economy of at least $19 billion. This was the highest per capita rate of death and property loss from fire of all the major industrialized nations in the world. The Commission found shortcomings in virtually all areas that could contribute to reducing these losses: knowledge of fire behavior; connection between fire science, safety standards, and building codes; fire incidence data; firefighting technology; burn treatment centers; etc. The report characterizes the American public as unaware of or indifferent to this grave threat to their well-being.

The Congress described this state of affairs as unacceptable. Within eighteen months, the Congress passed, and the President signed, the Federal Fire Prevention and Control Act of 1974 (FFPCA).

The FFPCA had a profound effect on how the United States would improve the fire safety of its citizens over the next 50 years. For the first time in the nation's history, it was explicit that this was to be a collaborative effort of government, scientists and engineers, the fire service, product manufacturers, testing labs, and codes and standards organizations. The setting of research and action priorities would be furthered by a national system of fire data.

The FFPCA created a Fire Research Center (which became the Center for Fire Research at the NBS and is now the **Fire Research Division, FRD)** to complement the National Fire Prevention and Control Administration (now the United States Fire Administration) and the National Academy for Fire Prevention and Control (now the National Fire Academy). The Center had the mission of "performing and supporting research on all aspects of fire with the aim of providing scientific and technical knowledge applicable to the prevention and control of fires." The FFPCA authorized the Center to perform, and/or support through grants, basic and applied research on:

- The chemistry and dynamics of unwanted fires;
- The nature, yields, transport, toxicity, and corrosion of combustion products;
- The early stages of structure and outdoor fires, to improve early detection and fire control;
- Improved methods of providing first aid to victims of fires;
- Simple and reliable tests for determining the cause of death from a fire;
- Mental health characteristics of arsonists and the prediction and cure of such behavior;
- Firefighter stress and the alleviation of such conditions;
- Design concepts for increasing fire safety within structures, consistent with habitability, comfort, and human impact;
- Tests, demonstration projects, and fire investigations in support of these activities; and
- Other aspects of fires that are important in pursuing the objectives of the fire research program.

The Act also directed wide dissemination of the results and their incorporation in building codes, fire codes, and other relevant codes; test methods; fire service operations and training; and standards.

In 1975, additional funding for supporting extramural fire research grants was transferred to NBS from the National Science Foundation's Research Applied to National Needs program.

NBS Initiation of its Role under the FFPCA of 1974

The FFPCA's authorization was extraordinarily broad, encompassing some disciplines of fire safety science that were already mature and others for which the basic concepts were only under discussion. Therefore, the NBS Director requested a long-range plan for selecting and implementing the NBS efforts under the Act. Completed in 1976, the Plan identified fire scenarios that accounted for most of the Nations' fire losses. For each scenario, there were technical tasks designed to reduce the frequency and/or severity of the germane fires.

The planners estimated that completion of the tasks would result in the technical basis for halving fire losses within 20 years. They also recognized that it might take more time to fully retrofit existing buildings and replace beds and furniture with less flammable items. By 1994, the fatalities from unwanted fires had been reduced by about one-third. By 2022, new fire safety standards and compliant products had reduced life loss by about one-half. These absolute reductions in loss of life occurred over a period when the population of the United States increased by a factor of more than 1.5 times.

As attested by the thirteen highlights described in this publication, the National Institute of Standards and Technology's (NIST) – NBS was renamed to NIST in 1988 – technical output provided the basis for many of the improvements in fire safety in the United States over the past 50 years.

Additional Reading:

The following references and those following each of the highlights are for those who wish to learn more about the subjects they accompany. Where available, each citation includes a Uniform Resource Locator (URL) that is active at the time of this publication. Some of these documents are only available for a fee or through a library with prepaid access, and others are technical in nature. In either case, the freely available document abstract provides additional insight into the subject matter.

- Gross D. 1991. "Fire Research at NBS: The First 75 Years." International Association for Fire Safety Science. https://publications.iafss.org/publications/fss/3/119/view/fss_3-119.pdf.
- America Burning: The Report of the National Commission on Fire Prevention and Control. 1973. Emmitsburg MD. United States Fire Administration. Amended in 1989 to include updated fire loss data. https://www.usfa.fema.gov/downloads/pdf/publications/fa-264.pdf.
- Wright RN. 2003. "Building and Fire Research at NBS/NIST 1975–2000," NBS BSS 179. Gaithersburg MD. National Institute of Standards and Technology, https://doi.org/10.6028/NIST.BSS.179.

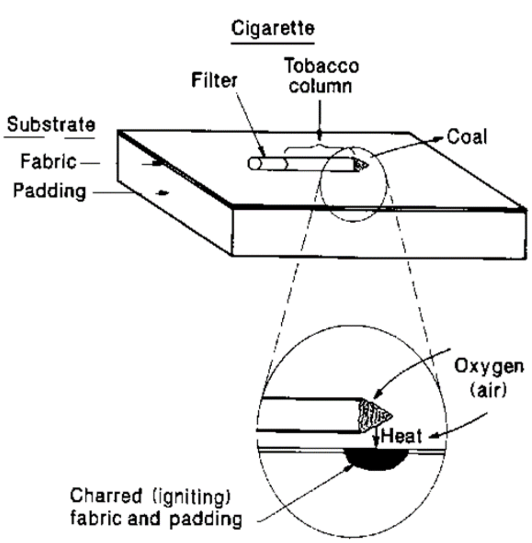
TESTS FOR CIGARETTE IGNITION RESISTANCE OF BEDS AND FURNITURE

Standard test methods for evaluating the smoldering ignition resistance of soft furnishings, particularly mattresses and residential upholstered furniture, have facilitated the regulation of these products. These regulations have significantly contributed to a reduction in fire-related fatalities.

Ignition of soft furnishings by cigarettes led to an estimated 27 % of residential fire deaths in the United States, by far the leading cause between 1971 and 1975. As shown in the figure below, when a lit cigarette falls on susceptible fabrics and padding materials, it can heat the materials sufficiently to initiate smoldering (non-flaming) combustion. This generates heat, toxic gases, and visible smoke, all of which can lead to injury or death. Life-threatening conditions can arise within 30 minutes and can be considerably accelerated if the smoldering transitions to a flaming fire.

NIST had begun research on these fire scenarios under the Flammable Fabrics Acts and was thus able to respond to a request from the Consumer Product Safety Commission (CPSC) to develop a viable and reproducible test method for measuring the Cigarette Ignition Resistance (CIR) of residential upholstered furniture (RUF).

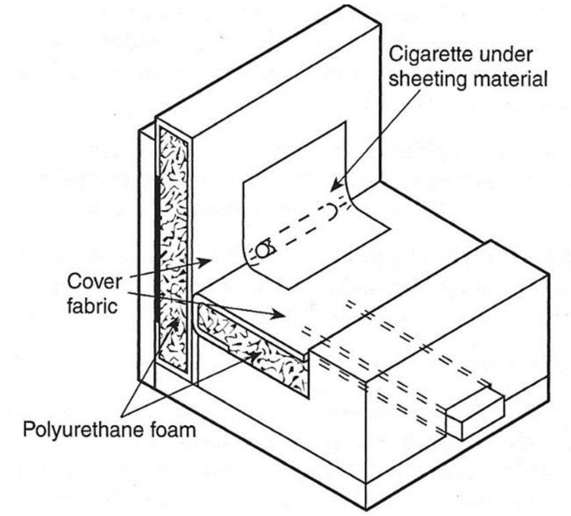
NIST staff first identified the commercial cigarette which was the strongest heat source. However, routine ignition testing of commercial RUF items was impractical since there were too many combinations of size, shape, upholstery fabric, and padding material. Thus, as shown in the figure on the facing page, the cigarette was used with a 250 mm (10 in.) chair mock-up to evaluate furniture padding materials and to identify classes of upholstery fabrics. Class A fabrics smoldered little and did not ignite natural or synthetic padding materials. Class B, C, and D fabrics required increasing sublayer thermal protection to prevent ignition. Good reproducibility of test results was obtained in a 55-laboratory study, and this mock-up research then became the basis for all regulatory testing.



Dynamics of a lit cigarette on a soft surface. (Credit: NIST)

In 1975, the California Bureau of Home Furnishings (BHF, now the California Bureau of Household Goods and Services) issued TB 117, its version of the NIST test method; this was refined over the following 38 years. The furniture industry adopted a similar but voluntary standard. Both were superseded in 2021 by 16 CFR Part 1640, Standard for the Flammability of Upholstered Furniture. This Federal standard that codified the 2013 version of TB 117 is promulgated by the CPSC. The National Fire Protection Association's standard, NFPA 260, is a similar but more advanced standard test method that, e.g., better measures the presence of smoldering. It is cited in the U.S. fire codes and the Life Safety Code as the basis for limiting the ignition of upholstered furniture in public buildings.

NIST staff also used their knowledge of cigarette ignition and smoldering fires to propose a test method for the resistance of mattresses to ignition by cigarettes, including recommended pass/fail criteria. The test cigarette was the same as was used for testing upholstered furniture fabrics and padding. The test method involved laying several such cigarettes at multiple locations on a completely bare mattress and on a second one where the mattress and the cigarettes were covered with sheets. The test output was whether any of the cigarettes led to sustained smoldering of the mattress. The U.S. Department of Commerce used this research as the technical basis for 16 CFR Part 1632, Standard for the Flammability of Mattresses and Mattress Pads. The responsibility for this regulation was transferred to the CPSC.



Schematic of the apparatus for testing RUF components. (Credit: NIST)

The cigarette used in these test methods was replaced with NIST Standard Reference Material (SRM) 1196 to achieve consistency of test results over time (See Page 28.)

This NIST research has had a profound effect on life safety. Between 1980 and 2004, fatalities from cigarette-initiated furniture and bed fires each decreased by about two-thirds. This was attributed to the accuracy of the CIR tests for soft furnishings, the replacement of pre-standard furnishings with compliant furniture and mattresses, the concurrent rise in installed residential smoke alarms (See Page 14.), and a decrease in the number of smokers. Since 2004, a further reduction in fatalities was attributed to regulation of the ignition propensity of cigarettes. (See Page 28.)

Additional Reading:

- Loftus JJ. 1978. “Backup Report for the Proposed Standard for the Flammability (Cigarette Ignition Resistance) of Upholstered Furniture, PFF 6-76,” NBSIR 76-1438, National Bureau of Standards, Gaithersburg MD, 243 p. https://books.google.com/books?hl=en&lr=&id=ua0zAAAAIAAJ&oi=fnd&pg=PA15&dq=loftus%3B+flammability&ots=XkOvncwPFa&sig=xvisY2mh_TWbLRKRfqCykma2tfM#v=onepage&q=loftus%3B%20flammability&f=true.
- NFPA 260, Standard Methods of Tests and Classification System for Cigarette Ignition Resistance of Components of Upholstered Furniture. 1983. National Fire Protection Association: Quincy, MA. 27 p. https://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards/detail?code=260. Current edition: 2024.
- 16 CFR Part 1632, 1984. Standard for the Flammability of Mattresses and Mattress Pads (FF 4-72, Amended). https://www.govinfo.gov/content/pkg/CFR-2019-title16-vol2/xml/CFR-2019-title16-vol2-part1632.xml.
- Technical Bulletin 117-2013, Requirements, Test Procedure, and Apparatus for Testing the Smolder Resistance of Materials Used in Upholstered Furniture. January 2013. California Bureau of Electronic & Appliance Repair, Home Furnishings, & Thermal Insulation: North Highlands, CA. 15 p. https://bhgs.dca.ca.gov/about_us/tb117_2013.pdf. Initial version: 1975.
- Ahrens M. 2021. “Soft Furnishing Fires: They’re Still a Problem,” Fire and Materials 45:8-16. https://doi.org/10.1002/fam.2874.

DRIVING RESIDENTIAL SMOKE ALARM ADOPTION

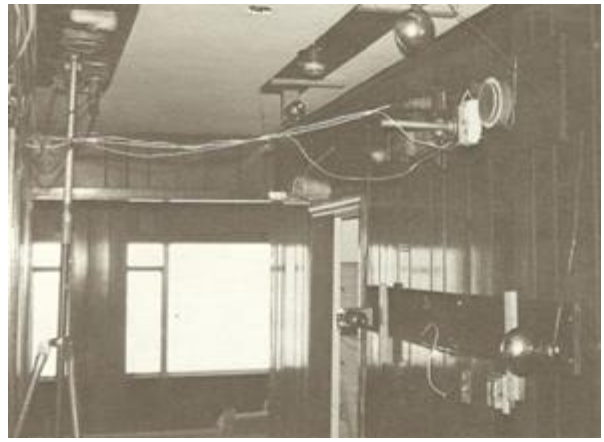
The home smoke alarm is credited as the greatest success story in fire safety in the last part of the 20th century because it reduced losses from most types of home fires. NIST performed and led collaborative research that provided the technical basis for the alarm location and smoke sensitivity standards. These standards led to the installation of smoke alarms in nearly all homes, saving thousands of lives each year.

The 1960s saw the invention of the first self-contained smoke alarm and the first battery-powered alarms. Initially sales were slow due to their high cost (as much as hundreds of dollars) and the lack of building and fire code requirements for their installation. In 1969, the U.S. Department of Housing and Urban Development (HUD) launched Operation Breakthrough, a demonstration program designed to stimulate the housing market through the development and adoption of new home building technologies and codes. HUD tasked the NBS National Bureau of Standards, NBS (now the National Institute of Standards and Technology, NIST) with developing model building code guidelines. NBS researchers included the installation of smoke alarms, based on prior work at the National Research Council of Canada (NRCC) that judged the detectors would substantially reduce life loss.

Following the destruction of many dwellings by Hurricane Agnes in 1972, HUD purchased 17,000 mobile homes (later called manufactured homes) for temporary housing and included the NBS recommendation to install smoke alarms in the procurement. Historically, loss of life and property in mobile home fires had been significantly higher than the average for all residential occupancies, and the experience with the HUD mobile homes was similar during the one to three years they were occupied. Surprisingly, there had been no fire deaths. This was attributed to smoke alarms being present and alerting occupants so they could safely evacuate or intervene, a true breakthrough. In 1975, the Mobile Home Manufacturing Association (now the Manufactured Housing Institute) adopted the policy that every manufactured home produced by a member company be provided with one smoke detector located outside the bedrooms.

NBS staff were curious about how well these devices performed in detecting fires. NBS and Underwriter' Laboratories Inc. (UL) conducted research in close collaboration with the residential smoke detector industry to develop a product approval standard that assured proper performance and reliability. The companies provided prototype designs and quickly revised them in response to the laboratory findings. This cooperative environment led to rapid improvements in the performance of detectors which benefited both the public and the industry. The result was the first edition of UL 217 in 1974. This standard introduced a new test box, in which smoldering cotton cord and a small pool of flaming (liquid) heptane were the smoke sources.

Recognizing that the complement to assuring the sensitivity of smoke alarms was a formal detector siting standard for their effectiveness in housing, NBS sponsored the Illinois Institute of Technology Research Institute (IITRI) and UL, again with the close collaboration of the manufacturing industry, in conducting research to develop a minimum product performance and siting standard for residential smoke alarms. They evaluated the effectiveness of commercially available products in homes that had been designated for demolition (the Indiana Dunes tests). The fires and their locations were representative of the major fatal fire scenarios of the time. The results became the basis for installation requirements as well as the number and locations of alarms in NFPA 74, Household Fire Warning Equipment. In 1993, this was renamed to NFPA 72, National Fire Alarm and Signaling Code.



Locations of smoke detectors in an Indiana Dunes test. (Credit: NIST)

The result of this research and its enabling of standards that are cited in the United States building and fire codes has been phenomenal. The annual production of smoke alarms, which in 1971 was approximately 50,000 units, is now at least 30 million units. The National Fire Protection Association (NFPA) and the United States Fire Administration (USFA) estimate that the percentage of homes with at least one installed smoke alarm rose from less than 10 % in 1975 to at least 92 % in 2000. Home smoke alarms were a major contributor to reducing the number of fire deaths by about half in that 25-year period.

Additional Reading:

- Beyler C, Lucht D, McNamee M, Johnson P, and Dubay C. 2017. The Affordable Home Smoke Alarm, Lyman Blackwell - 2015 DiNenno Prize Winner. Fire Science Reviews 62. https://doi.org/10.1186/s40038-016-0015-0.
- Bukowski RW, Waterman TE, and Christian WJ. 1975. "Detector Sensitivity and Siting Requirements for Dwellings," NBS-GCR 75-51. Gaithersburg MD. National Bureau of Standards. https://www.nist.gov/system/files/documents/2017/04/28/NISTGCR_75_51.pdf.
- Bukowski RW. 2001. "A History of NBS/NIST Research on Fire Detectors," in Proceedings of the 12th International Conference on Automatic Fire Detection. SP 965. Gaithersburg MD. National Institute of Standards and Technology. https://nvlpubs.nist.gov/nistpubs/Legacy/SP/nistspecialpublication965.pdf.
- UL 217, Safety Standard for Single- and Multiple-Station Smoke Detectors. 1974. Northbrook IL. Underwriters Laboratories, Inc. Modern version: 2015. (See Page 32 for the latest version which includes new technology.)
- NFPA 74, Household Fire Warning Equipment. 1978. Quincy MA, National Fire Protection Association.

MEASURING FIRE SIZE

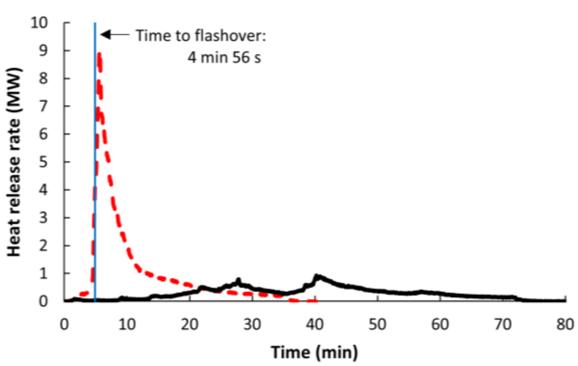
In a compartment fire, the heat generated by burning items increases the temperature of the air, making the space difficult for survival. The radiant heat from the flames and the elevated room temperature make combustibles burn faster and can lessen the capability of the walls, floor, and/or ceiling to contain the fire. Realizing this, in the 1950s fire scientists began developing apparatus for measuring the heat release rate (HRR) from burning items as small as a book and as large as a living room. The empirical bases behind these HRR determinations led to substantial error or variability, created operational difficulties, and required knowledge of the fuel's chemistry, which generally changes as it burns.

In the late 1970s, NIST staff discovered a direct link between the heat released from a burning material and the mass of oxygen consumed in the burning, ΔO_2. Calculations and testing of a large number of organic materials showed that the relationship was independent (within about five percent) of the chemistry of the combustible and whether the burning was complete (burning to CO_2 and water) or incomplete (generating significant CO and soot). In its simplest form, this is represented by:

$$\text{HRR (kJ)} = 13.1 \text{ kJ/g times } \Delta O_2 \text{ (g)}$$

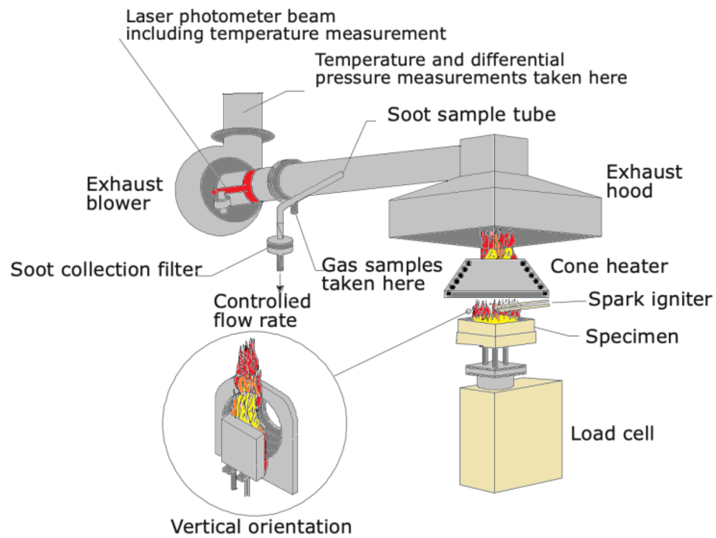
The heat release rate of the combustibles is the single most important variable in fire hazard assessment. NIST's discovery that oxygen consumption is a valid predictor of the heat release rate and subsequent invention of the cone calorimeter transformed heat release rate measurement and became the basis for fire safety design and commercial product standards around the world.

The figure below depicts the value of being able to measure HRR routinely and accurately. The red dashed curve (- - -) shows the HRR from a furnished room with an ordinary upholstered sofa that has been ignited with a small flame. The sofa (whose arms, back, and seat cushioning consist of padding material wrapped in a decorative upholstery fabric) burns rapidly, generating a peak HRR of 9 MW. In less than 5 minutes after ignition, the environment in a room containing such a sofa is too hot to survive. The black curve (—) shows the HRR from a room with a sofa that is similar, except that the padding material was wrapped with a fire barrier. This sofa burns so slowly that occupants of the room have at least 20 minutes to evacuate.



Heat release rate curves for a furnished living room including either a sofa with no fire barrier (dashed red curve) or a sofa containing a fire barrier (black curve). (Credit: NIST)

This measurement method was dubbed oxygen consumption calorimetry (OCC). OCC eliminated the shortcomings of prior HRR measurement methods and is now the dominant technique for measuring HRR worldwide. In 2016, OCC was the technical achievement selected to receive the second ever Philip J. DiNenno Prize, awarded by the National Fire Protection Association (NFPA) and considered the “Nobel Prize of public safety.” OCC is commonly used by manufacturers to characterize potentially combustible products and by regulators to limit the fire hazard of some commercial products. (See Page 26.)



Schematic of the cone calorimeter. (Credit: NIST)

In 1982, NIST staff invented the first device designed for OCC, the cone calorimeter. The figure to the right is a diagram of the apparatus. The top surface of a hand-sized test specimen is subjected to thermal radiation from a *cone*-shaped heater. This radiation heats the specimen as if it were in a real developing fire. The measurements of gas flow, temperature, and oxygen concentration are made continuously, and the output is a plot of the calculated HRR versus burn time. Of particular importance is the ease of determining the peak heat release rate (PHRR). The PHRR correlates with the potential for the transition from a local fire to a fire that involves all combustibles in the room, with a substantial increase of threat to occupants throughout a house.

There are now domestic and international standards for the fabrication and operation of the cone calorimeter, with more than 300 of these devices in use worldwide. There are also dozens of large OCC-based calorimeters being used to measure the HRR from a fire as large as a burning two-story house. In 1988, the cone calorimeter was awarded an R&D 100 Award, often called the “Oscar of Innovation,” and awarded annually to the top 100 innovations of the year in any field. In 2024, the cone calorimeter received the 7th Philip J. DiNenno Prize.

Additional Reading:

- Parker WJ. 1977. “An Investigation of the Fire Environment in the ASTM E84 Tunnel Test,” NBS Technical Note 945, Gaithersburg MD; National Bureau of Standards. An Investigation of the Fire Environment in the ASTM E 84 Tunnel Test - William J. Parker - Google Books.
- Huggett CM. 1980. “Estimation of Rate of Heat Release by Means of Oxygen Consumption Measurements.” Fire and Materials 4:61-65. https://doi.org/10.1002/fam.810040202.
- Babrauskas V. 1984. “Development of the Cone Calorimeter – A Bench-Scale Heat Release Rate Apparatus Based on Oxygen Consumption.” Fire and Materials 8:81-95. https://doi.org/10.1002/fam.810080206.
- ASTM E1354. 1990. Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter. West Conshohocken PA, ASTM International. Current edition: 2023.
- NIST Museum. 2023. The Cone Calorimeter: The Most Important Tool in Fire Safety Science. Gaithersburg MD: National Institute of Standards and Technology. Online. https://www.nist.gov/nist-museum/cone-calorimeter-most-important-tool-fire-safety-science.

FIRE SAFETY EVALUATION SYSTEM

In the United States, each occupiable facility must meet extensive sets of requirements (prescriptions) referred to as a *code*. A *building code* provides a minimum level of safety for the design and construction of the facility, so that it maintains its integrity in normal use and in the event of a natural or human-caused catastrophe. This includes provisions for structural safety, fire safety, health requirements, energy conservation, materials recycling, noise and air pollution, and accessibility. A *fire code* prescribes ongoing requirements relating to fire prevention; evacuation; explosion hazards arising from storage, handling, and use of dangerous materials or from other specific hazardous conditions. The fire code works in tandem with the building code since the building code includes the necessary construction requirements to enable fire safety.

The NIST-invented Fire Safety Evaluation System is the forerunner of performance-based facility design provisions in building and fire codes around the world. These provisions have enabled construction of iconic buildings and have substantially reduced the cost of retrofitting existing structures.

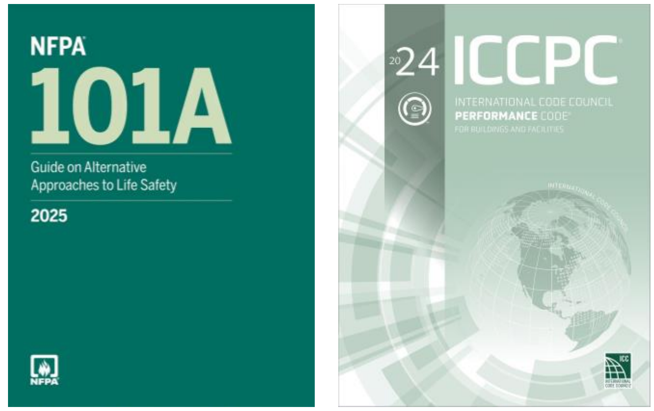
The building and fires codes work well for most buildings but might not accommodate new construction of unusual designs or innovative materials. There are also an increasing number of instances when a building is being repurposed or expanded, and the feasibility and cost of prescriptive code compliance are problematic.

In the 1960s, the United States Congress mandated that all healthcare facilities receiving federal funds conform to the requirements of the National Fire Protection Association (NFPA) Life Safety Code, NFPA 101. Most, if not all, such facilities were not in compliance and some closed. The operators of others took corrective actions, but many could not adapt existing buildings without a means to demonstrate that their fire safety level met that of NFPA 101. In 1975, the Department of Health, Education, and Welfare (now the Department of Health and Human Services) began a joint effort with NIST to create an assessment method that could assure at least a level of safety equivalent to compliance with NFPA 101.

The outcome of this research was the Fire Safety Evaluation System for Health Care Facilities (FSES-HCF), a quantitative system for grading healthcare facilities in terms of fire safety, especially for determining equivalence to NFPA 101. Three major concepts formed the basis for code equivalency: risk to occupants, the ability of the building and its fire protection systems to provide safety commensurate with the risk, and credit for the redundancy realized from multiple fire safety measures.

For a proposed new or retrofitted design proposal, the System compiled a table of points for each of the building factors that determine fire safety, including the type of construction, partitioning and interior finishes, hazardous activities, and fire alarm and suppression systems. Experts awarded points for each factor, and the sum of those points was compared to the sum for a hypothetical building that met the prescriptive requirements of NFPA 101. Estimating the cost of construction for each sufficiently safe design proposal enabled getting the most safety from limited budgets. In the case of one premier hospital seeking to modernize and increase capacity, the use of the FSES reduced the cost of compliance from an estimated $30 million to $50 million (well outside the hospital's resources) to less than $2 million. The estimated nationwide savings accruing to hospitals and nursing homes from 1983 to 1989 were approximately $1 billion in 1995 dollars, while at the same time greatly enhancing overall fire safety in hospitals.

The FSES-HCF was adopted by the NFPA in the 1981 edition of NFPA 101. NIST continued to develop FSESs for other facilities, including prisons and jails, board and care homes, and offices. In 1995, NFPA institutionalized FSESs with a dedicated committee that sustains a new standard, NFPA 101A, assuring that each FSES appropriately reflects the changing safety levels prescribed by building codes and regulations.



NFPA 101A and ICCPC codes. (Credit: NFPA and ICC)

The FSES is the conceptual forerunner of today's performance-based fire safety design, a discipline that applies detailed fire physics and current computational methods to achieve objectives similar to those of the FSES. Many building codes around the world have incorporated a performance-based option for building design. The International Code Council (ICC) Performance Code for Buildings and Facilities formalizes the identification of a desired level of performance for a particular building and a process for incorporating all aspects of building design into an appropriate solution.

Additional Reading:

- Nelson HE and Shibe AJ. 1980. "System for Fire Safety Evaluation of Health Care Facilities. NBSIR 78-1555-1, Gaithersburg MD. National Bureau of Standards. https://nvlpubs.nist.gov/nistpubs/Legacy/IR/nbsir78-1555-1.pdf.
- NFPA 101A. 1981. Guide on Alternative Approaches to Life Safety. Quincy MA. National Fire Protection Association. Current edition: 2025.
- Chapman RE. 1982. A Cost-conscious Guide to Fire Safety in Health Care Facilities. NISTIR 5863. Gaithersburg MD. National Bureau of Standards. https://nvlpubs.nist.gov/nistpubs/Legacy/IR/nbsir82-2600.pdf.
- Chapman RE and Weber SF. 1996. Benefits and Costs of Research: A Case Study of the Fire Safety Evaluation System. NISTIR 5863. Gaithersburg MD. National Institute of Standards and Technology. https://nvlpubs.nist.gov/nistpubs/Legacy/IR/nistir5863.pdf.
- Hurley MJ and Rosenbaum ER. 2015. Performance-based Fire Safety Design. Society of Fire Protection Engineers, Gaithersburg MD. 978-1482246551.
- 2021 ICC Performance Code for Buildings and Facilities. 2020. Washington DC. International Code Council. Current edition: 2024.

COMPUTER FIRE MODELS AND PRACTICAL APPLICATIONS

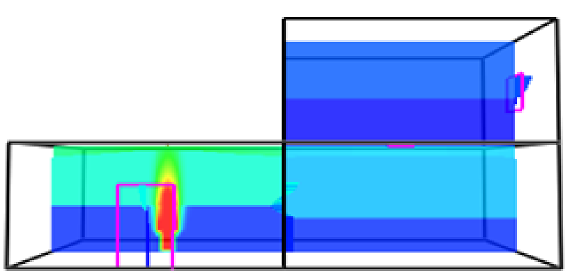
With the rapid growth in computational power in the latter half of the 20th century, fire safety professionals saw the potential for scientifically sophisticated, computer-based tools to improve on the simple algebraic equations previously used to predict fire behavior. NIST committed to developing such models that addressed various user communities' phenomena of interest. The models were to be based on sound science; to be supported by unprecedented output validation, code verification, and documentation; and to include an easily understood visualization of the complex model output.

NIST pioneered the development of two types of computational fire models whose evolution has continued over the subsequent 45 years, and which have become pre-eminent worldwide for both design (fire hazard estimation) and forensic (fire loss reconstruction) use.

The NIST-created computer fire models CFAST (zone model) and FDS (computational fire dynamics model) are the most widely used tools worldwide for designing the fire safety systems of prospective buildings and reconstructing the fires in established buildings.

Zone Modeling The Consolidated Fire and Smoke Transport zone model (CFAST) divides a room into upper and lower layers (zones) separated by a horizontal plane. The content and properties of each zone are spatially uniform. The user inputs fire growth and combustion product data, and simplified laws of physics determine the temperature in each layer, the height of the horizontal plane, and the spread of gases between the zones and through any room openings. CFAST can accomplish this in more than 60 rooms of a 10-story building in less than one minute on a personal computer. CFAST is used extensively to resolve civil litigation and to assess the equivalence of alternate approaches to providing building fire safety. The model is available for download free of charge at https://pages.nist.gov/cfast.

HAZARD I, the world's first computerized tool for estimating fire hazard, was a harbinger of the acceptance of zone models. It consisted of FAST (a CFAST predecessor) augmented by (a) a model of human behavior based on interviews with fire survivors, (b) a lethal smoke toxic potency calculator, and (c) embedded databases of materials fire properties. In a project of the National Fire Protection Association's (NFPA) Fire Protection Research Foundation (FPRF), HAZARD I successfully replicated the survival rate and cause of death profile for U.S. residential furniture fires, the deadliest scenario.



Smokeview rendition of the layer temperatures in a CFAST simulation of a small fire in a two-story house with a stairwell open to the second floor and a second-floor window. (Credit: NIST)

Computational Fluid Dynamics (CFD) Fire Modeling The Fire Dynamics Simulator (FDS) computes the three-dimensional, turbulent nature of flame spread, smoke dispersion, and heat release. FDS tracks the mixing of fuel and air, and its subsequent combustion over length scales far smaller than the fire itself and over sub-second time intervals.

FDS is a tool used worldwide by industry, academics, and government agencies and is available for download free of charge at https://pages.nist.gov/fds-smv. FDS provides practical design guidance for indoor fire protection, such as for smoke handling systems, smoke alarms, and automatic fire sprinklers. It is also the principal forensic modeling tool used for residential and commercial fire reconstructions, notably in the World Trade Center buildings. (See Page 24.) The Society of Fire Protection Engineers (SFPE) sponsors a training course on the use of FDS and Smokeview (see below).

Smokeview rendition of the smoke in a Fire Dynamics Simulator (FDS) simulation of a fire in a multi-story building. (Credit: NIST)

A forerunner of FDS, ALOFT (A Large Outdoor Fire Plume Trajectory), was also a physics based CFD model. Following the 1989 Exxon Valdez oil spill, ALOFT was developed to assess whether the spread of smoke downwind of a burning oil spill would pose a lesser hazard (at lower cost) than allowing the oil itself to harm wildlife and contaminate a shore. Validated by good agreement with large-scale, at-sea testing, and usable by on-site oil spill responders, this NIST model enabled the National Oceanic and Atmospheric Administration (NOAA) Office of Response and Restoration to establish in situ oil spill burning as a primary response technology rather than a method of last resort.

Scientific Visualization A single fire simulation can generate billions of values of temperature, gas and soot concentrations, and flow velocities. Understanding what has happened during the simulation requires software that presents the complex output as colorful videos, still frames, and two- or three-dimensional plots.

NIST staff developed Smokeview to do this for zone models such as CFAST and CFD models such as FDS. Smokeview can visualize fire realistically so that the user can "experience" the movement of flames, the loss of visibility due to soot, the flow and temperature of air as it moves to and from the fire zone, and the resulting temperature profiles of the surfaces.

Additional Reading:

- Peacock RD, McGrattan K, Forney GP, and Reneke P. 2023. "CFAST - Consolidated Model of Fire Growth and Smoke Transport (Version 7); Volume 1: Technical Reference Guide." Section I, Introduction and Overview, pp 1-6. NIST Technical Note 1889v1, Gaithersburg MD. National Institute of Standards and Technology. https://pages.nist.gov/cfast. Original version: 1993.
- Peacock RD, Jones WW, Bukowski RW, and Forney CL. 1991. "Technical Reference Guide for the HAZARD I Fire Hazard Assessment Method," Volume 2, Version 1.1. NIST Handbook 146. Gaithersburg MD. National Institute of Standards and Technology. https://nvlpubs.nist.gov/nistpubs/Legacy/hb/nisthandbook146v2-1991.pdf.
- McGrattan KD, McDermott RJ, Vanella M, Mueller E, Hostikka S, and Floyd J. 2024. "Fire Dynamics Simulator User's Manual." NIST SP 1019. Gaithersburg MD. National Institute of Standards and Technology. https://pages.nist.gov/fds-smv. Original version: 2000.
- Evans DD, Mulholland GW, Baum HR, Walton WD, and McGrattan KB. "In Situ Burning of Oil Spills." 2001. Journal of Research of the National Institute of Standards and Technology 106(1):231-78. https://doi.org/10.6028/jres.106.009.
- Forney GP. 2024. "Smokeview, A Tool for Visualizing Fire Dynamics Simulation Data; Volume 1: User's Guide." SP 1017-1. Gaithersburg MD. National Institute of Standards and Technology. https://pages.nist.gov/fds-smv. Original version: 2000.

QUANTIFIED SMOKE TOXICITY

NIST research quantified smoke toxicity, showing that fire deaths can be estimated from key gas concentrations. NIST also found that reducing ignition risk and limiting fire size can significantly decrease life loss, while regulating products based solely on smoke toxicity has been largely unsuccessful.

Fire survivors have long reported trouble breathing during their escape, and many fire victims were found to have only nonfatal skin burns, together suggesting that smoke inhalation could be an important cause of fire deaths. By the middle of the 20th century, combustion scientists knew that fires generated hundreds of gases, as well as liquid and solid aerosols, which are collectively called smoke. Soon experiments with laboratory animals indicated that exposure only to smoke from burning materials could be fatal.

Since the lethality differed among the tested materials, it seemed likely that the variation was due to the smoke chemistry and/or its quantity. This led to two practical questions:

1. Could the lethality of fire smoke be explained by the contributions of just a few toxic gases, thus simplifying the measurement of fire hazard?
2. Would restricting the use of some commercial products based on lethal toxic potency alone significantly reduce life loss in fires?

NIST staff addressed the first question by establishing a quantitative basis for smoke toxicity measurement. They exposed laboratory rats to smoke generated from both overheated and flaming materials and determined what concentration of smoke was lethal to the rats during various exposures (defined as the smoke or gas concentration times the duration of contact with the smoke or gas). NIST staff and grantees at the Southwest Research Institute then exposed rats to various concentrations of individual gases and combinations of these gases. Their findings showed that the contributions of just five combustion gases (CO, CO_2, HCN, HCl, and HBr), along with the effect of diminished O_2 concentration, could predict the smoke lethality of chemically diverse materials to within 30 %. NIST scientists named the relationship among the gases as the N-gas equation, where N was equal to six, as contrasted with the hundreds of fire gases. They also found that the rats were incapacitated (e.g., unable to move) at exposures of about one-third to one-half of the lethal exposure.

These results suggested that extensive and costly animal testing of the smoke from burning materials was not necessary. For nearly all materials composed of C, H, O, N, Cl, and Br atoms, the potential for lethality would be estimated from the N-gas equation, the concentrations of the N gases, and the duration of the exposure. Laboratory animal testing would then only be necessary if the chemistry of a material were suspected to lead to unusual smoke composition. If the lethality from the smoke exposure tests differed from the result predicted from the gas concentration measurements, a more thorough evaluation of the potential fire hazard would be in order. This approach became the basis of the first and only standardized toxic potency measurement method in the United States, as promulgated in the nominally identical NFPA 269 and ASTM E1678 standards.

Fire toxicologists have identified only two materials whose lethal toxic potency was well outside the 30 % uncertainty of the N-gas equation. One material, composed entirely of fluorine (F) and carbon (C) atoms, exhibited *extreme* toxic potency, i.e., animal deaths occurred when very little smoke was present. Further experiments found that this was due to the absence of hydrogen atoms in the test specimen, a situation that does not exist in realistic, life-threatening residential fires because of the concurrent burning of materials containing hydrogen atoms. The fluorine atoms end up in hydrogen fluoride (HF), which was then added to the list of N gases, raising N to seven. In non-NIST tests of the second (exploratory) material, the animals showed *unusual* toxicity, i.e., their symptoms were unlike those due to the N gases. Chemical analysis of the material, its additives, and the smoke showed that the burning created a nerve gas. The production of such materials was curtailed by materials manufacturers.

Addressing the second question required insight into the components of the fire process that lead to threats to life safety. While laboratory testing found a range of smoke toxic potency values, the risk of life loss from a burning product depends at least as heavily on other aspects of its contribution to fire severity. Most fire fatalities result from fires involving multiple materials, high burning rates, or people being very close to the smoldering or flames. Thus, products that (a) are difficult to ignite, (b) represent a small fraction of the fuel mass in a compartment, (c) burn slowly, and (d) generate little visible smoke are of lower risk even if their smoke toxic potency is above “normal.” Indeed, success to date in limiting life loss from the burning of commercial products has been achieved by reducing the probability of ignition and the maximum fire size. Attempts at regulating commercial products based solely on high smoke toxic potency have failed for lack of projecting a credible expectation of a substantial reduction in life loss.

Due to these findings and the increasing societal concern regarding live animal testing, there has been no new smoke toxicity research conducted at NIST in over two decades.

Additional Reading:

- Babrauskas V, Levin BC, et al. 1991. Toxic Potency Measurement for Fire Hazard Analysis. NIST Special Publication 827. Gaithersburg MD. National Institute of Standards and Technology. https://nvlpubs.nist.gov/nistpubs/Legacy/SP/nistspecialpublication827.pdf.
- ASTM International. 1995. ASTM E1678, Standard Test Method for Measuring Smoke Toxicity for Use in Fire Hazard Analysis. West Conshohocken PA. ASTM International. Current edition: 2024.
- National Fire Protection Association. 1996. NFPA 269, Developing Toxic Potency Data for Use in Fire Hazard Modeling, Quincy, MA. National Fire Protection Association. Current edition: 2022.

RECONSTRUCTION OF THE COLLAPSES OF WORLD TRADE CENTER BUILDINGS

The September 11, 2001 (9/11) attack on the United States using hijacked airliners shocked the world. The resulting fires led to the collapse of the two impact-damaged, 110-story towers (World Trade Center (WTC) 1 and WTC 2) in downtown Manhattan killing more than 2,700 building occupants, emergency responders, bystanders, and aircraft passengers and crew. The 47-story building WTC 7 collapsed later that day, also the result of uncontrolled fires. In response, the U.S. Congress passed the National Construction Safety Team Act (NCSTA) which expanded NIST's authority to investigate "events causing the failure of a building or buildings that has resulted in substantial loss of life or that posed significant potential for substantial loss of life." NIST quickly undertook an investigation to determine how and why the three buildings collapsed; why the injuries and fatalities were so high or low; how the buildings were designed, constructed, and operated; and aspects of current fire and building codes and standards that warranted revision.

In response to NIST recommendations following its investigation of the 9/11 disaster, numerous and substantive upgrades have been added to the nation's building and fire codes that will mitigate against future collapses of tall buildings and improve the safety of occupants and emergency responders.

While many high life-loss building fires during the previous century had been investigated, this reconstruction was unprecedented in its technical demands and societal importance. NIST staff obtained sufficient photographs and video of the three buildings that day to enable a visual rendering of the spread of the fires, the distortion of the buildings, and their eventual collapse. NIST and its contractors modeled the aircraft impact on each of the two towers, as well as the damage to each building structure and the thermal fire insulation on the structural members. The NIST Fire Dynamics Simulator computational software (See Page 19) was greatly enhanced to reproduce the fire spread and superimpose the generated heat on the equally innovative thermal-structural models of the respective buildings.

The airplanes did considerable damage to the columns and floor assemblies in WTC 1 and WTC 2. However, each tower withstood the impact and would have remained standing were it not for the dislodged structural insulation and the rapidly spreading, multi-floor fires ignited by the aircraft's burning jet fuel. The automatic fire sprinklers in the buildings might have controlled the flames, but the aircraft impact had damaged the water supply lines, rendering the sprinklers nonfunctional.

In WTC 1, the fire-weakened floors on the side opposite the aircraft impact sagged, pulling inward on the heat-weakened perimeter columns. As more columns weakened, the structure could no longer support its mass, and the building collapsed in 102 minutes. In WTC 2, the structural damage was more severe than that of WTC 1, and the building collapsed in just 56 minutes, also as a result of fire-weakened structural elements. WTC 7 was struck by the debris from the collapse of WTC 1. The structural damage was relatively minor, but the debris ignited furnishing fires on at least 10 floors. Over the next seven hours, without an available water supply for the sprinkler system, the fires spread around the building, weakening the floors and their connections to a critical interior column. The unsupported column buckled, initiating further structural weakening and the global collapse of the building.

The life loss in the towers was high because the aircraft destroyed the evacuation routes for nearly all occupants on or above the impact zones. The evacuation by those occupants who were below the impact zones was remarkably efficient, in part due to the towers being far less occupied than normal. Nearly all below the floors of impact escaped despite the unexpected collapses of the buildings. The unprecedented collapses were also responsible for the loss of emergency responders who were assisting in the evacuation. The occupants of WTC 7 began evacuating while the towers were burning, and WTC 7 was empty at the time of its collapse.

NIST recommended 31 improvements to address the fire safety of tall buildings, occupants, and emergency responders. NIST staff partnered with other professionals to effect changes in the nation's building and fire codes, including the following:

- Fire-resistance ratings of structural components must increase by one hour in buildings 128 m (420 ft) or taller.
- Members of the structural frame of a building to have the higher fire resistance rating commonly required for columns.
- Three times the bond strength of fireproofing to structural components throughout buildings 23 m (75 ft) to 128 m (420 ft) tall and seven times the bond strength throughout buildings taller than 128 m (420 ft).
- In buildings over 128 m (420 ft) tall, at least two water supply risers for each sprinkler zone, located in stair enclosures that are to be remotely located from each other.
- Exit stairways to be enclosed and meet minimum separation criteria.
- An additional exit stairway for buildings more than 128 m (420 ft) tall and an increase of 50 percent in exit stairway width in all new buildings with floor areas exceeding about 1,400 sq m (15,000 sq. ft).
- Specially protected elevators for occupant evacuation in fires and other emergencies for buildings over 128 m (420 ft).
- Luminous markings along the exit paths in buildings over 23 m (75 ft) tall.
- Radio coverage for emergency responders within the building to be as effective as public safety communication systems at the exterior of the building.
- Installed stair descent devices for use by mobility-impaired occupants.
- Structural design that meets the provisions in a new standard designed to keep modest local damage from resulting in the collapse of the entire building.

Many of these responses to the NIST recommendations have been incorporated into the Freedom Tower and the re-built WTC 7.

Additional Reading:

- Gann RG, ed. 2005. 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 Towers, NIST NCSTAR 1, National Institute of Standards and Technology, Gaithersburg, MD. https://doi.org/10.6028/NIST.ncstar.1.
- Gann RG, ed. 2008. Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Final Report on the Collapse of World Trade Center Building 7, NIST NCSTAR 1A, National Institute of Standards and Technology, Gaithersburg, MD. https://doi.org/10.6028/NIST.NCSTAR.1a.
- Phan LT, McAllister TP, Gross JL, and Hurley MJ, eds. 2010. "Best Practice Guidelines for Structural Fire Resistance Design of Concrete and Steel Buildings." NIST TN 1681. Gaithersburg MD. National Institute of Standards and Technology. https://nvlpubs.nist.gov/nistpubs/technicalnotes/nist.tn.1681.pdf.
- Boss A. 2023. "New Building Standard Paves the Way for Collapse-Resistant Structures." Gaithersburg MD. National Institute of Standards and Technology. https://www.nist.gov/news-events/news/2023/06/new-building-standard-paves-way-collapse-resistant-structures.

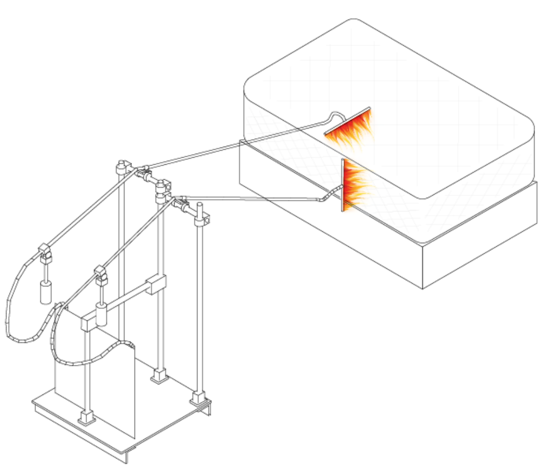
ELIMINATING DEATHS FROM FLAMING BED FIRES

Historically, bed fires were among the most hazardous fires in homes. These fires represented only 3 % of the fires in the United States but resulted in 16 % of the fatalities. Concerned about the prominent role of mattresses in flaming fires, the International Sleep Products Association (ISPA) teamed with NIST and the two regulatory authorities, the Consumer Product Safety Commission (CPSC) and the California Bureau of Home Furnishings and Thermal Insulation (BHFTI) (now the California Bureau of Household Goods and Services) to develop a fire safety regulation for mattresses.

The mattress industry redesigned their products to comply with a federal regulation, which is based on a NIST-developed test method. Fatalities from flaming bed fires decreased by about two-thirds within a decade, a period over which two-thirds of the pre-regulation mattresses had been replaced.

Reducing the hazard from a burning bed posed a difficult engineering and regulatory challenge since a made-up bed consists of multiple products purchased separately from different manufacturers. The mattress is typically supported on an upholstered or metal foundation and is surrounded by bedclothes (such as sheets, a blanket or comforter, and pillows). Measuring the fire contribution of each of the bed components was possible. However, determining how to burn each of these components separately and then combine their individual fire performance to represent the burning behavior of an assembled bed was beyond even today's scientific capability.

Beginning in 1999, NIST staff developed a more pragmatic approach, treating a set of bedclothes as a single product. The real-life ignition source (e.g., a match or candle) would ignite the bedclothes which would, in turn, become the (much larger) fire to which the mattress and foundation were exposed. NIST experiments with a variety of bedclothes sets led to the identification of a "standard" severely burning set of bedclothes and a map of where the most intense flames impacted the mattress and foundation. The staff then designed a twin burner that accurately and repeatably simulated the threat of the bedclothes fire to the mattress and foundation. The NIST test method involved exposing a mattress/foundation design to ignition by the burner and measuring the peak heat release rate (PHRR), the maximum heat generated as the bed burns, using oxygen consumption calorimetry. (See Page 16.)



Schematic of the twin burner being applied to a mattress/foundation set. (Credit: NIST)

Further testing and analysis led to the estimation of the PHRR of a "fire-safer" mattress/foundation. The PHRR from a non-conforming flaming bed was about 2 MW (twin-size) to 4 MW (king-size). At a heat release rate of about 1 MW in a modest-size bedroom, a local fire quickly involves all the other combustible materials in the room, the phenomenon called flashover. The environment within the fire room becomes lethal, and the fire and smoke spread to adjacent rooms and escape routes increases the risk of life loss elsewhere in the building. Data from the National Fire Incident Reporting System (NFIRS), maintained by the United States Fire Administration (USFA) and analyzed by the National Fire Protection Association (NFPA) and NIST, showed that reducing the potential for bedroom flashover should significantly reduce bed fire casualties.

The flames from the bed fire also had to be small enough that it was unlikely that nearby furnishings (e.g., an upholstered chair or a dresser) would be ignited, with the combined PHRR resulting in room flashover. NIST staff measured the heat required to ignite such items located at different distances from the burning bed. NIST's overall conclusion was that a mattress/foundation with a PHRR below 400 kW should limit fire spread and lead to a measurable and significant reduction in lives lost from flaming bed fires.

A California regulation by the BHFTI became effective on January 1, 2005. This was superseded by a federal regulation, 16 CFR Part 1633, issued by the CPSC, which became effective on July 1, 2007. The CPSC chose a limiting PHRR value of 200 kW during a 30-minute test. A requirement that the total heat released during the first 10 minutes of a test should not exceed 15 MJ further enhanced people's time for escape early in the fire. The manufacturers designed their new products, with ISPA providing examples of successful designs. The actual PHRR values of the compliant mattresses were typically below 100 kW.

In 2021, NIST analysis of the NFIRS database verified that this collaboration of fire scientists, product manufacturers, and regulators had been successful. By the end of the first decade of the low PHRR mattress sales, the annual number of lives lost from flaming bed fires had decreased by about two-thirds and reported injuries had decreased by about one-third. Using ISPA sales data and different models for mattress replacement by consumers, NIST estimated that two-thirds of the old mattresses had been replaced over the 10 years. These comparable values of avoided fatalities and old mattresses replaced suggest that when all pre-standard mattresses have been replaced, fatalities from flaming bed fires will become uncommon.

Additional Reading:

- Ohlemiller TJ, Shields JR, McLane RA, and Gann RG. 2000. "Flammability Assessment Methodology for Mattresses," NISTIR 6497, Gaithersburg MD. National Institute of Standards and Technology, 95 pp. https://doi.org/10.6028/NIST.IR.6497.
- Ohlemiller TJ and Gann RG. 2002. "Estimating Reduced Fire Risk Resulting from an Improved Mattress Flammability Standard," NIST Technical Note 1446, Gaithersburg MD. National Institute of Standards and Technology, 81 pp. https://doi.org/10.6028/NIST.TN.1446.
- 16 Code of Federal Regulations Part 1633. 2006. Consumer Product Safety Commission. Final Rule Standard for the Flammability (Open Flame) of Mattress Sets. Federal Register 2006:71(50):13472. https://www.ecfr.gov/current/title-16/chapter-II/subchapter-D/part-1633.
- Gilbert SW, Butry DT, Davis RD, and Gann RG. 2021. "Estimating the Impact of the Fire Safety Standard 16 CFR Part 1633 on Bed Fire Outcomes." Fire and Materials: 45(1)17-27; https://doi.org/10.1002/fam.2932.
- National Fire Incident Reporting System (NFIRS). https://www.usfa.fema.gov/nfirs/about.

STANDARD REFERENCE CIGARETTES FOR IGNITION TESTS

Even before the passage of the Federal Fire Prevention and Control Act of 1974, cigarettes were known to be the most common ignition source in fatal fires in the United States. While initial research and regulation focused on the ignited objects (beds and upholstered furniture), in the 1980s attention shifted to the cigarette itself. By 1993, research had established that reducing the ignition propensity of cigarettes (the likelihood that a cigarette would ignite another flammable object) was feasible and had developed prototypes of test methods to measure ignition propensity. In 2000, a major cigarette manufacturer successfully test-marketed a cigarette with reduced ignition propensity. In 2001, the State of New York Office of Fire Prevention and Control and NIST commenced research to support the first-ever rule requiring all cigarettes to be of reduced ignition propensity. In 2002, the NIST test method became an ASTM International (ASTM) standard, ASTM E2187; and on July 1, 2004, the New York rule went into effect. By 2011, there were similar regulations in all other U.S. States, generally citing the 2009 version of ASTM E2187.

NIST Standard Reference Material® (SRM) cigarettes have established and stabilized the difference in ignition propensity between the strong cigarettes used to test upholstered furniture and beds for ignition resistance and the required low ignition strength cigarettes for smoking. The two SRMs are a keystone in the substantial reduction in fatalities from cigarette-initiated fires.

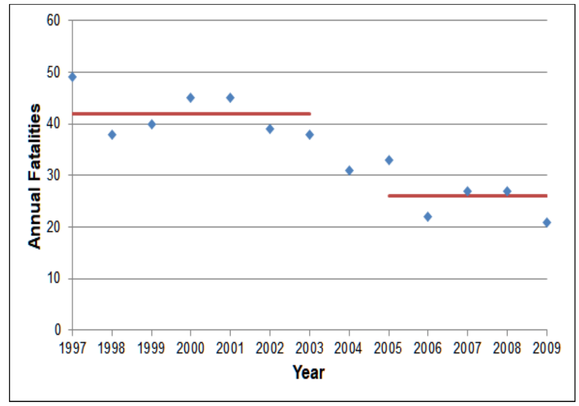
Results of trials (left to right): full-length burn of a non-FSC filter-tip cigarette; a non-FSC, non-filter-tip cigarette, and an FSC cigarette. (Credit: NIST)

Schematic of a cigarette showing the bands in the wrapping paper to slow burning rate. (Credit: NIST)

In the NIST test method, a trial begins when a lit cigarette is placed on a substrate composed of 10 sheets of filter paper. The outcome of a trial is whether the cigarette burns its full length or goes out. The figure on the left shows the results of trials of three distinct types of cigarettes. The test output is the percentage of 40 trials that result in a full-length burn (PFLB). The regulatory criterion is that the PFLB be no greater than 25. The packs of compliant cigarettes are labeled FSC, for fire standard compliant.

In today's commercial cigarettes, the paper wrapping the tobacco column typically contains circumferential bands. A band reduces the air passing through the paper to the smoldering tobacco, slowing the burning rate. Concurrently, some of the heat from the combustion is absorbed by the filter paper substrate. Both processes lower the temperature of the smoldering zone. The cigarette goes out when this temperature becomes too low for the tobacco to continue smoldering.

For the State regulations to be effective, it is essential that there be a "calibrator" for the test laboratories; and NIST developed specifications for and procured a large supply of a Standard Reference Material® (SRM) cigarette, designated SRM 1082. This ensures that (a) manufacturers and regulators all obtain the same PFLB for each commercial cigarette brand-style and (b) the performance of each laboratory performing the test does not change over time. The ASTM E2187 output value of SRM 1082 is 12.6 ± 3.3 PFLB, a value that is safely below the regulatory pass/fail criterion. SRM 1082 cigarettes became available in April 2005. Subsequent versions of ASTM E2187 require verifying the performance of the total test system and operator using a cigarette whose ignition propensity using ASTM E2187 has been established, noting that SRM 1082 is widely used for this purpose. The State of New York used SRM 1082 for quality control in its testing of more than 1,000 off-the-shelf brand-styles of cigarettes to verify compliance with its rule.



Annual fatalities from cigarette-initiated fires in the State of New York. (Credit: NIST)

Packs of standard reference cigarettes. (Credit: NIST)

The success of the regulations soon became clear. New York State experienced a 40 % decline in fatalities from cigarette-ignited fires. Five independent analyses of state or federal data averaged 30 % declines.

Meanwhile, NIST staff recognized that sustaining the life safety gains from these laws required that the commercial test cigarette (CTC) used in bed and furniture testing be a much stronger igniter than the FSC cigarettes. Two occurrences reinforced this need. NIST staff found that the PFLB values for CTC packs made from 1992 through 2008 had decreased by nearly half; and in 2008 the CTC manufacturer said that it would only make the FSC version, a low ignition strength cigarette.

The creation of a second SRM cigarette, SRM 1196, resolved both issues. Its specifications were based on the performance of the 1992 CTC, restoring the fire safety improvement that might have been lost due to the weaker CTCs. The purchase of a large supply of SRM 1196 cigarettes obviated such changes in test severity in the future. This SRM became available in September 2010. When the supply of the SRM approached depletion, NIST procured a replenishment batch, SRM 1196a.

The respective test standards now include the use of SRM 1196 or equivalent to calibrate the testing of mattress and furniture materials.

Additional Reading:

- Jones-Smith J and Harwood B. 1993. “Overview: Practicability of Developing a Performance Standard to Reduce Cigarette Ignition Propensity.” Bethesda MD. Consumer Product Safety Commission. https://www.nist.gov/system/files/documents/el/fire_research/Overview_Cigarette_Report.pdf.
- ASTM International. 2002. ASTM E2187, Standard Test Method for Measuring the Ignition Strength of Cigarettes. West Conshohocken PA. ASTM International. Current edition: 2024.
- Gann RG, Kim I, Lund SP, Guthrie WF, Robbins AR, Hnetkovsky EJ, and Davis RD. 2021. “The Roles of Standard Cigarettes in Assuring the Ignition Resistance of Soft Furnishings,” Fire and Materials 45:37-55. https://doi.org/10.1002/fam.2931.
- Standard Reference Materials. National Institute of Standards and Technology. https://www.nist.gov/srm.

PERFORMANCE OF FIREFIGHTING EQUIPMENT AND TACTICS

Firefighter line of duty injuries and deaths due to equipment failures and ineffective firefighting tactics raised alarms at fire departments, the National Institute of Occupational Safety and Health (NIOSH), the National Fire Protection Association (NFPA), the United States Fire Administration (USFA), and NIST. Prompted by these concerns, NIST researchers began conducting studies in the 1990s to reduce the risk to firefighters and the losses from the fires they attend. The following are recent successes in the research and the implementation of the results.

NIST has provided the technical basis for upgrading firefighting equipment standards that protects firefighters. NIST has applied fire dynamics to firefighting, leading to new and modified tactics that the fire service has adopted. The continuing benefit has been safer, more effective firefighting.

Personal Alert Safety Systems (PASS) When firefighters stop moving, their PASS devices alarm, indicating a possible emergency. Deaths have occurred when the device's signal could not be heard, and the firefighter could not be located. NIST found that some devices failed to operate properly at elevated fireground temperatures. NIST alerted NIOSH, which issued an emergency safety warning. Based on NIST input and data, a new requirement for operation at high temperature was added to the 2007 edition of NFPA 1982, Standard on Personal Alert Safety Systems.

Thermal Imaging Cameras These devices visualize heat from building occupants and firefighters, as well as hot spots from the fire. The camera images must distinguish these heat sources from a warm background while operating at elevated fireground temperatures. Initially there was no standard test or performance criteria for camera capability. NIST staff developed a test for determining how well and for how long a camera could detect a small temperature difference when the camera itself was at temperatures up to 260 °C (500 °F). These results became the technical basis for elevated temperature testing in the first edition of NFPA 1801, Standard on Thermal Imagers for the Fire Service in 2010. A fire department could now obtain these life-saving tools with certified precision.

Portable Radios Firefighters reported that some of their radios were unable to transmit information during fireground operations, which impedes fireground operations. NIST identified that the problem was due to a drift in radio transmission frequency at fireground temperatures. Data from these studies and input from the NIST researchers provided the technical foundation for the radio performance criteria in the 2021 first edition of NFPA 1802, Standard on Two-way, Portable RF Voice Communications Devices for use by Emergency Services Personnel in the Hazard Zone.

Self-Contained Breathing Apparatus (SCBA) Firefighters reported incidents of SCBA facepieces becoming opaque or melting during firefighting. Using room-scale experiments combined with computer modeling, NIST determined that the distortions resulted from exposure to high radiant heat flux from the hot fire environment. The staff then developed a radiant heat test and performance criteria for NFPA 1981, Standard on Open-Circuit Self-contained Breathing Apparatus (SCBA) for Emergency Services. As a result, new firefighter masks continue to protect the firefighter and their vision during fireground operations.

Fire-Dynamics-based Firefighting Between the late 1970s and the late 2000s, reported fires in structures had decreased by half, while firefighter fireground fatalities per 100,000 fires had increased by two thirds. The reasons were that (a) houses had become larger, with less air leakage (for energy efficiency), lightweight construction, and less compartmentation; and (b) the mass and burning rates of the furnishings had increased. The classic fire triangle shows that a fire needs fuel, air, and heat. Fire dynamics, the science of how fires start, spread, develop, and extinguish, adds the concept of rate: fires were growing faster from an early, fuel-limited state to an oxygen-limited state. The fire service needed to gain an understanding of the synergy among these changing factors and to adapt firefighting operations and training accordingly.

Over the past 20 years, NIST conducted research with the fire service to bring fire dynamics into the process of fighting today's fires. At the core was the concept of *wind-aided flame spread*. An oxygen-limited fire burns faster when a new supply of oxygen arrives, e.g., through an opened door or a broken window. This new air supply creates a *flow path*, the space between an inlet and an outlet through which heat and smoke move from a higher pressure to a lower pressure. The message was clear for firefighters: keep the wind or intake air at your back.

Fighting a fire burning in a wood-framed basement can be especially hazardous to firefighters on the floor above. NIST found that the large mass of wood in the basement can escalate a fire's intensity, while the insulation of common floor materials can keep main floor temperatures below 100 °C. Thus, even with a thermal image camera, firefighters might be unaware of the fire below their feet until they fall through the floor. Historically, firefighters fought their way down the stairs to suppress a fire. By doing this, they place themselves in the flow path from the fire in the basement to the open front door through which they had entered the house, a dangerous situation. NIST and Underwriters Laboratories (UL) conducted basement fire experiments, finding that applying water through a window into the fire area for just 60 seconds quickly mitigated both hazards.

NIST research has spawned a new approach to fire operations based on fire dynamics, validated with real-building tests, and delivered in a visually compelling manner via formal reports, compact discs, videos of the tests, streaming on multiple channels, and presentations to fire service organizations. Several of these studies have been incorporated into such training as the International Association of Fire Fighters' Fireground, Survival Course and courses taught by the USFA. The leadership of the Fire Department of the City of New York (FDNY) quickly added the fire dynamics-based findings to their firefighter training. In 2021, NFPA published the first edition of NFPA 1700, Guide for Structural Fire Fighting.

Additional Reading:

- Donnelly MK, Davis WD, Lawson JR, and Selepak MJ. 2006. "Thermal Environment for Electronic Equipment Used by First Responders." NISTIR 1474, Gaithersburg MD. National Institute of Standards and Technology. https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=101375.
- Donnelly MK, Davis MK, and Selepak MJ. 2007. "Performance of Thermal Imaging Cameras in High Temperature Environments." NIST TN 1491. Gaithersburg MD. National Institute of Standards and Technology. https://nvlpubs.nist.gov/nistpubs/Legacy/TN/nbstechnicalnote1491.pdf.
- Donnelly MK, Young WF, and Camell D. 2014. "Performance of Portable Radios Exposed to Elevated Temperatures." NIST TN 1850. Gaithersburg MD. National Institute of Standards and Technology. http://dx.doi.org/10.6028/NIST.TN.1850.
- Putorti A, Mensch A, Bryner N, and Braga G. 2013. "Thermal Performance of Self-Contained Breathing Apparatus Facepiece Lenses Exposed to Radiant Heat Flux." NIST TN 1785. Gaithersburg MD. National Institute of Standards and Technology. http://dx.doi.org/10.6028/NIST.TN.1785.
- Kerber S and Madrzykowski D. April 2009. "Evaluating Fire Fighting Tactics Under Wind Driven Conditions." 2-DVD set, available from the Fire Research Division, National Institute of Standards and Technology.
- Madrzykowski D. 2013. "Fire Dynamics: The Science of Fire Fighting." International Fire Service Journal of Leadership and Management 7:1-16. https://www.ifsjlm.org/sites/default/files/past-edition-pdfs/IFSJLM_Vol7.pdf.

UPGRADED SMOKE ALARM PERFORMANCE STANDARDS

New standards for smoke alarms and detectors, largely informed by NIST research, enhance their sensitivity to both smoldering and flaming fires, while reducing sensitivity to nuisance smoke from cooking. These advancements are expected to reduce fire severity and save lives.

After decades of declining fatalities from home fires, the numbers have been stable for the last 15 years. The smoke alarm technologies of the 1970s (ionization and photoelectric) had been remarkably effective in reducing losses from nearly all types of home fires. (See Page 14.) Since then, homes and the combustible products within them have evolved. For example, open floor plans became more common, the mass of combustibles increased, and furnishings became padded with faster burning flexible polyurethane foam (FPUF). Nuisance alarms, mostly from cooking, were common, and occupants responded by deactivating the stand-alone smoke *alarms* (whose operation is specified in ANSI/UL 217) and the smoke *detectors* (whose operation is specified in ANSI/UL 268) which transmit their fire "awareness" to a central control panel.

In the 1990s, NIST began formulating a plan to investigate smoke alarm performance in prevalent fire scenarios using modern furniture. NIST enlisted the Consumer Product Safety Commission, the United States Fire Administration, the Centers for Disease Control and Prevention, the Department of Housing and Urban Development, UL, the National Fire Protection Association, the National Research Council of Canada, the University of Maryland, and the smoke alarm manufacturers to guide this effort. In 2004, NIST reported the results of those small- and real-scale tests of residential smoke alarms. The measurements of temperature, smoke obscuration, and gas concentrations provided both insight into the functioning of the devices and a set of reference data from fires of current materials for evaluating future enhancements to alarm technology. This study also established that the times available for escape were far shorter than those from the 1970s. By 2008, the Underwriters Laboratories Inc. (UL) UL 217/268 Standards Technical Panel had formed a task group to discuss new fire tests and standards for the next generation of fire sensing.

NIST then conducted further research on smoke alarm response to flaming and smoldering upholstered chair fires, including the creation of a severe (cooked to well-done) and repeatable cooking activity representative of cooking nuisance sources. NIST also modeled the smoke concentrations at the ceiling (where smoke alarms are typically located) at the time when the smoke levels at head height were still low enough for occupants to escape. This would guide setting alarm activations to improve the odds of escape. The UL Panel used these data to arrive at three new room-scale tests to measure the sensitivity of a new generation of smoke alarm designs:

- Flaming of a flexible polyurethane foam (FPUF) used in furnishings,
- Smoldering of the same FPUF, and
- Broiling of two frozen hamburgers – a nuisance source.

The first two tests each include a low smoke concentration above which a device must alarm. These values took advantage of the UL finding that the optical properties of FPUF smoke differed from those of the cotton and heptane pool used in the original acceptance testing of smoke alarms. The third test included a smoke concentration below which the device must not alarm. NIST's role as an unbiased source of research was instrumental in gaining approval of the changes.

The result is a new set of *performance-based* requirements for ANSI/UL 217 and ANSI/UL 268 that are technology-independent and increase the time available for escape while enabling innovation in smoke alarm design. It is up to the manufacturers to devise how to meet the requirements in the new standard.

Finally, NIST assessed whether the new performance tests would demonstrably enhance smoke alarm performance compared to the currently available smoke alarms and whether the single nuisance source test is representative of a range of cooking nuisance scenarios. The smoke alarm models tested were from seven manufacturers and included both single-sensor and dual-sensor devices. None of the tested models would likely meet the FPUF test performance levels required in the updated ANSI/UL 217-2015. The broiling hamburgers test was considered to be a conservative test since it also challenged the majority of alarm models.

The 8th edition of ANSI/UL 217, which includes these new fire tests and acceptance criteria, was issued in October 2015, and the 7th edition of ANSI/UL 268 with the same suite of tests and acceptance criteria was approved and issued in January 2016. As of June 30, 2024, all new alarms and detectors must meet the new Standards.

Expectations for the new generation of residential smoke alarms are high since the certification requirements are based on solid science and verified in real-scale tests. Reductions in fire fatalities will be realized as building and fire codes cite the new standards, jurisdictions adopt the updated new codes, and consumers replace their old devices.

Additional Reading:

- McGree T. 2024. Smoke Alarms in U.S. Home Fires. Quincy MA. National Fire Protection Association. https://www.nfpa.org/education-and-research/research/nfpa-research/fire-statistical-reports/smoke-alarms-in-us-home-fires.
- Bukowski RW, Peacock R, Averill JD, Cleary TG, Bryner NP, Walton WD, Reneke PA, and Kuligowski ED. 2007. “Performance of Home Smoke Alarms, Analysis of the Response of Several Available Technologies in Residential Fire Settings.” NIST Technical Note 1455-1. Gaithersburg MD. National Institute of Standards and Technology. https://nvlpubs.nist.gov/nistpubs/Legacy/TN/nbstechnicalnote1455-1r2007.pdf.
- Cleary TG, 2010. “An Analysis of the Performance of Smoke Alarms,” Fire Safety Science 10:823-836. https://doi.org/10.3801/IAFSS.FSS.10-823.
- Cleary TG and Chernovsky A. 2013. “Smoke Alarm Performance in Kitchen Fires and Nuisance Alarm Scenarios.” NIST Technical Note 1784. Gaithersburg MD. National Institute of Standards and Technology. https://dx.doi.org/10.6028/NIST.TN.1784.
- Cleary TG. 2014, “Performance of Dual Photoelectric/Ionization Smoke Alarms in Full-Scale Fire Tests.” Fire Technology 50(3): 753-773. https://doi.org/10.1007/s10694-010-0147-z.
- Cleary TG. 2014., “Improving Smoke Alarm Performance – Justification for New Smoldering and Flaming Test Performance Criteria.” NIST Technical Note 1837. Gaithersburg MD. National Institute of Standards and Technology. https://dx.doi.org/10.6028/NIST.TN.1837.
- ANSI/UL 217, Safety Standard for Single- and Multiple-Station Smoke Detectors. 2015. Northbrook IL. Underwriters Laboratories, Inc. Latest version: 2025.
- Cleary TG. 2016. “A Study on the Performance of Current Smoke Alarms to the New Fire and Nuisance Tests Prescribed in ANSI/UL 217-2015.” NIST Technical Note 1947. Gaithersburg MD. National Institute of Standards and Technology. https://dx.doi.org/10.6028/NIST.TN.1947.

WILDLAND-URBAN INTERFACE FIRE LOSS MITIGATION

NIST has been a leader in researching fires at the wildland-urban interface, consistently translating this knowledge into actionable solutions through the development of measurement tools, code guidance, and best practices.

For millions of years, wildfires have been a natural and beneficial part of ecosystems. However, as the global human population has grown, so has the number of dwellings at the wildland-urban interface (WUI), which are areas where human development meets natural, undeveloped, terrain. Over the past 30 years, the spread of wildfires into built environments has escalated rapidly, leading to significant losses of property and lives. About one-third of housing units and more than 60,000 communities in the United States are currently at risk from WUI fires. Each year, these fires destroy thousands of structures and claim dozens of lives, with annual costs estimated in the hundreds of billions of dollars.

To gain reliable technical knowledge on the destructive nature of WUI fires, NIST invests in extensive fact-finding visits to post-fire sites. These efforts enable NIST to reconstruct events and gain insights that clarify how the fires unfold and thus understand how we might reduce WUI fire losses. NIST focuses on three key aspects of WUI fires: fire spread to and between buildings, protection of structures, and community-level planning efforts to protect against fire spread.

Fire Spread to and Between Buildings Fire spreads through the WUI via radiation, convection, and firebrands. NIST has applied its Fire Dynamics Simulator (See Page 20) to predict complex wildfire movement into contiguous fuel by radiant heat from flames and convection from hot fire gases. Fire radiation can ignite structures up to 100 m (300 ft) away. These simulations have also helped with planning intentionally set, hectare-size burns tp learn about WUI fire spread.

Firebrands, also called embers, are small pieces of burning material emitted by flaming trees and wooden structures. They are a major but previously overlooked factor in WUI fire spread. When carried aloft on wind currents, they can land on structures and create new fires several kilometers or miles ahead of the main fire.


NIST Dragon generating an ember shower. (Credit: NIST)

NIST has led studies to further understanding of firebrands and their behaviors. NIST staff created the NIST Firebrand Generator, also known as the "NIST Dragon." This device simulates wind-driven bombardment by firebrand showers. The NIST Dragon is the basis for the international standard ISO 6021, allowing labs worldwide to collect and share self-consistent data on firebrand behavior. NIST also created the "Emberometer" to measure firebrands in flight.

Protection of Structures Buildings are at risk from both fire and embers. NIST staff have studied how combustibles near a building, like landscaping, fences, and sheds as well as buildings themselves, can catch fire from flames and firebrands. Working with partners, NIST develops guidelines for protecting these combustible items, approaches to property maintenance, and recommendations for building codes to make homes in wildfire-prone areas more fire-resistant.

NIST found that embers can enter buildings through air vents and ignite materials inside. To study this, they worked with Japan's Building Research Institute, using the NIST Dragon to shower firebrands on a building inside a wind tunnel. Different vent grates were tested, and NIST staff found that firebrands stuck in the vent and burned until they fit through holes, including those less than 1 mm (0.04 in.). NIST continues to work with partners to create guidance on how to quantify these hazards.

Community Protection Fire behaves differently from other disasters. In the WUI, fires can spread rapidly through vegetation and structures. Since ample combustibles are stored within the community, even a small vulnerability to fire or embers can lead to the ignition and destruction of structures. This necessitates thorough hardening of both communities and individual buildings.

To address this, NIST, the California Department of Forestry and Fire Protection (CAL FIRE), and the Insurance Institute for Business & Home Safety (IBHS) developed the Hazard Mitigation Methodology (HMM). This science-based approach is built on data from post-fire observations, field analysis, and lab research. It considers factors like building separation and parcel layouts, showing how both community and structure hardening are essential for fire protection. CAL FIRE is using the HMM to retrofit six communities, an example that influences consideration by state and national codes. The United States Fire Administration (USFA) and NIST are working to make HMM part of the National Fire-Adapted Communities strategy. The International Code Council is also planning to include HMM principles in the next edition of the International Wildland-Urban Interface Code.

The ESCAPE methodology, which was issued by NIST in 2023 based on data from post-fire observations, focuses on evacuating small and intermediate WUI communities, including sheltering when there's not enough time to evacuate fully. ESCAPE is the only national WUI evacuation guide and is already being used by 30 California communities.

Additional Reading:

- Crowley C, Miller A, Richardson R, and Malcom J. 2023. “Increasing Damages from Wildfires Warrant Investment in Wildland Fire Management.” Washington DC. U.S. Department of the Interior Office of Policy Analysis. https://www.doi.gov/sites/doi.gov/files/ppa-report-wildland-fire-econ-review-2023-05-25.pdf.
- Rehm RG and Mell W. 2009. “A Simple Model for Wind Effects of Burning Structures and Topography on Wildland–urban Interface Surface-fire Propagation.” International Journal of Wildland Fire 18(3) 290-301. https://doi.org/10.1071/WF08087.
- Manzello SL, Suzuki S, Gollner MJ, and Fernandez-Pello AA. 2020. Role of Firebrand Combustion in Large Outdoor Fire Spread. Progress in Energy and Combustion Science 76(1). https://doi.org/10.1016/j.pecs.2019.100801.
- ISO 6021.2024. Firebrand Generator. Geneva. International Standards Organization.
- Maranghides A, Link ED, Mell WR, Hawks S, McDougald J, Quarles SL, Gorham DJ, and Nazare S. 2022. “WUI Structure/Parcel/Community Fire Hazard Mitigation Methodology.” NIST TN 2205. Gaithersburg MD. National Institute of Standards and Technology. https://doi.org/10.6028/NIST.TN.2205
- Maranghides A and Link ED. 2024. “WUI Fire Evacuation and Sheltering Considerations: Assessment, Planning and Execution: ESCAPE.” Presentation to the California Building Industry Association. https://cbia.org/wp-content/uploads/2024/04/Evacuation-Scenario-Considerations-Assessment-Planning-and-Execution-CBIA.pdf.
- “NIST’s Emberometer Could Gauge Threat of Wildfire-Spreading Embers.” August 18, 2021. https://www.nist.gov/news-events/news/2021/08/nists-emberometer-could-gauge-threat-wildfire-spreading-embers.

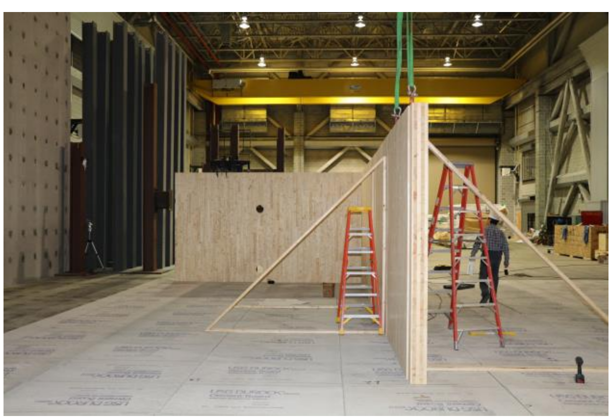
FIRE BEHAVIOR OF BUILDING CONSTRUCTION

A central objective of fire engineering is the prevention of structural collapse during uncontrolled fires. Room-scale testing at NIST in the early 20th century established a standard temperature-time exposure and fire endurance ratings for individual building construction elements. These ratings are central to building codes. Structural engineers have since found that properly designed composites of construction elements can achieve great stability, often at lower cost. Verification of enhanced performance has enabled the use of innovative building designs and materials. Accordingly, over the past century, the experimental facility for making such measurements has been expanded at NIST from the modest single compartment of the 1910s to the current multi-floor, multi-room National Fire Research Laboratory (NFRL).

NIST researchers have gathered data from large-scale tests on new building systems exposed to real fires. Understanding how fire weakens structures and causes them to fail is helping make buildings stronger and safer during severe fires, giving people more time to escape.

Completed in 2015, the NFRL allows researchers to conduct large fire experiments with well-characterized measurement of heat release rate while simultaneously applying mechanical loading (horizontal and vertical forces) to a structure. By testing entire structural systems, the effects of nearby parts of the building on the heated part and complex connection behaviors, like that between columns and girders, are included. Rather than studying fire endurance ratings resulting from standard fire temperature-time exposure, structural systems can be pushed to the point of failure and through controlled collapse during realistic fires. This allows engineers to understand how close the point of collapse can be safely approached and how collapse will progress if the building is stressed beyond its structural design limits. This leads to more resilient and economical building design.

The following three examples show how research conducted in the NFRL has contributed to the advancement of building codes and our understanding of structural performance in fire.



Construction of a CLT structure in the NFRL. (Credit: NIST)

In 2017, NIST staff, in collaboration with the National Research Council Canada (NRCC) and the National Fire Protection Association (NFPA) Fire Protection Research Foundation (FPRF), conducted large-scale experiments to study the impact of fires on Cross-Laminated Timber (CLT). CLT is glued layers of lumber with the grain of each layer at a right angle to its neighbors. CLT can enable faster and more sustainable construction. Concerns about fire growth and insufficient data on structural integrity hindered building code revisions allowing the use of CLT in buildings over six stories. These experiments helped establish the amount of CLT that can be safely exposed under various conditions, leading to an addition to the ANSI/APA PRG 320 standard and facilitated changes to the International Building Code to expand CLT use in North America.

In the aftermath of a strong earthquake, fires are often ignited due to damaged infrastructure or building contents, compounding the original hazard. In 2019, NIST examined the resistance to the horizontal force of steel wall construction under combined simulated earthquake and realistic fire conditions. The results provide guidance for the design of walls when significant lateral deformation is expected, to promote structural stability in the case of fire following earthquakes.

Result of a test of a steel wall under earthquake and fire conditions. (Credit: NIST)

Culminating in 2022, NIST's multiyear study examined how steel-concrete composite floor systems in steel-framed buildings react to fire and what causes them to fail. From tests of a full-scale, two-story steel frame with realistic connections and slabs, the research confirmed that steel reinforcement in the concrete is crucial for maintaining the integrity of composite floors under fire conditions. However, the minimum amount of steel reinforcement required by United States standards for ambient conditions may not be enough to keep the slab intact during a structurally significant fire. These experimental results are currently used for validation of high-fidelity numerical models to perform parametric studies and develop engineered design solutions, a necessary step in the performance-based design (AISC 360 Appendix 4, ASCE 7 Appendix E and ASCE Manual of Practice 138) of steel framed buildings subjected to fire. These results also provide insight into the fire performance and residual strength of a prescriptive code compliant floor assembly meeting the requirements of ASTM E119 and UL 263.

Construction of a steel-concrete composite floor for fire testing in the NFRL. (Credit: NIST)

Additional Reading:

- Bundy M, Hamins A, Gross J, Grosshandler W, and Choe L. 2016. "Structural Fire Experimental Capabilities at the NIST National Fire Research Laboratory." Fire Technology 52:959–966. https://doi.org/10.1007/s10694-015-0544-4.
- Su J, Lafrance P-S, Hoehler MS, and Bundy MF. 2018. "Fire Safety Challenges of Tall Wood Buildings – Phase 2: Task 2 & 3 – Cross Laminated Timber Compartment Fire Tests," FPRF-2018-01. Quincy MA. Fire Protection Research Foundation. https://www.nist.gov/system/files/documents/2018/02/14/task_2_3_report_-_clt_compartment_fire_tests.pdf.
- ANSI/APA PRG 320-2018. 2018. "Standard for Performance-Rated Cross-Laminated Timber." Tacoma WA. APA – The Engineered Wood Association. https://www.apawood.org/ansi-apa-prg-320.
- Hoehler MS, Andres B, and Bundy MF. 2019. "Influence of Fire on the Lateral Resistance of Cold-Formed Steel Shear Walls – Phase 2: Oriented Strand Board, Strap Braced, and Gypsum-Sheet Steel Composite." NIST Technical Note 2038. Gaithersburg MD. National Institute of Standards and Technology. https://doi.org/10.6028/NIST.TN.2038.
- NIST News. 2020. "How Fire Causes Office-Building Floors to Collapse." https://www.nist.gov/news-events/news/2020/03/how-fire-causes-office-building-floors-collapse.