# FIELD INVESTIGATION OF RESIDENTIAL SMOKE DETECTORS

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**EDITORAL NOTE: The article which follows raises serious questions regarding optimun placement of the smoke detectors which are required by Section 1127 of the Standard Building Code, and by similar provisions of the other Model Codes.**

**The author concludes, from an extensively instrumented study, that detectors placed on a second floor gave inadequate warning of fires occurring on the ground floor under certain conditions. This finding should lead to a search for improvement of response time, -perhaps by placement of detectors closer to the usual sources of fire. However, removal of single station alarm devices from the vicinity of sleeping rooms introduces a danger that the alarm would not be heard at all.**

**Several manufacturers of A-C operated units have devised means of transmitting an alarm-sounding condition from any one detector to all other detectors on the premises. One such system incorporates activation of a crystal transmitter in the line voltage circuitry which introduces an approximate 50,000 cycle signal on the power line. Receivers in the other detectors respond to such signal by activating their own alarm circuitry. This system is reported to add approximately $15 to the cost of each detector. Another, simpler system provides a third wire, or pair of wires, which permits the connection in parallel of the low voltage horn circuitry of from 6 to 10 individual detectors.**

**Thus far there has been developed only one interconnection system for battery operated detectors. By this system, an activated detector emits a coded signal which activates the building's burglar alarm. This would appear to be fairly expensive, -involving addition of signal emittors similar to garage door opener transmitters, receiving equipment, and a burglar alarm system.**

**It is to be hoped that the manufacturers of these devices, both AC and battery operated, will someday arrange for a simple interconnection between the low voltage horn circuitry of all detectors in a given building. Until such time as interconnection is possible, the building official must continue to insist on placement of the detectors where the alarm horn will be heard by sound asleep occupants even though this article indicates that borderline escape times might result.**

At the present time, standards for fire detector location in dwellings, as well as standards for fire detector sensitivity, are based mostly on laboratory data and engineering judgement without the benefit of extensive full-scale data to provide guidance. For example, as new methods of fire detection have developed, laboratory evaluations have been modified in attempts to provide realistic exposure environments; However, this has led to a multiplicity of evaluation techniques. These are only loosely interrelated, making comparative judgements difficult between detectors stimulated by different characteristics of fire. As more and more jurisdictions make dwelling fire detection mandatory, it becomes increasingly important to develop experimental data to back up and improve existing standards.

The primary purpose of this study was to investigate detector siting and sensitivity as they relate to escape potential in residential fire situations. Although a number of actual detectors were used in the investigation, it was not the intent of this project to judge the merits of the individual detectors used. The detectors were selected to provide a cross section of the several detection principles now available and to represent the current level of technology available in residential type detectors.

Two test buildings were used for the program. These homes, made available by the U.S. Department of the Interior (*National Park Service*), were scheduled for demolition as part of a land clearance program associated with the establishment and expansion of the Indiana Dunes National Lakeshore.

The primary test site (referred to as the J.R. Whitehouse residence) was a two-story brick structure with basement. Interior walls on the first and second stories were plaster on wood lath. The floors were wood. The basement walls were wood paneled. The building had a gas forced-air heating system, to which a central air conditioning unit was fitted for the summer test conditions. Registers were located in every room with returns in all first floor rooms except the bathroom. There were no returns on the second floor.

The second test site (referred to as the Lakeshore residence) was selected primarily because it employed a hot-water baseboard heating system. This building was a single story brick residence with basement. All walls were wood paneled. The first story had wood floors.

The buildings selected represent major variations in geometry. Since the prime vehicles for moving smoke throughout a residence are the fire itself and the HVAC system, the heating systems in these two buildings should be representative of most types of heating systems, with the possible exception of radiant heat and individual space heaters.

It was the plan of the research program to conduct a series of experiments in the primary test site over several seasons, so that the full range of outdoor conditions which significantly affect indoor conditions, e.g. heating, cooling, etc., would be encountered. The secondary test site was utilized only during the winter season since this would provide the maximum "stack effect" and since central air conditioning of a dwelling with hot water baseboard heat is not readily achieved.

Detector locations were selected in accordance with the four levels of protection defined in the 1974 edition of the National Fire Protection Association's Pamphlet No. 74, Standard for the Installation, Maintenance and *Use of Household Fire Warning Equipment*. Two detectors of each type with two different sensitivities were installed at each required detector location. At one of the detector locations the effect of wall versus ceiling mounting was investigated by installing some detectors on the ceiling and some on the wall for several experiments and then reversing the mounting.

Instrumentation for the experiments included light beams for measuring smoke obscuration on the ceiling in the room in which the fire was being burned, on the ceiling at each detector location, and at the 5-ft level along the primary escape path and in representative bedrooms. For this report the primary escape path refers to the normal route used by the occupants in exiting the building from the bedrooms.

Individual thermocouples and vertical thermocouple arrays were installed in the burn-room and the primary escape path and several representative locations throughout the dwelling. Equipment to monitor carbon monoxide, carbon dioxide, and oxygen levels was installed in the burn-room, escape path and representative bedrooms.

After a literature search, tenability limits were selected above which the normal escape path would be considered impassable. These limits were a smoke level of 0.07 OD/ft, a temperature of 150° F, or 400 ppm CO anywhere in the path. From these limits the time of untenability was determined for each test and performance curves were developed for both theoretical and actual detectors. The theoretical detector results are based on light beam measurements taken at detector locations and assume the detector can sense the condition with no time lag. Actual detector response was ahead of the theoretical times for some fires, probably due to individual detector characteristics.

Performance curves were developed to indicate the frequency of success that a given detector and location would provide for any required escape time. The success frequency for a given escape time is the percentage of the total number of experiments conducted in which that escape time or greater was obtained. Required escape time may vary considerably depending on size and configuration of the structure, and the age and physical condition of occupants. Times in the range of 120 to 300 seconds seem reasonable.

Both smoldering and flaming ignition fires were initiated in various rooms of the dwelling using upholstered furniture and mattresses typifying the respective rooms. The rooms selected were those which were shown to be involved in the highest percentage of fatal residential fire starts according to the National Fire Protection Association's Report FR72-1, "A Study of Fatal Residential Fires".

The detectors selected for use in these experiments were typical ionization, photoelectric, dual gate (combination ionization and resistance bridge) and rate-of-rise of heat detectors. One high sensitivity (1 percent per foot obscuration nominal) and one low sensitivity (2 percent per foot obscuration nominal) detector was used at each detector location. This was done to provide data on the response of various types of detectors in relation to realistic fire conditions, as well as to determine the differences in response time and escape time potential for two different levels of sensitivity of the same detector and type. The detectors selected were considered to be representative of the best detectors of their individual type at the time of selection. All detectors were connected to a 25-clock elapsed time indicator panel which indicated detection time to the nearest second after fire ignition.

The sensitivity of each detector employed in the test series was initially determined by Underwriters' Laboratories in accordance with the sensitivity test requirements of their applicable standards. The sensitivity of every detector was checked using the same methods after each series of experiments to insure that the detectors had not shifted in sensitivity.

The actual sensitivities of the detectors used are given in Table 1. Some units vary from the nominal 1 and 2 percent values requested due to variations in the different manufacturer's calibration techniques.

In total, 40 experiments were conducted in this program. Twenty-seven experiments at the primary test site, and 13 at the secondary site. Of these experiments, 60% were smoldering ignitions, 32.5% flaming ignitions and 7.5% other miscellaneous tests. This ratio of smoldering to flaming ignitions was selected to correlate approximately with NFPA's "Study of Fatal Residential Fires".

The ignition source for all smoldering ignitions was a 500-watt charcoal igniter with approximately 20 inches of exposed cal-rod. The charcoal igniter was placed in contact with the item to be burned and energized at time zero. The igniter was held in firm contact with the material for 120 seconds before removal. This generally resulted in a self-sustaining smoldering of the item. The U-shaped original charred area generally filled in completely within the first five minutes forming a circular charred area which grew radially outward at varying rates depending on the surface material. In most cases transition to flaming occurred not sooner than one hour after ignition and, in some cases, transition to flaming never occurred prior to test termination.

Flaming ignitions were achieved by positioning a small metal waste basket filled with loosely crumpled paper adjacent to the piece being ignited. A piece of folded newspaper was draped over the arm of a chair or a sheet placed on a mattress was arranged so that it hung down over the wastebasket. The contents of the wastebasket were ignited with a match at time zero.

The results for a typical flaming ignition experiment are shown in Table 2. This was a flaming ignition of a chair in the living room of the primary test site. The test was conducted during the winter with the heating system on.

The important points to note in this table are the order in which the detectors responded by type and the escape time (or time between detector

**Table 1. Detector Identification**

| Manufacturer Code | Type | Preset Sensitivity (%/ft) Theoretical | Measured | Clock Number |
|---|---|---|---|---|
| A | Photo | 1 | 1.19 | 1 |
| B | Dual Gate | 2 | 3.89 | 2 |
| F | ION | 2 | 2.81 | 3 |
| E | Photo | 1 | 0.96 | 4 |
| B | ION | 2 | 2.02 | 5 |
| E | Photo | 2 | 1.98 | 6 |
| F | ION | 1 | 1.61 | 7 |
| A | Photo | 2 | 1.4 | 9 |
| E | Photo | 2 | 1.81 | 10 |
| A | Photo | 1 | 1.27 | 11 |
| F | ION | 1 | 1.34 | 12 |
| F | ION | 2 | 3.04 | 13 |
| B | Dual Gate | 2 | 2.19 | 14 |
| ROR | ROR | 15F/min | 15F/min | 15 |
| H | ION | 1 | 1.91 | 16 |
| H | ION | 2 | 2.04 | 17 |
| H | ION | 1 | 1.81 | 18 |
| H | ION | 2 | 2.04 | 19 |
| ROR | ROR | 15F/min | 15F/min | 20 |
| ROR | ROR | 15F/min | 15F/min | 22 |
| A | Photo | 2 | 2.09 | 24 |
| E | Photo | 1 | 0.96 | 25 |

alarm and untenable conditions in the primary escape path) provided by each. Note that the ionization detectors responded first followed by the photo electrics. The minimum escape time provided by the slowest detector in this test was 344 seconds (5.73 minutes). The maximum escape time provided by the first responding detector was 904 seconds (15 minutes). These results are typical of the flaming ignitions conducted during the winter.

Table 3 shows the results of a typical smoldering ignition from the same series. This was again conducted during the winter in the primary test site but with the heating system off. In the case of the smoldering fires the photoelectric detectors are generally grouped first and the ionization detectors coming in later; however the ionization detector from manufacturer F responded within the photoelectric grouping. This generally faster response of the photoelectric detectors was typical of the smoldering ignition tests conducted. In this case, note that the minimum escape time provided by any smoke detector was 143 seconds (2.38 minutes) from the dual gate detector on the second floor. This detector generally responded poorly to smoldering fires primarily due to its poor sensitivity of 3.89%/ft, nearly the maximum sensitivity allowed by U.L. for detectors. Discounting this sample as being non-representative of normal production due to its poor sensitivity setting the minimum escape time then becomes 322 seconds (5.36 minutes). It is also interesting to note that the escape time provided by the first detector responding was approximately 1974 seconds (33 minutes). In comparing the escape times provided by all smoke detectors at a particular location it appears that the variations are more a function of sensitivity and detector design than detection method.

All data taken is recorded in the complete report of this test series, including curves showing the time histories of all of the various measured quantities throughout the buildings. These include temperature, light obscuration, and concentrations of carbon dioxide and carbon monoxide in the fire room, bedrooms, and positions along the escape route. It is our hope that much more information can be derived from this data than we have had the opportunity to discuss here.

In general, all smoke detectors responded well to all fires. The photoelectric type detectors seem to respond better to the smoldering type fires and the ionization detectors seem to respond better to the flaming fires. Both types however, provided adequate escape time for all fires when located on the same floor as the fire source.

There appeared to be no significant difference observed in the response of detectors mounted on the ceiling or on the wall. Response time and escape time potential was somewhat better for the higher sensitivity units as would be expected.

In the primary test site, the escape times obtained from detectors installed on the second floor responding to first floor fires seem somewhat marginal. According to NFPA/74 level four requirements for installing the detectors, there would be no detector on the first floor if there were no first floor bedrooms. The results of the experiments seem to indicate that this situation would result in marginal performance under many first floor fire conditions.

It should be noted that poor performance of 2nd floor detectors with 1st floor fires was accentuated in the summer, particularly for smoldering ignitions. Since all summer experiments were conducted with the HVAC system operating, summer experiments with no forced circulation may emphasize the effect further. These conditions are being studied in phase 2 of this project, currently under way.

The lakeshore test building with a 30-ft central hallway had a bedroom configuration which would require a smoke detector near one end of the hallway. An additional detector located at the other end of the hallway significantly increased escape time potential.

The response of the heat detectors employed was considerably different from the response of the smoke detectors. Rate-of-rise thermal detectors with a 50-ft space rating were installed on each detector board. In addition, in experiments 13 through 40 a similar rate-of-rise detector was included in the room of fire origin for each experiment. The results of the experiments indicate that these heat detectors, including the one in the room of fire origin, failed to respond to a majority of the fires. When they did respond, they were considerably slower than the smoke detectors and proved little or no escape time prior to occurrence of dangerous conditions

**Table 2. Test No. Jr-16**

| Clock No. | Type | Sensitivity (%/ft) | Alarm (s) | Escape Time (s) |
|---|---|---|---|---|
| | | FIRST FLOOR DETECTORS (CEILING) | | |
| 12 | I | 1.34 | 158 | 904 |
| 19 | I | 2.04 | 339 | 723 |
| 13 | I | 3.04 | 357 | 705 |
| 18 | I | 1.81 | 372 | 690 |
| 14 | DG | 2.19 | 384 | 678 |
| 11 | P | 1.27 | 389 | 673 |
| 10 | P | 1.81 | 438 | 624 |
| 25 | P | 0.96 | 443 | 619 |
| 9 | P | 1.40 | 540 | 522 |
| 15 | ROR | 15F/min | NO | -- |
| | | SECOND FLOOR DETECTORS (WALL) | | |
| 7 | I | 1.61 | 229 | 833 |
| 5 | I | 2.02 | 382 | 680 |
| 16 | I | 1.91 | 439 | 623 |
| 24 | P | 2.09 | 526 | 536 |
| 6 | P | 1.98 | 718 | 344 |
| 20 | ROR | 15F/min | NO | -- |
| | | SECOND FLOOR DETECTORS (CEILING) | | |
| 17 | I | 2.04 | 319 | 743 |
| 3 | I | 2.81 | 362 | 700 |
| 2 | DG | 3.89 | 488 | 574 |
| 4 | P | 0.96 | 556 | 506 |
| 1 | P | 1.19 | 658 | 404 |
| | | HEAT DETECTOR IN FIRE ROOM | | |
| 22 | ROR | 15F/min | 1502 | -440 |
| Thermocouple | Fixed Temp. | 150F | 1370 | -308 |
| Thermocouple | Fixed Temp. | 150F | 1510 | -448 |

**DATA**

Test No.: Jr-16 Fire Type: F (Chair) Season: Winter
Tenability Limits Exceeded: 1060s AC/Heat: On
Flame at: o s Test Terminated at: 1546 s
Fire Location: Living Room

in the primary escape path.

Thermocouple readings at the ceiling in the room of fire origin were used to evaluate the escape potential provided by a 135° F fixed-temperature heat detector assuming no thermal lag. These results indicate that zero thermal lag fixed-temperature heat detectors in every room would have little life saving potential in the residential fire situations simulated here.

The following conclusions were drawn from these experiments:

1. A residential smoke detector with small lag time, of either the ionization or photoelectric type, would provide more than adequate life saving potential under most residential fire conditions, when properly installed. Even in the case of rapidly evolving flaming ignition fires, the detectors would provide adequate warning before dangerous conditions were reached in the primary escape path.
2. While detectors set at nominal 2 percent-per-foot obscuration generally provided adequate warning, those detectors whose sensitivities were near 1 percent-per-foot provided a significant increase in escape time for smoldering fires. The effect was much smaller for flaming fires.
3. In these tests, fixed temperature 135° F or rate-of-rise heat detectors in the room of fire origin provided little life saving 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 remote from the fire.
4. Under forced air heating conditions, there appears to be very little difference in smoke levels obtained in the bedroom with the bedroom doors open or closed. Under central air conditioning, however, somewhat reduced smoke levels were realized in the bedrooms with closed doors. Experiments conducted with fires in closed bedrooms resulted in lethal condition in the bedroom before response of detectors outside the bedrooms. Thus, the person in the room of fire origin would not be warned in time unless the detectors were in the bedroom or the door was open. Since there was no increased hazard to the occupants from fires originating outside the bedroom when the bedroom doors were open and since the open doors would greatly increase the chances of saving the occupant when the fire starts in the bedroom, it may be best to sleep with bedroom doors open when detectors are present in the home.
5. Response times of detectors on the second floor for first floor fires were considered inadequate. Thus, it would appear that NFPA/74 should be revised to require at least one detector on each level of a residence, especially when central air-conditioning is involved.
6. Installation of one smoke detector at each end of a long central hall would significantly increase the escape time potential in comparison with one detector at one end of the hall.
7. Under expected residential fire conditions it appears that there is no difference in life saving potential between ionization and photoelectric detectors. Although some response difference is noticed depending on the type of combustion, (flaming or smoldering) the differences are minimal when compared on an escape time and life saving potential basis.
8. Smoke conditions produced by the fires indicate that there should be no significant difference in detection times for ceiling mounting or wall mounting within 12 inches of the ceiling. However, individual detectors with highly directional properties may function quite differently in these two positions.

**Table 3. Test No. Jr-18**

| Clock No. | Type | Sensitivity (%/ft) | Alarm (s) | Escape Time (s) |
|---|---|---|---|---|
| | | FIRST FLOOR DETECTORS (CEILING) | | |
| 25 | P | 0.96 | 1296 | 1974 |
| 10 | P | 1.81 | 1468 | 1802 |
| 12 | I | 1.34 | 1475 | 1795 |
| 11 | P | 1.27 | 1666 | 1604 |
| 9 | P | 1.40 | 1907 | 1363 |
| 14 | DG | 2.19 | 1918 | 1352 |
| 13 | I | 3.04 | 1965 | 1305 |
| 18 | I | 1.81 | 2076 | 1194 |
| 19 | I | 2.04 | 2222 | 1048 |
| 15 | ROR | 15F/min | NO | -- |
| | | SECOND FLOOR DETECTORS (WALL) | | |
| 4 | P | 0.96 | 1722 | 1548 |
| 17 | I | 2.04 | 2157 | 1113 |
| 1 | P | 1.19 | 2659 | 611 |
| 3 | I | 2.81 | 2703 | 567 |
| 2 | DG | 3.89 | 3127 | 143 |
| | | SECOND FLOOR DETECTORS (CEILING) | | |
| 7 | I | 1.61 | 1910 | 1360 |
| 24 | P | 2.09 | 2001 | 1269 |
| 6 | P | 1.98 | 2504 | 766 |
| 5 | I | 2.02 | 2863 | 407 |
| 16 | I | 1.91 | 2948 | 322 |
| 20 | ROR | 15F/min | NO | -- |
| | | HEAT DETECTOR IN FIRE ROOM | | |
| 22 | ROR | 15F/min | NO | -- |
| Thermocouple | Fixed Temp. | 135F | NO* | |
| Thermocouple | Fixed Temp. | 150F | NO* | |

*Ceiling Temp Never Exceeded 90°F

**DATA**

Test No.: JR-18 Fire Type: S (Mattress) Season: Winter
Tenability Limits Exceeded: 3270 s AC/Heat: Off
Flame At: None Test Terminated at: 3720 s
Fire Location: 1st Floor Bedroom

EDITORIAL NOTE:

This article has been condensed from the author's Report, NBSIR 76-1126, "Field Investigation of Residential Smoke Detectors". That report is a summary of the investigation and includes floor plans of the test buildings, charts showing the locations of the detectors, instrumentation, and test fires, and samples of the theoretical and actual detector performance curves. Copies are available at no charge by writing the author at National Bureau of Standards, Center for Fire Research, Washington, D.C. 20234.

Copies of the complete report (400 pages) describing all tests in great detail and including all of the data taken is available at a cost of $10.00 from NFPA Publication Dept., 470 Atlantic Ave., Boston, Mass. 92210. The title is "Detector Sensitivity and Siting Requirements for Dwellings" - NFPA SPP-43.