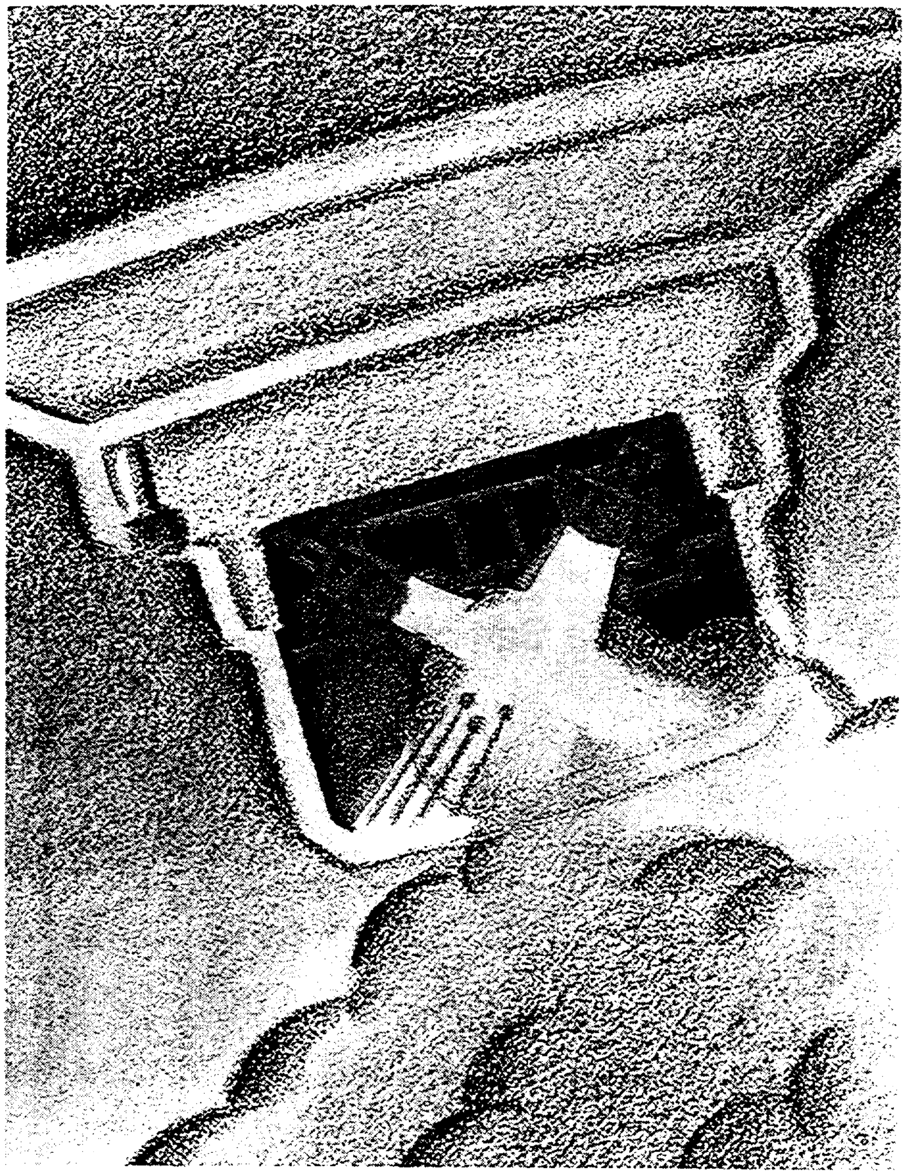


Richard W. Bukowski, P.E.

Studies Assess Performance of RESIDENTIAL

Current thinking on the performance of residential heat detectors compared to that of smoke detectors, as embodied in most U.S. codes, recently has been challenged.

This article assembles from the literature a comprehensive picture of what is known about the relative performance of these two detector types in residential fires. The studies cited here were identified in a recently published, comprehensive literature review[1] and are available in the open literature. In each case, the study has been summarized and its conclusions on heat and smoke detector performance are quoted.

Detector technology and standards during the 1960s

In the 1960s, the only fire detection devices available to homeowners specifically intended for use in the home were mechanically powered heat detectors, either the compressed-gas type or the spring-wound type.

These early devices, which originally were introduced to the market in 1955, had a UL space rating (an indicator of their sensitivity) of 25 feet, compared to the 70-foot rating of heat detectors being sold today. Using the relationship between the space rating and the time constant (τ) given in Table C-3.2.1.1 of the 1990 edition of NFPA 72E, *Automatic Fire Detectors*, this increase in space rating should equal an approximately fourfold increase in sensitivity.

The only smoke detectors then available were commercial-style photoelectric (scattering) types that were operated from a fire alarm control panel. These early photoelectric detectors demonstrated a slow response because their designs restricted smoke entry into the sensing chamber and because the typical 90° scattering angle was inefficient for the dark smoke particles that flaming combustion produced.

At that time, federal regulations required that installations of ionization-type detectors be individually licensed and that detectors be tested annually for leakage of the radioactive source material. After about 10 years of testing data indicated that no leakage ever occurred, these regulations were withdrawn in the late 1960s.

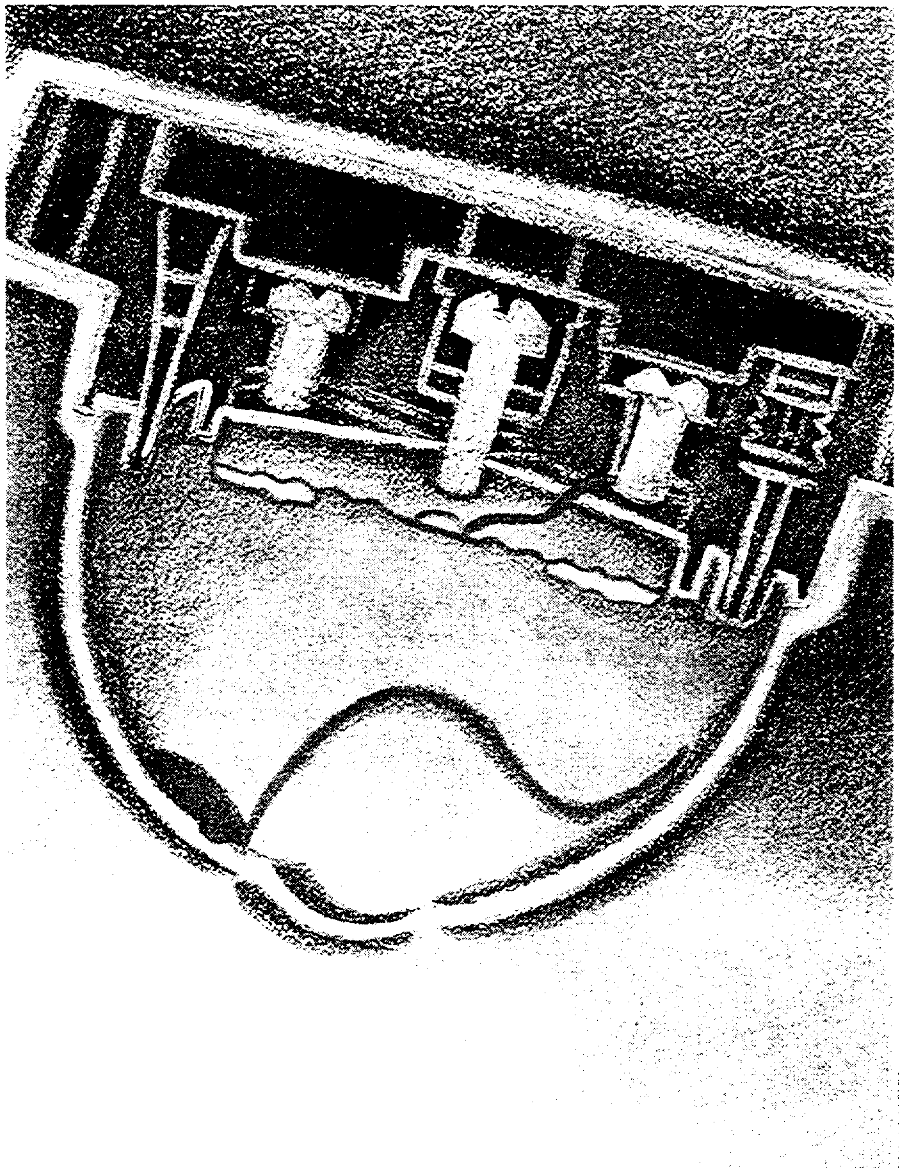
When the first edition of NFPA 74, *Household Fire Warning Equipment*, was published in 1967, the minimum requirement for a residential fire alarm system was a heat detector in every room and a smoke detector outside the bedrooms, all connected to a control panel. It is estimated that such systems were installed in fewer than 1 percent of U.S. homes because of the cost—about $1,500 for a small house.

Studies conducted during the 1960s

The earliest direct comparison of the performance of smoke and heat detectors in a residential setting was a study published by John McGuire and Brian Ruscoe of the National Research Council of Canada in 1962.[2] They examined reports of fatal fires in residential dwellings, classified as "unshared separate dwellings," that occurred between 1956 and 1960, resulting in 342 deaths.

Based on their judgment, (italics mine), they estimated the lifesaving potential if detectors had been installed in the dwellings in two configurations:

- a fixed-temperature heat detector activating at 150°F (66°C) in the area of fire origin—in effect, a heat detector in every



This review of the literature presents a comprehensive picture of the performance of residential detectors in fire tests.

DETECTORS

room, or

- two smoke detectors, one outside the sleeping room(s) or at the head of the main staircase in a two-story dwelling and one at the head of the basement stairs (if there was a basement).

The researchers concluded that the smoke detectors would have saved 41 percent of the 342 victims and that heat detectors would have saved 8 percent.

In 1960, the Los Angeles Fire Department conducted the first experiments on the performance of residential fire detection systems; the results were reported in the *NFPA Quarterly* in 1963.[3] The tests were designed to evaluate the detectors' ability to respond to two very different types of fires: smoldering fires initiated in an upholstered chair by dropped smoking materials, and fast, relatively smokeless fires in containers of trash.

The department conducted 13 tests in four different one- and two-story dwellings of ordinary construction. Tests 5 through 13 included photoelectric smoke detectors, and all the tests used spring-wound, residential heat detectors; these were the first independent tests of these devices reported in the literature. The results of the tests are summarized in Table 1.

The report concluded with a series of observations:

"In the slow, smoldering fires conducted during these tests:

"1. Disabling and near-lethal concentrations of carbon monoxide gas were recorded prior to the sounding of heat-activated fire alarms.

"2. Temperatures within the dwellings remained near ambient until such time as the upholstered furniture being burned burst into flames.

"3. Before operation of a heat-activated device, visibility within the dwelling was diminished to the point where, in bright, sunny, daylight conditions, people would be unable to rely on sight (as a means of receiving adequate warning) for evacuating the premises.

"4. In all tests in which smoke detectors were used, the smoke-activated device operated prior to the development of serious concentrations of carbon monoxide or smoke.

"In the rapid-burning rubbish fires conducted during these tests:

"1. Heat-activated devices operated soon after ignition of the fire and before serious carbon monoxide or smoke concentrations were in evidence.

"2. Smoke devices did not respond as long as the fire was free burning."

The next experimental study of detector performance reported was conducted by the Bloomington Fire Department in Minnesota in May 1969.[4] The tests took place in a 900-square-foot (84-square-meter) dwelling with two bedrooms and a bathroom on the first floor, an attic containing one bedroom, and an unfinished basement.

Smoke detectors were located in two first-floor halls outside the bedrooms and at the top of the attic stairway, and there was an additional smoke detector in the attic. Rate-of-rise heat detectors were placed in every room and adjacent to each smoke detector, and a single fixed-temperature heat detector was located in the attic bedroom. All the detectors were commercial types, connected to a fire alarm panel, rather than the single-station types common today.

Five tests were conducted "...to determine the reaction of various types of detectors to typical dwelling fires." The published report presented a summary of the results with a minimum of commentary and no statement of conclusions.

The first test involved a smoldering fire simulated by placing a roll of corrugated cardboard on a hotplate in the basement. Four detectors responded—three smoke detectors and one rate-of-rise heat detector—before conditions became untenable, although by the time the last three activated—two smoke detectors and the heat detector—conditions in the base-

One Is Not Enough

Richard W. Bukowski, P.E.

People are losing their lives in homes that contain *working* smoke detectors. We all have heard about fatal fires that occurred after the occupants had failed to replace a detector's battery or disabled a detector that sounded an alarm once too often because of smoke from cooking. But cases also have been reported where the detector was working and the fire department was at a loss to explain why the victims died.

While a few of these cases are a real mystery, many can be explained by the tests discussed in the accompanying article. For example, the Indiana Dunes tests showed that *having a smoke detetector on every floor level* provided 3 minutes' warning in 89 percent of the experiments. But they also showed that a single smoke detector outside bedrooms provided 3 minutes' warning in only 35 percent of the experiments. That is why NFPA 74 requires *smoke detectors on every level* as a *minimum.* (Italics mine.)

All too often, fatal fires that occur where working detectors are present begin on the first floor of a dwelling where the only detector is located outside second-floor bedrooms. In other fires, a closed door prevents smoke from reaching the detector. By the time the detector sounds an alarm, the escape path is blocked, the occupants perish unless they can escape through a window.

Survivors of some of these fires have said, "If only someone had told me I needed more than one detector, I certainly would have bought more." Sadly, some survivors have said that the fire department told them they needed "a smoke detector" to be safe, and they thought that meant only *one* detector.

A call to action

We must make sure the message we deliver to the public is the right one: *The absolute minimum number of smoke detectors needed in every home is one outside each separate sleeping area in the immediate vicinity of the bedrooms and one on each additional level of the family living unit, including the basements* (see paragraph 2-1.1.1 in the 1989 edition of NFPA 74). (Italics mine.) The more detectors there are, the safer the home will be.

Since smoke detectors are inexpensive, many people can afford to install one in every room. But smoke detectors should not be installed in kitchens, bathrooms, attics, or attached garages; detectors in these locations should be heat detectors.

People need to understand that a detector you cannot hear is worthless—and a detector that is more than one floor distant from the bedrooms cannot be heard in those bedrooms.

They also should be aware that a detector with a battery that is dead or missing, even for a few days, also is worthless. By replacing the batteries at least once a year, they'll always have an operating detector. The small investment of time and money spent replacing a battery can prevent a family tragedy.

ment were reported to be "quite noxious."

Test 2 involved an overheating electric motor in the kitchen. Five smoke detectors operated during the test, but no heat detectors activated. No comments were recorded on conditions in the home at the time the detectors activated.

Test 3 involved an overloaded electric cord under an upholstered chair in the living room. Four smoke detectors operated at times ranging from 1 minute 15 seconds to 12 minutes, and five heat detectors activated—four at 13 minutes and one at 15 minutes.

The report states that "Observers noted that when the first (smoke) detector operated, the living room was still tenable, but during the next 10 minutes (before the first temperature-sensitive detector operated), the smoke became unbearable."

Of special interest is the comment that "Besides the detectors shown in the diagrams, a spring-wound fixed-temperature device had been placed in the living room for test 3. That device operated 14 minutes after the arc." (The time that the cord began arcing was taken as the time of fire ignition.) Thus, the spring-wound heat detector located in the room of fire origin did not respond until several minutes after smoke conditions in the living room were considered "unbearable."

The fourth test involved a grease fire in the kitchen. The smoke detector in the front hall operated first. It was followed 1 minute later by the rate-of-rise heat detector adjacent to the stove in the kitchen, and then by the smoke detector in the rear hall 15 seconds later.

The final test involved a fire in a plastic wastebasket filled with trash in the kitchen, below the draperies. A smoke detector in the rear hall operated first, at 1 minute. It was followed by the smoke detector in the front hall at 3 minutes and by the rate-of-rise detector in the kitchen, the room of fire origin, at 3¼ minutes.

These tests were the first to demonstrate that smoke detectors *remotely located* from the room of origin consistently operated *before* heat detectors—in these tests, the more sensitive rate-of-rise type detectors—that were *in the room of fire origin.* (Italics mine.)

TABLE 1

Test Results

Test	Building	Test Fire	Smoke Detector Activation Time	Heat Detector Activation Time
1	3 room, 1 story	Chair	None present	119 min.
2	3 room, 1 story	Mattress	None present	Did not activate
3	3 room, 1 story	Chair	None present	84 min.
4	3 room, 1 story	Mattress	None present	95 min.
5	6 room, 1 story	Chair	38 min., 45 sec.	Did not activate
6	6 room, 1 story	Sofa	5 min., 40 sec.	64 min., 40 sec.
7	5 room, 1 story	Chair	25 min.	2 hours, 9 min.
8	5 room, 1 story	Fiber drum/ trash	6 min.	5 min.
9	10 room, 2 story	Chair	21 min.	1 hour, 40 min.
10	10 room, 2 story	Chair	49 min.	Did not activate
11	10 room, 2 story	Box/trash	Did not activate	1 minute
12	10 room, 2 story	Box/trash	Did not activate	3 minutes
13	10 room, 2 story	Chair	1 hour, 40 min.	Did not activate

Detector technology and standards during the 1970s

By the start of the 1970s, the technology of residential fire detection was changing rapidly. About 1965, the single-station, ac-powered, photoelectric smoke detector was developed, but it was not effectively marketed until the appearance of battery-powered ionization-type devices in 1969 and 1970. Problems with the response of the early smoke detectors were being recognized and corrected. Mechanically powered heat detectors similarly were improved to increase their sensitivity and reaction time; spacing was increased to 30 feet, 50 feet, and eventually to 70 feet.

By the time the experiments discussed in this section were conducted, at mid-decade, the performance of the heat detectors and smoke detectors used in the tests was significantly improved over those used in prior tests and was essentially equal to that of current devices.

The 1974 edition of NFPA 74 was the first to recognize the potential benefits of having fewer than one device in every room. This standard contained a controversial system of "levels of protection."

In this system, the minimum level—level 4—required a single smoke detector outside bedrooms and one at the top of a basement stairway, following the earlier recommendations of McGuire and Ruscoe. The maximum level—level 1—required a traditional heat or smoke detector in every room and a smoke detector outside bedrooms. The controversy related to the fact that levels 2 through 4 were based solely on the judgment of the committee and no verifying tests were performed.

To resolve these concerns, the National Bureau of Standards (now the National Institute of Standards and Technology) contracted with the IIT Research Institute (IITRI) and Underwriters Laboratories to conduct a thorough study. This became known as the Indiana Dunes Study, which will be discussed in the next section.

Studies conducted during the 1970s

In 1974, the Japan Housing Corporation (JHC) sponsored a study of fire detector performance in residences.[5] Tests were carried out in two typical Japanese dwellings: a three-room, single-story structure with a 350-square-foot (32.4-square-meter) floor area, and a five-room, single-story house with a 485-square-foot (45-square-meter) floor area.

As in most Japanese houses, each room was closed off from the rest by doors because of the lack of central heating. The same situation is present in older houses in the United Kingdom, for the same reason. Fixed-temperature (140°F, 60°C), heat detectors, rate-of-rise thermal detectors, and smoke detectors were provided in every room.

Ten experiments were conducted and the following conclusions were made:

"1. The difference in operation times between a heat detector and a smoke detector is mainly dependent upon the time lag in smoke production and temperature-rise. For example, in...detecting a fire due to an oil stove, there is no time lag in operation time between a smoke detector and a rate-of-rise type/ Class 2 spot detector, while a fixed-temperature type detector takes much time to respond.

"2. It is desirable to provide detectors [on] a room-to-room basis in [a] Japanese dwelling house, because the movement of [the] fire stream from the fire room to another [room] may be largely delayed due to many partitions such as sliding doors and transoms particular to the Japanese dwellings.

"3. From the viewpoint of safety for human life, smoke detectors are naturally desirable. However, [because of] the possibilities of false alarm, it is recommendable to avoid the use of smoke detectors [in] kitchens and bathrooms. Since there are many, but relatively narrow, rooms in a Japanese dwelling house and it is impracticable to provide every room with smoke detectors on account of economy, it is also recommendable to provide the rate-of-rise type/Class 2 spot detectors primarily and the fixed-temperature type/

special class [detector] with [a] nominal operation temperature of 60°C secondarily.

"4. Rooms in a JHC apartment house from which fire detectors are allowed to be omitted on account of construction cost are [the] toilet room and bathroom, where there are few sources of ignition. And if [it is] provided with [a] self-closing door, the vestibule is also included in the above-mentioned category."

At about the same time, IITRI and UL were beginning their tests in the United States in three houses scheduled for demolition as part of the expansion of the Indiana Dunes National Lakeshore Park.

In all, 76 experiments were performed in two phases of testing.[6,7] Both photoelectric- and ionization-type smoke detectors were installed in hallways—to correspond to the level 4 requirement of the 1974 edition of NFPA 74—and in the room of fire origin, so that a "smoke detector in every room" system could be evaluated. Since the Dunes tests are well-known and were heavily reported, I will not summarize them here.

Heat detector performance was judged by thermocouple readings taken at the smoke detector locations in the room of origin. In tests performed the first year, activation was presumed to occur when the thermocouple read 150°F (66°C), but both spring-wound and gas-powered 50-foot-rated devices were used in tests the second year in response to complaints from the heat detector industry.

Three of the reports' eight conclusions relate to the comparative performance of heat and smoke detectors:

"1. A residential smoke detector of either the ionization or photoelectric type with [a] small time lag would provide more than adequate lifesaving potential under most real residential fire conditions when properly installed....

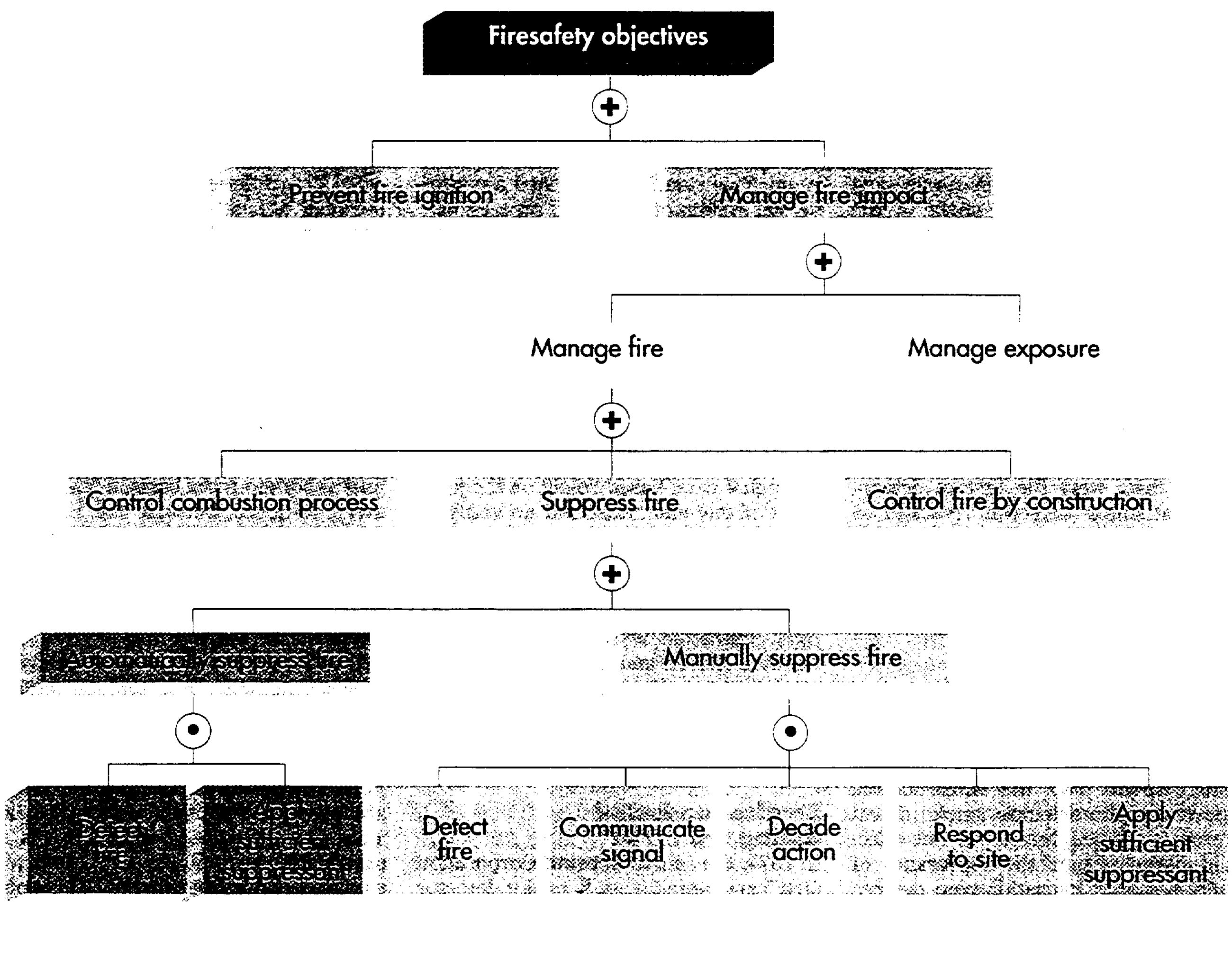
"3. Fixed-temperature (135°F, 57°C) or rate-of rise heat detectors in the room of fire origin provided little lifesaving potential. These detectors failed to respond to a majority of the fires, and when they did respond, they were considerably slower than smoke detectors located [at a] remote [distance] from the fire.

"5. Response time of detectors on the second floor for first-floor fires should be considered inadequate. Thus, it would appear that NFPA 74 should be revised to require at least one detector on each level of the residence."

After the results of the first year's tests were published, a Massachusetts advisory board performed an independent analysis of the data to support proposed state legislation requiring residential detectors.[8] In this analysis, a desired escape time of 3 minutes was assumed—between the time the detector alarmed and the time conditions were considered impassable anywhere along the primary egress route *within* the house. Escape through windows was not considered.

The performance of various detector arrangements was tabulated. The advi-

Excerpt From NFPA 550, Firesafety Concepts Tree



Automatic Sprinklers Are Needed, Too

Russell P. Fleming, P.E.

Automatic sprinklers are heat detectors and are recognized as alarm-initiating devices in numerous building and fire codes. But by no means should automatic sprinkler protection be equated to heat detection in terms of their overall impact on fire safety.

Like a heat detector, a sprinkler usually can be expected to respond at a later point of fire growth than a smoke detector. Once it has responded, however, an automatic sprinkler begins to fight the fire. Water from the sprinkler is expected to suppress or control the fire, reducing the rate of heat release and preventing the rapid development of untenable conditions.

In most studies comparing the relative effectiveness of smoke and heat detectors, success is measured by the ability of the detector to provide several minutes of warning before untenable conditions develop. While heat detection alone might fail in many of these instances, heat detection combined with automatic suppression generally would succeed, since the development of untenable conditions is precluded.

It is not surprising that in the past, some studies concluded that heat detectors alone might provide almost no escape time, especially in fast-developing fires. During the residential sprinkler development program in the late 1970s, it was found that sprinklers protecting typical residential furnishings often activated just as the heat-release rate of the fire was beginning a dramatic exponential increase.

In freeburn testing of the upholstered-furniture corner scenario, used as the basis for the residential sprinkler program, the convective heat-release rate of the fire was about 10,000 Btu (175 kW) per minute 2 minutes after ignition, but it increased to 200,000 Btu (3,500 kW) per minute within 1 additional minute.[1] This is basically the difference between the burning rate of a trash-basket fire capable of activating a fast respcnse sprinkler and the burning rate of fully involved upholstered furniture capable of causing flashover in a small room.

The difference between detection alone versus combined automatic detection and suppression is clearly demonstrated in NFPA 550, *The Firesafety Concepts Tree*, in which the box labeled "detect fire" and the box labeled "apply sufficient suppressant" must connect through an "AND" gate to reach the box labeled "automatically suppress fire." Automatic sprinklers combine those two elements successfully and achieve automatic fire suppression. From that point, the route to the fire safety objective consists solely of "OR" gates. When you "automatically suppress fire," you proceed to "suppress fire," "manage fire," and "manage fire impact," and reach the "fire safety objective" at the top of the tree.

Without automatic suppression, the "detect fire" box must be linked through an "AND" gate with "communicate signal," "decide action," "respond to site," and "apply sufficient suppressant" in order to reach the "manually suppress fire" box. Each of these additional steps takes time, and during these crucial minutes the fire can easily grow to deadly proportions.

With a properly designed, installed, and maintained automatic sprinkler system, the fire is quickly controlled or suppressed, achieving the fire safety objective of protecting life and property.

1. B.G. Vincent, *Heat Release Properties for Three Selected Large-Scale Fuel Packages*, Factory Mutual Research Corporation, December 1985.

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sory board found that a smoke detector on every level provided the desired 3 minutes of escape time in 89 percent of the experiments, compared to 11 percent for a heat detector in the fire room—in effect, a detector in every room.

The clear and decisive results of the Indiana Dunes tests and the analysis of the Massachusetts report resulted in changes to NFPA 74; the 1978 edition required smoke detectors on every level as the minimum requirement. Similar requirements subsequently were adopted in nearly every state and in many cities and counties in the United States, as well as in other countries.

After the first Dunes report was published, the experimental design and the test results were questioned in a *Fire Journal* article by E.L. Gallagher,[9] who represented the heat detector industry through a trade association, the Fire Equipment Manufacturers Association. A rebuttal by the National Bureau of Standards appeared in a subsequent issue of *Fire Journal*.[10]

In 1974, Factory Mutual Research Corporation performed another set of experiments that examined the performance of detectors in apartments.[11] The apartments were in high-rise buildings, although the height of the buildings had no impact on the results.

The test geometry consisted of a one-bedroom, 753-square-foot (70-square-meter) apartment that opened onto a 58-foot (17.7-meter) corridor. Ionization- and photoelectric-type smoke detectors and fixed-temperature (135°F, 57°C) and rate-of-rise heat detectors were used. The performance of the detectors was judged in 19 experiments on their ability to provide 2 minutes of warning before tenability criteria in the apartment were exceeded.

Pertinent conclusions reached in this study include the following:

"2. The ionization detector performed adequately in the protectable flaming fire starts and, in general, inadequately in the smoldering fire starts.[12]

"3. The photoelectric smoke detector did not perform adequately anywhere in the protectable flaming fire starts, but was adequate almost everywhere in the apartment in the smoldering fire starts of long duration.

"4. Both detector types performed adequately, by a wide margin, in the kitchen fires when located close to the fire. However, those detectors located at remote locations from the kitchen fires did not respond adequately.

"5. Neither of the heat detectors performed adequately, regardless of the fire and detector location."

In 1978, the Minneapolis Fire Department conducted a series of experiments to examine the performance of smoke and heat detectors in residences.[13] The test house was a four-bedroom, two-story dwelling with a basement. Smoke detectors and heat detectors (135°F, 57°C), were located on each floor level, near the central stairway. Eight tests were conducted with fires in various rooms on each floor.

The conclusions of the investigators included the following:

"Heat detectors alone should not be relied upon for early life safety warning in any area or room in the home.

"...both ionization and photoelectric types of smoke detectors gave good early warning of lethal conditions in the area of the detector, but are affected by barriers that prevent smoke travel (closed doors) and bad locations (dead-air spaces, etc.)."

In 1979, the Australian Department of Housing and Construction published a report on a series of four detector experiments conducted in a three-bedroom brick cottage.[14] Both ionization- and photoelectric-type smoke detectors and thermal (fixed-temperature, rate-of-rise) detectors were used.

Regarding the performance of the thermal detectors, the report stated that "Generally, the performance of thermal detectors in this type of fire environment showed them to be ineffective in providing time for occupants to move before escape paths become untenable. In the first three tests, the detectors either failed to operate or operated only after extinguishing procedures had commenced and the house was thoroughly smoke-logged."

On the performance of the smoke detectors, the report concluded that "The sensitivity of all the domestic smoke detectors tested was sufficient to trigger [an] alarm before escape paths became untenable."

A final study, equal in scope to the Dunes tests, was conducted by the Los Angeles Fire Department in 1978, but it was not published until 1983.[15]

This study, often referred to as the California Chiefs' Tests, has an interesting history. After the article by E.L. Gallagher was published, Gallagher decided to organize his own tests to prove his points of contention with the Dunes tests and, presumably, to demonstrate the value of heat detectors. He sought the assistance of the California Fire Chiefs' Association, which eventually conducted the tests, essentially following Gallagher's recommendations.

A three-bedroom, one-story test house and a two-bedroom, two-story test house were obtained in an area being razed for the extension of a runway at Los Angeles Airport. The houses were completely furnished, down to dishes in the kitchen and toothbrushes in the bathrooms.

In all, 71 experiments were conducted, from which the following conclusions on detector reliability were drawn:

"4. Smoke detectors (ionization or photoelectric) are more reliable than heat detectors as early warning devices for dwelling fires.

"5. Heat detectors alone may provide no escape time."

Summary

This article reviews 10 independent studies conducted in four countries over a 20-year period in which 206 experiments were reported. All the studies were conducted to evaluate the performance of residential heat and smoke detectors in providing life safety for the occupants in residential fires.

All 206 experiments were real-scale tests in houses or apartments, and most of them used actual items—upholstered furniture, mattresses, wiring, motors, trash, etc.—as the fire source. All the tests used standard heat and smoke detectors installed in typical locations in the test houses. All the detectors were available for purchase at the time the tests were conducted, and all were calibrated to alarm at levels of heat and smoke consistent with devices available in stores.

All the studies presented conclusions that were essentially identical:

- When either ionization or photoelectric smoke detectors are located outside the bedrooms and on each level of a house, they provide adequate warning to allow the occupants to evacuate through their normal egress routes in most residential fire scenarios; and
- Even when heat detectors are located in the room of fire origin—in effect, requiring a heat detector in every room—they do not provide adequate warning in most fire scenarios.

In every case where the reports elaborate on where a heat detector might be used, they state that heat detectors should be used only in kitchens or other areas where smoke detectors cannot be used, such as garages and attics. These comments are identical to the current requirements in NFPA 74 regarding heat detectors.

An international literature search for publications dealing with the subject of fire detection systems was recently completed.[16] This review identified 975 citations, 100 of them in foreign languages, that were published in the past 15 years. As of June 1991, the cut-off date for inclusion in the bibliography, no studies other than those cited here—and one in which only smoke detectors were tested[17]—were published in the open international literature that dealt with this topic.

Editor's note: The conclusions presented in this article regarding "heat-activated devices" were based on the tests of detectors, not sprinklers.

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1. R.W. Bukowski and N.H. Jason, *International Fire Detection Literature Review and Technical Analysis*, National Fire Protection Research Foundation, Quincy, Mass., 1991.

2. J.H. McGuire and B.E. Ruscoe, *The Value of a Fire Detector in the Home*, Fire Study No. 9, National Research Council of Canada, Division of Building Research, Ottawa, Ont., Canada, December 1962.

3. "Fire Detection Systems in Dwellings—Los Angeles Fire Department Tests," *NFPA Quarterly*, Vol. 56, No. 3 (January 1963), pp.201-215.

4. "Home Fire Alarm Tests," *Fire Journal*, Vol. 65, No. 4 (July 1971), pp. 10-15.

5. Y. Eguchi, "Automatic Fire Detection in Japanese Dwellings," Association of Fire Alarms of Japan, U.S./Japan Cooperative Program on Natural Resources, Panel on Fire Research and Safety, October 19-22, 1976, Tokyo, Japan, *Fire Detection*, Vol. 6, pp. 1-15.

6. R.W. Bukowski, T.E. Waterman, and W.J. Christian, *Detector Sensitivity and Siting Requirements for Dwellings*, NBSGCR 75-51, National Bureau of Standards, 1975, 343 pp. Available from National Technical Information Services; order no. PB247483.

7. S.W. Harpe, T.E. Waterman, and W.J. Christian, *Detector Sensitivity and Siting Requirements for Dwellings—Phase 2*, NBSGCR 77-82, National Bureau of Standards, 1977, 379 pp. Available from National Technical Information Services; order no. PB263882.

8. Rexford Wilson, *Computer Analysis of Data on Fire Detectors Available for Purchase in Massachusetts*, Massachusetts Fire Prevention, Fire Protection Board, Commonwealth of Massachusetts, Boston, Mass., 1976.

9. E.L. Gallagher, "FEMA: NBS Tests Do Not Reflect Reality, *Fire Journal*, Vol. 71, No. 2 (March 1977), pp. 19, 38-41.

10. R.G. Bright, "NBS Answers FEMA's Criticisms of the Indiana Dunes Tests of Residential Smoke Detectors," *Fire Journal*, Vol. 71, No. 5 (September 1977), pp. 47-49, 99.

11. G. Heskestad, *Escape Potentials From Apartments Protected by Fire Detectors in High-Rise Buildings*, FMRC Report RC74-T-15, Factory Mutual Research Corp., Norwood, Mass., 1974.

12. In this report, the author refers to protectable and unprotectable fires. Where the combination of detector location, fire location, and fire growth rate resulted in the single means of egress from the apartment being blocked prior to the time that the first heat or smoke combustion products reached the closest detector location, the test was classified as unprotectable.

13. D. Ozment, *1976 Bicentennial Home Smoke Detector Test*, Minneapolis Fire Department Bureau of Fire Prevention, Minneapolis, Minn., 1976.

14. P. Johnson and A.W. Moulen, *Fire Detection in Typical Cottage*, Technical Record 453, Department of Housing and Construction, Chatswood, N.S.W., Australia, November 1979.

15. *The California Fire Chiefs' Association Residential Fire Detector Test Program*, Los Angeles Fire Department with assistance from California State University at Los Angeles, under contract to the International Association of Fire Chiefs' Foundation, 1983.

16. Bukowski and Jason, *International Fire Detection Literature Review and Technical Analysis*.

17. P.F. Johnson and S.K. Brown, "Smoke Detection of Smoldering Fires in a Typical Melbourne Dwelling," *Fire Technology*, Vol. 22, No. 4, 1986, pp. 295-340.

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