# Executive Summary

According to estimates by the National Fire Protection Association and the U. S. Fire Administration, U. S. home usage of smoke alarms rose from less than 10 % in 1975 to at least 95 % in 2000, while the number of home fire deaths was cut nearly in half. Thus the home smoke alarm is credited as the greatest success story in fire safety in the last part of the $20^{th}$ century, because it alone represented a highly effective fire safety technology with leverage on most of the fire death problem that went from only token usage to nearly universal usage in a remarkably short time. Other highly effective fire safety technologies either affect a smaller share of the fire death problem (e.g., child-resistant lighter, cigarette-resistant mattress or upholstered furniture) or have yet to see more than token usage (e.g., home fire sprinkler, reduced ignition-strength cigarette).

A seminal component that underpinned this success was the existence of a comprehensive, independent set of tests conducted in 1975-76 that clearly demonstrated the potential of smoke alarms to save lives. These were the so-called Indiana Dunes tests sponsored by The National Institute of Standards and Technology, NIST, (then the National Bureau of Standards) and conducted by Illinois Institute of Technology Research Institute and Underwriters Laboratories.

In the past few years questions were being raised about the efficacy of some smoke alarm technologies, whether the numbers and locations in homes still represented the optimum configuration, and if multi-sensor designs (as are becoming popular for commercial fire alarm systems) might perform better or produce fewer nuisance alarms. Some simply thought that it was time to reexamine the technology in light of its importance to public safety. To this end a consortium of four federal agencies and Underwriters Laboratories (with in-kind support from several others) funded this project.

The present work followed a design similar to that used in the Indiana Dunes tests. Tests were conducted in actual homes with representative sizes and floorplans, utilized actual furnishings and household items for fire sources, and tested actual smoke alarms currently sold in retail stores. Smoke alarm performance was quantified in terms of the escape time provided by groups of alarms installed in accordance with typical code provisions. While some of the smoke alarms were modified by their manufacturers to provide continuous, analog output from their sensors (which allowed the analysis of the performance of multi-sensors and decision algorithms) these were compared to identical models purchased from retail stores and included in all tests. Additionally a separate study of nuisance alarm sources was conducted because this was identified as an important issue in a prior study by the U.S. Consumer Product Safety Commission.

The fire emulator/detector evaluator (FE/DE) is a single-pass "wind tunnel" at NIST designed to reproduce all relevant conditions needed to assess the performance of spot-type particulate, thermal and gas sensor detectors or combination detectors. Specifically, the FE/DE allows for the control of the flow velocity, air temperature, gas species, and aerosol concentrations at a test section wherein detectors and sensors are exposed to these environmental conditions . Included in this report are complete data from tests conducted in the FE/DE apparatus and calibrations for all of the alarms and detectors used in this study. Calibration in the FE/DE of the alarms used in the current study showed that the sensitivity of the alarms was consistent with manufacturer ratings and, on average, of equivalent sensitivity to those used in the 1975 study. The average sensitivity measured for all alarms tested was 5.1 %/m ± 1 %/m (1.5 %/ft ± 0.4 %/ft). In the 1975 study, the average of all alarms tested was 6.3 %/m ± 2 %/m (1.9 %/ft ± 0.7 %/ft). While the average for the 1975 tests is higher, the uncertainty in the data overlaps.

An analysis of residential fire statistics was conducted for this study to identify the important fire scenarios that were included in the study. Flaming and smoldering upholstered furniture and mattresses account for the top four most deadly fire scenarios. Flaming cooking materials are involved more than five times more frequently than any other material. These scenarios included the top five ranked by number of deaths, and among the top ten ranked by frequency of occurrence.

Fire produces heat, smoke, and toxic gases, all of which can threaten human life. In these experiments environmental parameters that have an impact on human response were measured. Parameters include temperature rise, toxic gas production, and smoke obscuration. Aspects of these that can be measured directly include the gas temperature, mass loss of the burning item, species concentrations, including CO, $CO_2$, $O_2$, and other gases. Two different geometries of residential structures were used for the tests. The manufactured home geometry represented an array of residential layouts. The arrangement of the manufactured home was sufficiently generic as to represent an apartment, condominium, or small ranch house, in addition to a manufactured home, although it did include a sloped ceiling throughout the structure. The primary partitioning of the 84.7 $m^2$ (911 $ft^2$) home consisted of three bedrooms, one full bathroom, one kitchen/dining area, one living room, and two hallways. The 139 $m^2$ (1495 $ft^2$) two-story home was a brick-clad 3 bedroom home. The first floor consisted of a foyer, den, family room, kitchen, dining room, bathroom, and stairwell to the upstairs. The home did not have a basement. The 2-car garage was accessible from the first floor den. The second floor consisted of a stairwell to the downstairs, hallway, 2 bathrooms, and two smaller bedrooms and one master bedroom. A total of 36 tests were conducted in the two homes; 27 in the manufactured home, and 8 in the 2-story home.

The experimental design provided data on the performance of alarms in various installation arrangements. Groups of alarms were located in the room of fire origin, at least one bedroom, and in a central location on every level. Thus, by considering the alarm times of devices in various locations against tenability times for any test it was possible to determine the escape time provided by various installation arrangements including every room, every level with or without every bedroom, and single detectors. Since both ionization and photoelectric types were included at each location the performance by sensor type was also quantified.

Smoke alarms of either type installed on every level generally provided the necessary escape time for different fire types and locations. Adding smoke alarms in bedrooms increased the escape time provided, especially for smoldering fires. These tests quantified an increased escape time for fires starting in the bedroom.

The results obtained were similar to those of the earlier work. Both common residential smoke alarm technologies (ionization and photoelectric) provided positive escape times in most fire scenarios with the ionization type reacting earlier to flaming fires and the photoelectric type reacting earlier to smoldering fires. The main difference from the earlier work is that the amount of escape time provided is consistently less. For example, average times to untenable conditions for flaming tests was 3 min compared to 17 min in the prior work. While some of this difference may be attributed to the tenability criteria used in the current study, it is also clear that fire growth in the current tests are significantly faster than in the earlier tests. For flaming fire, time to alarm activation and measurement of elevated temperatures in the room of fire origin support this faster fire growth observation. However, the smoldering fire scenarios are very difficult to reproduce experimentally and tenability times in the present study have an uncertainty (based upon one standard deviation) which overlaps the uncertainty from the 1975 study. Therefore, caution should be exhibited in drawing conclusions based upon comparisons of smoldering tenability times between the two studies. It is important to note that while both the 1975 study and the current study attempted to use a representative sample of available and important furnishings, each study included only a small fraction of those available in the marketplace. Still, this study is consistent with other recent studies of furniture and mattresses, even though there may be significant differences in the burning behavior between items of furniture.

Activation times for other fire detection technologies were also collected. As expected, CO alarms respond best to fires which produce considerable quantities of carbon monoxide during the combustion process, i.e., smoldering fire scenarios and the closed-door flaming mattress (which smoldered after the room of fire origin became oxygen limited). Tell-tell sprinklers and heat alarms responded to the flaming fire scenarios as well as to the smoldering fire scenarios after a transition to flaming combustion. Activation times of these devices support the current practice of use only in conjunction with smoke alarms.

Nuisance alarms in residential settings from typical cooking activities, smoking or candle flames are affected by the properties of the aerosol produced and its concentration, the location of an alarm relative to the source, and the air flow that transports smoke to an alarm. This is not surprising, as the same observations have been made in the fire tests here and other studies. This study provides a detailed set of data that can be used to address several issues involving nuisance alarms and reinforces current suggested practices. Clearly, the advice that alarms not be installed close to cooking appliances if at all possible is valid. These results show that homeowners who are able to move the location of an alarm that frequently experiences nuisance alarms would do well to maximize its distance from cooking appliances while keeping it in the area to be protected. It was observed that ionization alarms had a propensity to alarm when exposed to nuisance aerosols produced in the early stages of some cooking activities, prior to noticeable smoke production. This phenomenon could be particularly vexing to homeowners who experience such nuisance alarms. Carbon monoxide electrochemical cells at all alarm locations gathered data on the level of carbon monoxide produced during the tests and transported to the alarms. These data in conjunction with the complete fire test series data could be used to verify combined smoke/CO alarm algorithms.

The FE/DE nuisance source tests captured salient features of some of the manufactured home tests. More work needs to be done to produce a set of tests and the performance criteria that covers a significant range of residential nuisance sources, and would assure a benefit in terms of nuisance alarm reduction. This work is part of ongoing research with the FE/DE at NIST. The nuisance alarm study also represents a wealth of data valuable in establishing (amazingly for the first time) test methods and criteria for what a smoke alarm should not respond to. Testing labs are examining NIST's unique FE/DE apparatus to replace the current, product specific test apparatus that do not allow multi-sensor devices to be evaluated.

The present work has produced an extensive database of documented data on typical residential fires. All data collected in the tests are available in electronic form (http://smokealarm.nist.gov) and are already being used by the smoke alarm industry to improve their products, by the product approval agencies to improve testing procedures, and by researchers to validate and improve fire models.

The present work has considerable potential for communicating important fire safety messages to the public. The material has been made freely available and NIST plans to produce examples and is willing to work with others wishing to do the same.