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Field

# ~~Filed~~ Investigation of Residential Smoke Detectors

Richard W. Bukowski

Center for Fire Research
Institute for Applied Technology
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Washington, D. C. 20234

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Final Report

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

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**U.S. DEPARTMENT OF COMMERCE, Elliot L. Richardson,** ***Secretary***

**Edward O. Vetter,** ***Under Secretary***

**Dr. Betsy Ancker-Johnson,** ***Assistant Secretary for Science and Technology***

**NATIONAL BUREAU OF STANDARDS, Ernest Ambler,** ***Acting Director***

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# FOREWORD

This paper is excerpted from the report "Detector Sensitivity and Siting Requirements for Dwellings," R. W. Bukowski, et al., Report No. NBS-GCR-75-51 available from National Technical Information Services, Springfield, Va. 22151, order number PB 247483 ($10.00 per copy).

Only the key points relating to detector response, effectiveness, location, and sensitivity have been included herein. The full report contains all of the raw data, observations, and data analysis for these tests.

FIELD INVESTIGATION OF RESIDENTIAL SMOKE DETECTORS

Richard W. Bukowski[1]

Abstract

A test program was undertaken to evaluate the effect of sensitivity and placement of residential smoke detectors on their response to fires in homes. The tests were conducted in two homes scheduled for demolition and used actual furnishings in typical configurations. In addition to the detector response times, the homes were highly instrumented with data on smoke, temperature, and gas concentration measured for all tests.

The tests showed that smoke detectors can be highly effective in providing adequate warning of a fire before conditions in the home become dangerous.

Key words: Detector sensitivity; detector siting; escape time; fire tests; heat detectors; residential fires; smoke detectors.

## 1. INTRODUCTION

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 simulated 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

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[1] Mr. Bukowski is presently a Research Engineer in the Program for Fire Detection and Control Systems in the Center for Fire Research at the National Bureau of Standards.

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.

## 2. EXPERIMENTAL PROCEDURE

### 2.1. Description of Test Buildings

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. (For room layouts see figures 1 through 3). 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 (fig. 4). 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.

### 2.2. Research

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 location (figs. 5-7) were selected in accordance with the four levels of protection defined in the 1974 edition of NFPA/74. 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 (figs. 8-10) 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 (1.5-m) 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 (figs. 11-13) 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 (figs. 13-16).

Both smoldering and flaming ignition fires were initiated in various rooms of the dwellings using upholstered furniture and mattresses typifying the respective rooms (figs. 17-19). The rooms selected were those which showed the highest percentage of fatal residential fire starts in NFPA records [1][2].

## 2.3. Detectors

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 to realistic fire conditions, as

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[2]Numbers in brackets refer to the references listed at the end of this paper.

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 (UL) 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.

## 3. RESULTS

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 data on residential fires [1].

The ignition source for all smoldering ignitions was a 500-watt charcoal igniter with approximately 20 inches (0.508 m) of exposed cal-rod. The charcoal igniter was placed in contact with the item to be burned and energized from 120 Volts AC 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

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 |

mattress 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 alarm and untenable conditions in the primary escape path) provided by each. Note that the ionization detectors responded first followed by the photoelectrics. 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 general 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 sensitivity of 3.89%/ft (0.086 OD/m), 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 detectors at a particular location it appears that the variations are more a function of sensitivity and detector design than detection mode.

All data taken is recorded in the source report, 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

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 |
| TC | FT | 150F | 1370 | -308 |
| TC | FT | 150F | 1510 | -448 |

Data

Test No.: Jr-16    Fire Type: F (Chair)    Season: Winter

Tenability Limits Exceeded: 1060 s    AC/Heat: On

Flame at: 0 s    Test Terminated at: 1546 s

Fire Location: Living Room

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 | — |
| TC | FT | 135F | NO* | — |
| TC | FT | 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 s Test Terminated at: 3720 s

Fire Location: 1st Floor Bedroom

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.

## 4. DISCUSSION OF RESULTS

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.

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.

After a literature search, tenability limits were selected above which the normal escape path would be considered unpassable. These limits were 0.07 OD/ft (0.02 OD/m) at the 150 °F or 400 ppm CO anywhere in the path. (For a discussion of the selection of limits of tenability see Appendix A of this paper.) 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.

The performance curves (figs. 20-25) indicate the frequency of success (ordinate) that a given detector and location would provide for any required escape time (abscissa). 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. The curves are separated into response by 1% or 2% detectors to smoldering or flaming fires[3] in one test building. Some curves show the differing effects of winter and summer conditions where important.

The theoretical smoke detector performance is shown in figure 20 for two escape criteria, 0.03 and 0.07 OD/ft (0.009 and 0.02 OD/m). The choice of these escape criteria has a

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[3] For example S, 2% refers to 2% detectors and smoldering ignitions and F; 1% refers to 1% detectors and flaming ignitions.

small effect on the theoretical results. The curves show that both the theoretical and actual detectors provide inadequate protection (mostly negative escape times) when fires and detectors are on different floors.

In the primary test site, the escape times obtained from detectors installed on the second floor responding to first floor fires seem somewhat marginal (as shown in fig. 22). 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. This is shown by comparing figures 21 and 22. 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 (9.15-m) 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. This is shown in figure 23 where A and B are detector locations at either end of the hall.

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 (15.24 m) 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 provided little or no escape time prior to occurrence of dangerous conditions 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 (57 °C) fixed-temperature heat detector assuming no thermal lag. These results indicate that no thermal lag fixed-temperature heat detectors in every room would have little life saving potential in the residential fire situations simulated here. The curves for the heat detectors are given in figures 24 and 25.

## 5. CONCLUSIONS

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 building 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 (actual) 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 (57 °C) 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. During forced air heating 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 obtained in the bedrooms with the doors closed.

Experiments conducted with fires in closed bedrooms resulted in lethal conditions in the bedroom before response of detectors outside the bedroom. 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 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 time 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 centrally air-conditioned.

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 (30 cm) of the ceiling. However, individual detectors with highly directional properties may function quite differently in these two positions.

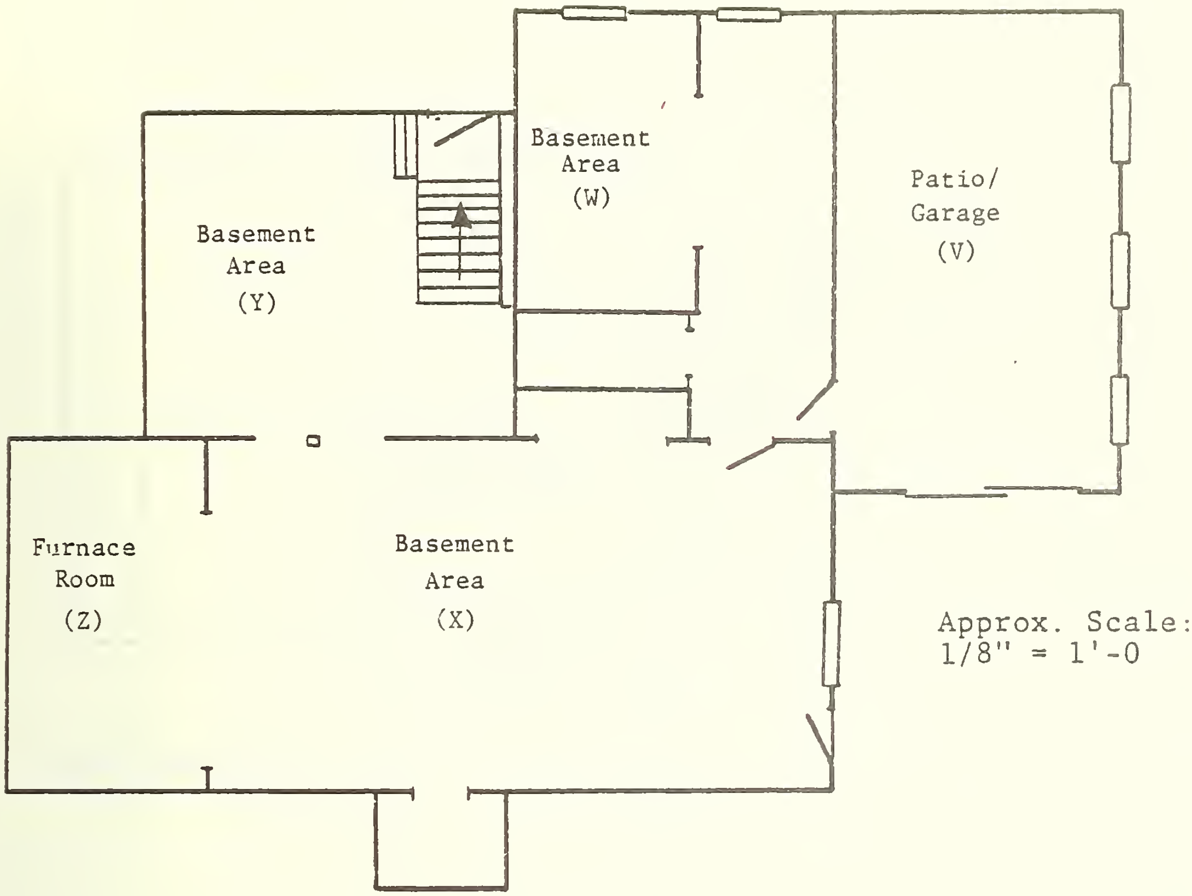



Figure 1. Room Identification: Basement Floor Plan — J.R. Whitehouse Residence

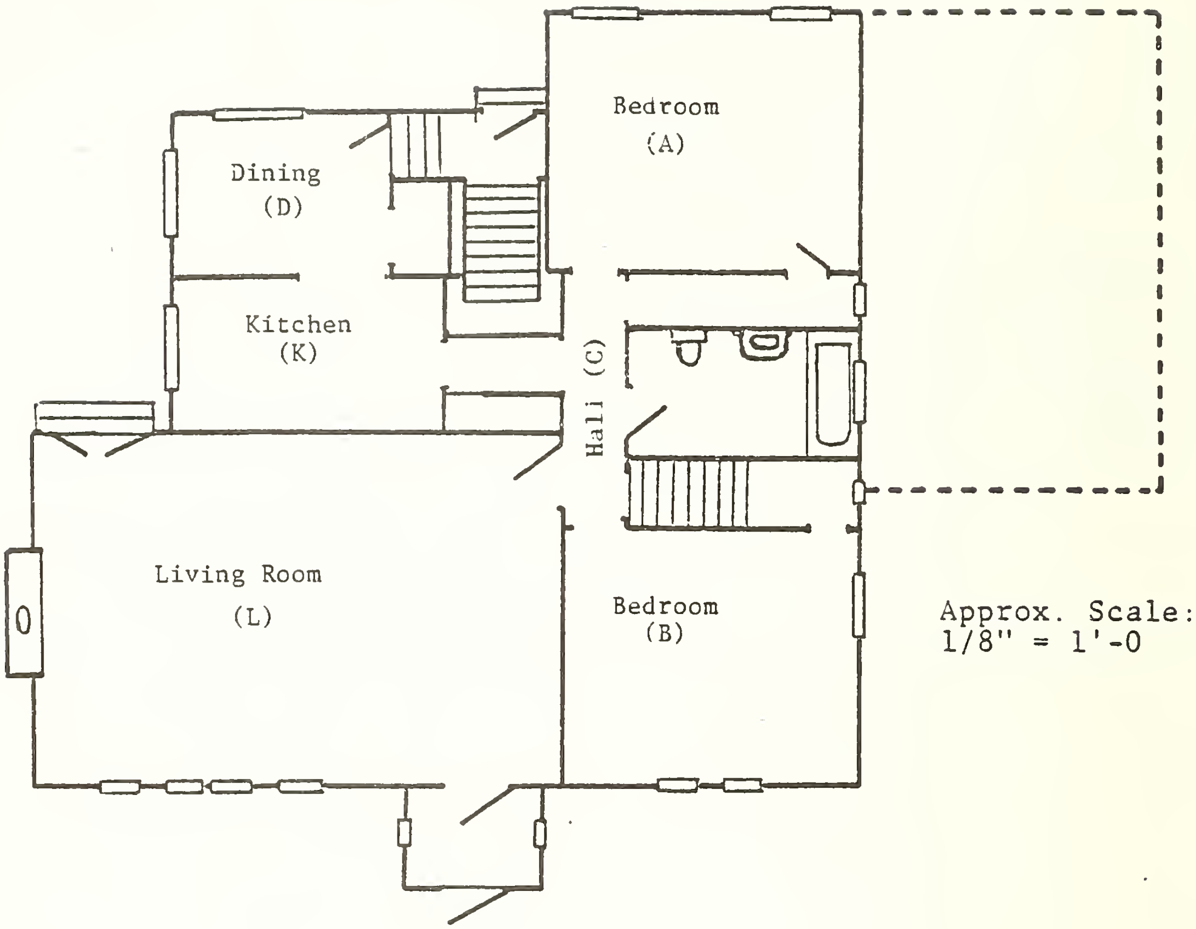



Figure 2. Room Identification: 1st Floor Plan — J.R. Whitehouse Residence

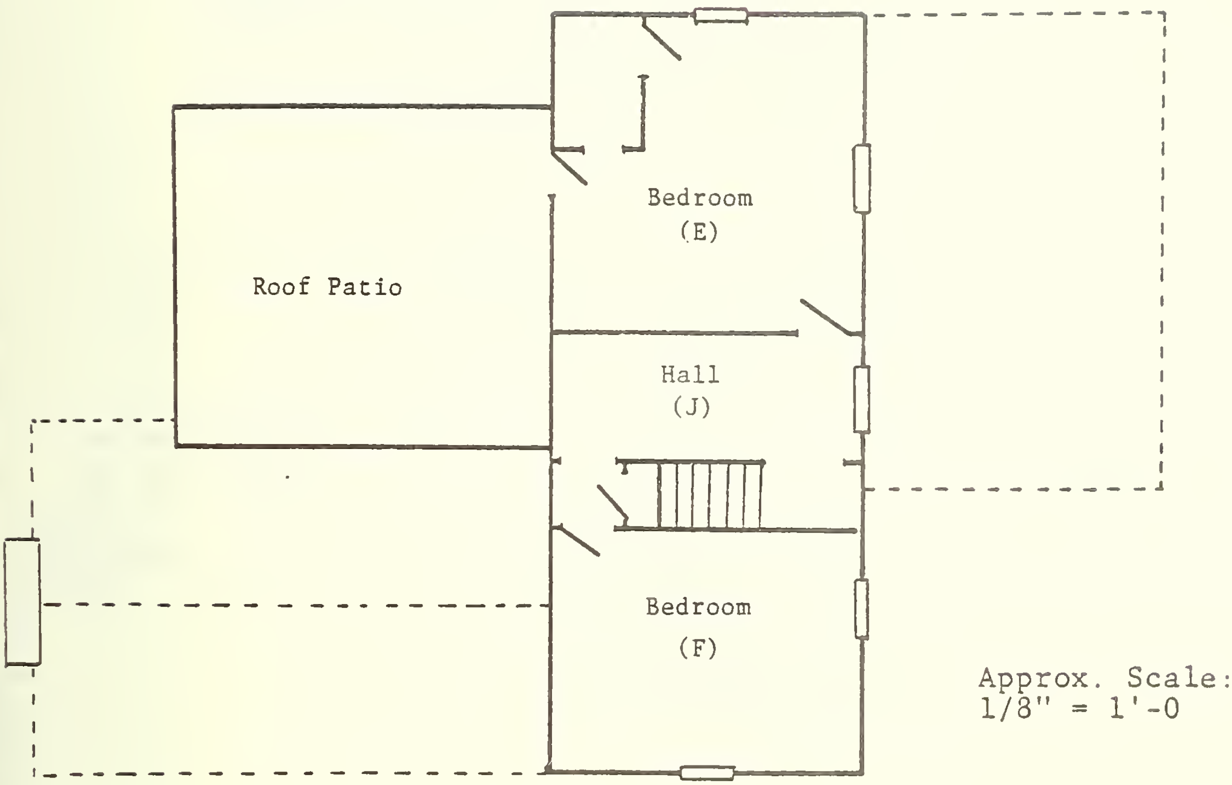



Figure 3. Room Identification: 2nd Floor Plan — J.R. Whitehouse Residence

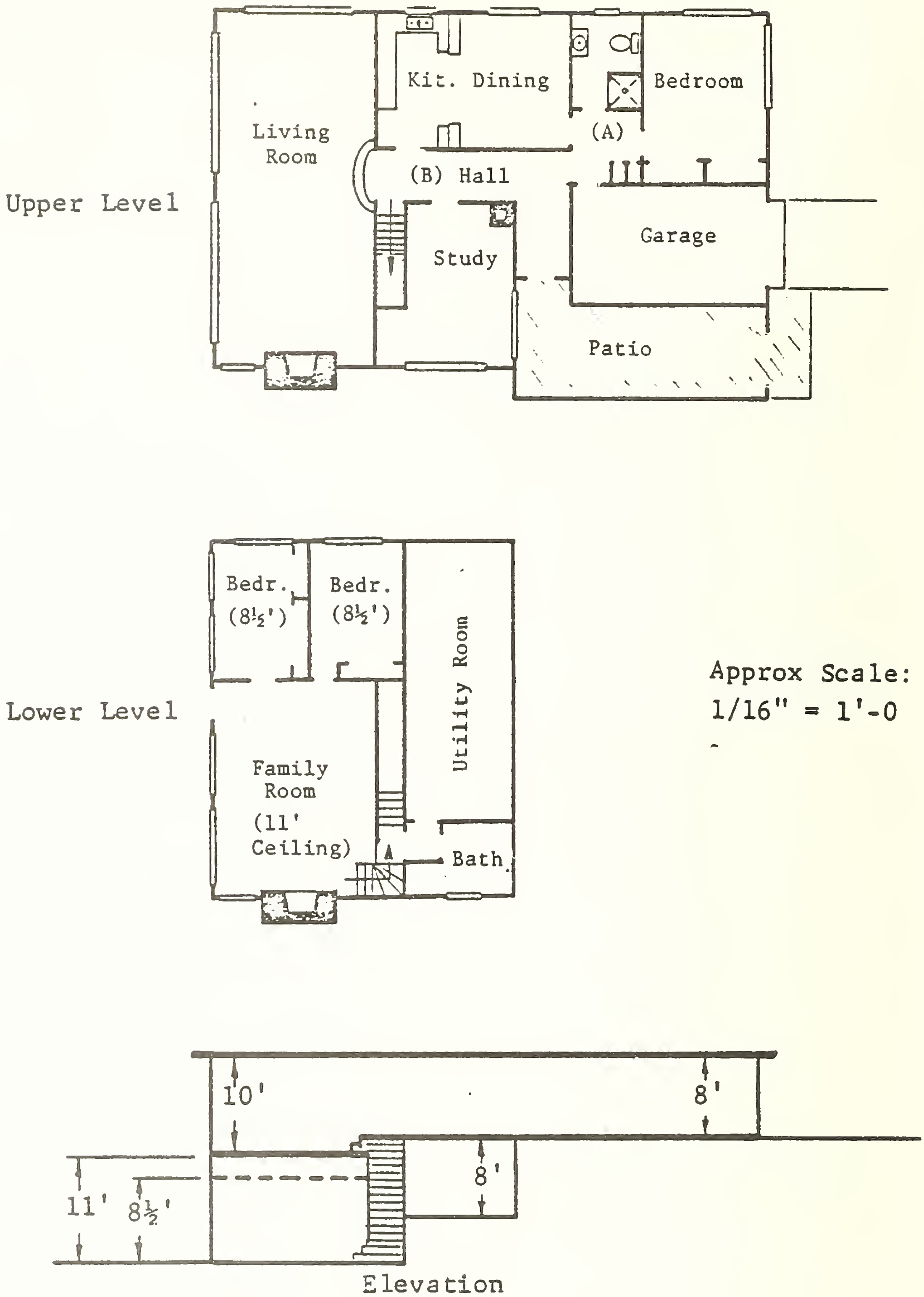
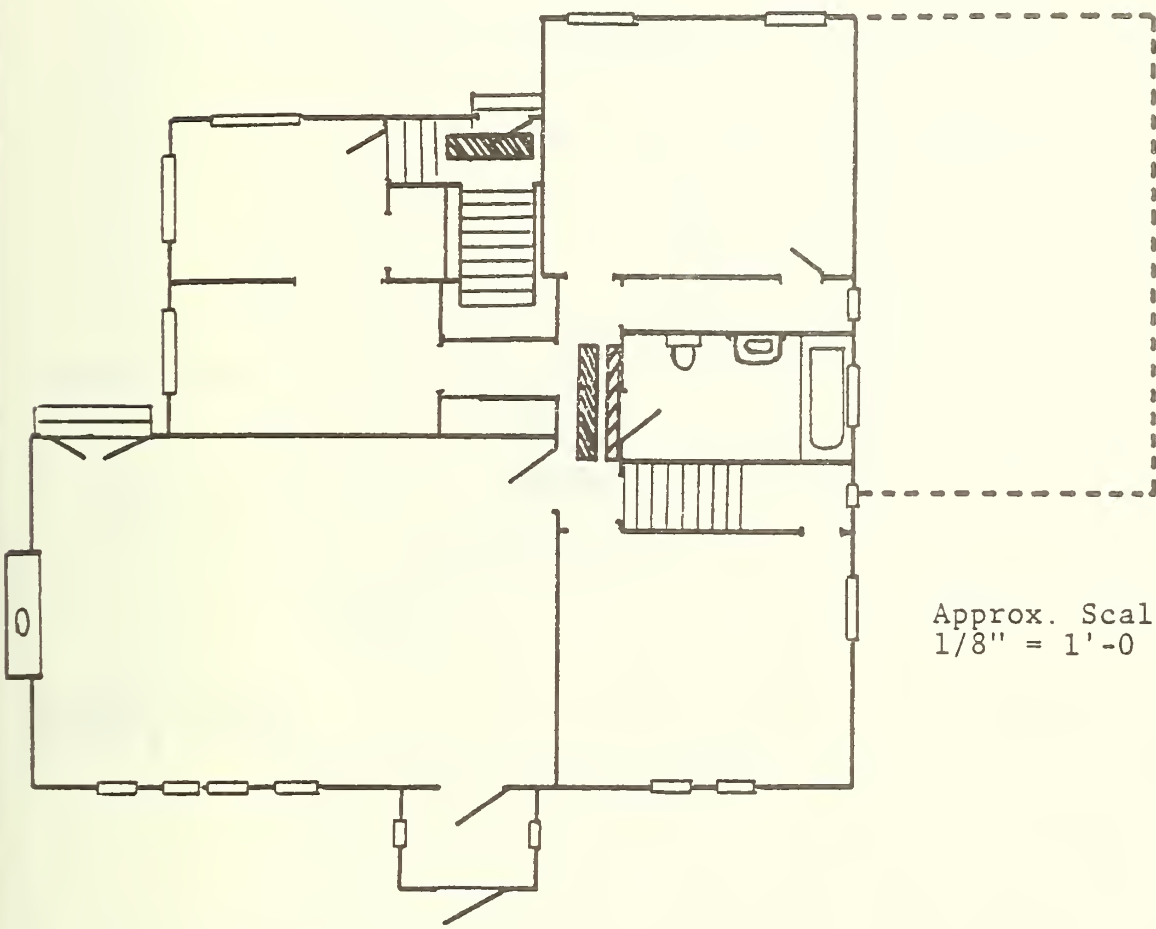



Figure 4. Room Identification: Floor Plan — Lakeshore Residence

KEY

Ceiling Mounted

Wall Mounted, 9 In. Below Ceiling



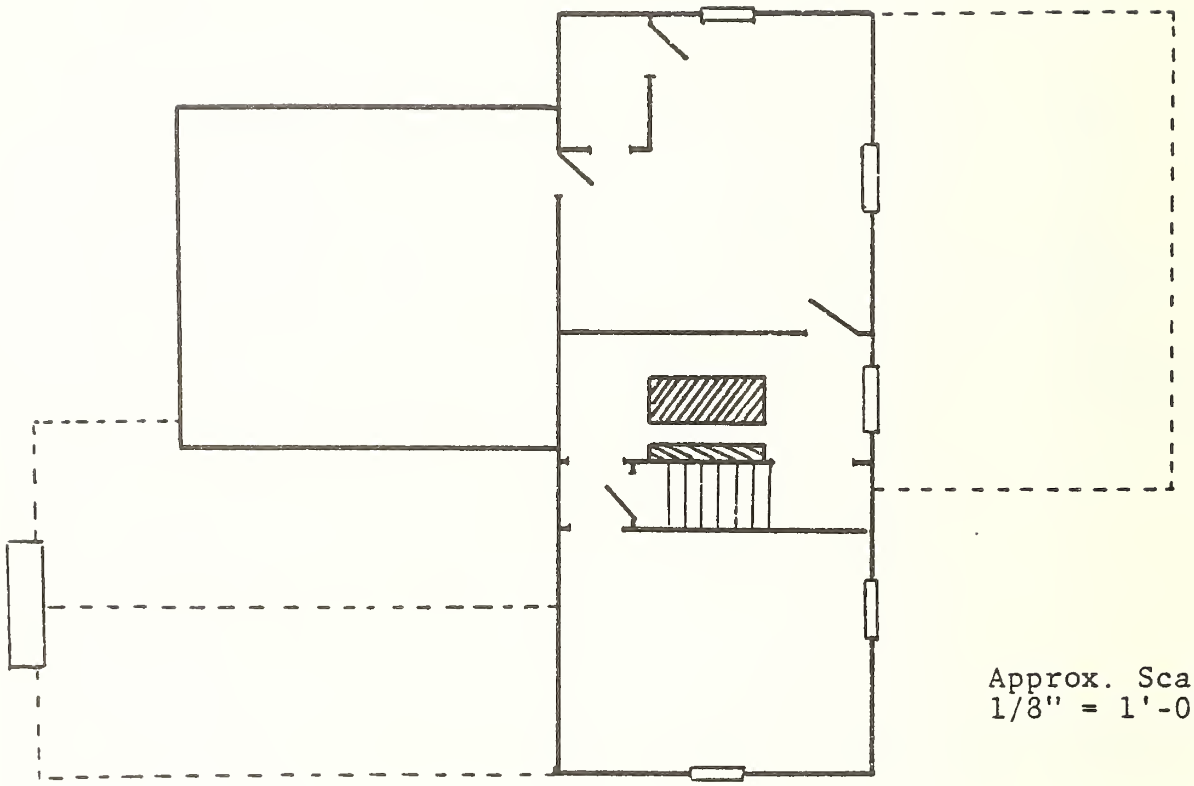

Approx. Scale:
1/8" = 1'-0

Figure 5. Detector Locations: 1st Floor Plan — J.R. Whitehouse Residence

KEY

Ceiling Mounted

Wall Mounted, 9 In Below Ceiling



Approx. Scale:
1/8" = 1'-0

Figure 6. Detector Locations: 2nd Floor Plan — J.R. Whitehouse Residence

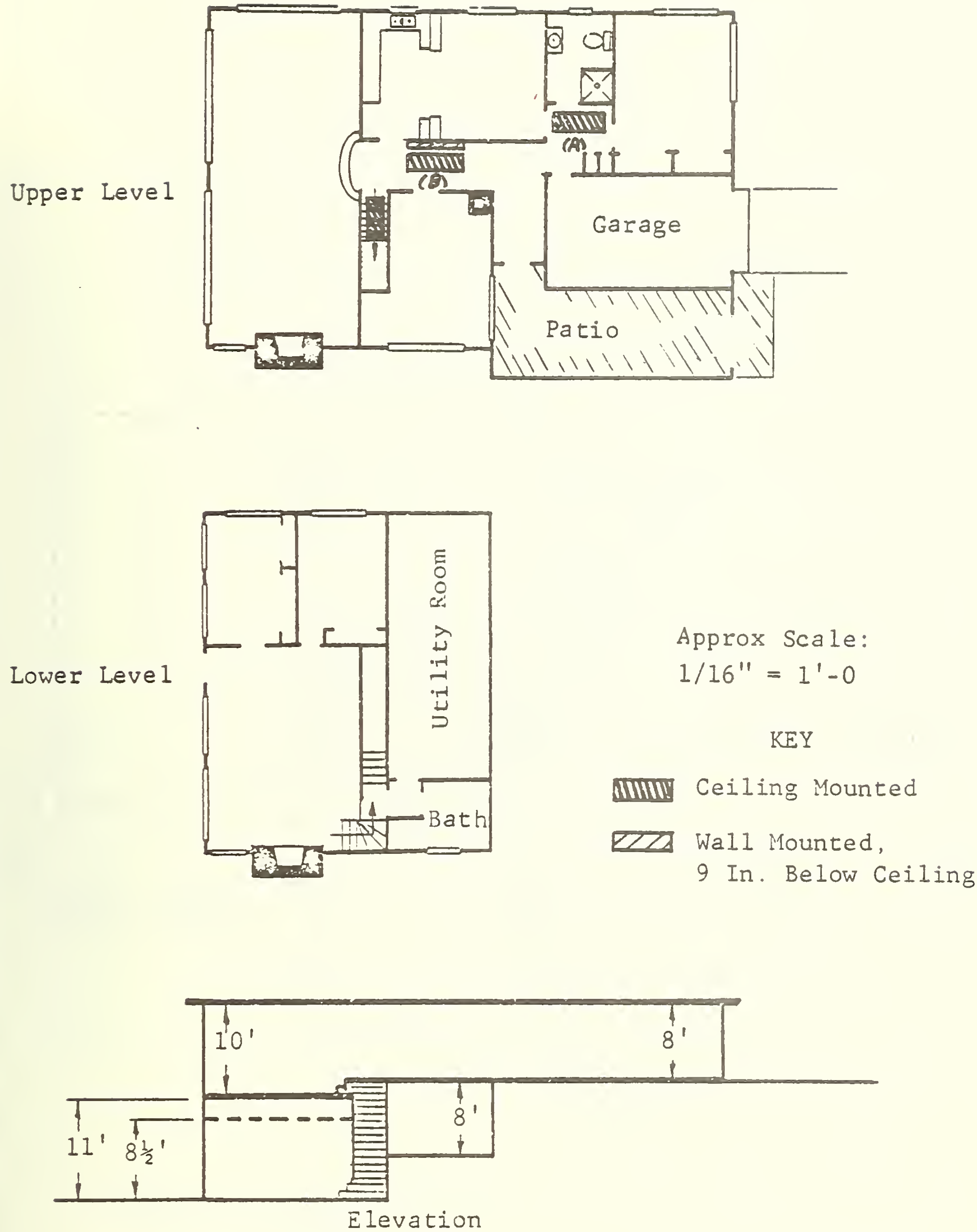



Figure 7. Detector Locations: Floor Plan — Lakeshore Residence

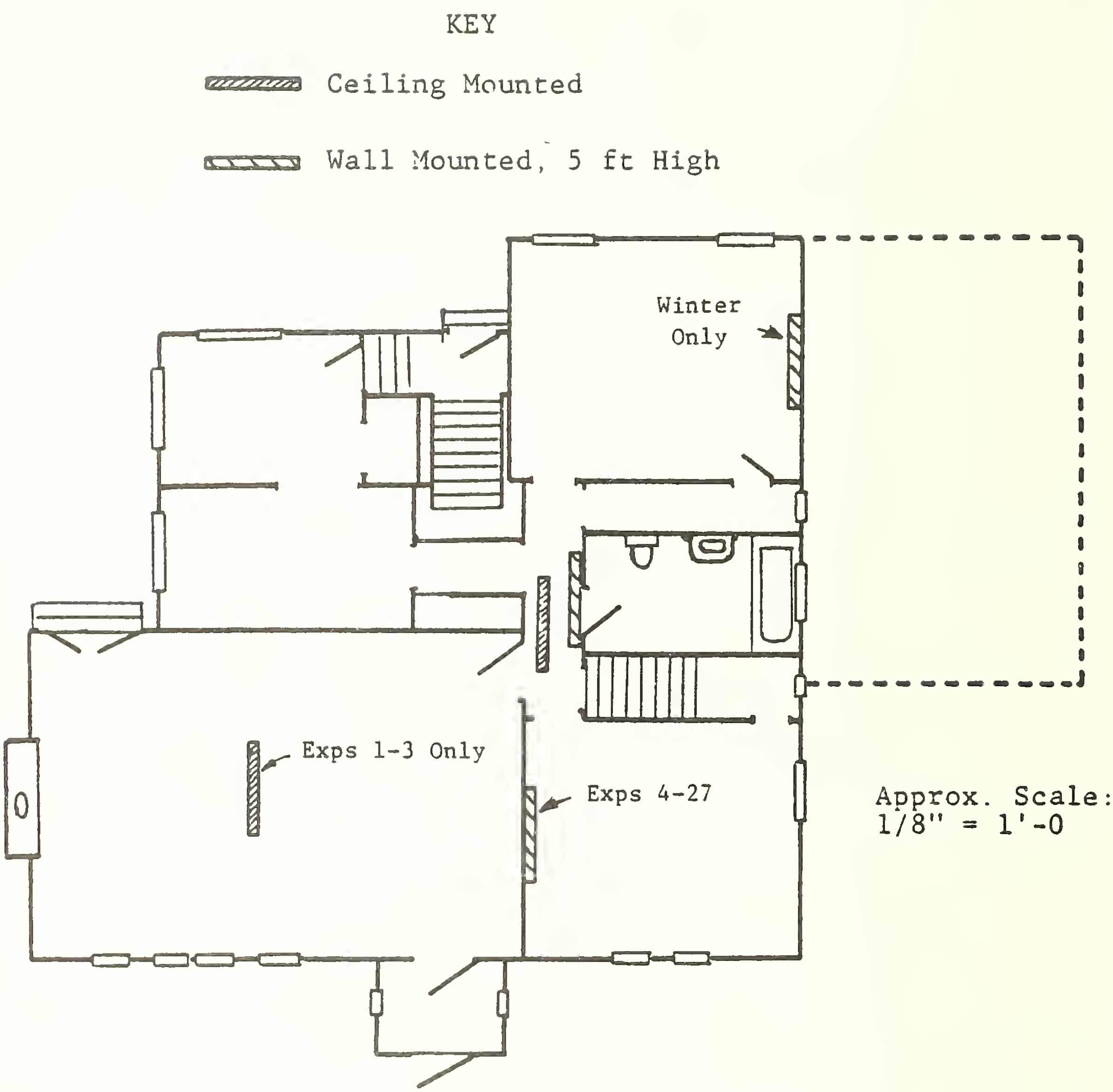



Figure 8. Fixed Light Beam Locations (Smoke): 1st Floor Plan — J.R. Whitehouse Residence

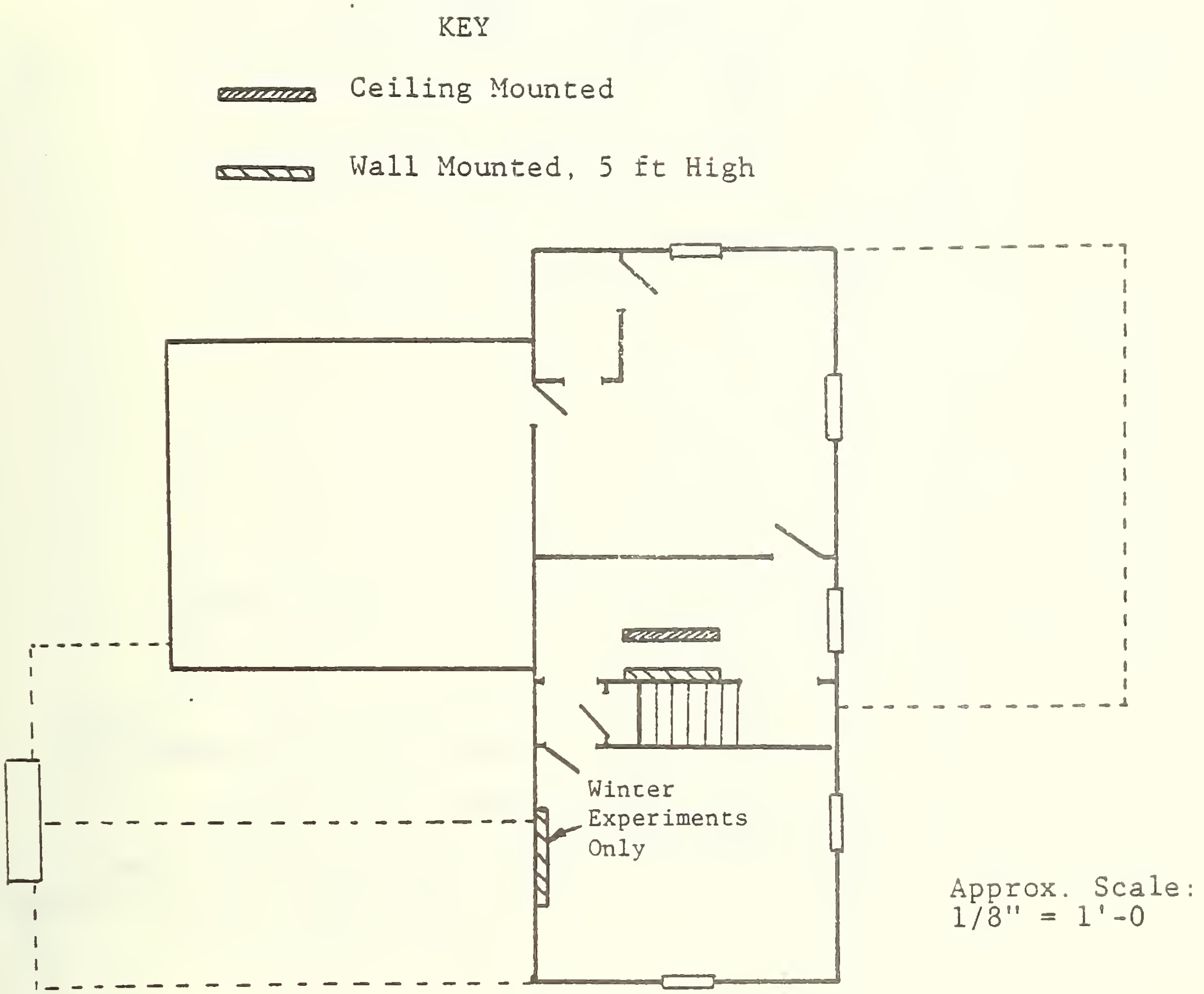



Figure 9. Fixed Light Beam Locations (Smoke): 2nd Floor Plan — J.R. Whitehouse Residence

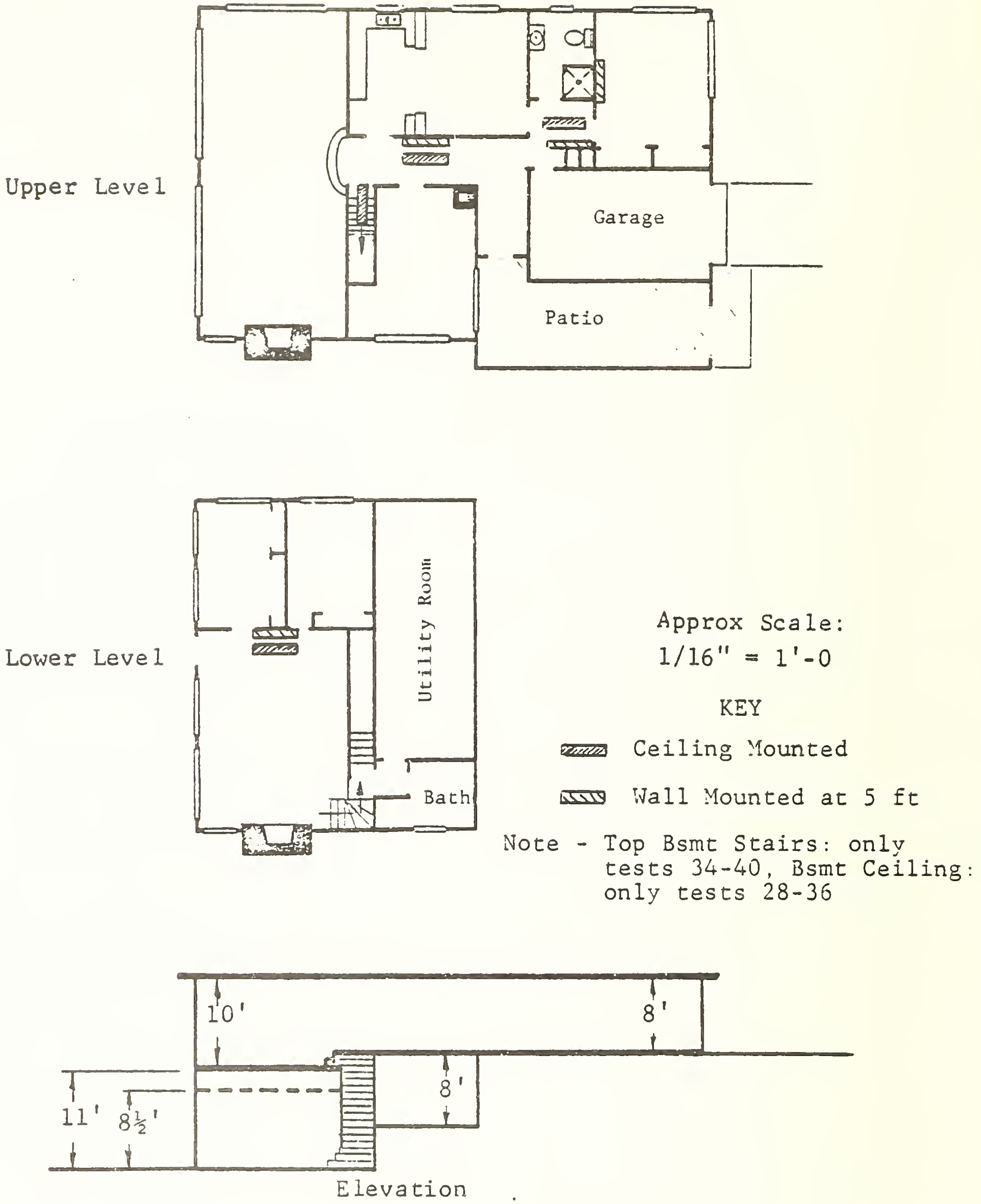



Figure 10. Location of Light Beams for Smoke Measurements (Except for Ignition Room): Floor Plan — Lakeshore Residence

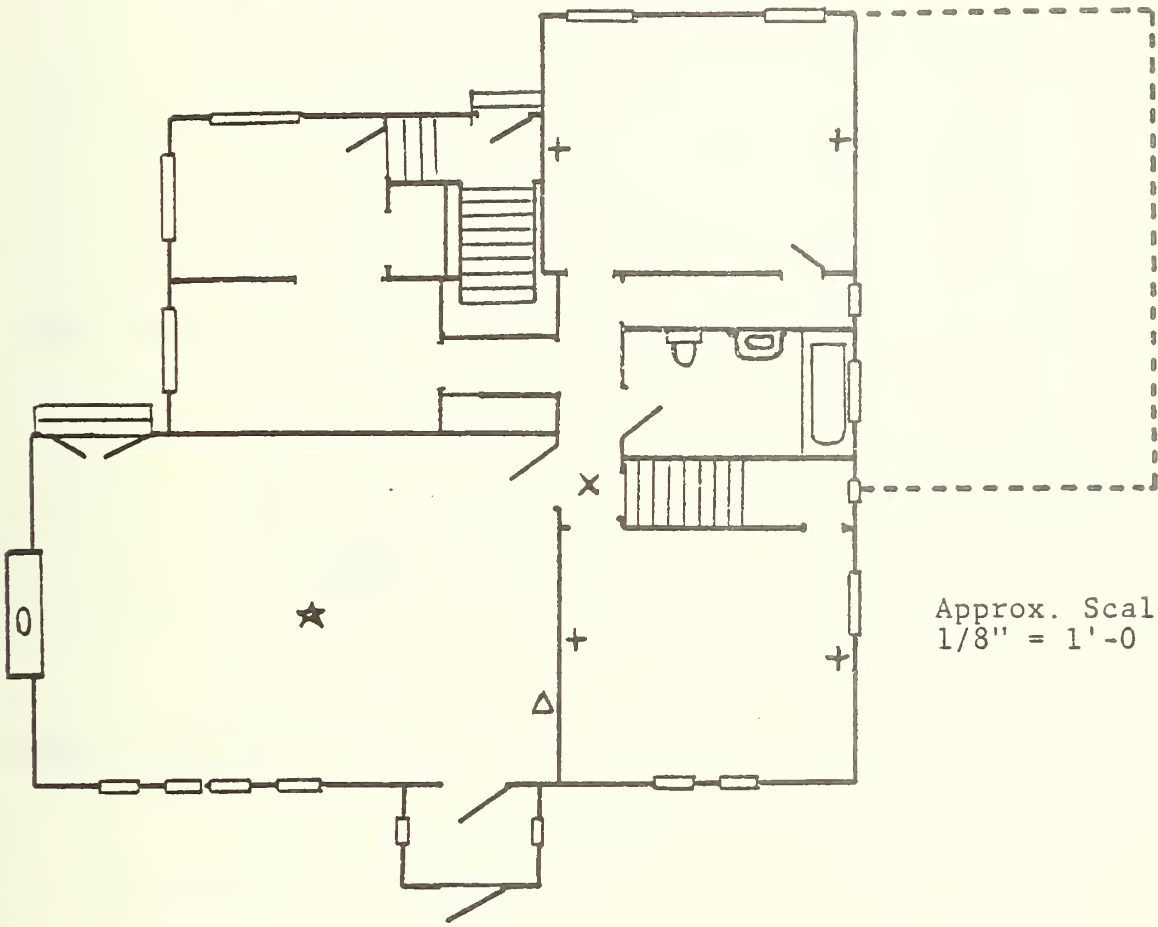
KEY

× Thermocouple Profile

+ Thermocouples 5 ft High

△ Thermocouple 4 in Above Hot Air Register

★ Ceiling Thermocouple (13 ft High)



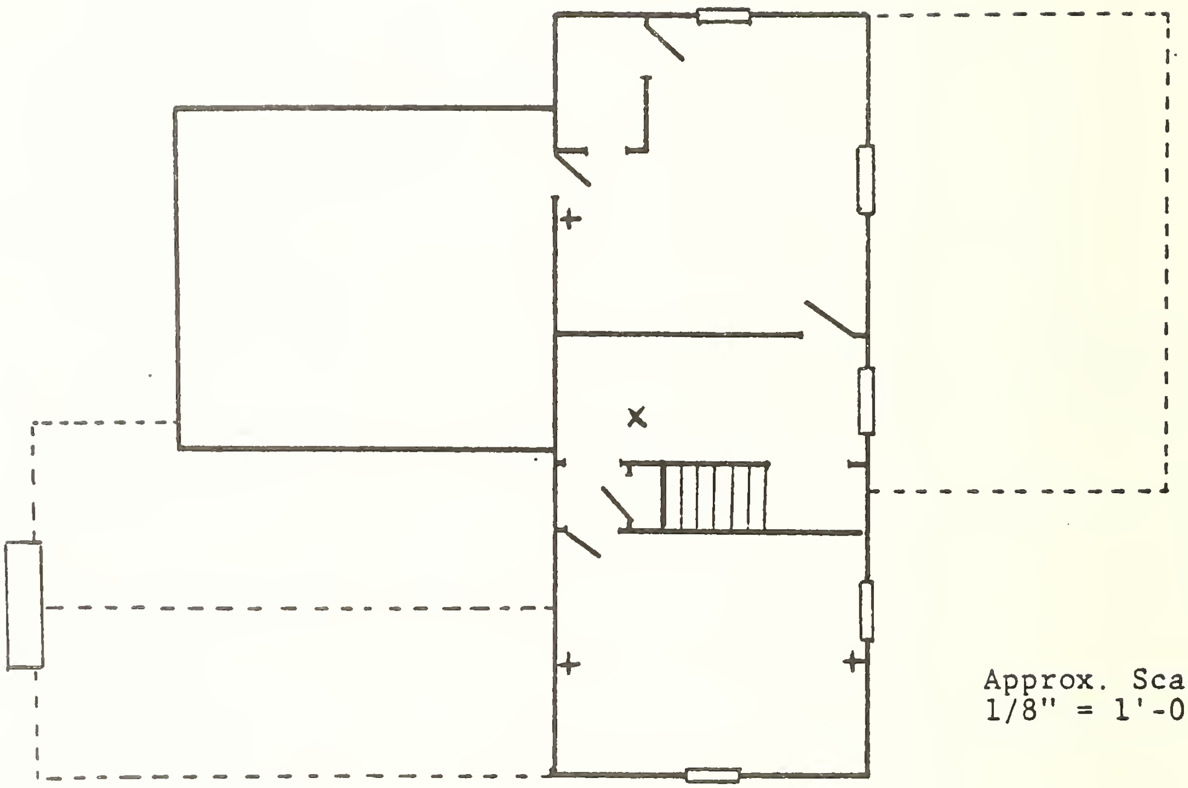
Approx. Scale:
1/8" = 1'-0

Figure 11. Fixed Temperature Measurements: 1st Floor Plan — J.R. Whitehouse Residence

KEY

× Thermocouple Profile

+ Thermocouples 5 ft High



Approx. Scale:
1/8" = 1'-0

Figure 12. Fixed Temperature Measurements: 2nd Floor Plan — J.R. Whitehouse Residence

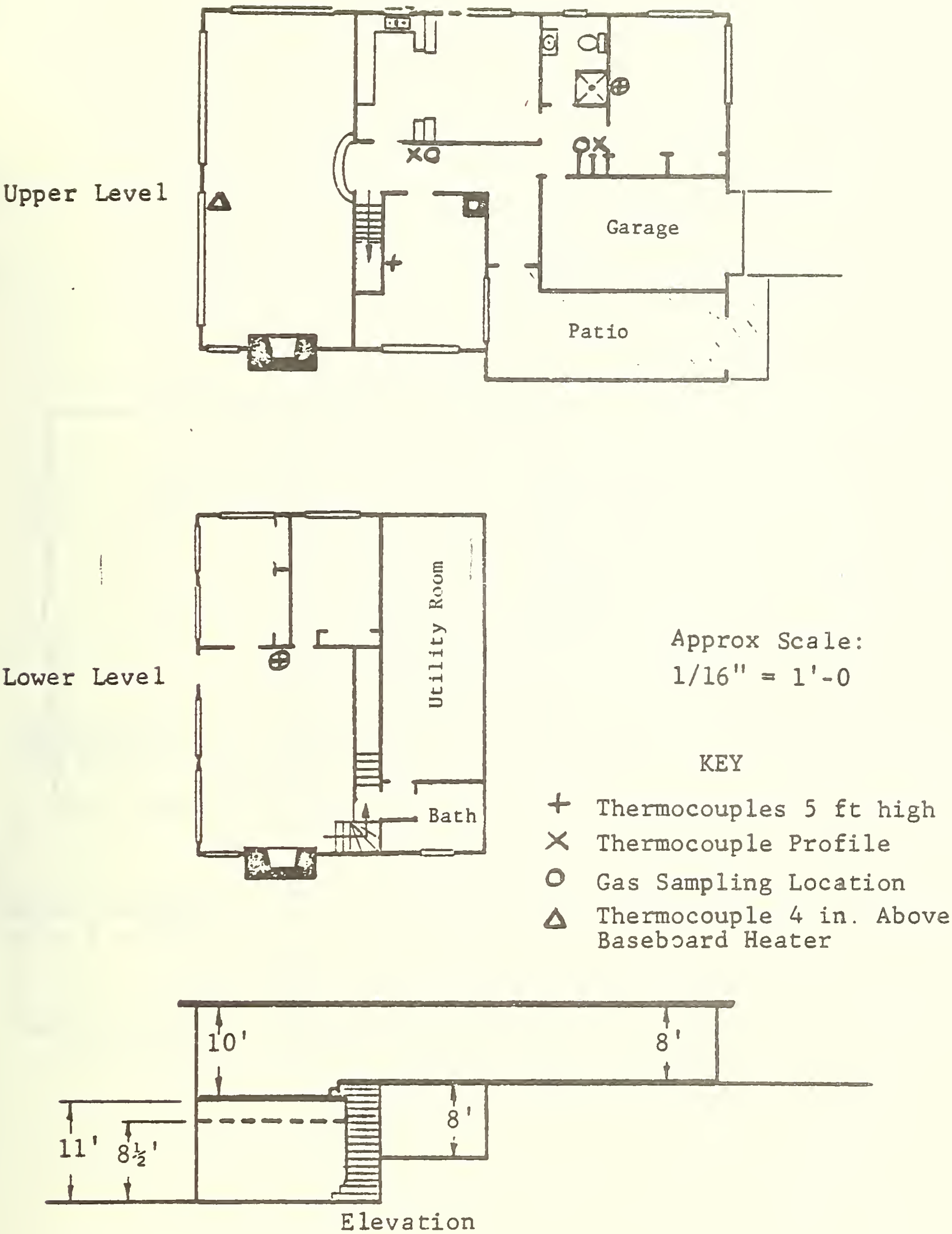
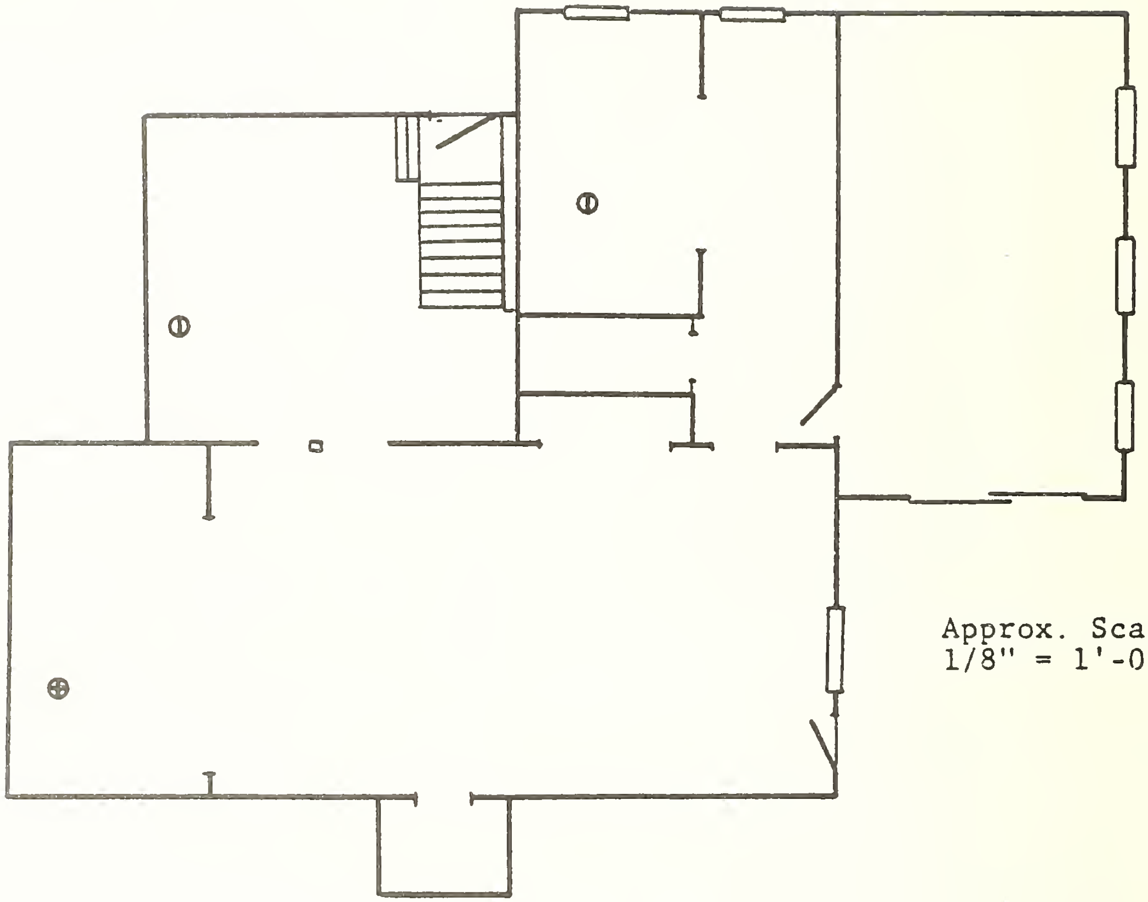



Figure 13. Fixed Temperature Measurements and Gas Sampling Locations: Floor Plan — Lakeshore Residence

KEY

Summer Experiments

Winter Experiments



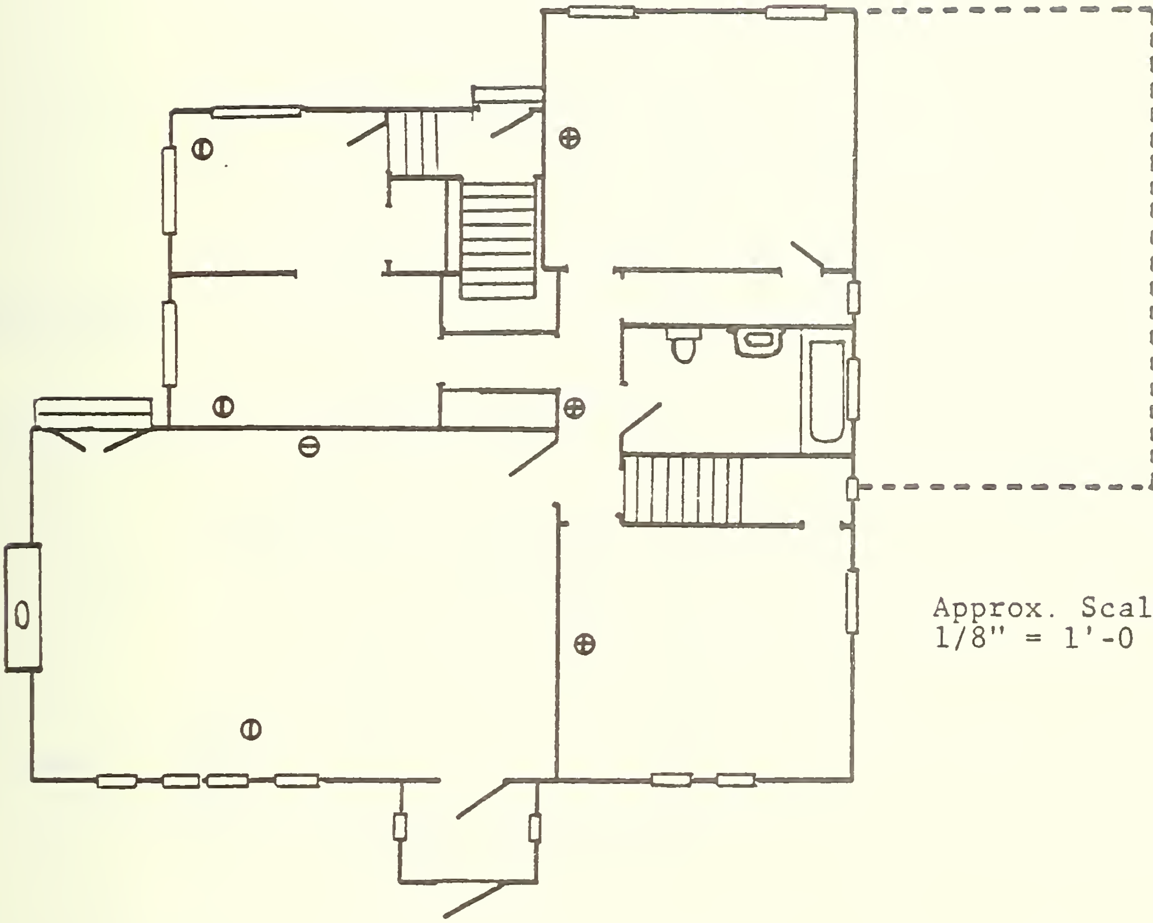
Approx. Scale:
1/8" = 1'-0

Figure 14. Gas Sampling Locations: Basement Floor Plan — J.R. Whitehouse Residence

KEY

Summer Experiments

Winter Experiments



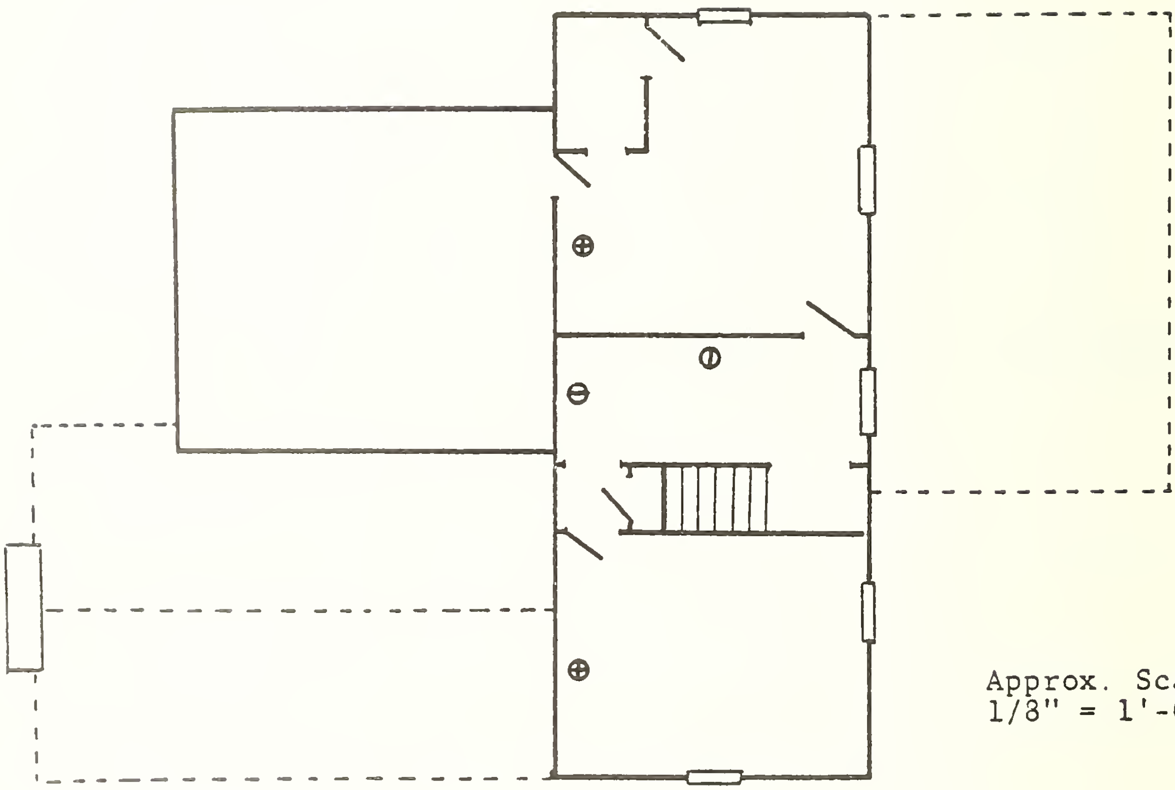
Approx. Scale:
1/8" = 1'-0

Figure 15. Gas Sampling Locations: 1st Floor Plan — J.R. Whitehouse Residence

KEY

⦶ Summer Experiments

⊖ Winter Experiments



Approx. Scale:
1/8" = 1'-0

Figure 16. Gas Sampling Locations: 2nd Floor Plan — J.R. Whitehouse Residence

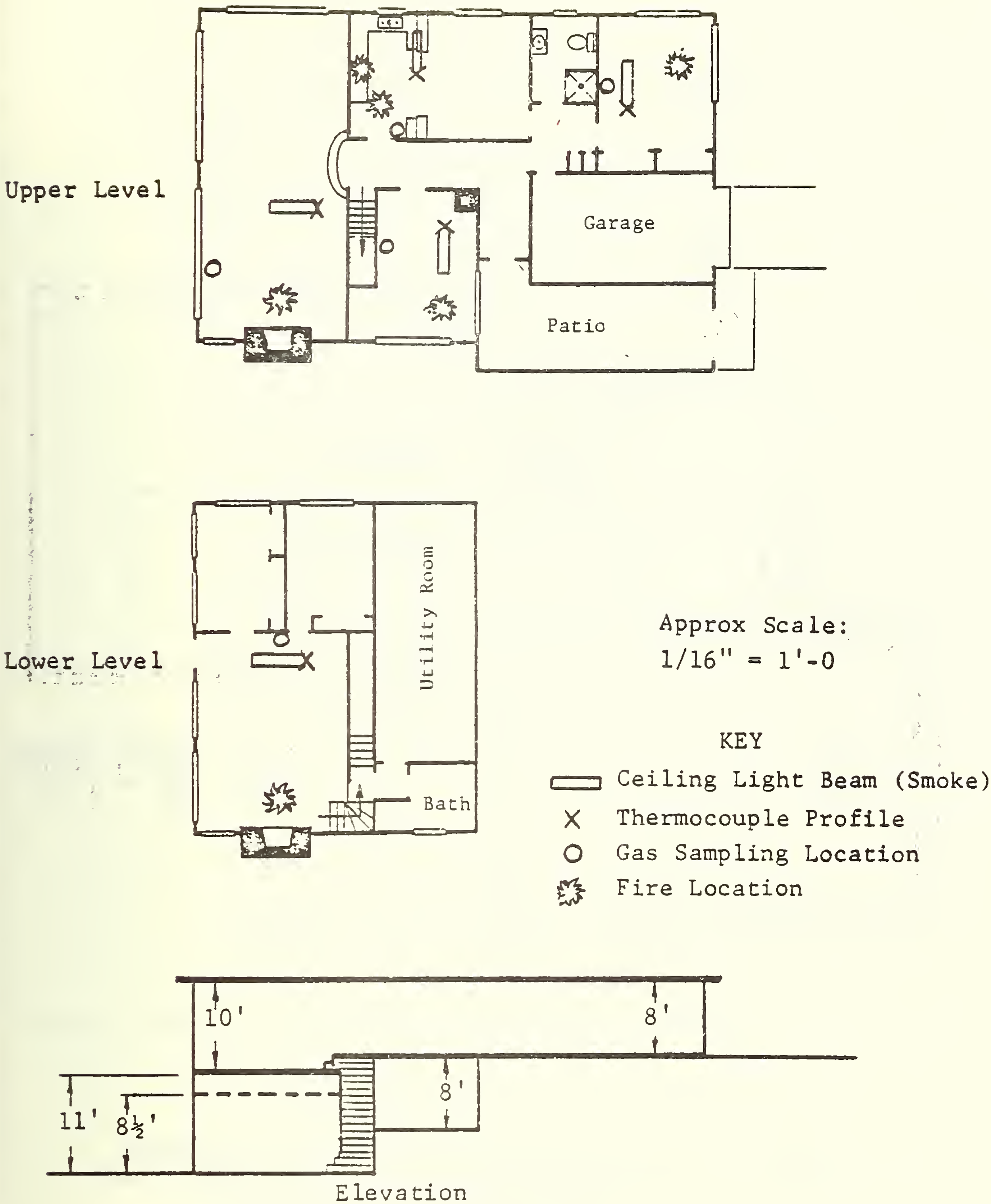



Figure 17. Fire Locations and Portable Ignition Room Instrumentation: Floor Plan — Lakeshore Residence

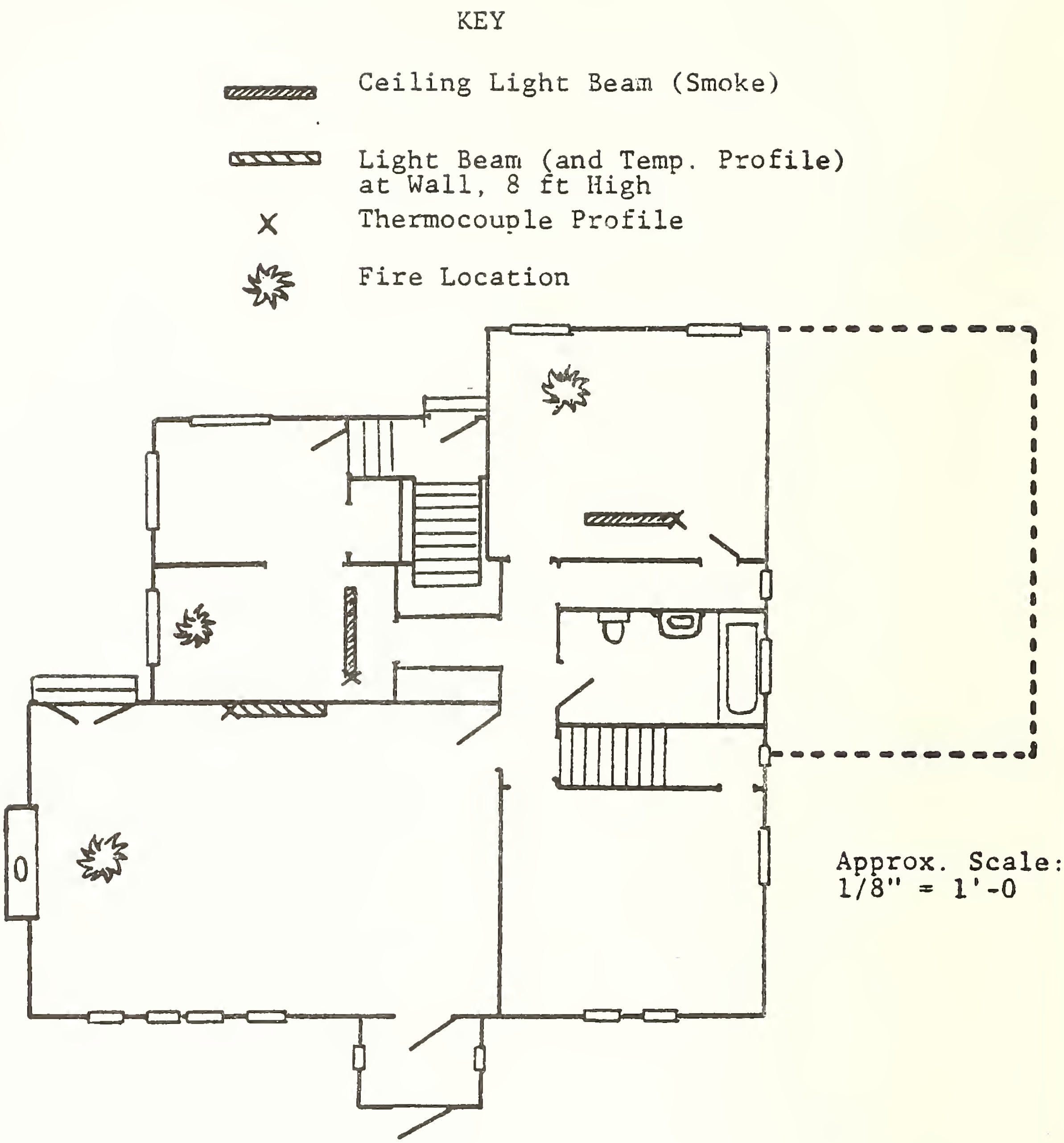


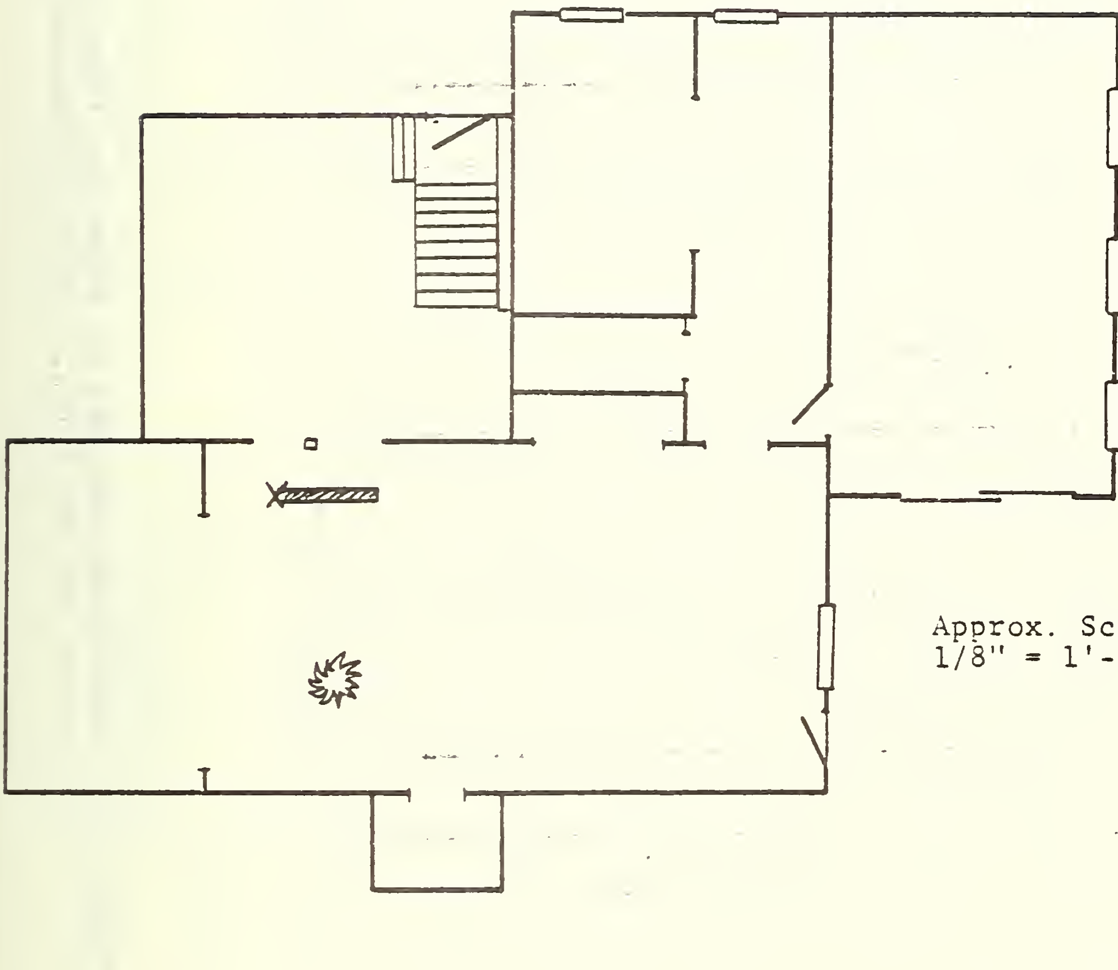

Figure 18. Fire Locations and Portable Ignition Room Instrumentation: 1st Floor Plan — J.R. Whitehouse Residence

KEY

Ceiling Light Beam (Smoke)

X Thermocouple Profile

Fire Location



Approx. Scale:
1/8" = 1'-0

Figure 19. Fire Locations and Portable Ignition Room Instrumentation: Basement Floor Plan — J.R. Whitehouse Residence

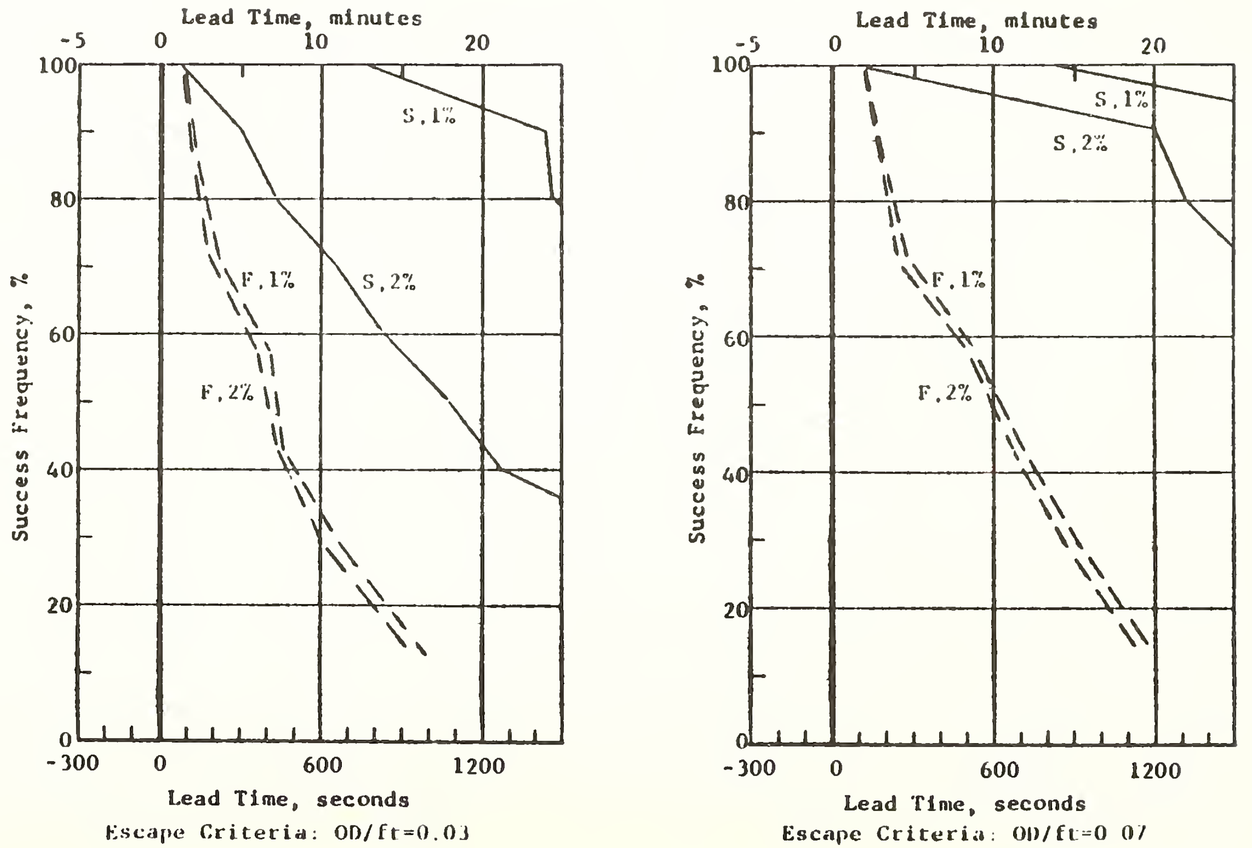



Figure 20. Theoretical Ability to Sense 1st Floor Fires: Detectors on 1st and 2nd Floor. (J.R. Whitehouse Residence)

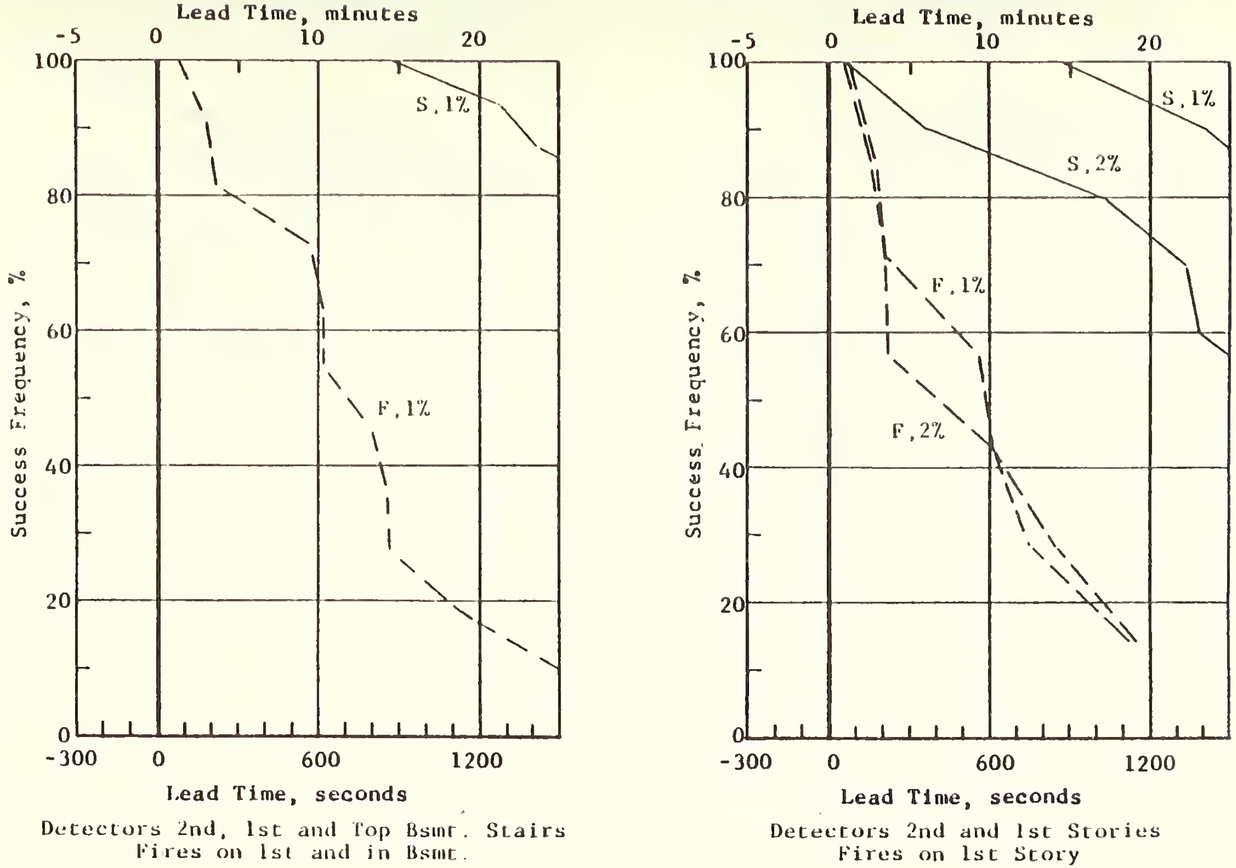



Figure 21. Ability of Detector "E" to Sense Fires (J.B. Whitehouse Residence)

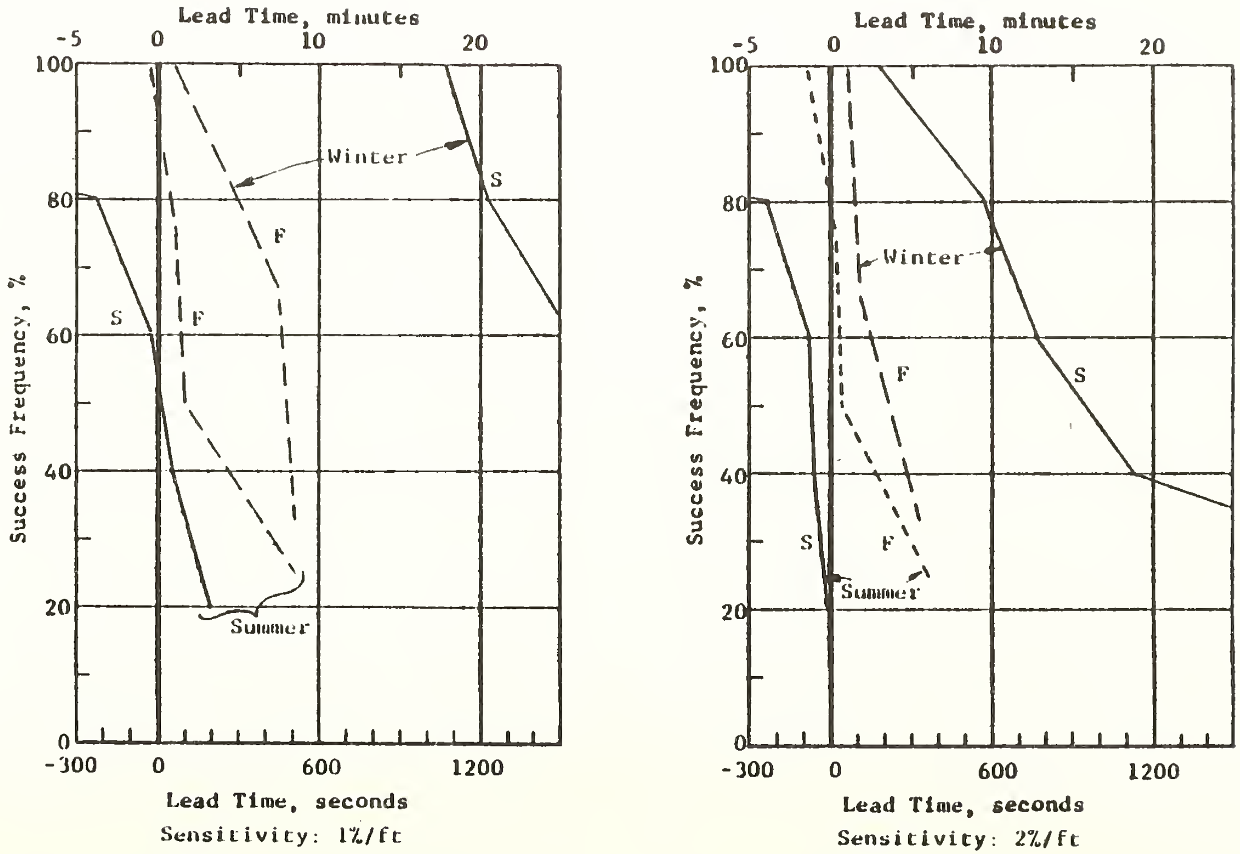
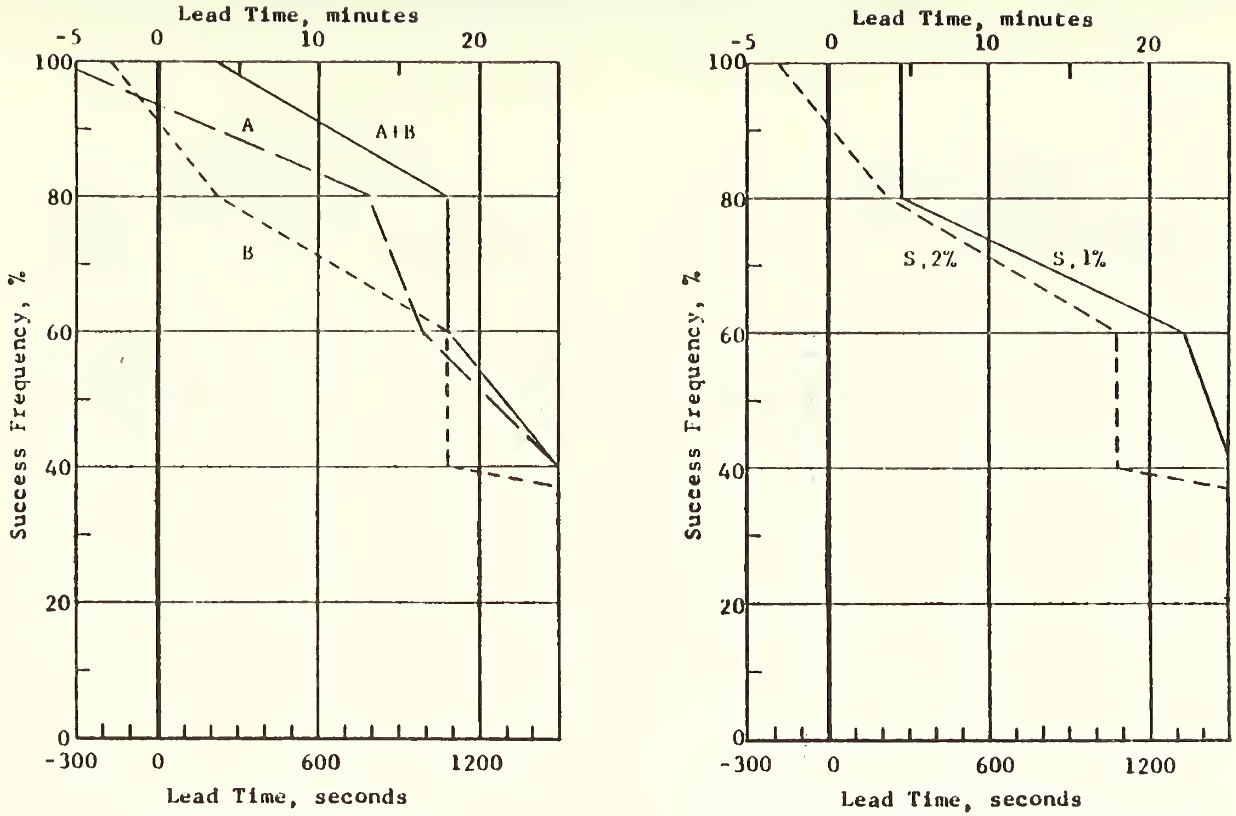



Figure 22. Ability of Detector "E" on 2nd Story to Sense Fires on 1st Story. (J.B. Whitehouse Residence)




Effect of Location, S,2%

Effect of Sensitivity at Location "B"

Figure 23. Ability of Detector "E" to Sense 1st Story Fires. (Lakeshore Residence)

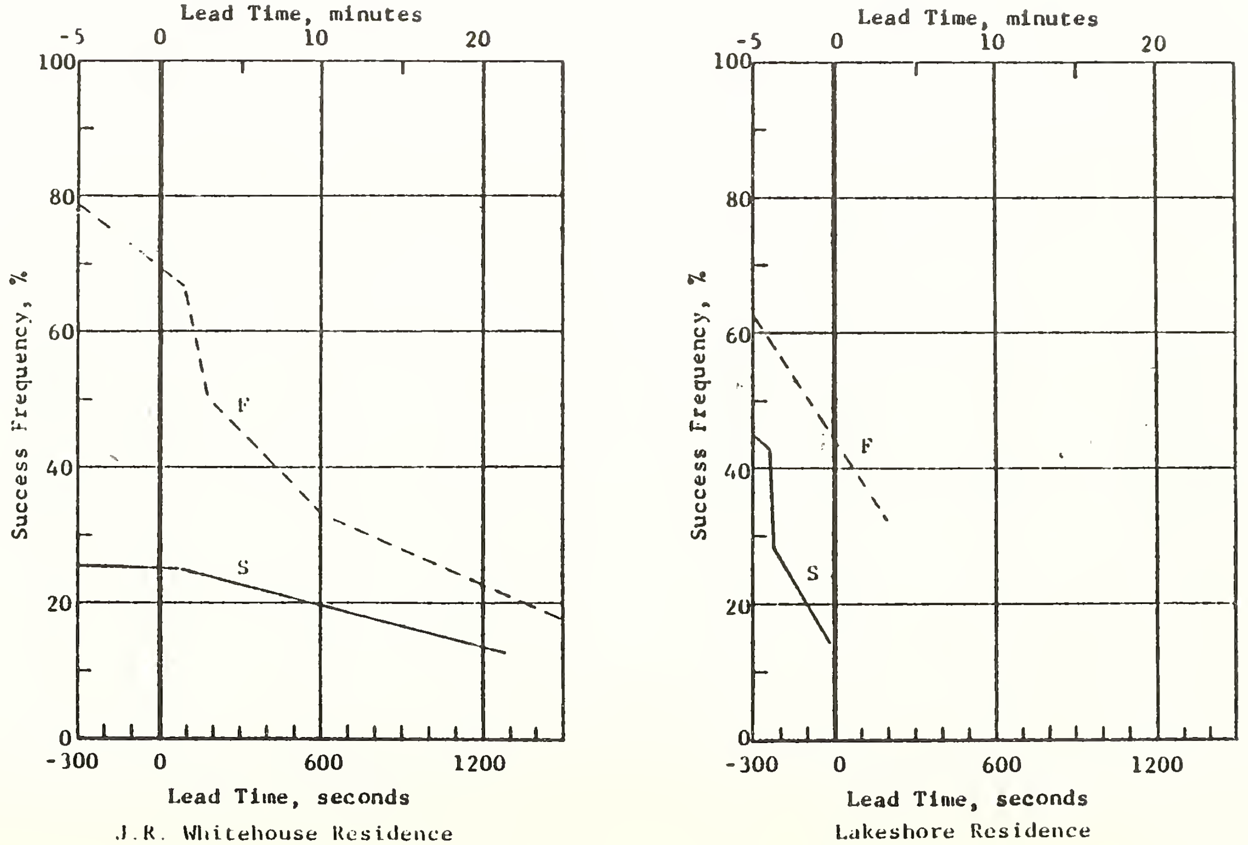



Figure 24. Ability of "Rate-of-Rise" Detector in Room of Ignition to Sense Fires. (Winter Experiments)

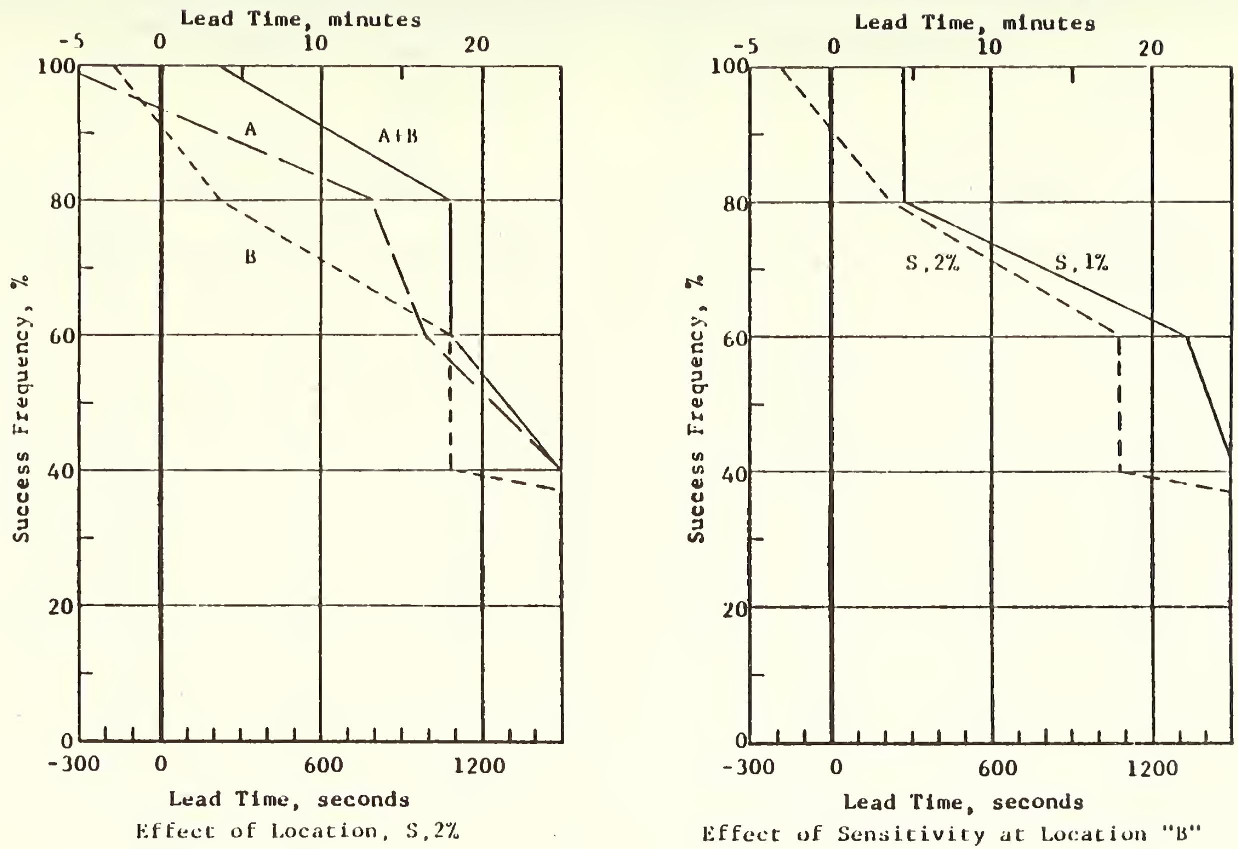



Figure 23. Ability of Detector "E" to Sense 1st Story Fires. (Lakeshore Residence)

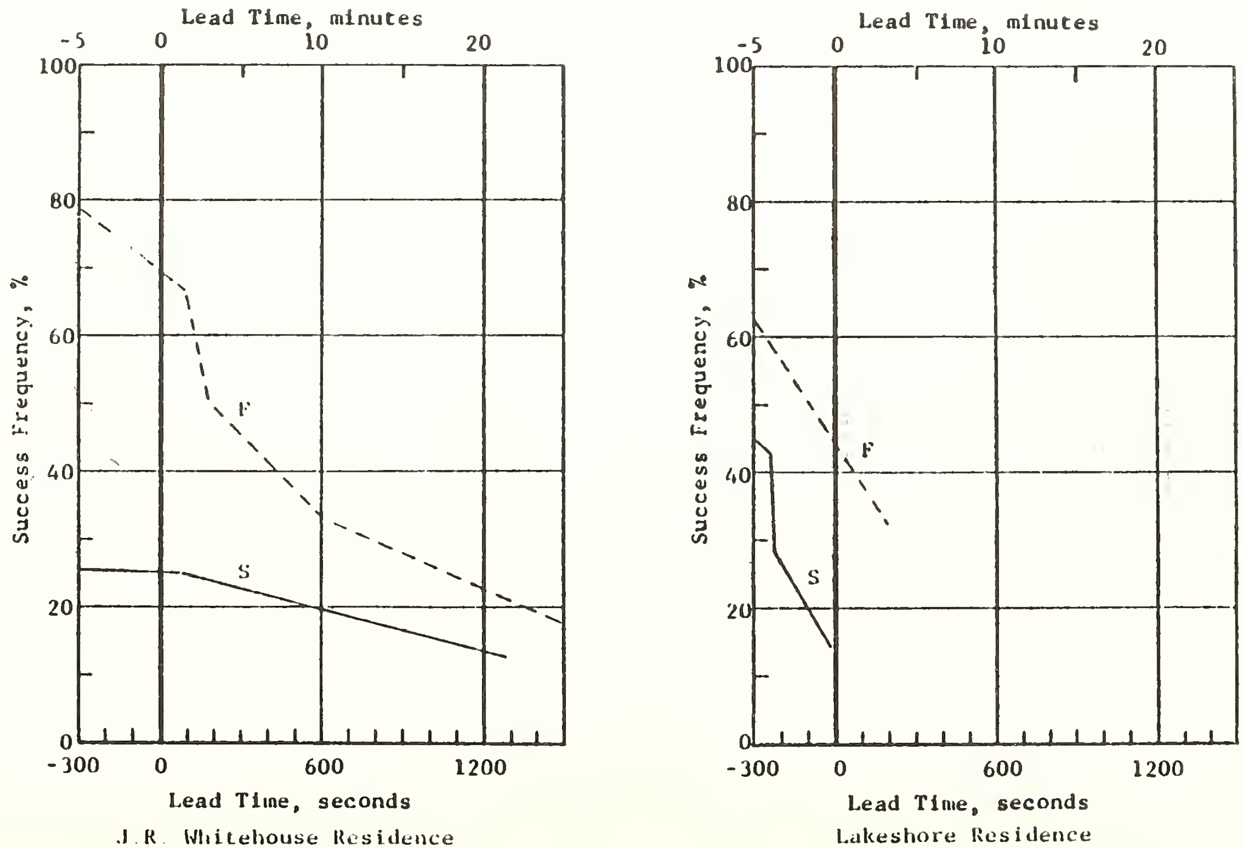



Figure 24. Ability of "Rate-of-Rise" Detector in Room of Ignition to Sense Fires. (Winter Experiments)

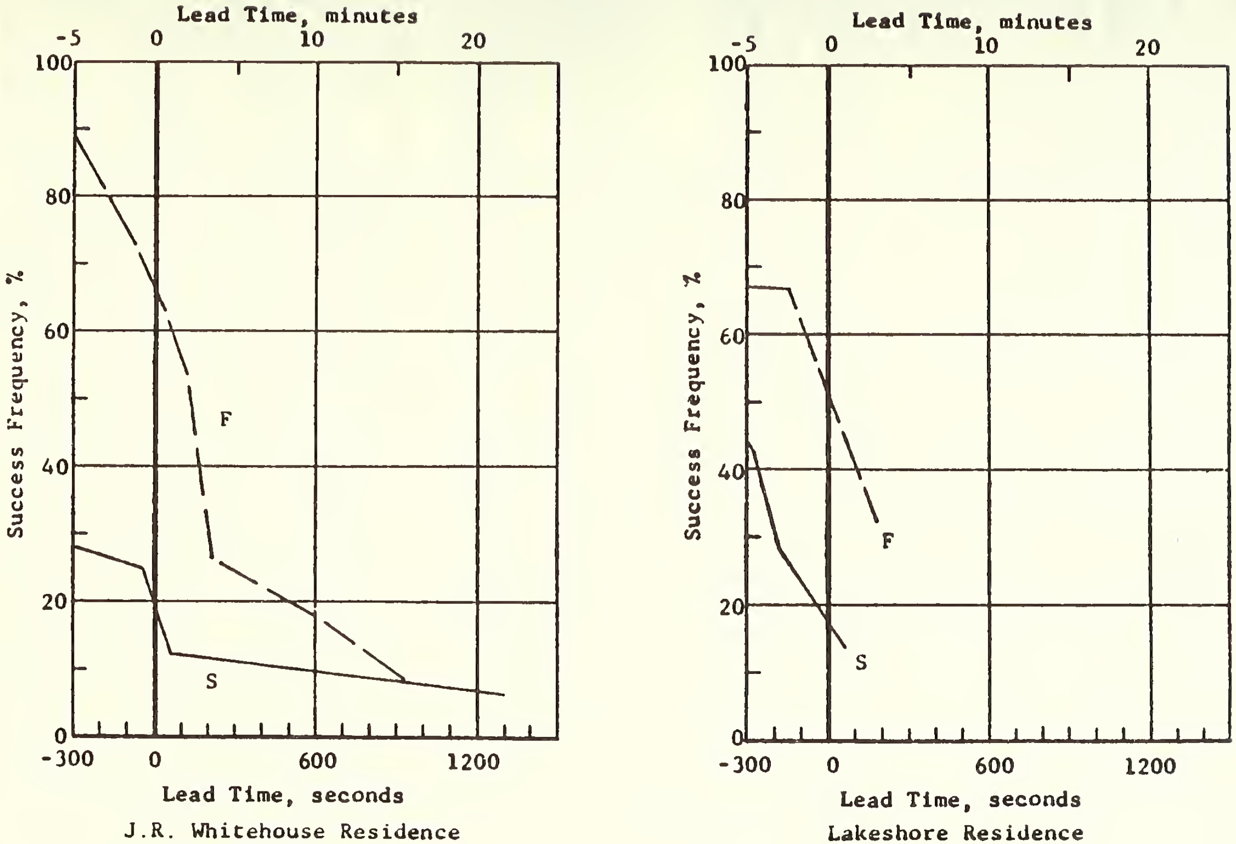



Figure 25. Ability of "No-Lag" 135 °F Heat Detector in Room of Ignition to Sense Fires

## APPENDIX A. ESCAPE CRITERIA

In order to judge adequacy of the warning provided by various detectors used in this study, measurements were made of temperatures, carbon monoxide concentrations, and light obscuration at 5 ft above the floor in bedrooms and along routes of escape to ground level doors. Critical values adopted as the limits beyond which escape would not be possible were optical density of 0.07 per ft, temperature of 150 °F, or a time-averaged concentration of CO of 0.04 percent over a one-hour period. The basis for these choices are given in the following paragraphs. In all of the present experiments, the limiting value of light obscuration was reached first, and thus the escape times cited are based on this criterion of untenability.

### A1. Critical Smoke Level

Presently, there does not appear to be any completely satisfactory way to specify the tenability limits in terms of optical properties of smoke. The situation would be complicated enough if only light transmission through smoke were important, but the effects of respiratory and eye irritation on behavior and visual accuity are also involved.

Table 1 shows some frequently-cited values of critical smoke level from the literature. Obviously, a wide range of smoke densities is represented there. Among references [2-5], at least a rough consensus can be found for a critical optical density of 0.07 per ft over a viewing distance of about 15 ft, when only light obscuration is involved.

References [6] and [7] cite critical smoke densities which are said to take account of eye irritation. The optical density of 0.002 per ft derived from reference [6] is probably unreasonably low because it represents the onset of apprehension rather than the limit of endurance of the observers. The optical density of 0.07 per ft derived from reference [7] is said to be based on the results of the Los Angeles School Burns No. 2 [8]. Nowhere in those results is a critical value of 20 percent light transmission over a 10 ft path length to be found. As a matter of fact; reference [8] mentions only that 80 percent obscuration is the critical value for tenability, but identifies neither the location nor the length of the light path. From the information given in reference [8] and its predecessor study [9], it is possible to surmise that the light beam subject to 80 percent obscuration might have been as short as 11 ft or as long as 60 ft. It appears most probable that the light beam involved a double traverse of a corridor 10-15 ft wide, or a path length of 20-30 ft. The critical optical density for that case would be 0.023 to 0.035 per ft. On this basis, it appears more reasonable to assign a critical optical density of about 0.03 per ft to the results of the Los Angeles School Burns. Rasbash [10] reassessed his earlier work and later work by Jin [11-13] and concluded that his original correlation [2] represents a useful worst condition which includes in an approximate way the effects of eye irritation. From a study of behavior of people in fires by Wood [14], he also judged that a minimum visibility for escape from fire is about 30 ft, and that this corresponds to an optical density of 0.08 per meter or 0.025 per ft. Thus, the best estimates now possible suggest limits of 0.03 to 0.07 per ft for the critical optical density.

For the dwelling fire situation, escape routes are not usually long and are familiar to occupants. Thus, it appears reasonable to adopt a critical smoke level of 0.07 per ft along escape routes.

Table A1. Frequently-Cited Critical Smoke Levels

| Source | Minimum Light Transmission (%) | Viewing Distance (ft) | Optical Density (per ft) | Criteria Applied |
|---|---|---|---|---|
| Rasbash [2] | 10<br>10.5<br>12.6 | 10<br>15<br>20 | 0.10<br>0.065<br>0.045 | (Empirical correlation* of visibility of illuminated objects) |
| Kingman, et al. [15] | 5 | 2 | 0.65 | Visibility of sign held 4 ft away and illuminated by hand-held lamp in smoke-filled room |
| Shern [6] | 80 | | 0.002 | Apprehension in observers without OBA in smoke-filled room |
| Shern [6] | 60 | | 0.0044 | Judgement of observers with OBA in smoke-filled room |
| Gross, et al. [4] | 16 | 10 | 0.079 | Assumed value |
| Los Angeles Fire Dept. [7] | 20 | 10 | 0.070 | Visibility and eye irritation of observers in smoke-filled corridor |
| Bono and Breed [4] | 10 | 11.3 | 0.088 | Visibility of illuminated exit signs photographed from outside smoke-filled room |
| Malhotra [5] | 11 | 14.8 | 0.064 | Visibility of illuminated signs observed from outside smoke-filled room |

*Correlation: $V = 1.40/D^{.767}$

where: d is optical density per meter
V is distance of vision in meters

## A2. Critical Carbon Monoxide Concentrations

The toxicology of carbon monoxide is probably better understood and more fully reported than that of other constituents of fire gases; nevertheless there are areas of considerable disagreement concerning its effects. This is true particularly for long-term exposure to low concentrations of carbon monoxide. Table 1 shows the physiological effects of carbon monoxide as reported by various sources. A reasonable one-hour limit of 0.04 percent may be inferred from these data.

Since all of the data in table 1 are for situations wherein carbon monoxide concentration does not vary with time, it is reasonable to expect that the minimum concentration allowable in a fire situtation will be greater than 0.04 percent. This is because the carbon monoxide concentration will be near zero at the start of the fire, and will increase with time as fire gases permeate the space. If the carbon monoxide concentration increases linearly with time, the maximum concentration attained will be twice the average concentration.

The treatment due to Minchin [16] suggests that the average carbon monoxide concentration, rather than the maximum, is the appropriate indicator of physiological response. Thus, it appears that a logical one-hour limit for a fire situation in which carbon monoxide increases linearly with time would be one having a maximum average carbon monoxide concentration of 0.04 percent.

The data indicate that carbon monoxide concentration does in fact increase almost linearly with time during the time periods of interest, and a time-average concentration of 0.04 percent has been chosen as the critical level. In only 2 of the 40 experiments did cabron monoxide concentrations approach this level before the optical density reached 0.07 per ft. Nevertheless, the occurrence of the critical optical density preceded the occurrence of critical carbon monoxide levels in all of the experiments.

Table A2. Allowable Carbon Monoxide Levels from Various Sources

| Reference | Carbon Monoxide (%) | Exposure | Physiological Effect |
|---|---|---|---|
| Bowes and Field [17] | 0.1 | 1 hr | Unstated |
| Pryor, et al. [18] | 0.04 | 4 hr | Lethal |
| | 0.04 | 2 hr | Collapse |
| | 0.04 | 1 hr | Headache |
| | 0.03 | 3 hr | Collapse |
| | 0.03 | 1.5 hr | Headache |
| | 0.02 | 4-5 hr | Collapse |
| | 0.02 | 2-3 hr | Headache |
| Yuill [19] | 1.5 | 5 s | Lethal |
| | 0.3 | 5 min | Lethal |
| | 0.15 | 30 min | Lethal |
| | 0.045 | 2 hr | Lethal |
| Gross, et al. [20] (Based on refs. [21, 22 and 23]) | 0.005 | 8 hr | None |
| | 1.0 | 2-5 min | Lethal |
| Autian [24] | 0.01 | 8 hr | None |
| Minchin [16] | 0.1 | 45 min | Collapse |
| | 0.05 | 90 min | Collapse |

## A3. Critical Temperature

The maximum temperatures to which humans may be exposed are not well defined, and thus are subject to considerable controversy. Yuill's [19] data showing a four-hour limit of 130 °F indicates that the appropriate temperature limit for escape from a dwelling must be somewhat higher. The value of 150 °F was adopted as the criteria of untenability in reference [9], and this appears to be the minimum which could be considered applicable to the present experiments. This temperature was never exceeded at the five-foot level along an escape route before untenable smoke occurred. Hence, adoption of any limiting temperature above 150 °F would lead to identical conclusions in this study.

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**16. ABSTRACT** *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*


A test program was undertaken to evaluate the effect of sensitivity and placement of residential smoke detectors on their response to fires in homes. The tests were conducted in two homes scheduled for demolition and used actual furnishings in typical configurations. In addition to the detector response times, the homes were highly instrumented with data on smoke, temperature, and gas concentration measured for all tests.

The tests showed that smoke detectors can be highly effective in providing adequate warning of a fire before conditions in the home become dangerous.


**17. KEY WORDS** *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)* Detector sensity; detector siting; escape time; fire tests; heat detectors; residential fires; smoke detectors.

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