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# Full-Scale Fire Tests With Automatic Sprinklers in A Patient Room. Phase II

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National Bureau of Standards
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Final Report

Prepared for:

**U.S. Department of Health and Human Services
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# FULL-SCALE FIRE TESTS WITH AUTOMATIC SPRINKLERS IN A PATIENT ROOM. PHASE II

John G. O'Neill, Warren D. Hayes, Jr., and Richard H. Zile

Abstract

The Center for Fire Research conducted a series of full-scale fire tests in a patient room and corridor arrangement to examine the use of automatic sprinklers in patient rooms of health care facilities. This is a report of twenty-one (21) fire tests in which either mattresses with bedding or clothing wardrobes served as the burning items.

Test results indicated that actuation of both pendant and horizontal sidewall sprinklers in the patient room acted to cool and redistribute the combustion products in the patient room and in the corridor away from the flowing sprinkler. This phenomenon resulted in total obscuration throughout the test area. It was demonstrated that the use of a fast response, (low thermal inertia) sprinkler resulted in significantly less smoke obscuration in the mattress and bedding fires.

Sprinkler spray distribution measurements were made to develop criteria for the position of privacy curtains with respect to the automatic sprinklers in the patient room. Recommended installation criteria are provided.

Analysis of the test results indicated that the combustible clothing wardrobe fire resulted in room flashover in a nonsprinklered test. In several tests with sprinklers, flashover did not occur, however, estimated hazardous thresholds for carbon monoxide were still exceeded in the test area. It was determined that the combustible construction of the wardrobe primarily contributed to the high concentrations of carbon monoxide.

Key Words: Clothing wardrobes; health care facilities; hospitals; mattresses; smoke movement; sprinkler systems.

## 1. INTRODUCTION

The Center for Fire Research (CFR) at the National Bureau of Standards (NBS) and the Department of Health and Human Services (HHS) are jointly conducting a life safety/fire safety research program which began in 1975. The program consists of projects in the following areas: decision analysis, fire and smoke detection systems, smoke movement and control, automatic extinguishment, and the behavior of institutionalized populations in fire situations.

The initial full-scale fire tests concerning the use of automatic sprinklers in patient room fires began in August 1977. An interim report (Phase I) has been published which presented the results of this initial investigation [1][1]. The project was resumed in January 1979 and the results of this second phase of the investigation on automatic sprinklers are presented in this report.

The role of automatic sprinklers in providing life safety in health care facilities continues to be an item of considerable interest among the various parties who share responsibilities in assuring that adequate fire safety is provided in health care facilities.

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[1] Numbers in brackets indicate the literature references at the end of this paper.

These parties include code making officials, legislators, and regulatory agencies, as well as the administrators of the health care facilities. These various groups are examining the range of fire safety requirements, from mandatory installation of automatic sprinklers throughout all health care facilities to selective requirements for sprinklers which relate to the type of construction, the size of the facility, the provisions for other fire safety equipment and the relative mobility of the occupants. An example of this interest, reflecting the relative importance of the issues, is the consideration of a bill introduced into the United States House of Representatives, "To amend the Social Security Act to require automatic sprinklers in all nursing facilities certified for participation in the Medicare or Medicaid program, and to provide for direct low-interest Federal loans to assist such facilities in constructing or purchasing and installing the automatic sprinkler systems." [2] Although this bill has not yet become law, there is continuing interest in mandating the installation in all skilled nursing facilities and intermediate care facilities participating in Medicare and Medicaid [3].

The use of sprinklers in health care facilities has been of high interest not only to those parties previously mentioned, but also to those who are developing alternative approaches to fire safety in buildings. The Center for Fire Research has recently developed a quantitative system for grading fire safety in health care facilities [4]. This rating system is based on achieving a level of safety equivalent to the Life Safety Code 1973 Edition [5]. The rating system is used to determine how combinations of fire safety equipment and building construction can provide equivalency to the Code. The system, therefore, assigns a quantitative value to the installation of automatic sprinklers as well as to other fire safety equipment. The basis for the value is the relative merit for providing life safety which automatic sprinklers may have in relation to alternative types of fire protection equipment.

What evolves from all of these activities -- that is, the consideration of national legislation, the development of consensus technical standards and the development of a quantitative measurement technique for fire safety -- is the need to understand what an automatic sprinkler system contributes toward the total fire safety system in a health care facility.

The objective of the CFR research program is to develop technical information on the effectiveness of sprinklers in health care facilities. The program is designed to partially fill the gap in available knowledge for those responsible for establishing fire safety requirements and for researchers who are quantifying the impact of sprinklers on room fires. In addition to developing this input, the analysis of experimental results has generated ideas of where current sprinkler system technology can be improved.

## 2. SUMMARY OF THE INITIAL INVESTIGATION

Since the results of the initial CFR sprinkler project [1] served as a foundation for much of the work in this second phase, the key findings are summarized here. In that investigative series full-scale tests were conducted, in which a patient bed and bedding served as the burning items. The following major conclusions were reached;

a. Critical levels for smoke obscuration were reached in the burning bedding tests prior to sprinkler operation, potentially impeding the rescue of the patient in the adjacent bed and the use of the corridor as an exit way Following sprinkler operation, total obscuration (> .9 OD/m) occurred from floor to ceiling throughout the test area.

b. The presence of a privacy curtain in the fire room interfered with the extinguishing performance of the sprinkler.

c. The distribution of carbon monoxide (CO) concentrations shifted after sprinkler actuation. Concentrations were the highest at the floor level after sprinklers operated. Prior to sprinkler operation the highest concentrations were recorded at the highest measuring point, 1.7 m (5 ft 8 in) above the floor in the doorway.

d. The CO concentrations in general did not reach what were considered hazardous thresholds except in tests in which the privacy curtain stayed in place. The privacy curtain delayed extinguishment of the fire and resulted in significantly higher concentrations of CO. Calculated carboxyhemoglobin (COHb) eventually exceeded a critical level of 25 percent at the adjacent patient level. The data suggested that a more optimal location of the sprinkler with respect to the curtain, or the use of privacy curtains which do not extend to the ceiling, may enhance the extinguishing action of the sprinkler and reduce the CO concentration.

e. The presence of the Class C wall finish in this room arrangement and for this fire scenario did not play a role in the fire development and subsequently did not affect the fire control of the sprinkler.

## 3. SCOPE OF WORK

The series of full-scale fire tests and sprinkler spray distribution tests was based on fire scenarios involving either bedding and mattresses or clothing wardrobes in a two-patient room environment. These furnishings represented typical contents in patient rooms of health care facilities and in the test procedures they served as the principal burning items. The experimental procedure for the sprinkler evaluation was limited to the flaming ignitions of these items. Smoldering ignitions of bedding materials were conducted in conjunction with this program to examine the performance of fire detectors. The results of that investigation will be provided in another report.

The location of the sprinklers and the water flow design parameters used in this test series essentially followed current established installation standards [6]. In addition, the sprinklers used in the series met the current Underwriters Laboratories (UL) Standard 199 [7]. The project did, however, include some tests in which a simulated rapid response sprinkler operated at flow rates less than that required in the current installation standard. In those tests, only the simulated fusible element of the sprinkler differed from the sprinklers currently listed by UL. The scope of the project did not include the use of sprinklers with spray patterns different from currently available sprinklers meeting the UL standard.

In the fire tests where mattresses and bedding materials served as the burning items, there was no attempt to assess the effects of adverse conditions on a patient in the burning bed in the fire room. A reasonable assessment would have required a complex arrangement of instrumentation which would have, at best, provided limited information. Therefore, the scenario for the mattress and bedding fires was based on the assumption that the patient in the bed which serves as the burning item either removed himself from the bed or was rescued. Analysis of the test results for life safety was considered for: a) a patient in an adjoining bed, b) for patients and staff exiting in the corridor adjacent to the room, and c) for a patient in a remote room at the end of the test area corridor.

It was also assumed that the door between the burn room and the corridor remained open during the fire, i.e., the door had not been closed by actions of the staff nor by means of an automatic closing device. It was further assumed in the analysis of the data that the patient in the adjoining bed had not escaped nor been removed during the time of the fire test.

## 4. OBJECTIVES

### 4.1 Overall Project Objective

The overall objective of this project is to develop engineering design information on the use of automatic sprinklers to minimize life loss and injury in the event of fire in health care facilities. The effectiveness of the sprinklers was measured in terms of:

a. Overall fire control.

b. Time available for evacuation of patients in the fire area.

c. Maintaining tolerable environmental conditions for patients who cannot be evacuated.

To this end, current design criteria for sprinklers contained in the National Fire Protection Association (NFPA) Standard 13 [6] and fire safety requirements in the current NFPA Life Safety Code 101 [8] are specifically examined to determine if these criteria can be improved, based on both life safety and cost effectiveness of system designs.

### 4.2 Phase II Specific Objectives

Within the above overall program objectives, specific objectives were set for the experimental work planned for this phase of the project. Several of these evolved from the interim results summarized in section 2. The objectives of this phase included investigations into the following:

a. the impact of sprinklers on clothing wardrobe fires

b. the use of horizontal sidewall sprinklers in patient room fires

c. the impact of a simulated fast response sprinkler on smoke obscuration

d. the impact of a fan coil unit, make up air supply and an exhaust system on fire growth and environment conditions throughout the test area

e. the quantification of the impact of a privacy curtain which shields the sprinkler spray during a bed fire.

## 5. EXPERIMENTAL DETAILS

### 5.1 Test Area, Construction Details

The fire test area consisted of a simulated patient room, corridor, and lobby located in a building previously used as a military barracks building. Figures 1 thru 6 provide detailed dimensions, as well as the instrumentation and sprinkler system plans. Table 2 lists the instrumentation installed in the fire test area.

The room where test fires were initiated, the "burn room", was lined with 13 mm (1/2 in) cement asbestos board screwed to steel studs and channels over 13 mm (1/2 in) vinyl covered gypsum board. For several tests included in this report, the walls surrounding the bed or the wardrobe were covered with prefinished lauan plywood paneling, 4 mm (5/32 in) thick, fastened to nominally sized 1 x 2 in furring strips. The paneling had a Class C flamespread rating (ASTM E-84). In the tests where the impact of a combustible ceiling finish was examined, 13 mm (1/2 in) wood fiber .6 x 1.2 m (2 x 4 ft) ceiling tiles were installed in the burn room. The tiles which had a Class D flame spread rating (ASTM E-84), were screwed directly to the cement asbestos board with the unpainted surfaces of the tiles exposed. The flooring throughout the test area was asphalt tile. The room opened into a 2.4 m (8 ft) wide corridor and adjacent lobby with walls and ceiling lined with 13 mm (1/2 in) cement asbestos over 13 mm (1/2 in) vinyl covered gypsum board as in the burn room.

Prior to test N-40, a simulated heating, venting and air conditioning (HVAC) system was installed in the burn room. The HVAC system consisted of a supply duct mounted high in the wall, and an exhaust duct in the lower opposite wall as shown in figures 1 and 2. The air flow rate for the burn room was based on criteria contained in the Minimum Requirements of Construction and Equipment for Hospitals and Medical Facilities [9]. This standard requires a minimum ventilation rate of 2 air changes per hour for patient rooms with zero pressure difference between the patient room and corridor. For this sized room the flow rates for both supply and exhaust were established at 1.2 $m^3$/min (42 $ft^3$/min) to give the minimum air change rate without creating an air flow between the patient room and corridor. In several tests (see Table 1) a fan coil unit as shown in figures 1 and 3 was installed to provide recirculated air in the room. A separate system provided conditioning for the burn room to maintain a limited range of temperature and relative humidity conditions in the burn room throughout the series of tests. These test conditions are described later in sections 8 and 9. The fan coil unit was set at a low speed which recirculated air in the burn room at an approximate rate of 3.4 $m^3$/min (120 $ft^3$/min).

### 5.2 Automatic Sprinkler System

The layout of the automatic sprinkler system is shown in figure 7. The steel piping extended above the fire resistive ceiling and was supplied through a fire hose connection at the building exterior. The water supply was provided through 15 m (50 ft) of fire hose connected to a 1892 ℓ/min (500 gal/min) pump which was interconnected with a pressure tank to maintain a residual pressure between 414 and 621 kPa (60 and 90 psi). A gate valve and flow meter at the fire hose connection permitted regulation of flow to the sprinkler system. Prior to each test the flow rate was calibrated through an open sprinkler orifice of the same type of sprinkler head to be used in the fire tests.

For the tests reported here the outlets in the corridor piping system were plugged. An initial water flow for the sprinkler in the patient room was established at 102 ℓ/min (27 gal/min) to provide the equivalent specified minimum flow resulting from one sprinkler head operating if the system is hydraulically designed in accordance with NFPA Standard No. 13. The standard requires a minimum average density[2] of 4.1 mm/min (0.10 gal/min/ft$^2$) for this type of occupancy. The standard, however, states that for this type of room arrangement the system must be designed to provide this density with the sprinkler in the burn room plus two operating outside the room. Since the required average density is 4.1 mm/min (0.10 gal/min/ft$^2$) for all three sprinklers operating, the actual density in the burn room with only the single sprinkler operating will be more than the 4.1 mm/min (0.10 gal/min/ft$^2$). For the system calculated for the test area, the actual flow in the burn room with only that sprinkler operating was 102 ℓ/min (27 gal/min), resulting in an average 6.9 mm/min (0.17 gal/min/ft$^2$) density in the burn room.

Sprinklers used in the project included 13 mm (1/2 in) and 10 mm (3/8 in) pendant sprinklers and 13 mm (1/2 in) horizontal sidewall sprinklers which meet the requirements of UL 199 [7]. The sprinklers incorporated link-and-lever fusible elements with temperature ratings of 71°C (160°F) or 74°C (165°F). The range of temperature for fusible elements allowed in a health care facility (low hazard occupancy) is 57° to 74°C (135° to 165°F) [6]. The intent was to use a typical fusible element, operating in the higher part of the allowable range of temperatures, and not specifically designed for rapid response.

In tests where sprinklers were manually operated to simulate a fast response, open sprinklers of the same type described above were used. The sprinkler system piping was primed with water and a plug inserted in the open orifice to prevent flow until the system was charged at a given time during the test.

In addition to the active sprinkler head connected to the sprinkler system, three other dry sprinkler heads were also placed at the center of the burn room ceiling. The purpose was to obtain data on response times of other types of sprinkler heads in the full-scale fire tests. The dry sprinkler heads were pressurized by nitrogen which was pumped through copper tubing placed above the fire resistive ceiling. A pressure switch was connected into the tubing which led to each sprinkler head and, when the sprinkler operated, the pressure switch activated a relay which stopped a clock. Thus, response times relative to time of ignition were automatically recorded. The dry sprinkler heads included the following fusible elements [12]:

Rapid-response 57°C (135°F) (commercially available)

Fusible bulb 74°C (165°F)

Link lever 74°C (165°F) duplicate of wet sprinkler head

---

[2] Sprinkler density is defined as average water flow rate per unit area protected by the sprinkler(s). The appropriate metric equivalent for sprinkler density as used in various sprinkler installation standards is mm/min [10] [11]. This equivalency is derived as follows:

$$\frac{1\ \text{gal}}{\text{min-ft}^2} = \frac{40.7\ \ell}{\text{min-m}^2} = \frac{(40.7 \times 10^{-3})\text{m}^3}{\text{min-m}^2} = \frac{40.7\ \text{mm}}{\text{min}}$$

## 5.3 Instrumentation

The instrumentation used in the test series is shown in figures 1 thru 6 and listed in table 2. In the mattress and bedding tests, various heat and smoke detectors were placed in the burn room and in the corridor. Response times of these devices were recorded automatically by activation of relay which stopped a clock, as with the dry sprinklers. The results of the detector operations will be included in a separate report. All tests were recorded with 35 mm slide cameras or on video tape with separate coverage in the burn room and down the length of the corridor. Generally, all instrumentation channels were recorded at 10 second intervals on a magnetic tape data acquisition system. During the wardrobe tests, however, the channels were recorded at 6 second intervals for the first six minutes of the test. This was the maximum scanning rate for the data acquisition system.

Thermocouples measured gas and surface temperatures throughout the test area and locations are shown in figures 1 thru 6. Thermocouples were chromel-alumel type, 0.51 mm (24 gauge).

Calibrated, water-cooled heat flux meters measured total heat flux at the adjacent patient level and across the corridor from the burn room.

The patient bed and the trash container which served as the initiating fire source were placed on a steel platform (see figure 8), which was suspended from a load cell mounted above the ceiling, to monitor weight loss rate during each test. However, due to limitations in the test facility and time constraints of the project schedule, a load cell was not installed for the clothing wardrobes. As discussed later under test procedures the wardrobes and contents were weighed before and after the tests.

The velocity of air and gases entering and leaving the burn room and moving along the corridor were measured with directional low velocity probes placed in the doorway and corridor. This type of probe was developed by Heskestad [13], and the description and construction details of these devices are provided in the reference. The differential pressure was measured with a calibrated diaphragm-type pressure transducer. Calibration techniques were provided by McCaffrey and Heskestad [14]. The equation for velocity is:

$$\frac{2\Delta p/\rho}{\mu} = C(Re)$$

$\Delta p$ = measured differential pressure

$\rho$ = gas density (calculated from temperature of thermocouple next to probe)

$\mu$ = gas velocity

$C(Re)$ = constant dependent on Reynolds number
$C = 1.08$ according to McCaffrey and Heskestad

Continuous gas measurements included CO, $CO_2$ and $O_2$. Sampling tubes for CO, $CO_2$ and $O_2$ were located at the adjacent patient level and in the doorway at .05 m (2 in) and 1.5 m (5 ft) above the floor. In addition, CO was measured at four different elevations in the corridor at 4.0 m (15 ft) west of the burn room as well as in the lobby (or remote area) at .9 m (3 ft) from the floor. CO in the burn room, in the doorway, at two locations in the corridor and in the lobby was measured with nondispersive, infrared analyzers. The CO at the remaining two locations in the corridor was measured by electrochemical analyzers. This difference was due to the availability of analyzers and the ranges needed at the given locations. These ranges are given in the instrumentation list in table 1. Electrolytic oxygen cells were used to measure $O_2$ concentrations. All gases were drawn through dry ice traps to remove condensable vapors and particulates before the analysis. $CO_2$ in the burn room was also measured by infrared analyzers.

Smoke meters developed by Bukowski [15] were used to measure light obscuration in the doorway to the burn room and in the corridor and lobby. Locations are shown in figures 1 thru 6. This type of smoke meter is essentially an extinction beam consisting of a collimated light source and a light sensor separated by a one-meter long path through the smoke. The obscuration is measured by the magnitude of attenuation of the light seen by the detector.

As discussed later in section 8 this project included an investigation into the use of simulated fast response sprinklers with thermal inertias lower than standard sprinklers. The simulated fast response sprinklers were characterized by a dynamic heating measurement proposed by Factory Mutual Research Corporation (FM). The dynamic heating measurement is determined by use of a proposed test developed by FM to measure response of sprinklers [16]. The test method is based on the assumption that in actual fire situations, the sprinkler fusible element is primarily heated by convection and the effect of radiation on the element is relatively small. The dynamic heating measurement of the fusible element is expressed as the time constant $\tau$; where

$$d(\Delta T_L)/dt = \tau^{-1}(\Delta T_g - T_L)$$

where $\Delta T_L$ is the increase in temperature of the fusible element (relative to ambient or initial temperature) and $\Delta T_g$ is the excess temperature of the gas; $\tau$, therefore, has units of time. Heskestad and Smith found that selected standard sprinklers when tested in a "plunge test apparatus" varied in terms of $\tau_o$ from 100 to 280 s at a reference velocity, $\mu_o$ = 5 ft/s.

In order to model fusible elements with different $\tau$ factors in full scale fire tests, FM manufactured brass discs designed and verified for different $\tau$ factors. The discs were geometrically similar to fusible elements but varied in thicknesses which resulted in varying dynamic heating characteristics. In order to simulate fast response sprinklers three different discs, provided by FM, were placed near the operating sprinkler in the CFR patient room tests. The $\tau$ factors of the discs were 9.0, 14.4 and 21.5 s respectively. The temperatures of the discs were measured with the data acquisition system during the tests to predict sprinkler response. (Prototype sprinklers with a $\tau$ = 21 s were used in a residential sprinkler test program in Los Angeles, California.)

## 6. ELEMENTS OF HAZARD ANALYSIS

Consistent with specific objectives mentioned in section 4, the test results were measured in terms of the following:

° Fire spread

° Heat flux

° Toxic gases

°Smoke obscuration

### 6.1 Fire Spread

In this phase of the project performance of center ceiling sprinklers and horizontal sidewall sprinklers were evaluated in terms of controlling fires involving institutional type mattresses and bedding and clothing wardrobes. Since the water spray and water absorption of the mattresses following sprinkler operation complicated the weight loss measurements from the load cell instrumentation, visual examinations of the burned mattress were made after each test to determine the approximate amount of material consumed by the fire. The wardrobes and clothes were weighed prior to each test. Following each test the wardrobes and what contents were remaining were also weighed after they were allowed to dry for several days. These total weight loss values were used in the analysis of the results as discussed later in this report.

In addition, combustible wall and ceiling finishes, when included in the tests, were examined to determine the extent to which they had become involved in the fire. Film and video records were also used to assess the impact of these finishes on the results of the tests. Ceiling temperature data in the burn room and in the adjoining corridor were examined to determine relative performance of the sprinklers in cooling the gas layer at the ceiling.

## 6.2 Heat Flux

Any consideration of limiting conditions adverse to human safety should include the potential hazard of burn injuries. A critical level of heat flux for human exposure is a function of time, since a sustained exposure to a lower flux exceeding the injury threshold can result in a burn injury equivalent to that of a short exposure at higher flux. In the fire scenario selected for these tests, the patient in an adjacent bed would be in the most immediate danger. The operating automatic sprinkler could be expected to reduce rapidly the heat flux imposed at the adjacent level. A value of 0.95 $W/m^2$ (18 $BTU/ft^2$-min) radiant flux was selected as the threshold for feeling pain based on information provided by Dinman [17] and Parker and West [18].

## 6.3 Smoke Levels

Limiting levels of smoke obscuration for human safety were determined for two separate hazards in this fire test scenario. The first concern was the rescue of a patient in the adjacent bed in the room of fire origin. The second involved the use of the corridor and lobby adjacent to the room of origin as an exit way. Two critical levels of obscuration were considered, one measured at the doorway to the patient room and the other in the corridor and lobby. Critical levels selected for each location were based on investigations by Jin [19, 20]. Jin recommended limits on obscuration based on not reducing the walking speed below that of a blindfolded subject walking in a smoke free environment. This obscuration was approximately equivalent to an OD/m = 0.25.

The estimated hazardous level for smoke obscuration as measured at 1.5 m (5 ft) elevation in the corridor and lobby was therefore, established as an OD/m = 0.25. The estimated hazardous threshold for the doorway to the patient room was established an OD/m = 0.5, due to the relatively shorter distance to enter and rescue a patient in the room of fire origin. This level was measured horizontally at 0.3 m (1 ft) from the top of the door.

## 6.4 Gas Concentration

The quantities of CO and $CO_2$ were measured along with $O_2$ depletion. It should not be inferred that CO and $CO_2$ are the only toxic gases which are significant in terms of having adverse effects on humans in fires. These were the only two measured, however, because of experimental uncertainties in measuring and evaluating the toxic effects of other gases. It is known, in any case, that CO and $CO_2$ are always generated in building fires, and high concentrations of CO have been associated with a large percentage of fire fatality victims [21].

Critical limits or thresholds were selected for CO, $CO_2$ and $O_2$ depletion based on previous studies which examined the adverse effects on humans. Specific thresholds for this study were based on quantities which are believed to result in incipient incapacitation of healthy persons. Incipient incapacitation for this analysis can be considered the point at which environmental conditions could have an adverse effect on the ability of a person to function reliably. The critical levels or thresholds should not be interpreted as precise boundaries but rather as an approximation, based on the literature concerning average healthy individuals. The unique characteristics of the occupancy type being assessed would affect the magnitude of the levels which would result in adverse effects.

In health care facilities occupants in varying states of health may be more severely affected at the critical levels established here than in occupancies where most persons are not physically impaired. It would be impossible to determine every critical level which may adversely affect patients with varying physiological problems. Therefore, by practical necessity, the criteria established here are based on the incipient incapacitation of healthy persons, and would serve as upper limits for health care occupancies.

A critical level of 8 percent $CO_2$ was established for this program based on tabulations presented by Kimmerle [22]. A minimum oxygen concentration of 14 percent was selected based on Pryor and Yuill's study [23]. However, determining critical levels of CO is a much more complex issue. What makes CO toxic is that it reduces the oxygen carrying capacity of the blood. CO forms carboxyhemoglobin in the blood and, therefore, the percent COHb is the more precise measure of CO toxicity. The CFR has tentatively used a methodology for determining a critical level of COHb from CO concentrations based on previous studies by others. Stewart derived an equation of COHb from experiments with human volunteers [24]. The volunteers were subjected to very high concentrations of CO and their COHb levels were then measured. CO uptake is directly proportional to the breathing rate which is approximately 6.5 ℓ/min for an individual at rest. The breathing rate increases with activity and also from exposure to $CO_2$. A 4 percent concentration of $CO_2$ will more than double the breathing rate [25]. Since both of these factors must be considered in a fire situation, a breathing rate was established as 18 ℓ/min. The equation for determining COHb% is:

$$\Delta COHb\% = 5.98 \times 10^{-4} (\Delta t) [CO]^{1.036}$$

where $\Delta t$ is time in minutes and CO is concentration in ppm. An initial value of 0.75 percent COHb was established from information provided by Alarie and Zullo [26] was used in the computation. A 25 percent calculated COHb was established in this study as the level of COHb at which incipient incapacitation may occur [22].

In addition to the threshold for time-rated accumulation, another limit must be selected for CO exposure. Instantaneous doses of high levels of CO must also be considered due to the physiological effects such as cardiac arrythmia [27] which can occur independently of the effects of increased COHb. Claudy [28] reported on the effects of exposure to high concentrations of CO. The results of his work indicate that incipient incapacitation may occur with only a few short breaths at an exposure level of 10,000 ppm CO. And, at a slightly higher concentration of 12,800 ppm Claudy reported that unconsciousness could occur in 2 to 3 breaths, followed by death in 1-3 minutes. Based on this an instantaneous threshold of 10,000 ppm (1.0 percent by Vol) CO was selected as a criterion, in addition to the time integrated exposure resulting in COHb level of 25 percent.

## 7. SPRAY DISTRIBUTION TESTS

### 7.1 Background

A major finding from earlier work in this research program indicated that a privacy curtain placed between the burning bed and the sprinkler interfered with the extinguishing performance of the sprinkler [1]. Figure 9 illustrates the position of the privacy curtain with respect to the sprinkler as installed in the previous fire tests. Although the spray from the sprinkler cooled the heated gases in the burn room, the mattress continued to burn. By the end of the tests the mattresses were nearly totally consumed. In those tests the concentrations of carbon monoxide were higher than in other tests where there was no privacy curtain installed. Estimated carboxyhemoglobin levels, based on CO measurements as measured at the adjacent patient level, eventually exceeded the estimated hazardous threshold of 25 percent. The higher concentrations of carbon monoxide were apparently due to the position of the privacy curtain, which shielded the burning bed from the water spray and adversely affected the extinguishing performance of the sprinkler.

### 7.2 Test Plan and Procedure

Based on these previous findings an investigation was conducted to quantify the interference of the privacy curtain in terms of spray distribution; and to develop recommendations concerning the location and arrangement of the privacy curtain with respect to the sprinkler. A simple collection container array was installed in the burn room at the location of the bed to obtain spray density measurements over the horizontal plane of the bed, as shown in figures 10 and 11.

The results of these non-fire tests clearly indicated that the privacy curtain as installed in the previous fire tests severely blocked the water spray from the sprinkler. Figures 12 and 13 provide a comparison of results of one of the pendant sprinkler tests with and without the privacy curtain. Repeated tests with other models of pendant sprinklers and a horizontal sidewall sprinkler provided similar results.

The investigation then proceeded to determine design information on the placement of the privacy curtains with respect to the sprinkler to minimize the impact of the curtain on the spray distribution.

Initially criteria were established for the minimum spray density which was necessary to extinguish a fire involving a mattress and bedding. Following a series of full-scale tests at Factory Mutual Research toward the development of a reduced scale sprinkler for residential fires, Kung and others suggested a critical application density of 1.4 mm/min (0.033 g/min/ft$^2$) for halting fire spread underneath a urethane foam mattress [29].

In determining the maximum likely boundary condition for the distance of the privacy curtain from a center ceiling sprinkler, spatial criteria contained in the Minimum Requirements of Construction and Equipment for Hospitals and Medical Facilities [9] served as a basis for modeling the spatial layout in a typical two patient sized room similar to the room in which the tests were conducted. Figure 14 illustrates the spatial arrangement of a bed in a two bed patient room. The requirements referenced above call for a minimum 8 m$^2$ (80 ft$^2$) per person in multiple patient rooms with a minimum 106.7 cm (42 in) clearance between the foot of the bed and the opposite wall. It is assumed that a minimum clearance of 62 cm (24 in) is provided between the side of the bed and the wall to allow access for staff. It is further assumed that the privacy curtain is located not less than 30.5 cm (12 in) from the patient bed and therefore not greater than 38.1 cm (15 in) from a pendant sprinkler located in the center of the room.

The location of the sprinkler meets the criteria contained in National Fire Protection Association Standard 13, Installation of Sprinkler Systems [6]. The distance of the sprinkler from a wall should not exceed 2.3 m (7.5 ft). (For this type of occupancy, the standard allows under certain conditions a maximum distance of 2.7 m (9.0 ft) from a wall. Due to the spatial limitations of the test facility this condition was not examined.)

The Underwriters Laboratories Product Standard includes spray distribution tests including one which measures the distribution of a single sprinkler [7]. The test apparatus consists of a row of collectors which rotates below the sprinkler at a distance of four feet below the deflector. Figure 15 illustrates the location of the collectors below the sprinkler as well as the typical discharge densities measured for a "Standard" sprinkler flowing at 56.8 ℓ/min (15 g/min). This figure further illustrates that the impact of an obstruction such as a privacy curtain is dependent not only on the clearance measured vertically from the deflector to the top of the obstruction, but also on the distance of the privacy curtain away from the sprinkler. For example, a screen located at position d' would create a greater obstruction than at position d.

To facilitate the experimental work, a plywood screen was fabricated and it served in the place of the privacy curtain. As various tests were conducted with sprinklers flowing at 102 ℓ/min (27 g/min) the screen was raised and lowered and moved to various positions horizontally in an effort to determine the position boundaries for the cases where the critical density could not be obtained. During the experimental work it was noted that variations existed among standard pendant sprinklers of different manufacturers, such that, the spray from one tended to project more water directly parallel to the plane of the deflector than others. Therefore, measurements were made for various 12.5 mm (1/2 in) pendant sprinklers in order to insure that recommendations developed from the experimental work were not biased toward the most favorable spray pattern. One sprinkler, of a given manufacturer and model, was selected for the remaining tests to establish the position criteria. This sprinkler, noted as sprinkler A, was selected since it had the least favorable spray pattern, of the various sprinklers examined, with regard to the obstruction of the privacy curtain.

Spray distribution measurements were also conducted with the horizontal sidewall sprinkler to determine the impact on the sprinkler spray pattern. The simulated curtain was placed 40.6 cm (16 in) from the foot of the bed and 68.6 cm (27 in) from the corridor wall and the height of the curtain varied for each measurement. The flow from the sprinkler was also set for 102 ℓ/min (27 g/min) to provide an average density of 6.9 mm/min (.17 g/min/ft$^2$).

### 7.3 Results

In all of the spray distribution tests it was observed that the collectors which were placed along the wall collected most of the water which hit the wall. While the wetting of the wall may be an important benefit, the quantities of water collected in these containers do not reflect the actual density for that "slice" of the horizontal plane of the protected surface. Therefore, data obtained from these containers were not included in the calculation of the average density over the plane of the bed.

#### 7.3.1 Pendant Sprinklers

The results of the tests verified that the effective spray density reaching the bed was dependent on both the vertical distance of the top of the privacy curtain from sprinkler deflector and, the horizontal distance of the curtain from the sprinkler. With the screen placed directly beneath the deflector of the sprinkler, there was no adverse affect on the effective density reaching the bed. As it was moved from the sprinkler toward the bed the screen was progressively lowered to achieve the minimum density criterion of .033 $g/min/ft^2$. See figures 16 thru 20 for the results of the tests which served as the basis for the recommended installation criteria shown on figure 21. These criteria provide the minimum vertical distances from the sprinkler deflector to the top of the curtain as a function of the distance of the curtain away from the sprinkler.

#### 7.3.2 Horizontal Sidewall Sprinklers

The horizontal sidewall sprinkler was found to project a high percentage of the discharged water toward the ceiling and in a radial direction, horizontal to the center line of the orifice. This spray pattern reduced the impact of the privacy curtain on the horizontal sidewall sprinkler as compared to the pendant sprinkler. The results indicated that a minimum average effective density could be achieved over the plane of the bed if the height of the privacy curtain was equal to or lower than the height of the horizontal sidewall sprinkler as shown in figures 22 and 23.

## 8. MATTRESS AND BEDDING FIRE TESTS

### 8.1 Background for Current Investigation

In the initial investigation, Phase I it was determined that of the four measures of hazard (Section 6), smoke obscuration exceeded the estimated hazardous thresholds in all of the tests involving sprinklers. In tests where the polyurethane mattresses and bedding served as the burning items, smoke obscuration exceeded 0.5 OD/m in the patient room doorway 1.7 m (5 ft 8 in) from floor and 0.25 OD/m at 1.5 m (5 ft) above the floor in the corridor before the sprinkler actuated. Following sprinkler actuation the entire test area became totally obscured e.g. > 0.9 OD/m. Data from various instruments located in the patient room doorway indicated that the smoke layer was pushed down to the floor and the flow of combustion products was from the patient room into the corridor and was greatest near the floor. As shown in figure 24, data from test N-37 indicated that prior to sprinkler actuation the highest concentrations of CO in the burn room area were recorded at the highest sampling point, 1.7 m (5 ft 8 in) in the doorway[3]. Following sprinkler actuation, however, the concentrations at this location were less than those recorded before the sprinkler operated and less than concentrations recorded at lower elevations in the doorway and in the burn room. Concentrations of CO at these lower elevations increased significantly after sprinkler actuation. (These concentrations remained below the defined hazardous thresholds.) The shifting in CO and visible smoke particulate according to the elevation in the burn room and in the doorway indicated that the sprinkler spray acted to redistribute the smoke layer and subsequently create severe obscuration within a short time after actuation.

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[3] The CO data in this analysis were used as an indicator for measuring the relative quantities and location of combustion products throughout the test area.

## 8.2 Revisions in Instrumentation

The data from the previous tests had verified that the smoke was redistributed in the burn room and burn room doorway. It was not known, however, if the sprinkler acted also to redistribute the smoke in the corridor away from the immediate area of sprinkler flow. Therefore, in preparation for this phase of the project, the instrumentation was expanded and revised from the earlier fire tests in an attempt to better quantify the movement of smoke in the corridor. As described in detail in paragraph 5.1 and table 2, thermocouples, velocity probes, smoke meters and CO analyzers were installed in the corridor, 4.6 m (15 ft) west of the burn room doorway in order to obtain a profile of smoke movement and CO concentrations during the tests.

## 8.3 Variation in Sprinkler Heads

The findings of the initial investigation were based on the results of tests using a ceiling mounted pendant sprinkler in the center of the room. In the earlier work reversal of the flow of gases through the doorway was attributed at least in part to the air entrainment of the sprinkler spray. The question arose whether or not the movement of smoke would differ with the use of a horizontal sidewall sprinkler, which could be expected to have different air entrainment characteristics from the pendant sprinkler. Therefore, this phase included an investigation of patient room fires with the installation of horizontal sidewall sprinklers.

## 8.4 Experimental Arrangement and Procedure

For this phase of the project, the same type of mattress and bedding previously selected for the initial investigation served as the burning item. The mattress was a polyurethane innerspring type specified for use in health care facilities. The bedding consisted of a cotton water repellant drawsheet, two cotton/polyester sheets, a cotton/polyester bedspread, a cotton/polyester pillowcase and a pillow which consisted of shredded polyurethane foam filling in a cotton cover. Details of the mattress and bedding are contained in table 3.

The ignition sequence for the mattress and bedding fires was the same as used in previous CFR studies including the initial patient room sprinkler tests [1, 30]. A small polyethylene trash container containing approximately 450 g (1 lb) of combustibles was placed next to the bed between the bed and the east wall for each test. The container was placed in contact with the bedspread with the top of the container 2.0 cm (8 in) from the top of the bed as shown in figure 8. Each test began at the time the contents were ignited with a paper match. The earlier CFR work referenced above reported good repeatability using this ignition sequence.

Prior to each test the burn room was conditioned to a relative humidity (RH) of 40 to 60 percent, and an ambient temperature range of 18 to 27°C (65 to 80°F). The moisture content of wood paneling was within the range of 5 to 8 percent before each test. All of the bedding and waste container items were kept in a 50 percent RH conditioning room at a temperature of 21°C (70°F) for at least 24 hours prior to each test to maintain a consistent moisture content in these items from test to test.

The sprinkler flow rates for each test were obtained by flowing water through the orifice of an open sprinkler (deflector removed) of the same manufacturer and model as that planned for the fire test. A gate valve was operated in coordination with a flow meter until the desired flow was obtained. At that point a quarter turn valve placed in series with the gate valve was closed to shut off the system. While the calibration flows were made the water pump for the site was kept continuously in operation. In all of the tests other than those in which a rapid response sprinkler was simulated, a fully operable automatic sprinkler for the next test was installed after the valve was closed. Following installation of the automatic sprinkler the valve was reopened.

In tests where a fast response sprinkler was simulated, as discussed later, an open sprinkler was immediately installed with an elastomeric plug inserted in the orifice to prevent leakage of water in the sprinkler system piping on the downstream side of the shut valve. The control valve remained closed until at a selected point in the test, the valve was manually operated. The time of actuation was based on ceiling gas temperature measurements or temperatures of the calibrated discs. Since the sprinkler piping was primed with water, the sprinkler flowed immediately after the control valve was opened.

During the fire tests the water pump was kept in operation to maintain the same residual pressure on the sprinkler system. During sprinkler operations the flow meter was monitored to insure that the desired flow was maintained during the test.

## 8.5 Test Results and Analysis

### 8.5.1 Standard Pendant and Horizontal Sidewall Sprinkler Tests

During this phase of the investigation, and following the revision of the facility instrumentation, a test was conducted with a standard 74°C (165°F) fusible element pendant sprinkler under the same test conditions as test N-25 in the previous series [1]. This test (N-37) reflected an installation following current sprinkler criteria for this type of facility as described in paragraph 5.2 with the flow set to provide an average density of 6.9 mm/min (.17 g/min/$ft^2$). The results of the test were similar to test N-25 of the previous series.

The sprinkler operated at 370 s following ignition in test N-25 and 330 s in test N-37 and at the time of sprinkler actuation, the estimated smoke obscuration hazardous thresholds were exceeded in the burn room doorway, the corridor and the remote lobby area. As in the previous tests, there was total obscuration (> 0.9 OD/m) from floor to ceiling following sprinkler actuation.

The test involving the horizontal sidewall sprinkler (test N-39) produced results similar to the test with the pendant sprinkler. The major difference was the longer time to sprinkler actuation. The horizontal sidewall sprinkler actuated at 388 s and a tell-tale sprinkler of the same manufacturer and temperature rating located at the center ceiling operated at 331 s.

As shown in figure 25, the center ceiling gas temperatures reached 270°C with the sidewall as compared to 200°C in test N-37, center ceiling pendant sprinkler. The horizontal sidewall sprinkler effectively controlled the fire and rapidly cooled the temperatures in the burn room. CO concentrations were generally low; the maximum concentration at the adjacent patient level was 0.097 percent and estimated COHb reached 14.2 percent at the end of the test, 30 minutes after ignition. The maximum heat flux measured at the adjacent patient level was .47 W/$cm^2$ (8.9 BTU/sq. ft. min.) which is well below the hazardous threshold. As in the previous tests, smoke obscuration exceeded hazardous thresholds at the patient room doorway and in the corridor before the sprinkler operated. A video recording and instrumentation in the corridor indicated that smoke level lowered to within .9 m (3 ft) of the floor before sprinkler operation. Following sprinkler operation, the entire test area became totally obscure (> 0.9 OD/m) as in the previous tests, as shown in figures 26 thru 28. Velocity measurements in the doorway indicated that the combustion products were projected out into the corridor at floor level. Essentially, the same redistribution of gases occurred as in the previous tests with ceiling mounted pendant sprinklers.

### 8.5.2 Movement of Smoke and CO - Analysis of Data

As mentioned previously, the impact on smoke movement by the sprinkler was significant, especially in the doorway where velocity measurements, smoke meters, and gas measurements indicated a reversal of flow of smoke through the doorway and the shifting of peak CO concentrations from ceiling to floor level. Figure 24 provides the record of CO measurements in the burn room and doorway for test N-37. As in test N-25, in the previous series, concentrations of CO shifted after sprinkler actuation at 330 s. The CO data from the corridor instrumentation tree indicated that the sprinkler acted to redistribute the smoke layer (represented by the CO measurements) away from the immediate area of sprinkler actuation. Figure 29 gives the CO measurements at the corridor tree prior to sprinkler actuation. Following the initial sprinkler flow higher concentrations were recorded at 0.9 m (3 ft) and 1.5 m (5 ft) from the floor, with values in excess of 0.1 percent CO recorded. The concentrations measured near the ceiling were lower than those measured at the other elevations following sprinkler actuation.

The concentrations of CO measured at all locations were low and estimated COHb levels did not exceed a hazardous threshold of 25 percent. The increase in CO in the corridor and the redistribution of the CO throughout the test area, however, verified that, in these types of fires, the sprinkler acted to lower the smoke layer throughout the test area and to project the combustion products from the patient room into the adjoining corridor at a more rapid rate than before the sprinkler operated. This resulted in the severe smoke obscuration recorded throughout the test area which in an actual health care facility could seriously hamper the movement of staff and patients in the adjoining corridor.

An analysis of the data revealed that the smoke filling rate in the test area was roughly proportional to the fire growth rate as reflected in the record of gas temperatures measured at ceiling in the center of the burn room. Figures 30 and 31 demonstrate this correlation where the depth of the smoke layer is defined as the time a smoke meter located in the doorway or in the corridor measured an obscuration of 0.25 OD/m. This boundary value for the smoke layer was arbitrarily established in this analysis in order to assess the impact of sprinkler response time as a function of the estimated depth of the smoke layer in the test area. (As mentioned in section 6.3, 0.25 OD/m was selected as a hazardous threshold for visibility and personnel movement in the corridor.) In figures 30 and 31 the rate of fire growth is indicated by the ceiling temperature scale on the right ordinate and the depth of the smoke layer is indicated by the elevation measurements in the test area on the left ordinate.

Figure 30 provides the results of test N-37 in which a pendant automatic sprinkler was installed in the center of the room. Although the sprinkler had a temperature rating of 74°C (165°F), the thermal lag of the fusible element was such that the sprinkler finally operated at 330 s. At this point the ceiling gas temperature had reached 200°C near the sprinkler and the smoke layer had lowered to approximately 0.9 m (36 in) from the floor.

This lag was even more significant in test N-39 in which a horizontal sidewall automatic sprinkler was located over the door. The sprinkler had a temperature rating of 71°C (160°F) and at time of actuation, 388 s, the smoke layer was less than .9 m (36 in) from the floor. See figure 31.

By plotting the smoke filling rate on the same time axis as the ceiling gas temperatures, one can see that a fusible element operating at approximately 57°C (135°F) would actuate the sprinkler when the volume of smoke in the patient room and corridor was significantly less than when the standard 74°C sprinkler actually operated. Since the instrumentation as well as visual observations revealed that the flowing sprinkler acted to lower and redistribute the smoke layer, it follows that if a sprinkler operated sufficiently early enough in the fire, there would be minimal smoke including CO present to be redistributed by the sprinkler. Based on this, the project focused on the investigation of sprinklers operating at an earlier stage of the fire development and their impact on smoke movement.

## 8.6 Simulated Rapid Response Sprinkler Tests

### 8.6.1 Preliminary Test

In test N-37, a tell tale sprinkler which was rated for 57°C (135°F) operating temperature and designed for rapid response, operated at 285 s. At this time, as shown in figure 30, the center ceiling gas temperature was approximately 120°C (248°F) and the smoke layer in the corridor had lowered to within 1.2 m (4 ft) from the floor.

This suggested that a fusible element with a thermal inertia lower than exists for current technology sprinklers was necessary if the sprinkler was expected to operate shortly after the gas temperature near the sprinkler reached its nominal temperature rating.

Initially, a test (N-38) was conducted to determine the feasibility of preventing the smoke obscuration from reaching hazardous theresholds by actuating the sprinkler sufficiently early in the fire. This test included the same mattress, bedding, and waste container ignition sequence described earlier. The sprinkler system consisted of an open 10 mm (3/8 in) pendant sprinkler arranged to flow 64.3 ℓ/min (17 g/min) which provided an average density of 4.1 mm/min (.10 g/min/ft$^2$) in the burn room. As described in section 5.2, the open sprinkler was fitted with a resilient plug, and the system piping was primed with water downstream of a closed control valve.

During the fire test the gas temperature measured near the sprinkler was continuously monitored. To simulate the rapid response, the sprinkler valve was opened at 10 s after the time the center ceiling gas temperature reached 57°C (135°F) at the sprinkler. The sprinkler was opened at 105 s into the test and the subsequent smoke obscuration was very low throughout the test area. The maximum obscuration measurements at 1.7 m (5 ft 8 in) in the burn room doorway and at 1.5 (5 ft) in the corridor were 0.10 and 0.086 OD/m respectively. These levels were considerably below the estimated hazardous thresholds.

The results of this test indicated that for this type of fire, the smoke obscuration problem both before and after sprinkler operation could be greatly reduced by means of a sprinkler with a low thermal inertia fusible link which would operate soon after the ceiling gas temperature reached 57°C. (The temperature rating of 57°C was selected as a minimum since this follows criteria contained in NFPA 13 [6] and UL 199 [7]. The criteria evolve from the need to establish the minimum sprinkler temperature rating above expected ambient temperature conditions.)

### 8.6.2 CFR Patient Room Tests

Following test N-38, this investigation sought to quantify the dynamic heating parameter of a successful fast response sprinkler in terms of the suggested FM Plunge Test discussed in 5.3. Three discs provided by FM were installed in the burn room ceiling near the sprinkler prior to test N-40. In addition a fusible link from a self-contained pressurized heat detector was installed at the ceiling. In prior tests, response times obtained for this detector, which had a temperature rating of 57°C (135°F), indicated that it responded considerably earlier than the 57°C sprinkler. Since the link was similar in basic design to current sprinkler fusible links, (although of significantly less mass) it was decided that it would be useful to key sprinkler response to this link and at the same time obtain data on the temperatures of the discs.

Test N-40 was conducted under the same conditions as test N-38 except that the simulated HVAC system described in section 5.1 was installed and placed in operation. The sprinkler was operated at the time when the heat detector link activated, 225 s. At this time the $\tau$ = 21 s disc reached 62°C, (144°F). The results indicated that smoke obscuration did not reach hazardous thresholds at the patient room doorway, 1.7 m (5 ft. 8 in) elevation and, only briefly exceeded the threshold of 0.25 OD/m obscuration measured 1.5 m (5 ft) above the floor in the corridor. See figures 26 thru 28. This test was repeated (N-47) and provided the same results. Figures 26 thru 28 also indicate the results of previous tests in which standard fusible element sprinklers were used.

In addition to tests N-40 and N-47 which examined the performance of a pendant sprinkler with a fast-response fusible element, two tests were conducted with the horizontal sidewall sprinklers which included simulated fast-response fusible elements. The sprinkler was arranged to flow 102 ℓ/min (27 g/min) to provide an average density of 6.9 mm/min (.17 g/min/ft$^2$).

In the first test, N-42, the heat detector link and the discs were installed near the horizontal sidewall sprinkler. In this first test, the simulated HVAC system was not incorporated into the test. Therefore, the environmental conditions during the test were the same as N-39 in which a standard fusible element horizontal sidewall sprinkler was used. At 266 s into the test the heat detector fusible element (57°C temperature rated) activated and the sprinkler valve was opened. The temperature of the $\tau$ = 21 s disc was 57°C at time of activation. Smoke obscuration throughout the test area was significantly less than in test N-39. The smoke obscuration as measured at the doorway briefly exceeded the 0.5 OD/m estimated hazardous threshold and peaked at .83 OD/m, but it stayed generally below the threshold. The smoke obscuration measured at the 1.5 m (5 ft.) elevation in the corridor exceeded the threshold of 0.25 OD/m. Maximum obscuration peaked at 0.61 OD/m, but generally the obscuration was below 0.30 OD/m throughout the test period.

This test was repeated (N-45) with the simulated HVAC system incorporated into the test. In this test, the heat detector link near the horizontal sidewall sprinkler actuated at 177 s and the control valve was immediately opened. Due to an unexpected instrumentation failure early in the test, smoke obscuration measurements in the doorway were not recorded. However, the measurements in the corridor as well as the visual observations indicated that smoke obscuration was not as severe as in test N-39 nor in the previous simulated fast response sprinkler test, N-42. As shown in figure 27, at approximately 480 s, the smoke obscuration rose to slightly above the 0.25 OD/m level where it remained until around 960 s when the obscuration increased to approximately 1.0 OD/m. See figure 28 for smoke obscuration data in the remote lobby area.

### 8.7 Discussion

The tests discussed in this section were conducted in a limited volume test area which represented a typical patient room and corridor arrangement but it did not represent as great a volume as would likely be in a smoke zone in a health care occupancy. Therefore, limited extrapolation can be made for other geometries and larger volumes.

Despite the limitations which prevent extensive extrapolation to other building sizes, the experimental work reported here clearly demonstrates that a lower thermal inertia or fast response sprinkler can reduce significantly the impact of smoke obscuration for a patient room mattress and bedding fire. Since the lowering of the heated gas layer and severe obscuration was immediate in and near the patient room, where the conventional sprinkler operated, this phenomenon suggests that the obscuration problem is severe near the room of fire origin regardless of the volume of the building or smoke zone. The impact of the fast response sprinkler, in reducing the smoke obscuration problem in and near the room of fire origin, could enhance the rescue by staff of the patients closest to the fire.

## 9. WARDROBE FIRES

### 9.1 Test Plan and Procedure

One of the objectives of this program was to assess the impact of sprinklers on wardrobe fires in patient rooms. The clothing wardrobe and the bedding and mattress represented types of furnishings which could become the predominant burning items in a patient room fire. In a limited number of fire tests conducted by IIT Research Institute (IITRI) for the American Health Care Association, test fires started inside clothing wardrobes resulted in a very rapid rise in room temperatures and high concentrations of CO [31]. The wardrobe fire, therefore, was included in the CFR project in order to assess the impact of sprinklers on what was estimated to be a very severe fire in a patient room.

There was a concern that it might not be possible to obtain wardrobes manufactured of the same materials from a commercial supplier over an extended period during which the test fires would be conducted. Therefore, the wardrobes were fabricated at CFR for this project, since it was necessary to use wardrobes of the same types of materials from test to test. They were constructed of 1/2 inch unfinished Douglas fir plywood and their dimensions are shown in figure 32. These dimensions were taken from catalogs of commercial wardrobe manufacturers.

In an effort to develop a reproducible test fire, the same loading was initially used in each test. The loading consisted of various fabrics which represent materials found in clothing today. A description of the fabrics used in this "standard" loading are listed in table 4. The materials were placed on wire coat hangers and arranged loosely in the wardrobe to provide a clear space between each hung fabric. This arrangement was chosen since it was desirable to have a fire which would develop rapidly inside the wardrobe. A cardboard box containing crumpled newspaper was placed on the floor of the wardrobe and the newspaper served as the pilot flame inside the wardrobe. Each wardrobe test started when the crumpled newspaper was ignited with a match. Following ignition the left hand door was closed tightly while the right hand door was left partially opened resulting in a 7.6 cm (3 in) opening along the vertical edge of the door.

### 9.2 Nonsprinklered Wardrobe Fire

In order to obtain a baseline for evaluating the performance of sprinklers when exposed to combustible wardrobe fires, a nonsprinklered fire test (N-54) was conducted. The test was actually carried out after several wardrobe tests with sprinklers because of a concern that the "dry" test would result in extensive damage to the test facility instrumentation, potentially resulting in an adverse affect on the program timetable.

The initial rate of fire growth was essentially the same as in the sprinklered tests. With no other furnishings in the room, flashover occurred at approximately 120 s into the test. See figure 33. At this time all hazardous thresholds were exceeded throughout the test area. Several smoke meters in the corridor and in the doorway were damaged by heat and much of that data was lost. Measurements made at the key elevations in the doorway and in the corridor, however, indicated that hazardous thresholds had already been exceeded prior to the instrument failures. The test was terminated at 480 s when an open sprinkler was activated. Figures 33 through 40 provide important data including burn room ceiling gas temperatures, smoke obscuration and CO measurements.

### 9.3 Pendant Sprinkler Tests

In the initial wardrobe test, N-48, a standard 71°C (160°F) pendant sprinkler was installed and arranged to provide the 6.9 mm/min (.17 g/min/$ft^2$) density. As expected the fire quickly enveloped the interior of the wardrobe and gas temperatures in the burn room rose rapidly. Following actuation of the sprinkler, the ceiling gas temperatures were lowered; however, the fire could still be seen burning inside the wardrobe for approximately 60 s following the initial flow of the sprinkler. Eventually, the smoke obscuration wiped out the view from a window in the corridor across from the burn room doorway.

Analysis of the data from this test indicated that concentrations of CO were very high throughout the test area. The instantaneous hazardous threshold of 1 percent was exceeded not only in the patient room but also in the remote lobby area. Estimated COHb percentages also well exceeded the hazardous threshold of 25 percent.

This test was repeated (N-49) and the overall results were the same as in N-48. The fire developed rapidly inside the wardrobe and, although CO concentrations were slightly less than in N-48, hazardous thresholds were exceeded or approached in the burn room at the adjacent patient level, at the 1.5 m (5 ft) elevation in the corridor as well as in the remote lobby area. Figures 33 thru 40 provide the ceiling temperatures in the burn room and the CO data as measured at several key locations, as well as smoke obscuration and heat flux.

In both of these tests the lauan plywood paneling described in Section 5.1 was installed on the walls adjacent to the wardrobe. The paneling did not become involved in these sprinklered fires.

### 9.4 Horizontal Sidewall Sprinkler Tests

Using the same wardrobe fire scenario, a test was conducted using a standard 71°C (160°F) horizontal sidewall sprinkler set to provide a 6.9 mm/min (.17 g/min/$ft^2$) density. The sprinkler was installed over the door as in the previous mattress test (N-39) and as shown in figure 7.

The initial fire development was as rapid as in the previous tests and following sprinkler actuation, the fire was visible for a brief time inside the wardrobe. As in the previous tests the visibility was limited soon after sprinkler operation. A major difference, however, was noted in the CO concentrations, compared to the previous tests with the pendant sprinkler. CO concentrations were significantly lower; an instantaneous threshold level of 1 percent was not reached, and the 25 percent COHb was exceeded only in the burn room at the adjacent patient level at 1000 s after ignition. The test was repeated, (N-51) and approximately the same results were obtained. Figures 41 thru 49 provide the record of ceiling gas temperature measurements as well as the CO data, smoke obscuration and heat flux data.

The record of total weight loss for the four tests was consistent with the CO data. The data also indicated that the horizontal sidewall sprinkler achieved better fire control than the pendant sprinkler. Total weight losses were less than in the pendant sprinkler tests as shown in table 5.

In the initial analysis of the results, it was believed that the orientation of the partially open wardrobe door with respect to the direction of the spray from the horizontal sidewall sprinkler allowed more water to penetrate the interior of the wardrobe. Spray distribution measurements were made in nonfire tests for both the pendant and horizontal sidewall sprinklers operating at the same flow rates as in the actual fire tests. The results of the tests are shown in figure 50. The spray measurement tests indicated that no more water penetrated the wardrobe with the horizontal sidewall sprinkler than with the pendant sprinkler.

The greater extinguishing performance of the horizontal sidewall sprinkler over the pendant sprinkler was apparently not due to a greater flow density inside the wardrobe. At least two possibilities can be postulated for the distinct differences:

a. The droplet size of the spray from the horizontal sidewall sprinkler was such that they penetrated the intense fire plume from the wardrobe and achieved more rapid extinguishment. (To date the droplet sizes have not been measured for these sprinklers.)

b. The spray from the horizontal sidewall sprinkler located over the door was somewhat parallel to the flow of combustion air into the wardrobe. The spray may have been entrained in the combustion air stream.

The reasons for the differences between the two types of sprinklers are not immediately clear and need further investigation. These differences are significant in terms of the impact of sprinklers on life safety and could have an effect on design recommendations. As the CO data, in particular, demonstrate, the prevention of flashover by the sprinkler is not the only benefit necessary for insuring life safety outside the room of fire origin. Limiting the generation of toxic gases must also be considered, which in these fires was dependent upon the extinguishing performance of the sprinkler.

## 9.5 Packed Wardrobe Test

As mentioned previously it was intended in the scope of the project to incorporate a wardrobe test fire that would represent a severe but not unusual fire scenario for a fire occurring in a patient room. Therefore, a wardrobe of combustible construction with contents consisting of clothing fabric loosely packed was selected as the burning item. In order to verify this choice, and to obtain data on a different wardrobe loading, a test was conducted with a wardrobe packed tightly with clothing items. The sprinkler system consisted of a 71°C (160°F) pendant sprinkler set to provide a density of 6.9 mm/min (.17 g/min/ft$^2$). The results of the test, N-58, as shown in figures 51 thru 55 indicated that this test was less severe than previous tests where the loosely packed wardrobe served as the burning item. Table 5 gives the weight of the loading used in this test.

The significant difference in the severity of the fires between the tightly and loosely packed wardrobe fire was the contribution of the wardrobe itself. The total weight losses between these tests indicate that wardrobes with the loosely packed loading contributed much more fuel to those fires and therefore contributed to the significantly higher CO concentrations recorded throughout the test area.

## 9.6 Noncombustible Wardrobe Tests

The analysis of the results of the various wardrobe tests clearly indicated that the contribution of the wardrobe itself influenced greatly the severity of the fire in terms of the estimated hazardous thresholds. The CO data with the record of total weight losses demonstrate this correlation.

Two tests were conducted with a wardrobe of steel construction to assess the impact of a fire involving a noncombustible wardrobe and to determine if the hazard could be diminished. Because of unexpected delivery delays from commercial suppliers, a steel wardrobe of the exact size as the wooden wardrobes could not be obtained. A smaller one shown in figure 32 was selected.

In the first test, N-59 the same loading as in the previous tests was placed in the wardrobe. Although the clothing fabrics were not as loosely packed due to the narrower width, the loading was still loose enough to allow a very rapid involvement of the contents. Although the initial fire growth was similar to the combustible wardrobe tests, the overall test results indicated that it was significantly less severe. CO concentrations and estimated COHb percentage did not reach hazardous thresholds. Only the estimated thresholds for smoke obscuration were exceeded. A second test N-60 was conducted with a steel wardrobe which was tightly packed with clothing. The purpose was to assess the impact of a higher fuel load in a noncombustible wardrobe and to compare the results with the test involving the packed combustible wardrobe. While the loading was reduced because of the smaller volume in the steel wardrobe, the density was the same. The key results of both noncombustible wardrobe tests are shown in figures 51 thru 55.

## 9.7 Simulated Rapid Response

Analysis of the disc temperature data from the sprinklered wardrobe tests indicated that fast response sprinklers would have operated only 10 to 15 s prior to the actual standard sprinklers. A review of the photogrpahic record of the test showed that at the time the discs reached 57°C the fire was just beginning to issue from the wardrobe. Two tests were conducted, each simulating a fast response, $\tau$ = 21 s 57°C fusible element; one test (N-53) with the pendant sprinkler and the other (N-52) with a horizontal sidewall sprinkler. The purpose of the tests was to determine if the extinguishing performance of the sprinklers could be improved with the fast-response sprinkler. As shown in figures 33 thru 49, and in table 5, no significant improvements were noted for either sprinkler over the standard fusible element sprinklers. It appeared as though the fire growth rate inside the wardrobe had reached the point where the spray from the fast response pendant sprinkler could not extinguish the fire any better than the standard fusible element sprinkler.

## 9.8 Combustible Ceiling Tests

Another goal of the project was to examine the impact of sprinklers on fires in patient rooms with a combustible interior finish. Again, a boundary condition was sought in the formulation of the test plan. Since the lauan plywood paneling surrounding the wardrobe did not play a role in the fire tests when sprinklers were installed, the investigation keyed upon assessing the impact of a combustible ceiling in these types of fires. The ceiling consisted of wood fiber ceiling panels, described in section 5.1, fastened directly to the existing burn room ceiling.

All of the previous tests indicated that the horizontal sidewall sprinkler wetted the ceiling throughout the burn room. Therefore, it was considered unnecessary to investigate a combustible ceiling fire where a horizontal sprinkler was installed since a ceiling fire would not present a challenge to this type of sprinkler protection.

Therefore the tests were conducted with only the ceiling pendant sprinkler system. Since the combustible wardrobe fire with the loosely packed fuel loading typically projected an intense flame plume onto the ceiling prior to sprinkler actuation, the wardrobe with a light loading was selected as the initial burning item. In the first test, N-55 the ceiling became ignited just over the wardrobe. Following sprinkler actuation there was no further evidence of sustained burning at the ceiling. Following the test an examination of the ceiling revealed that approximately half of the ceiling was not damaged by the fire. The corridor ceiling gas temperature data indicated that a corridor sprinkler might have been actuated had it been installed. The question then arose as to the impact of multiple sprinklers operating, whereby the flow from the burn room sprinkler would be reduced from the initial flow. This test was repeated with a procedure worked out to simulate this reduction in flow due to multiple sprinkler head operations. A dry sprinkler of the same type as in the burn room was placed in the corridor ceiling outside the burn room doorway. The test procedure provided that at the time the dry sprinkler actuated, the flow to the burn room sprinkler would be reduced to a flow of 64.3 ℓ/min (17 g/min) which would provide an average density of 4.1 mm/min (.10 g/min/ft$^2$). This envisions the minimum design density of 4.1 mm/min (.10 g/min/ft$^2$) considering the sprinkler in the patient room plus two in the adjoining corridor flowing [6]. In the test, however, the corridor sprinkler did not activate and the flow to the burn room was maintained for the 6.9 mm/min (.17 g/min/ft$^2$) density. The results of the test were essentially the same as in N-55.

Finally, a test was conducted to reflect an extreme sprinkler location, to assess the impact of the combustible ceiling in a patient room equipped with sprinklers. The condition, although unrealistic, reflected the extreme limits of the installation criteria [6].

A pendant sprinkler was installed in the burn room with the deflector .25 m (10 in) below the combustible ceiling. A sprinkler was selected which tended to project a minimum amount of water up toward the ceiling and the flow rate was set for 64.3 ℓ/min (17 g/min). The combustible wardrobe with the light loading served again as the initial burning item. As expected the ceiling became well involved in fire above the wardrobe prior to operation of the sprinkler and the ceiling continued to burn for approximately 60 s following the initial sprinkler flow. At that point the fire at the ceiling appeared to be controlled. Following the test an examination of the ceiling indicated that it had been deeply charred above the wardrobe, but was undamaged on the opposite side of the sprinkler away from the wardrobe. See figures 56 and 57 for results.

The results of these tests indicated that the fire involving the combustible ceiling inside the patient room was controlled by the sprinkler. The involvement of the ceiling caused by the intense fire plume from the wardrobe did contribute to the total CO concentrations. As shown in figure 58, CO concentrations were higher in these two tests than in N-48 with the noncombustible ceiling.

## 10. SUMMARY AND CONCLUSIONS

For the given room arrangement, fire scenario and test conditions selected, and the limited tests conducted to date, the following summary and conclusions appear justified.

a. The type and location of a privacy curtain in a patient room should be coordinated with the location of the sprinkler protecting the room. The results of spray distribution measurements reported here suggest that the privacy curtain should be located as close as possible to the ceiling pendant sprinkler with the top of the curtain located below the sprinkler deflector. For horizontal sidewall sprinklers the results of this study indicate that the top of the curtain should be located no higher than the height of the sprinkler on the wall.

b. The combustible clothing wardrobe fire represents an extremely severe fire which can result in flashover in the room of fire origin without additional fuel contribution from other combustibles. The unsprinklered test fire resulted in flashover in the room of fire origin and all smoke obscuration and carbon monoxide thresholds were exceeded in the test area.

c. The contribution of the combustible wardrobe itself was the dominant factor in fires where high concentrations of carbon monoxide were recorded. Significantly lower concentrations were recorded in tests involving noncombustible wardrobes with similar contents.

d. Automatic sprinklers demonstrated the ability to limit some of the hazards caused by the combustible wardrobe fires, but carbon monoxide concentrations exceeded estimated hazardous thresholds throughout the test area in the tests where pendant sprinklers were installed. The carbon monoxide concentrations were significantly less in tests with horizontal sidewall sprinklers. Although the reasons for this improved performance are not completely understood, these sprinklers extinguished the fire more rapidly than the pendant sprinklers and, thus, limited the involvement of the combustible wardrobe.

e. Both the pendant and horizontal sidewall sprinkler sprays acted to redistribute combustion products in the burn room in which the sprinklers operated, as well as in the adjacent corridor and remote lobby in the test area. The redistribution of the combustion products resulted in essentially total obscuration (optical density > 0.9 OD/M) throughout the test area.

f. The use of a fast response sprinkler (pendant or horizontal sidewall) reduced significantly the smoke obscuration in the patient room doorway and adjacent corridor in a flaming mattress and bedding fire. The reduction of smoke obscuration can enhance rescue efforts directed toward patients in and near the room of fire origin.

g. The use of simulated fast response sprinklers in combustible wardrobe fire tests did not improve the overall performance of either the pendant or horizontal sidewall sprinklers.

h. The presence of a combustible ceiling in the room of fire origin contributed to the energy release in the test fires and the concentrations of CO in the test area when it was exposed to the intense fire plume generated by the wardrobe fires. The combustible ceiling of Class D Flame Spread Rating did not adversely affect the overall performance of sprinklers in the burn room in controlling fire growth.

i. For the tests conducted with the combustible wall paneling around the wardrobe, the wall finish did not become involved in the fire and did not adversely affect sprinkler performance.

j. The modest air movements created by the fan coil unit and simulated supply and exhaust air system did not significantly influence sprinkler response nor the concentrations of smoke and CO recorded during the tests.

## 11. ACKNOWLEDGEMENTS

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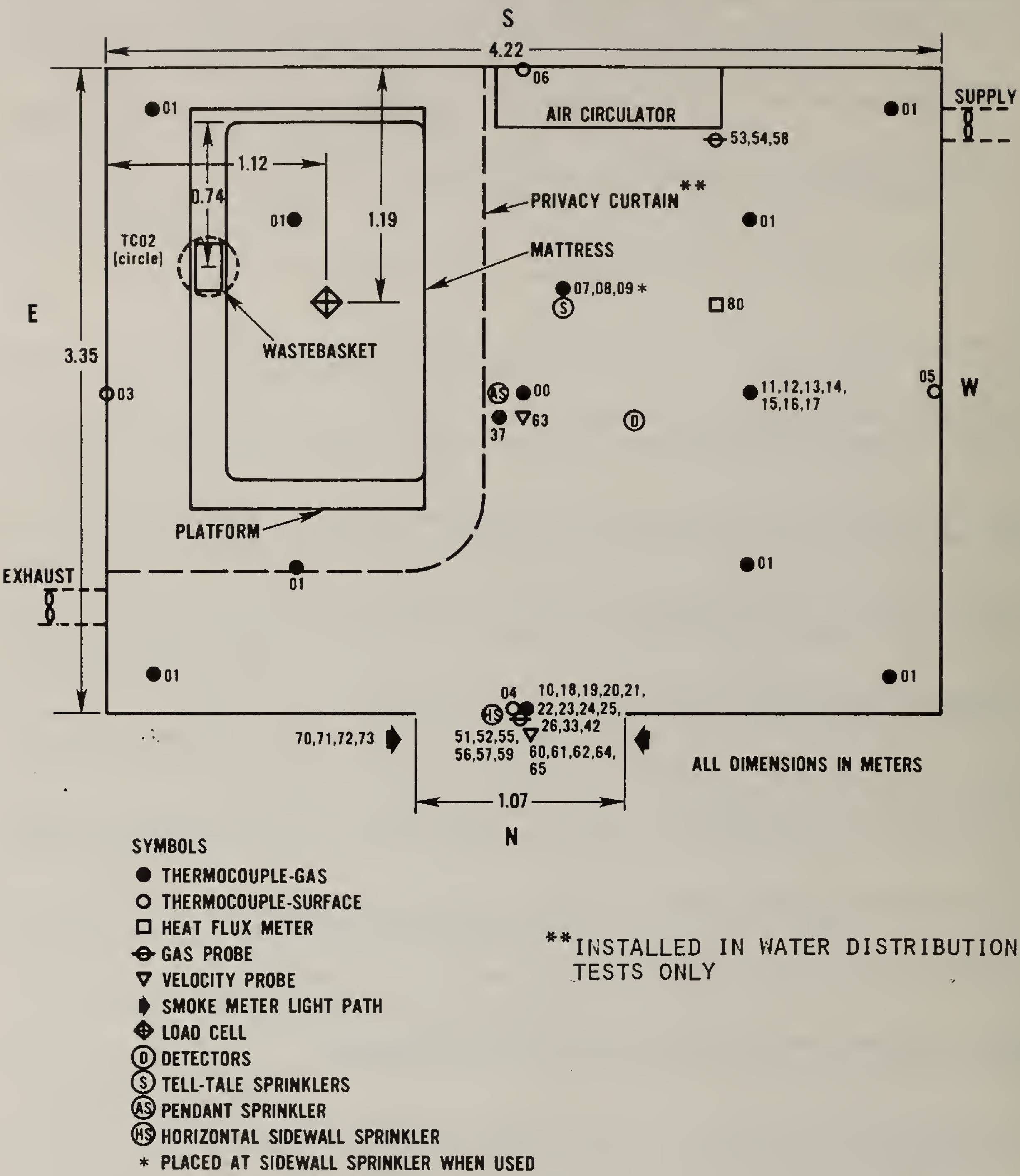



Figure 1. Burn room floor plan--mattress series

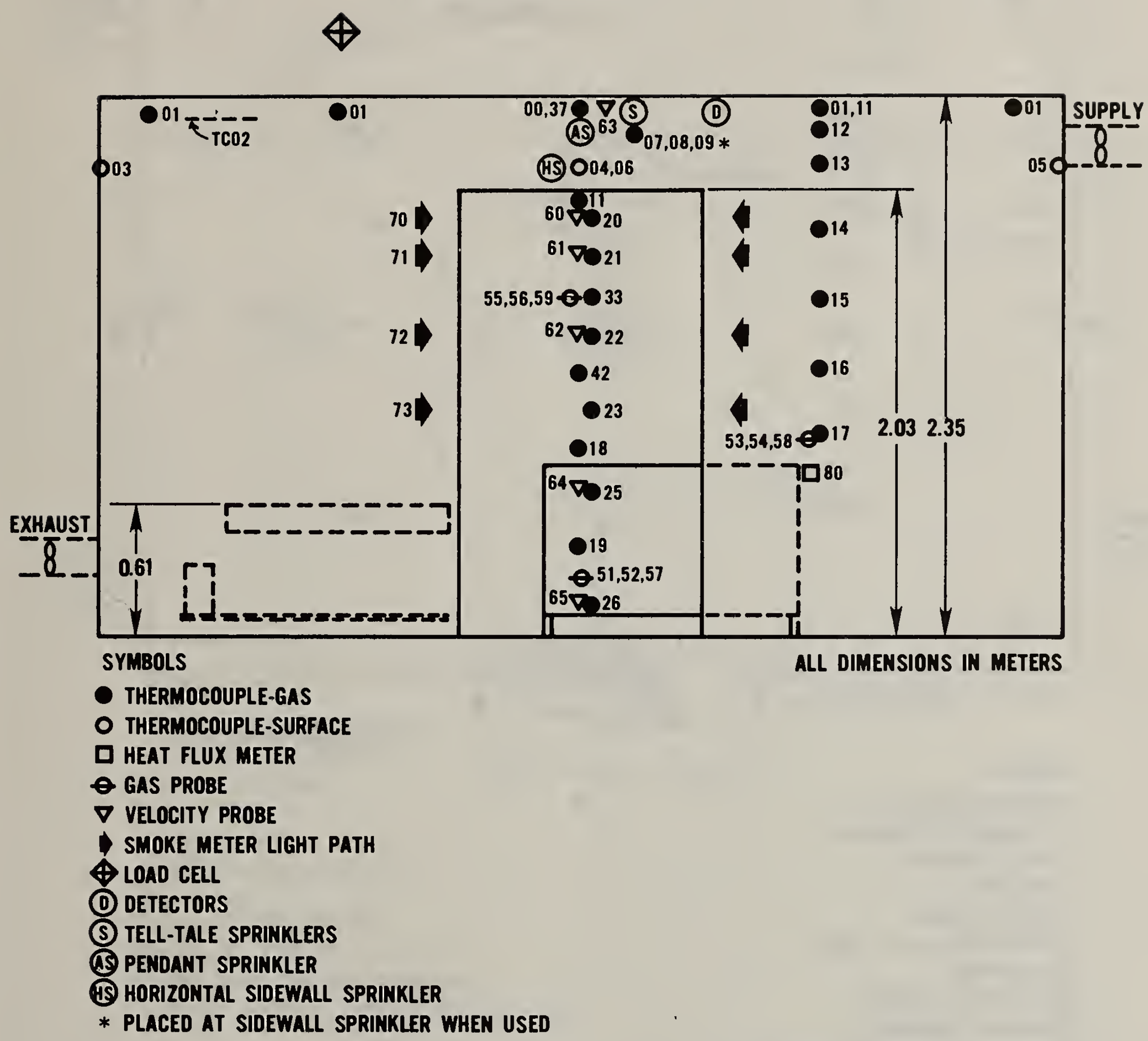



Figure 2. Burn room elevation--mattress series

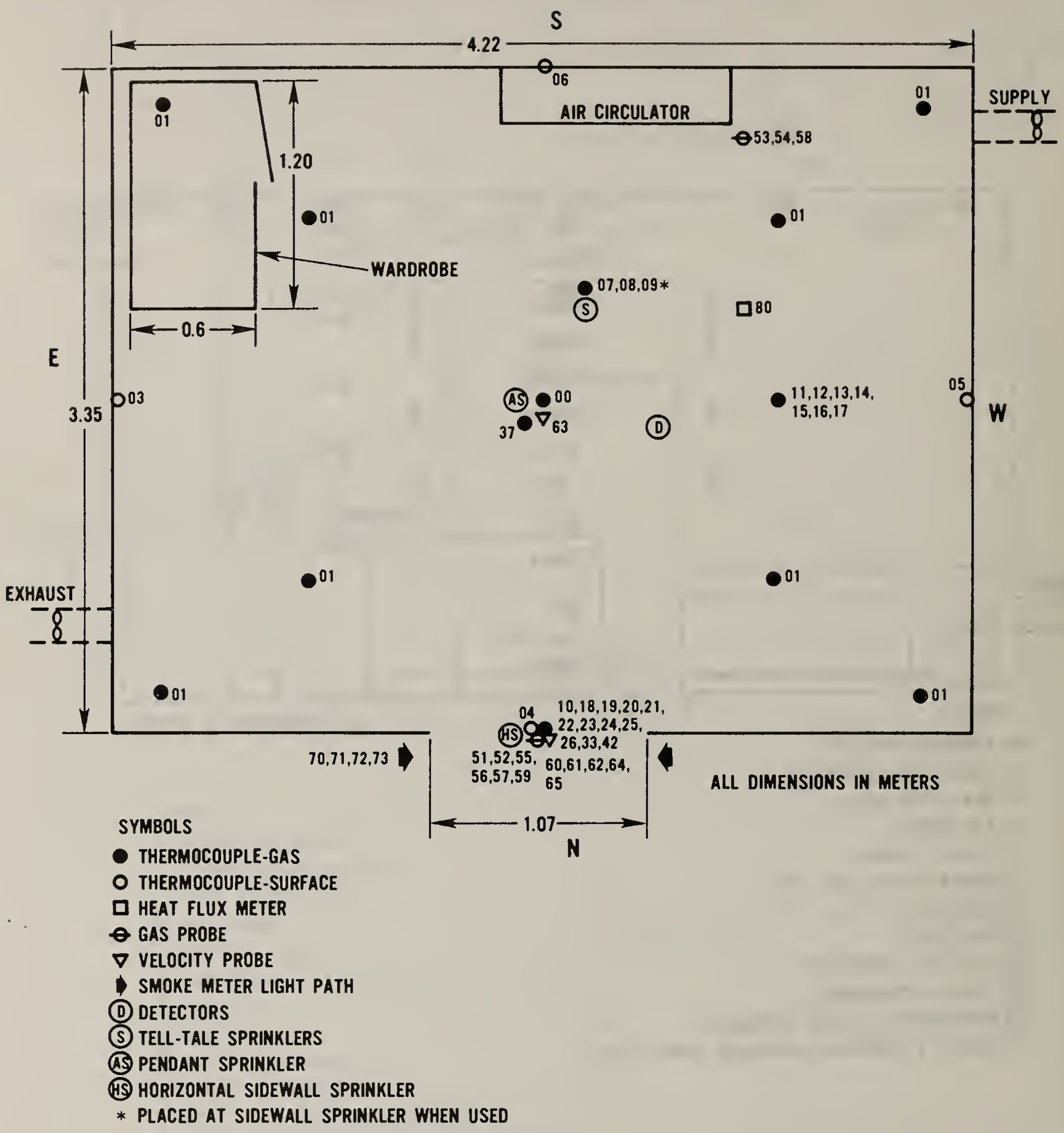



Figure 3. Burn room floor plan--wardrobe series

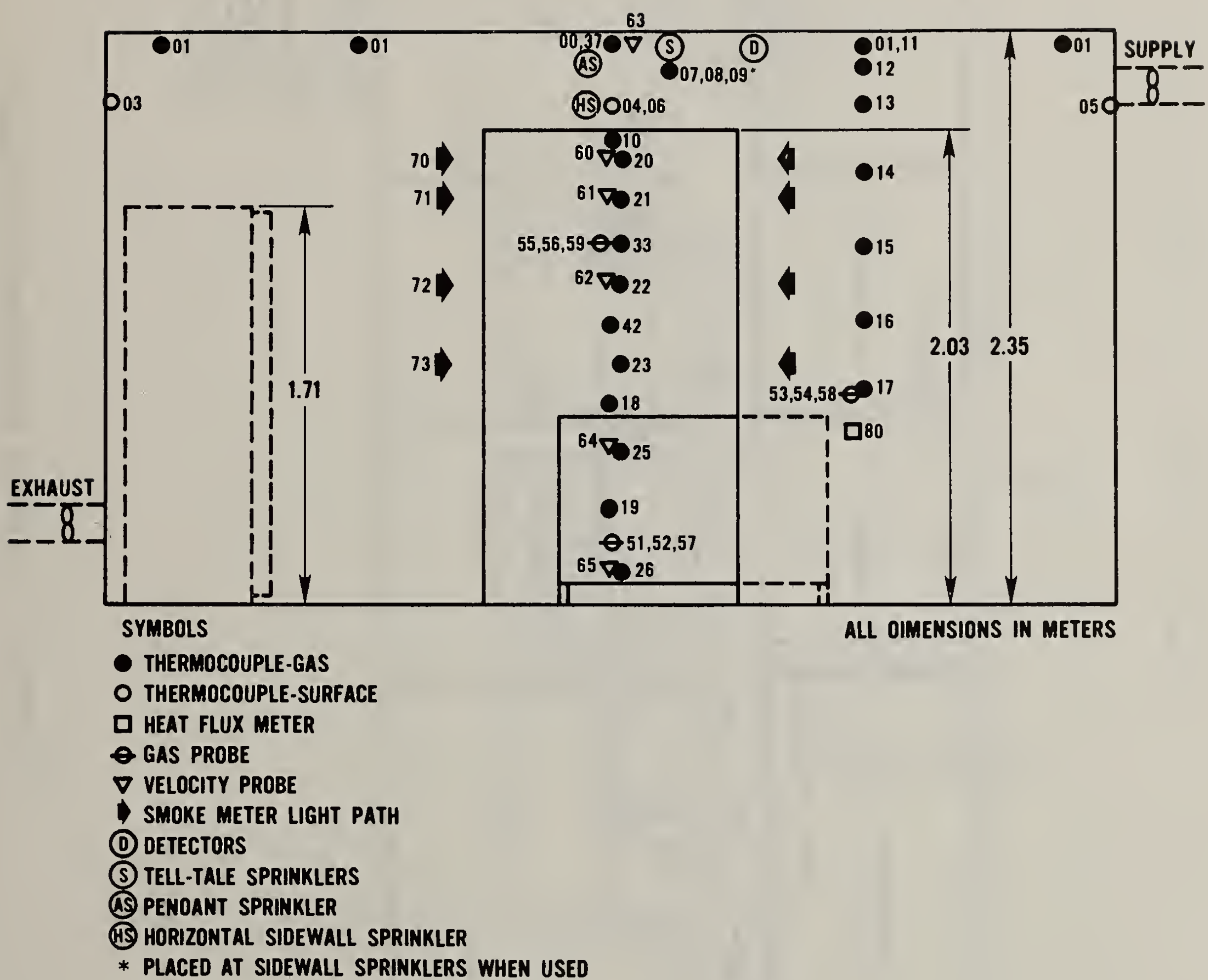



Figure 4. Burn room elevation--wardrobe series

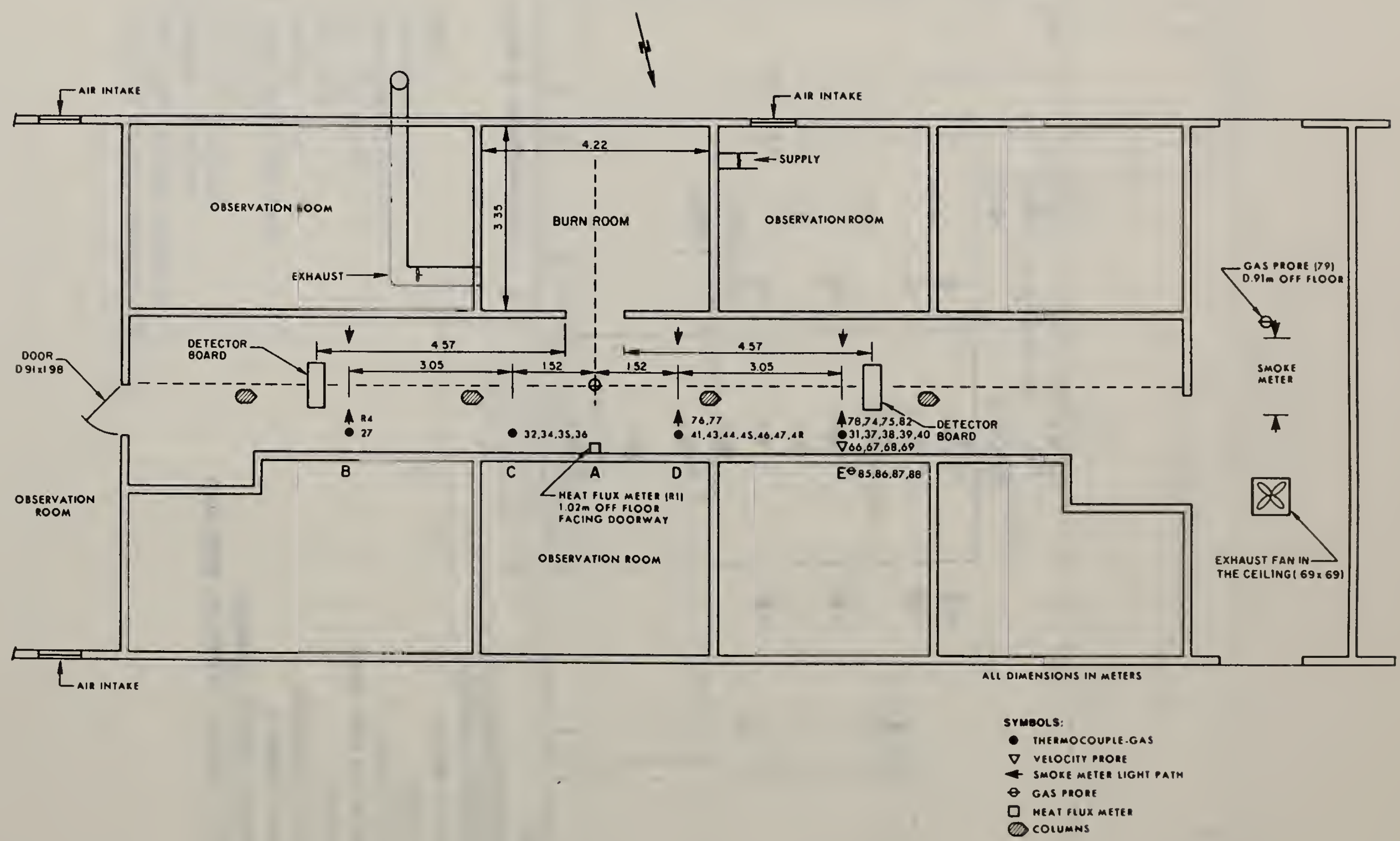



Figure 5. Corridor and lobby floor plan

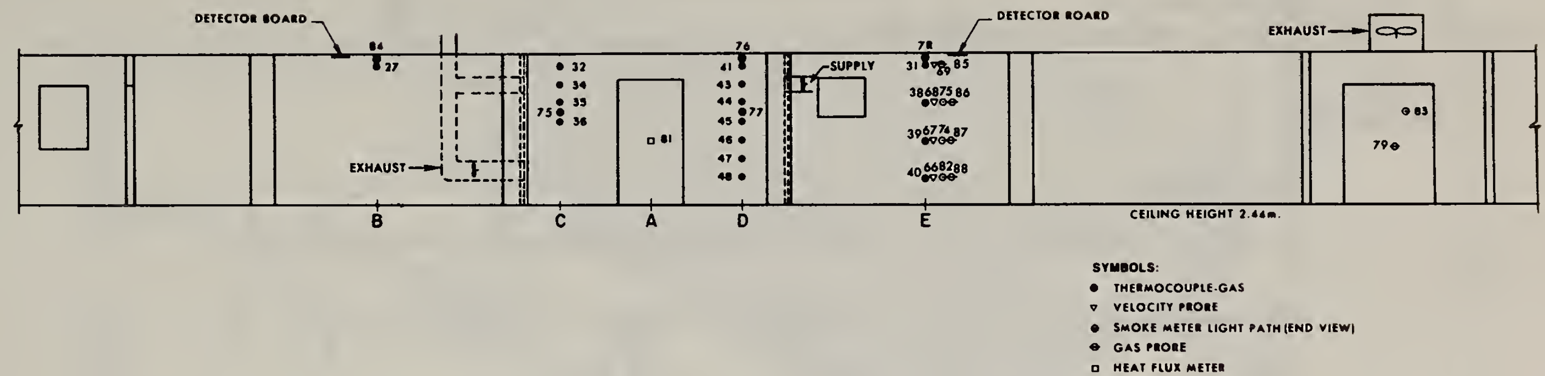



Figure 6. Corridor and lobby elevation

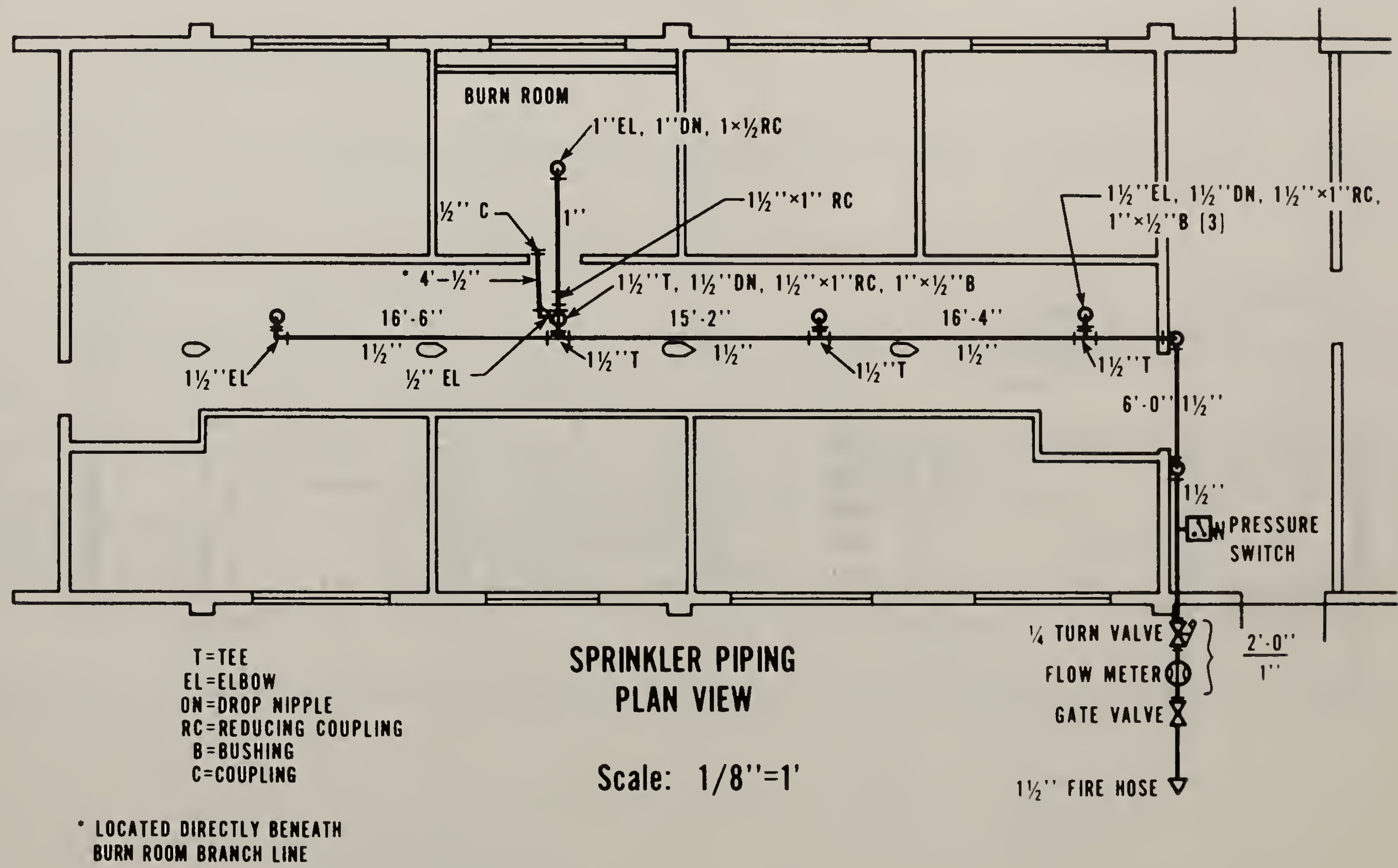



Figure 7. Sprinkler system plan view

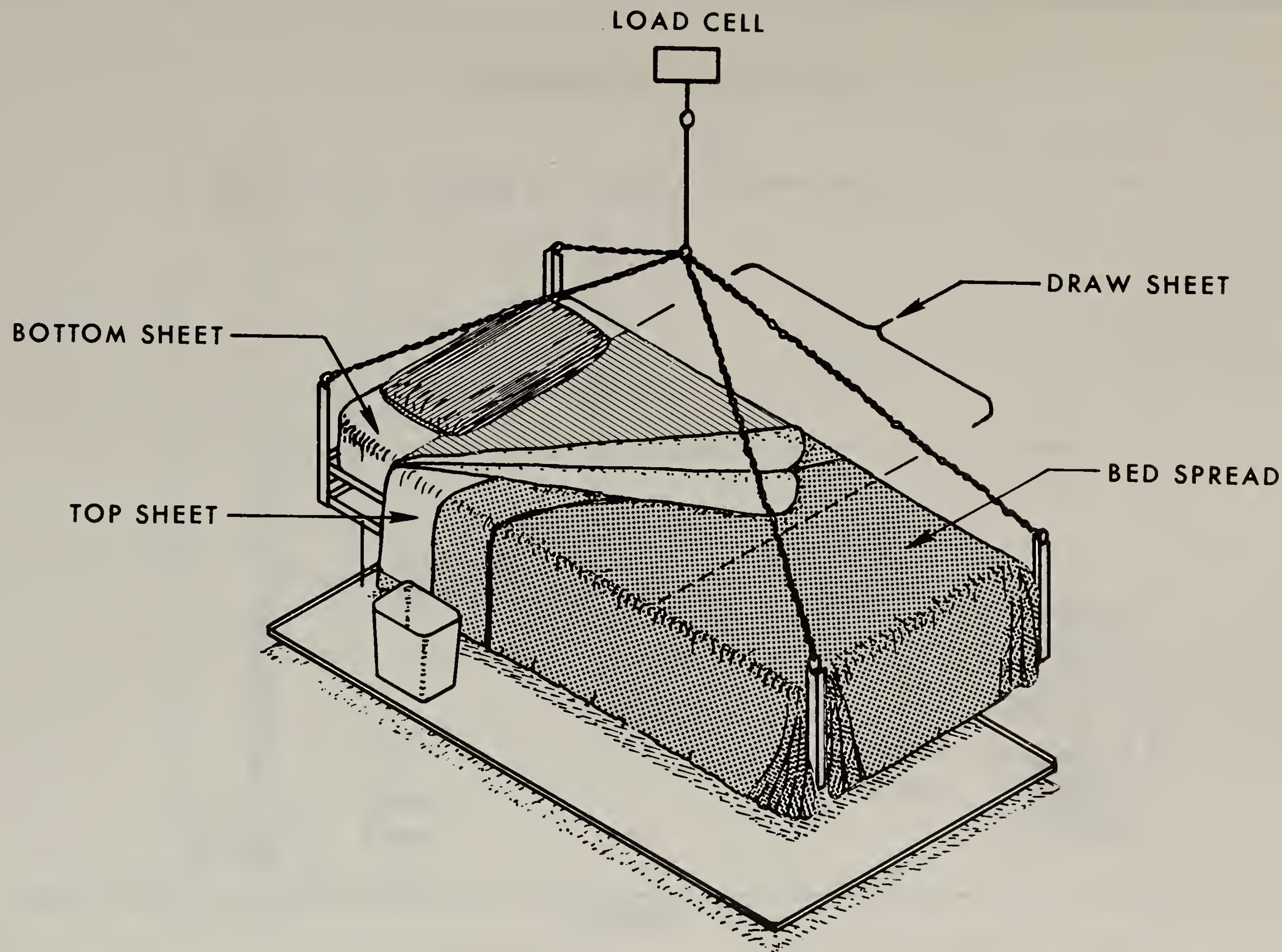



Figure 8. Load cell suspension for mattress and bedding

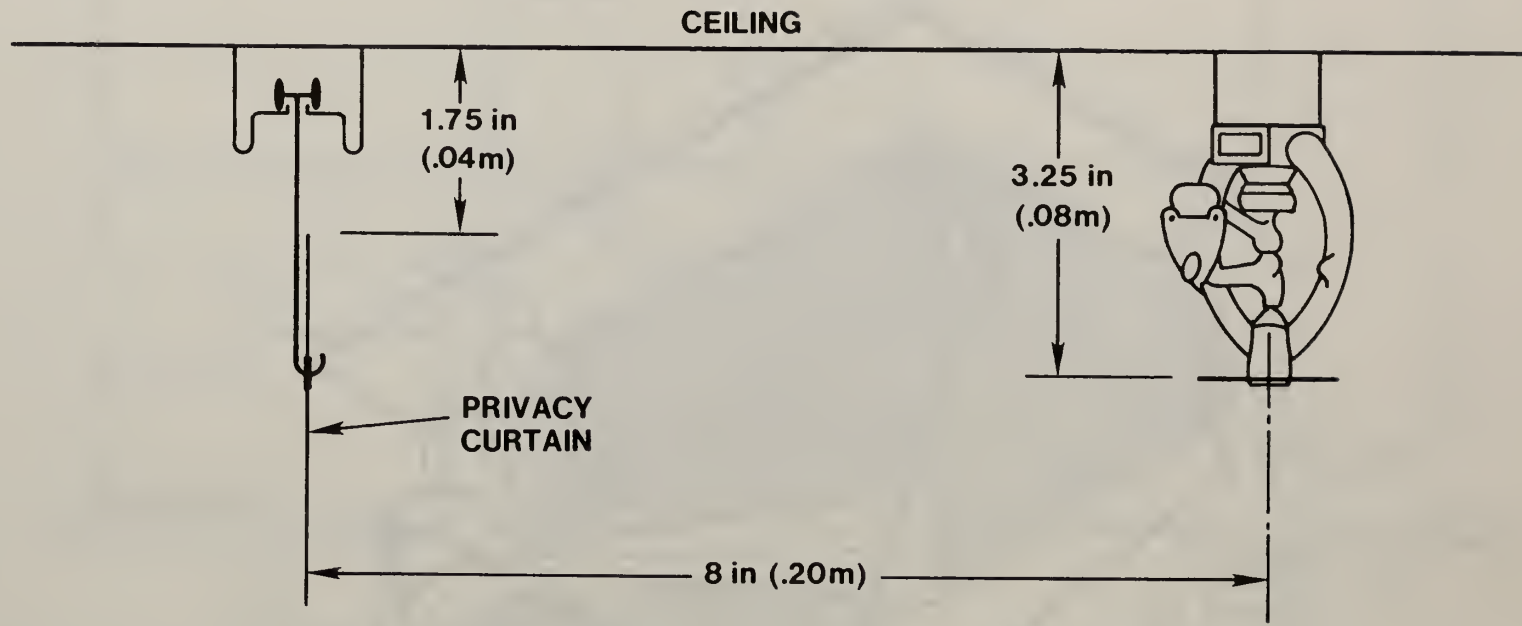



Figure 9. Privacy curtain details

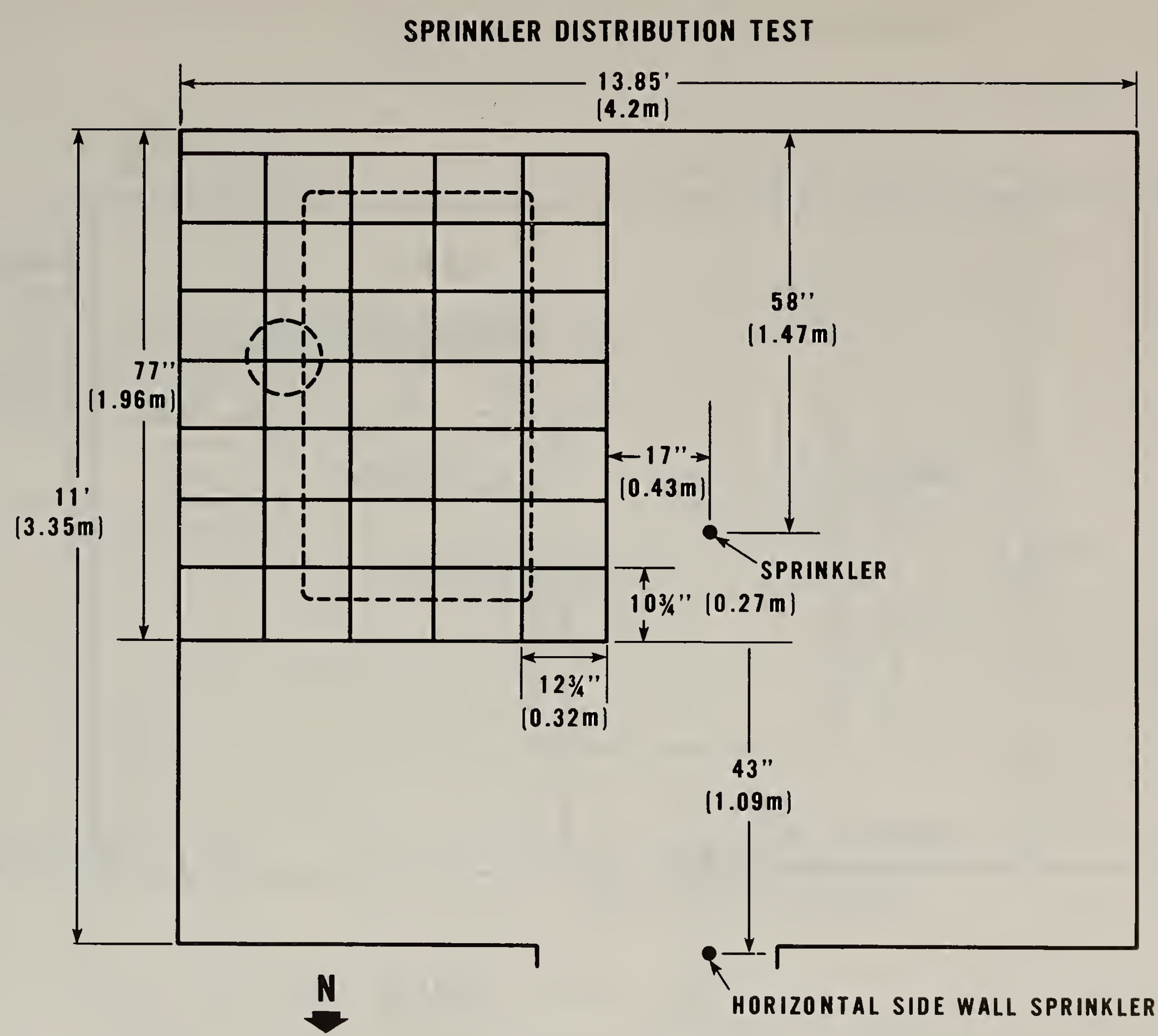



Figure 10. Burn room plan view

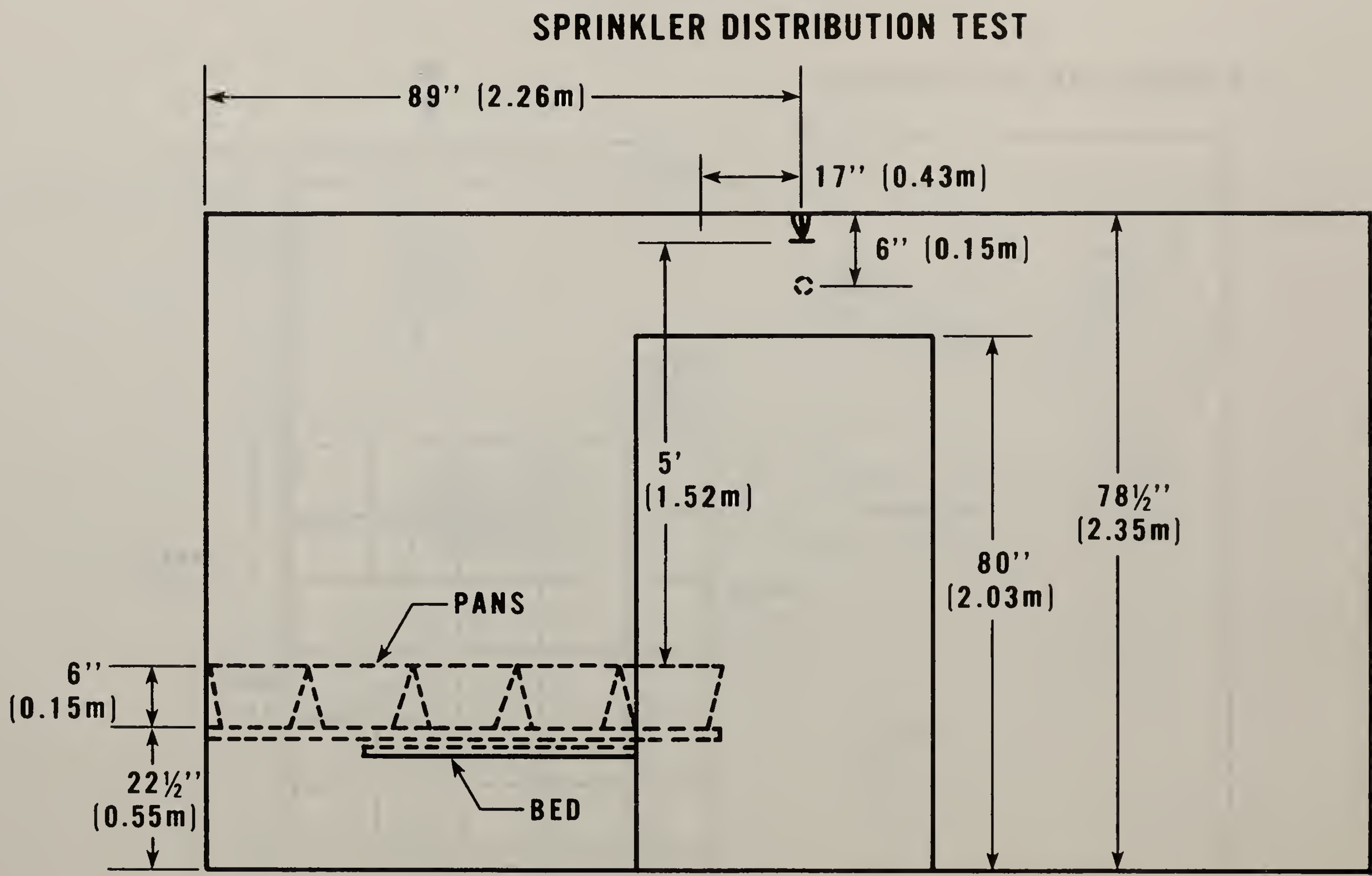
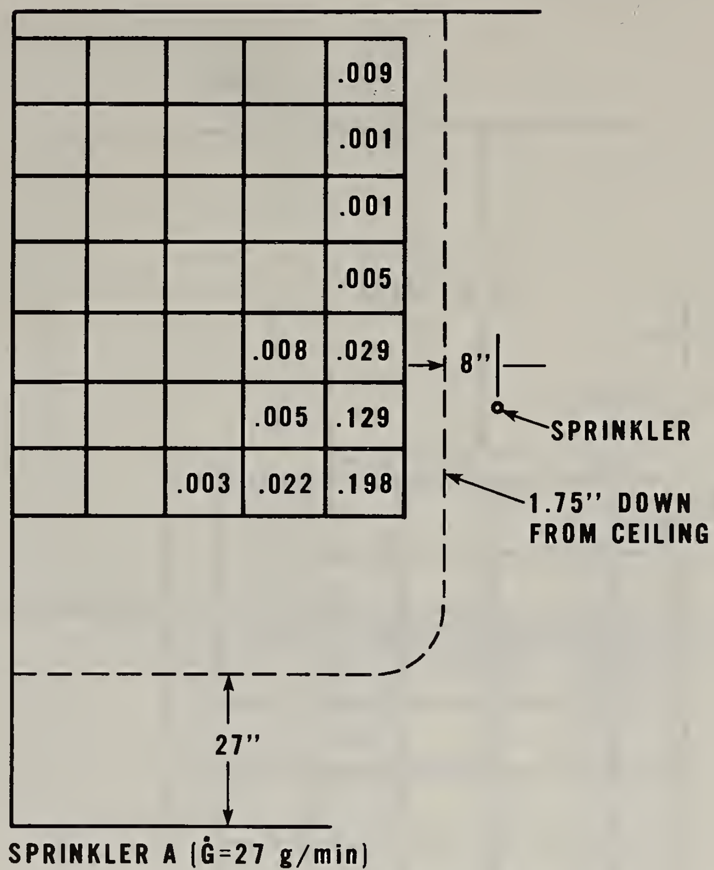
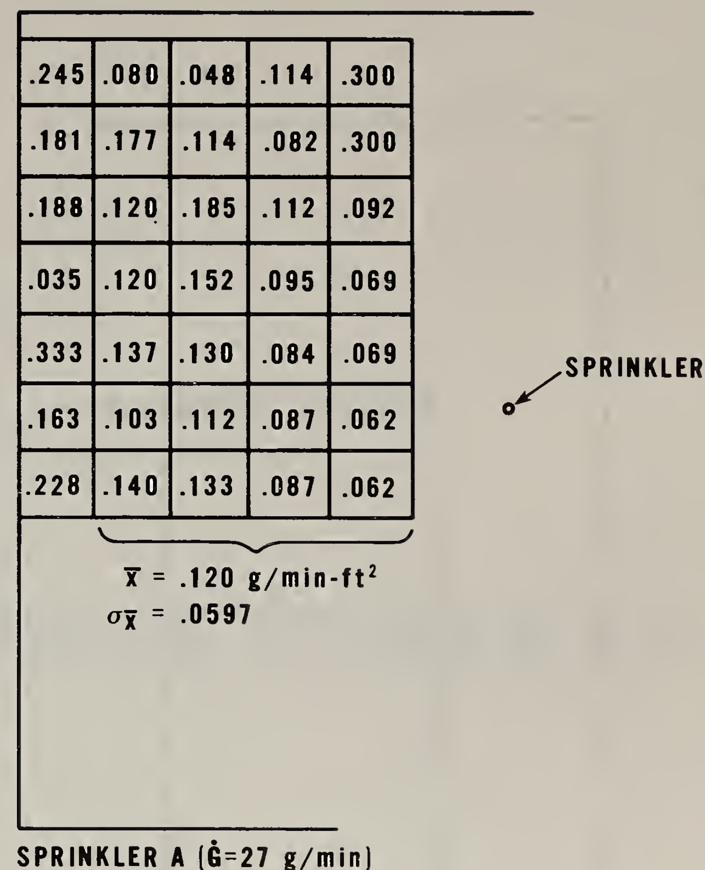



Figure 11.  Burn room doorway elevation




| | | | | |
|---|---|---|---|---|
| | | | | .009 |
| | | | | .001 |
| | | | | .001 |
| | | | | .005 |
| | | | .008 | .029 |
| | | | .005 | .129 |
| | | .003 | .022 | .198 |

Figure 12. Sprinkler distribution--privacy curtain in place




| | | | | |
|---|---|---|---|---|
| .245 | .080 | .048 | .114 | .300 |
| .181 | .177 | .114 | .082 | .300 |
| .188 | .120 | .185 | .112 | .092 |
| .035 | .120 | .152 | .095 | .069 |
| .333 | .137 | .130 | .084 | .069 |
| .163 | .103 | .112 | .087 | .062 |
| .228 | .140 | .133 | .087 | .062 |

$\overline{X} = .120$ g/min-ft$^2$
$\sigma_{\overline{X}} = .0597$

Figure 13. Sprinkler distribution--no privacy curtain

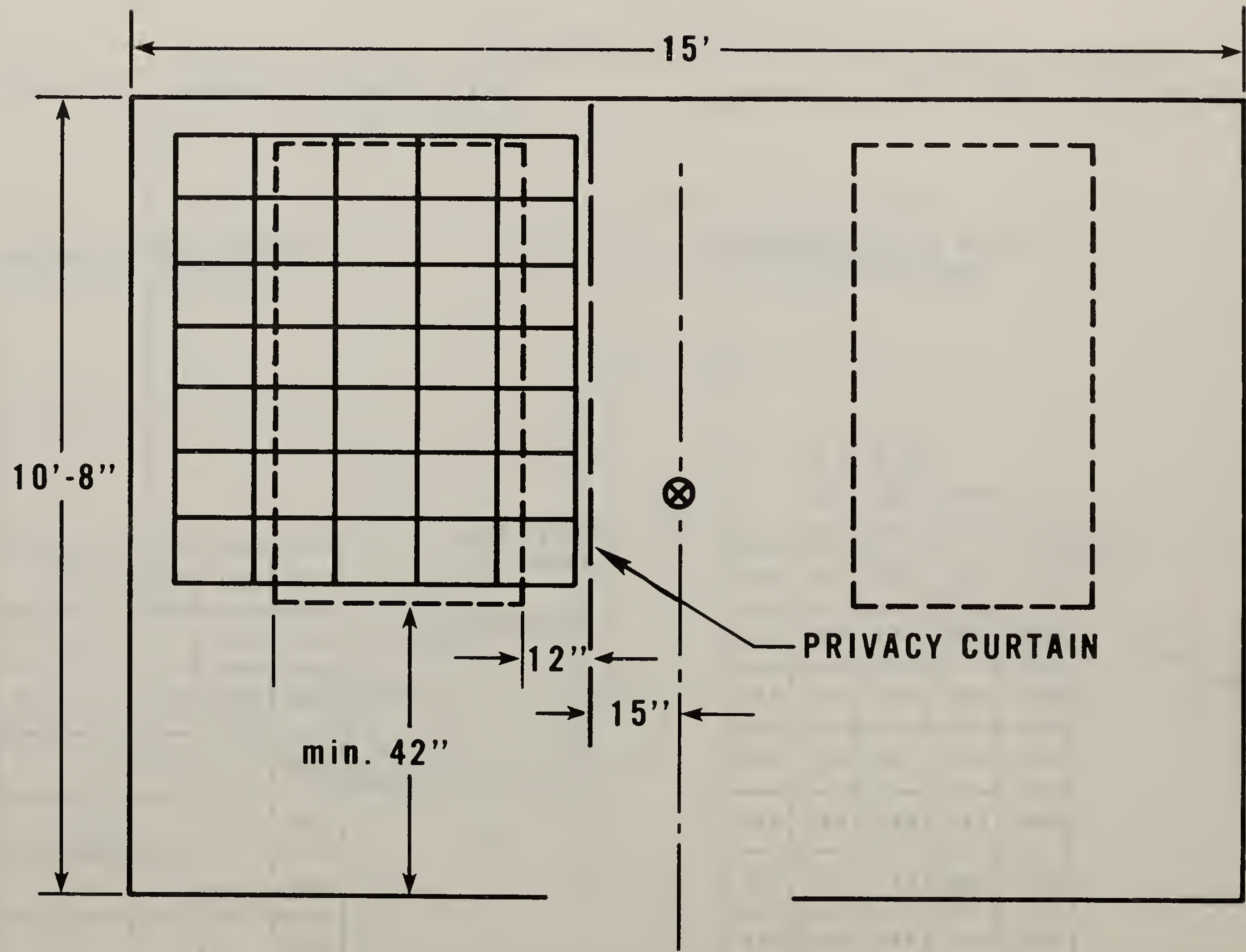



Figure 14. Model two patient room

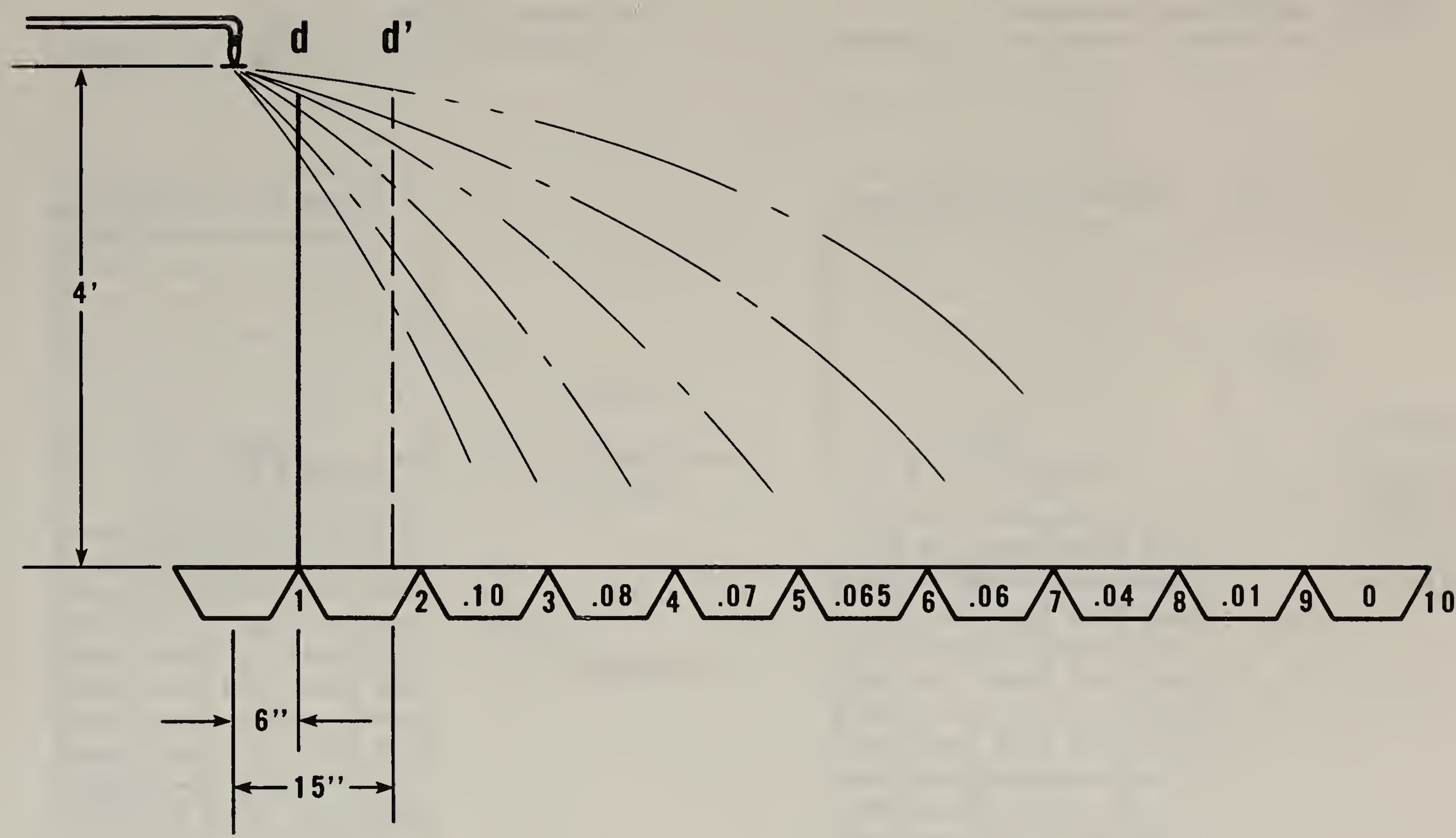
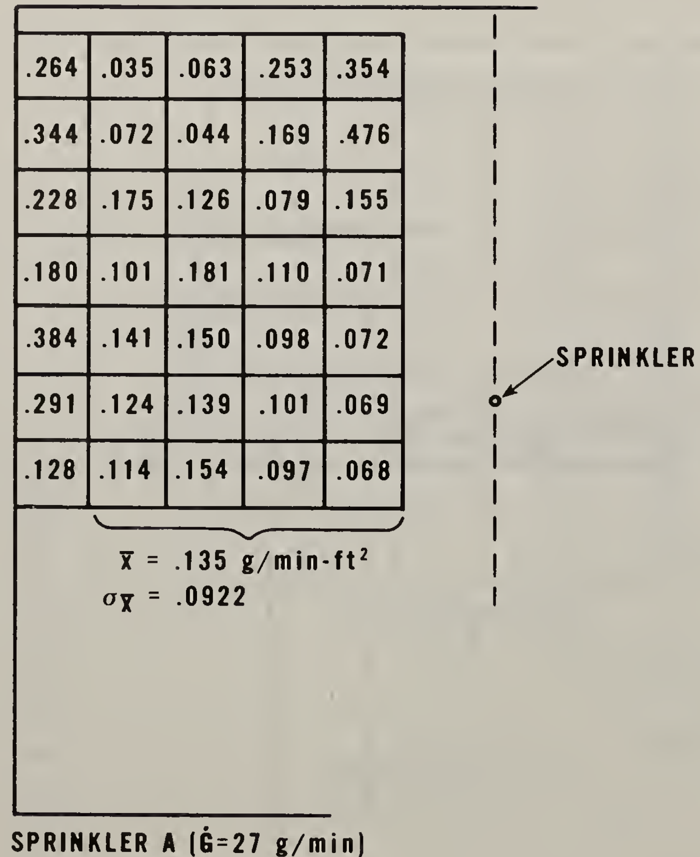


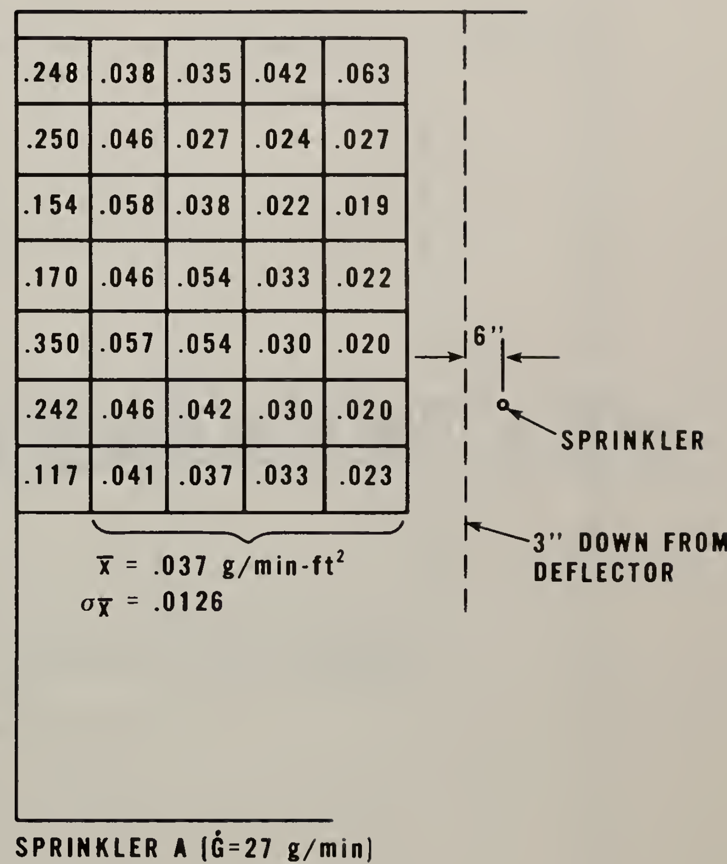

Figure 15. Typical distribution for standard sprinkler



| | | | | |
|---|---|---|---|---|
| .264 | .035 | .063 | .253 | .354 |
| .344 | .072 | .044 | .169 | .476 |
| .228 | .175 | .126 | .079 | .155 |
| .180 | .101 | .181 | .110 | .071 |
| .384 | .141 | .150 | .098 | .072 |
| .291 | .124 | .139 | .101 | .069 |
| .128 | .114 | .154 | .097 | .068 |



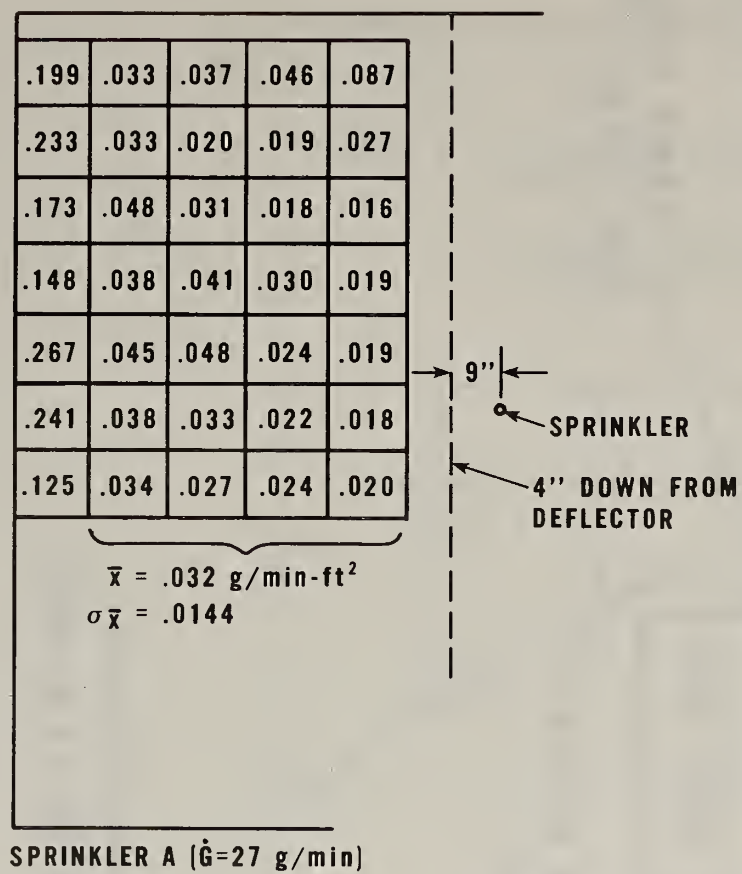
Figure 16. Sprinkler distribution--privacy curtain directly under sprinkler



| | | | | |
|---|---|---|---|---|
| .248 | .038 | .035 | .042 | .063 |
| .250 | .046 | .027 | .024 | .027 |
| .154 | .058 | .038 | .022 | .019 |
| .170 | .046 | .054 | .033 | .022 |
| .350 | .057 | .054 | .030 | .020 |
| .242 | .046 | .042 | .030 | .020 |
| .117 | .041 | .037 | .033 | .023 |

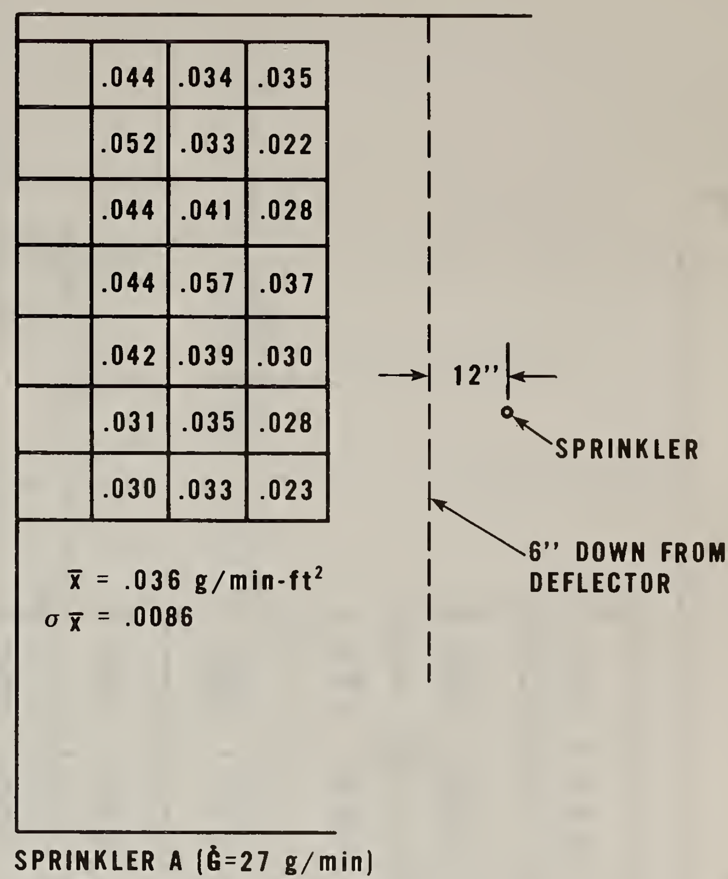


Figure 17. Sprinkler distribution--privacy curtain, 3 in down and 6 in away from sprinkler



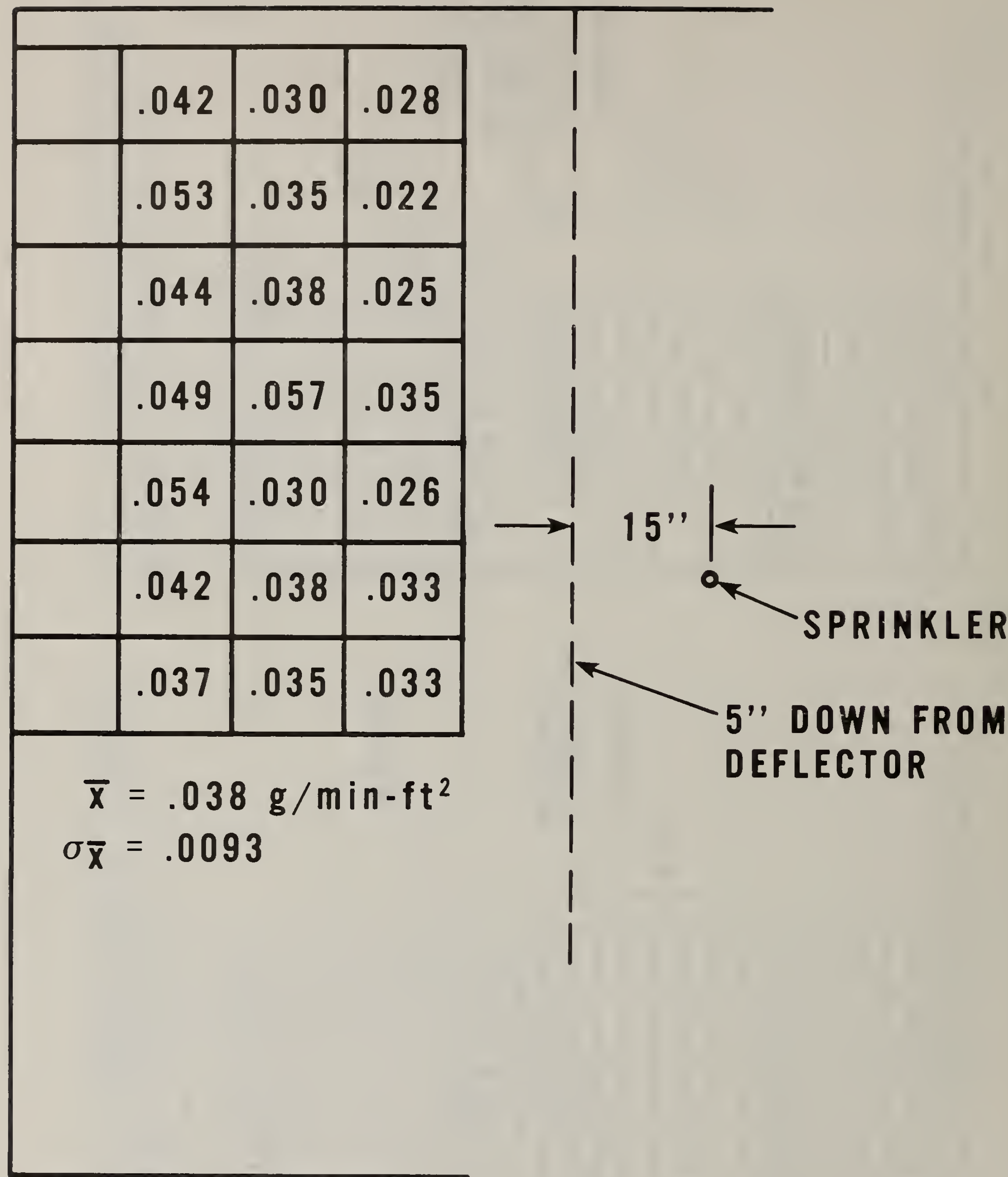

| | | | | |
|---|---|---|---|---|
| .199 | .033 | .037 | .046 | .087 |
| .233 | .033 | .020 | .019 | .027 |
| .173 | .048 | .031 | .018 | .016 |
| .148 | .038 | .041 | .030 | .019 |
| .267 | .045 | .048 | .024 | .019 |
| .241 | .038 | .033 | .022 | .018 |
| .125 | .034 | .027 | .024 | .020 |

Figure 18. Sprinkler distribution--privacy curtain, 4 in down and 9 in away from sprinkler




| | | | |
|---|---|---|---|
| | .044 | .034 | .035 |
| | .052 | .033 | .022 |
| | .044 | .041 | .028 |
| | .044 | .057 | .037 |
| | .042 | .039 | .030 |
| | .031 | .035 | .028 |
| | .030 | .033 | .023 |

Figure 19. Sprinkler distribution--privacy curtain, 6 in down and 12 in away from sprinkler




SPRINKLER A ($\dot{G}$=27 g/min)

Figure 20. Sprinkler distribution--privacy curtain, 8 in down and 15 in away from sprinkler

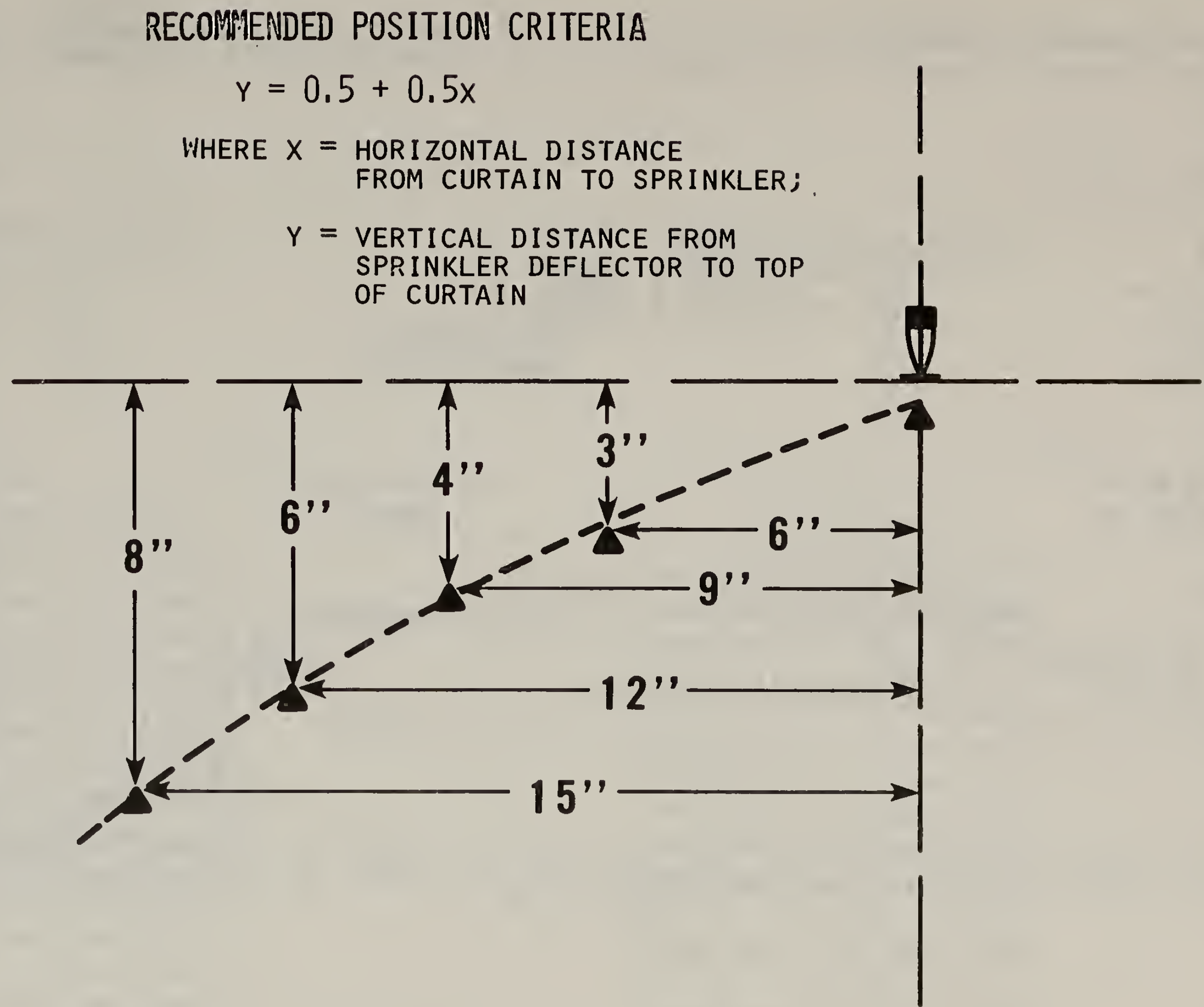



Figure 21. Minimum vertical clearances, sprinkler deflector to top of privacy curtain

| | | | | |
|---|---|---|---|---|
| .105 | .063 | .079 | .109 | .160 |
| .057 | .046 | .041 | .035 | .039 |
| .044 | .035 | .050 | .039 | .029 |
| .033 | .027 | .082 | .048 | .031 |
| .022 | .020 | .065 | .084 | .054 |
| .014 | .014 | .024 | .050 | .068 |
| .008 | .011 | .022 | .038 | .052 |

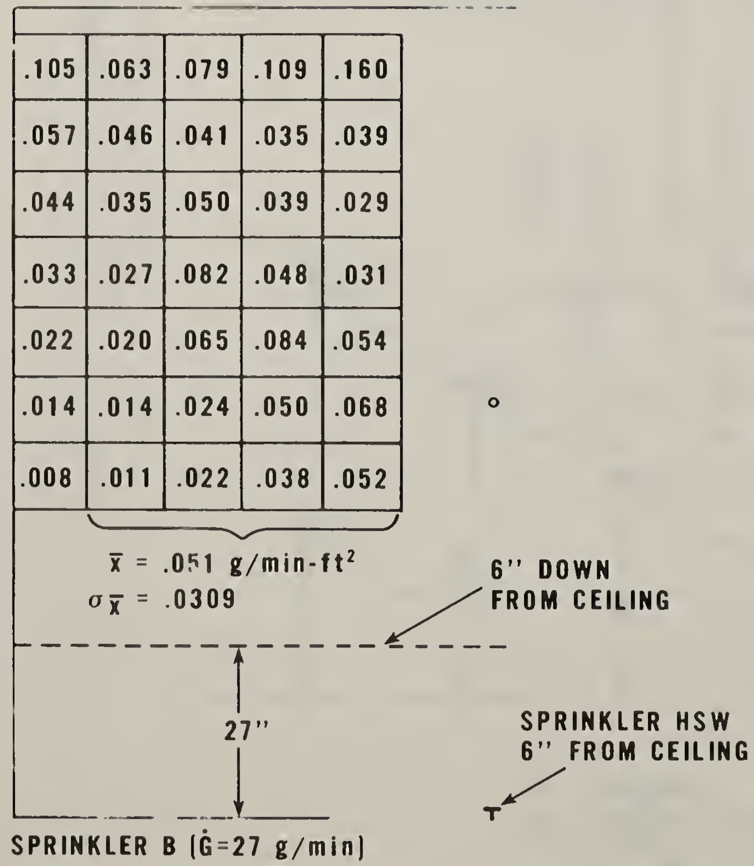



Figure 22. Sprinkler distribution--privacy curtain 6 in from ceiling

| | | | | |
|---|---|---|---|---|
| .144 | .074 | .114 | .164 | .212 |
| .065 | .054 | .048 | .046 | .054 |
| .050 | .046 | .044 | .042 | .038 |
| .041 | .035 | .054 | .046 | .035 |
| .030 | .024 | .071 | .084 | .057 |
| .023 | .016 | .027 | .046 | .063 |
| .014 | .014 | .022 | .034 | .046 |

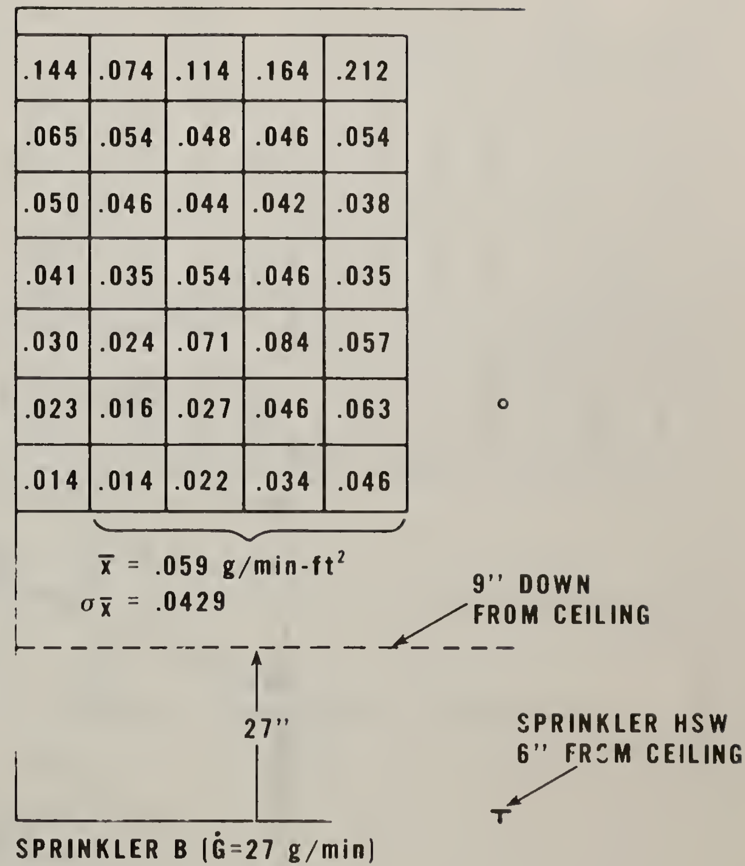



Figure 23. Sprinkler distribution--privacy curtain 9 in from ceiling

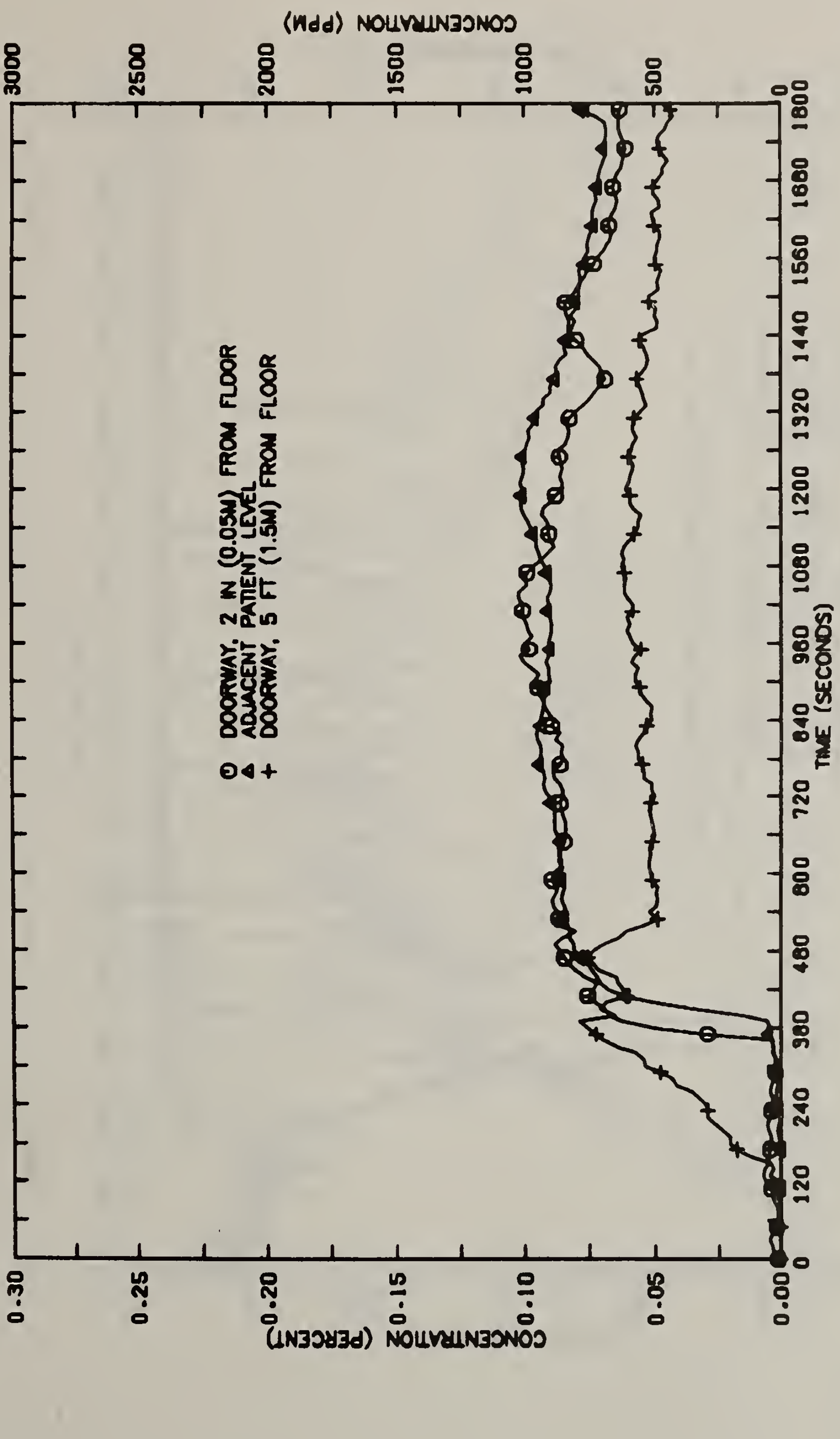



Figure 24. Carbon monoxide concentrations (test N-37)

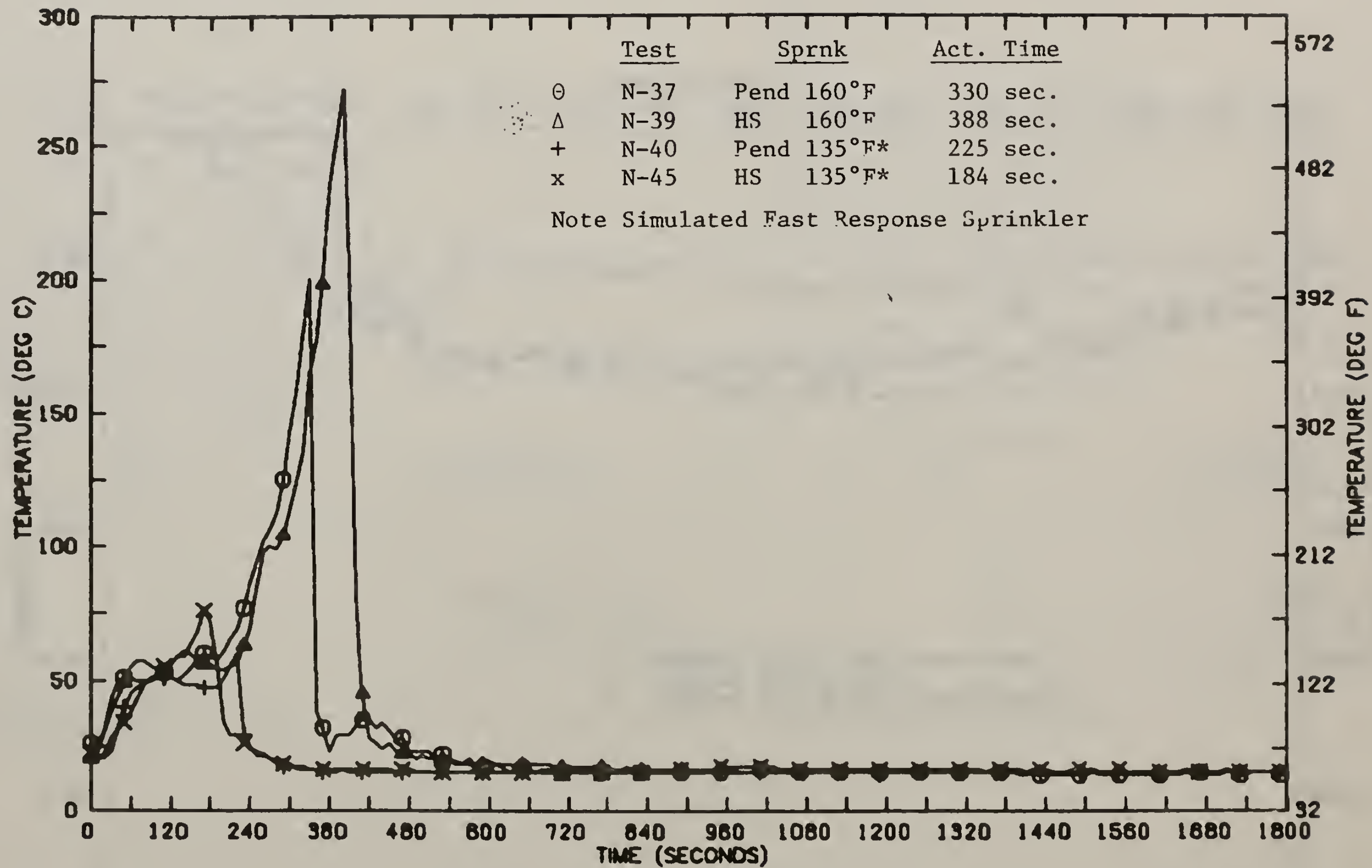



Figure 25. Center of ceiling air temperature

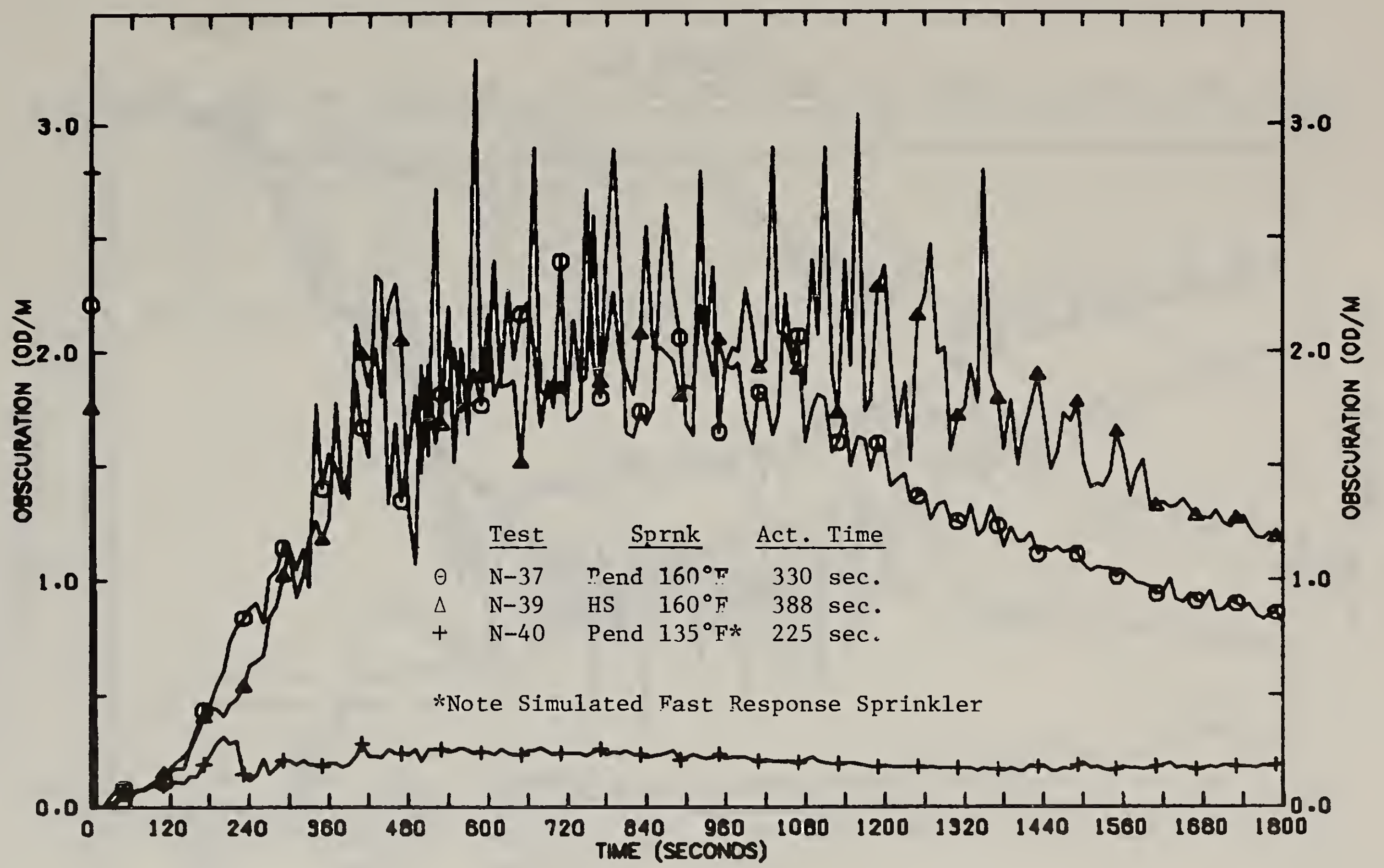



Figure 26. Smoke obscuration at 1.7 m (5 ft 8 in) level in doorway

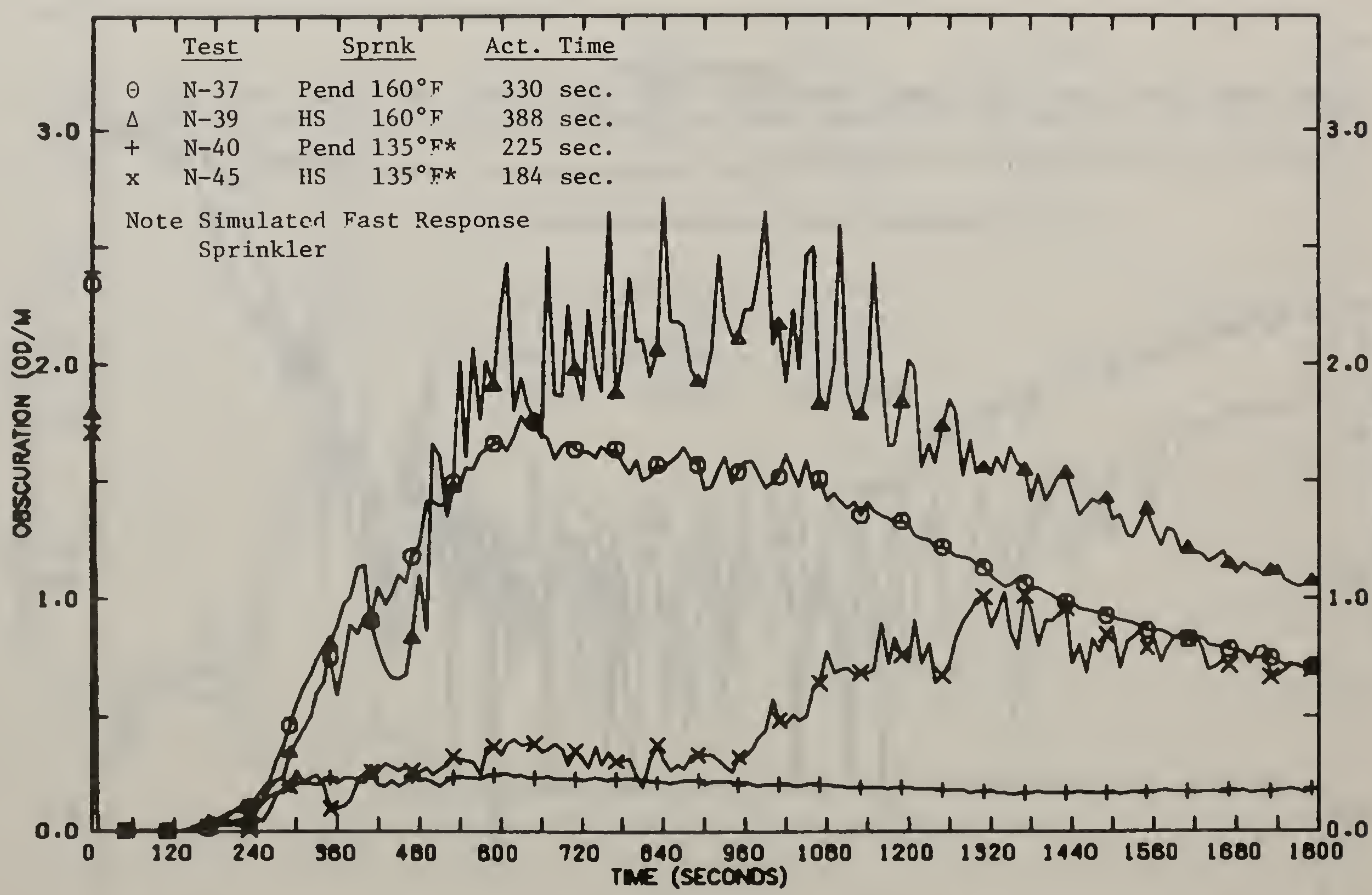



Figure 27. Smoke obscuration at 1.5 m (5 ft) level in corridor

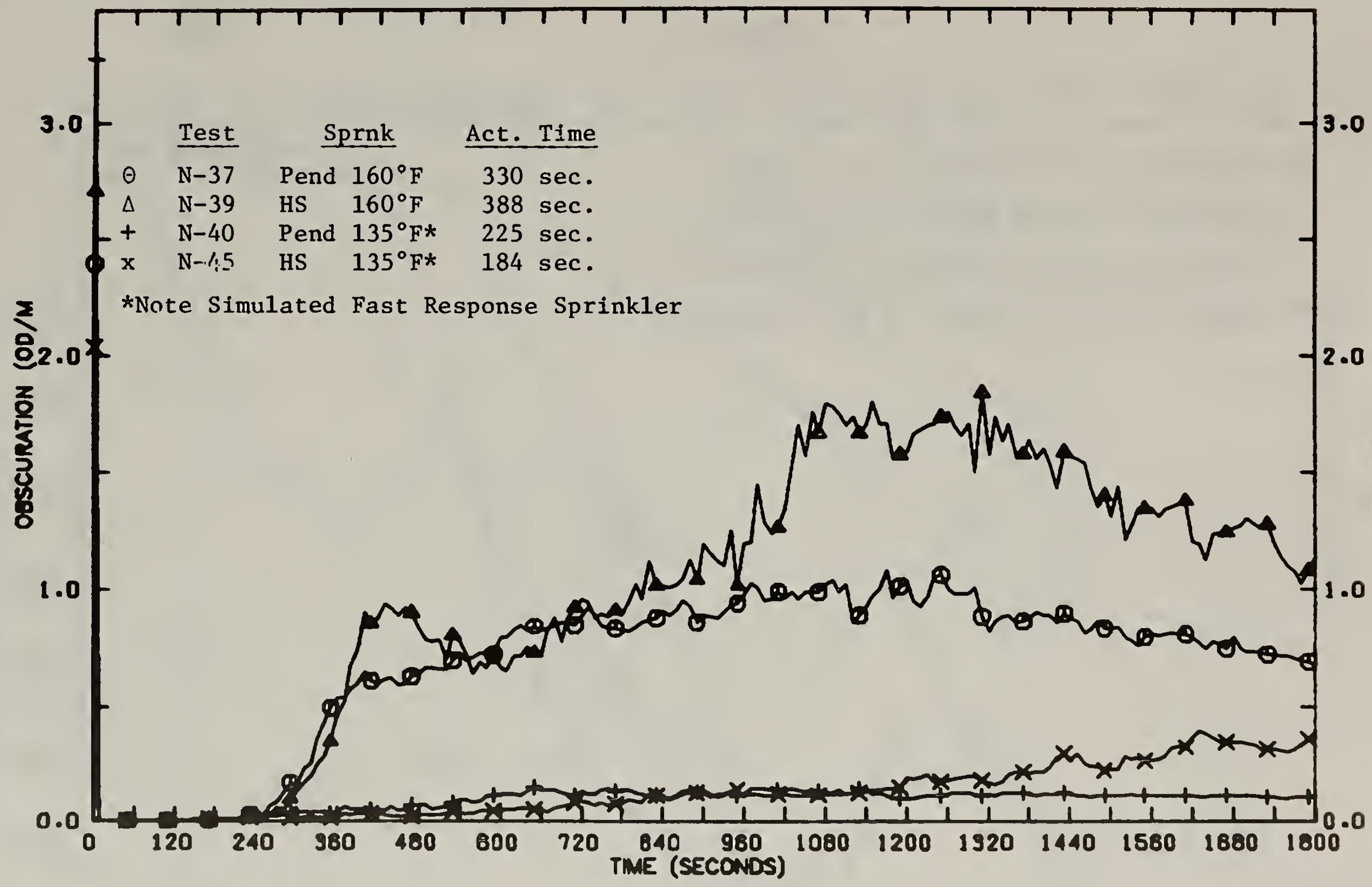



Figure 28. Smoke obscuration at 1.5 m (5 ft) level in lobby

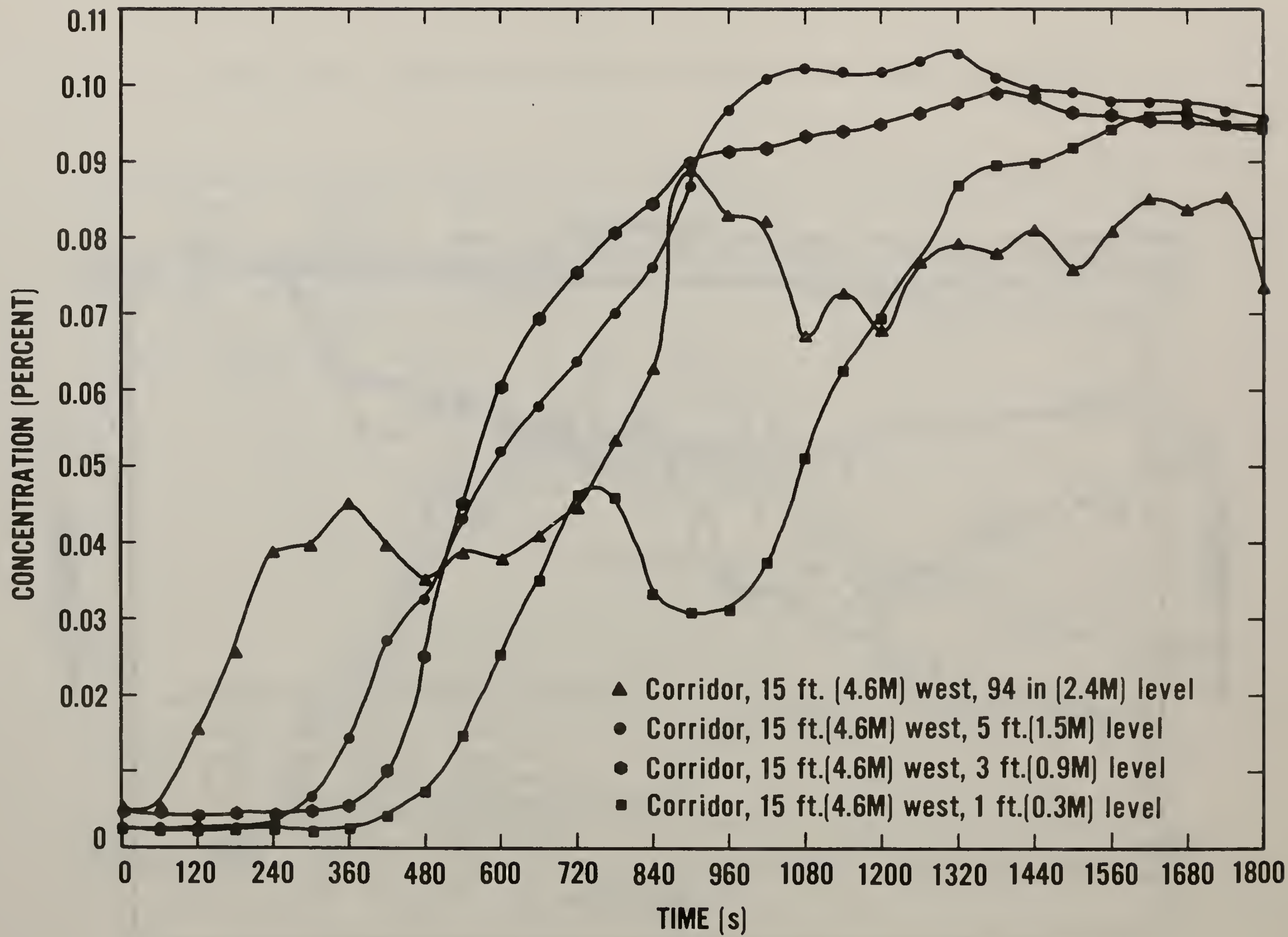



Figure 29. Carbon monoxide concentration--corridor

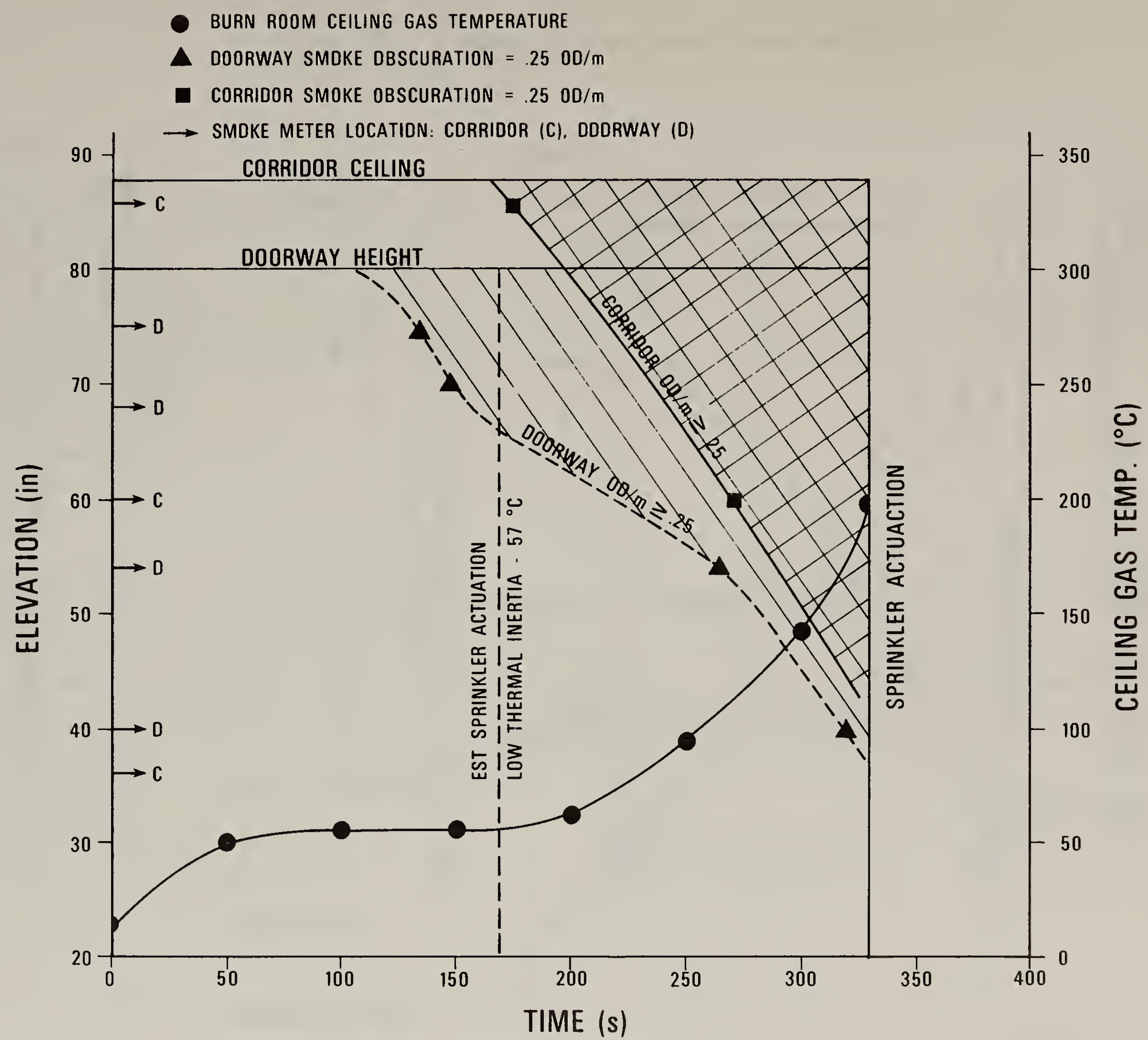



Figure 30. Smoke filling rate (test N-37)

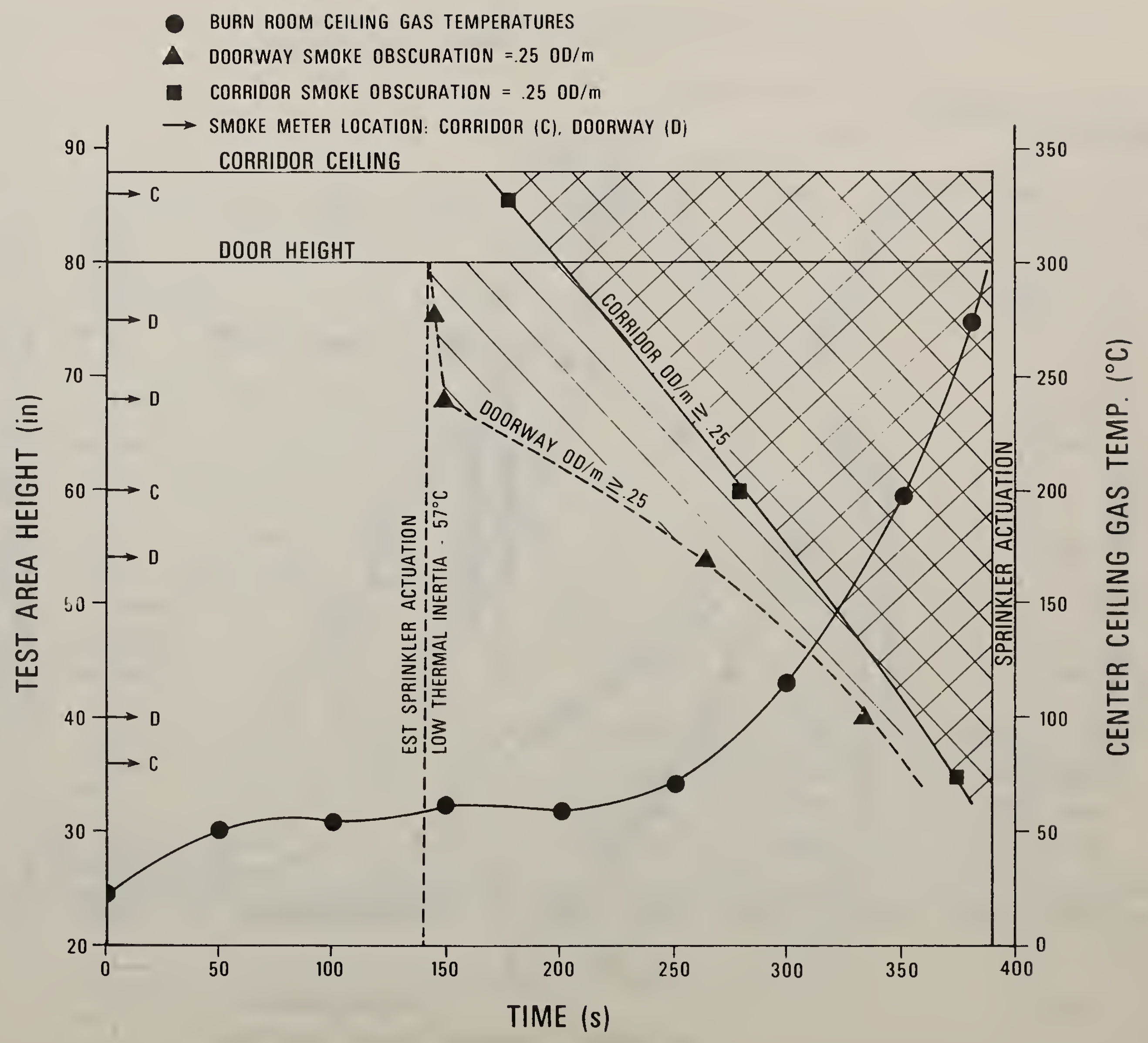



Figure 31. Smoke filling rate (test N-39)

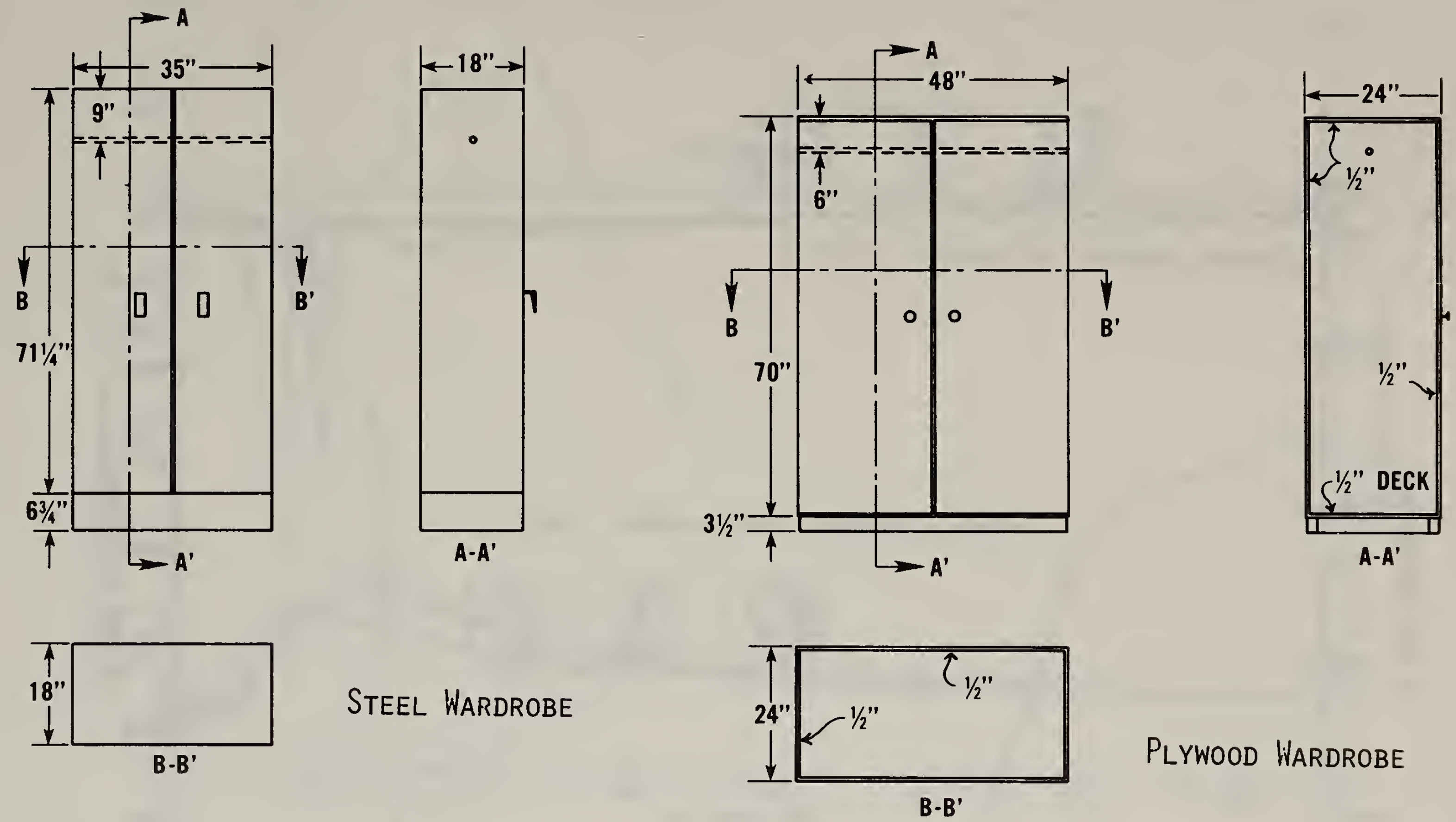



Figure 32. Wardrobe construction details

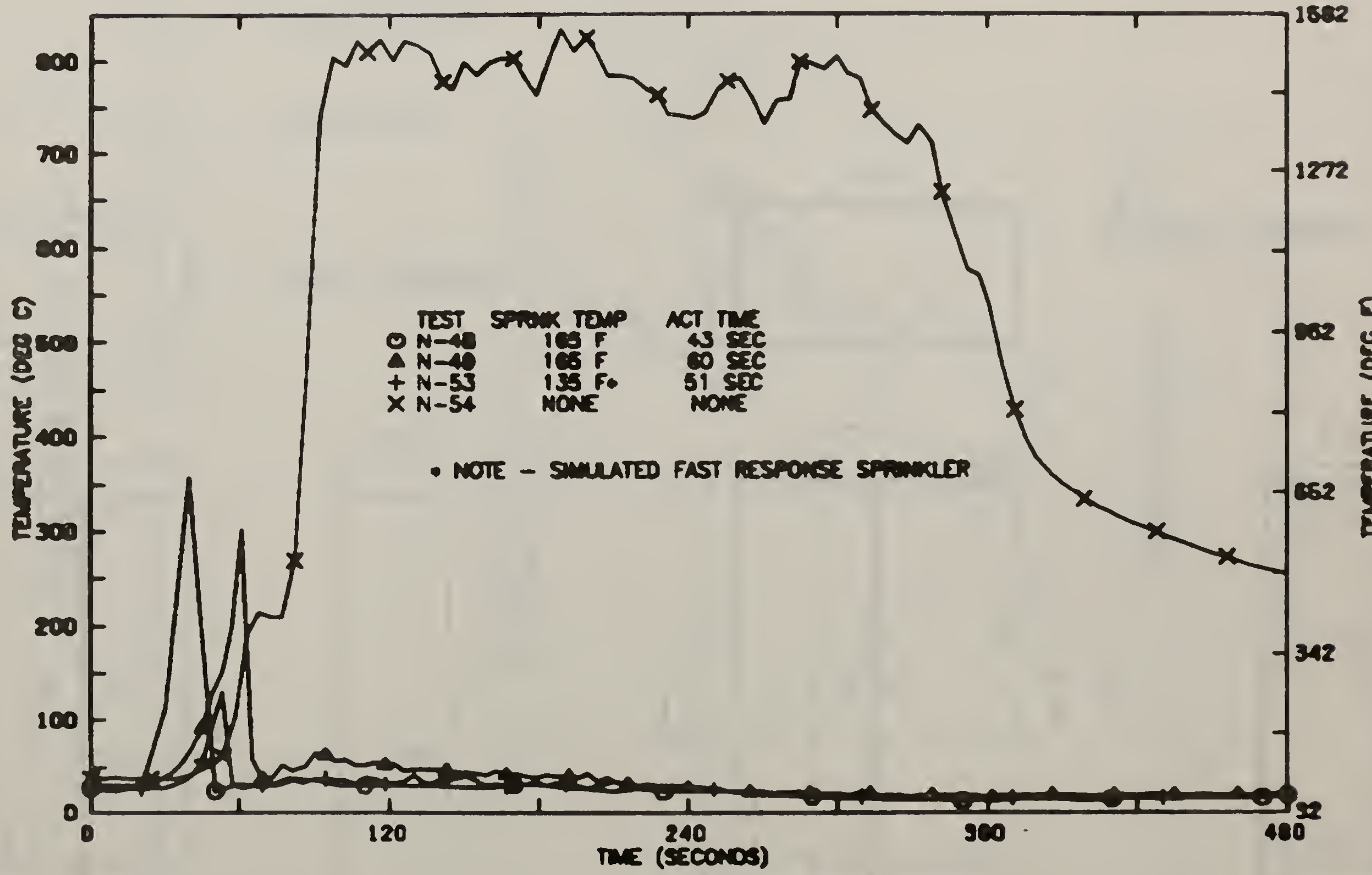



Figure 33. Center of ceiling air temperature, wardrobe fire tests--center ceiling pendent

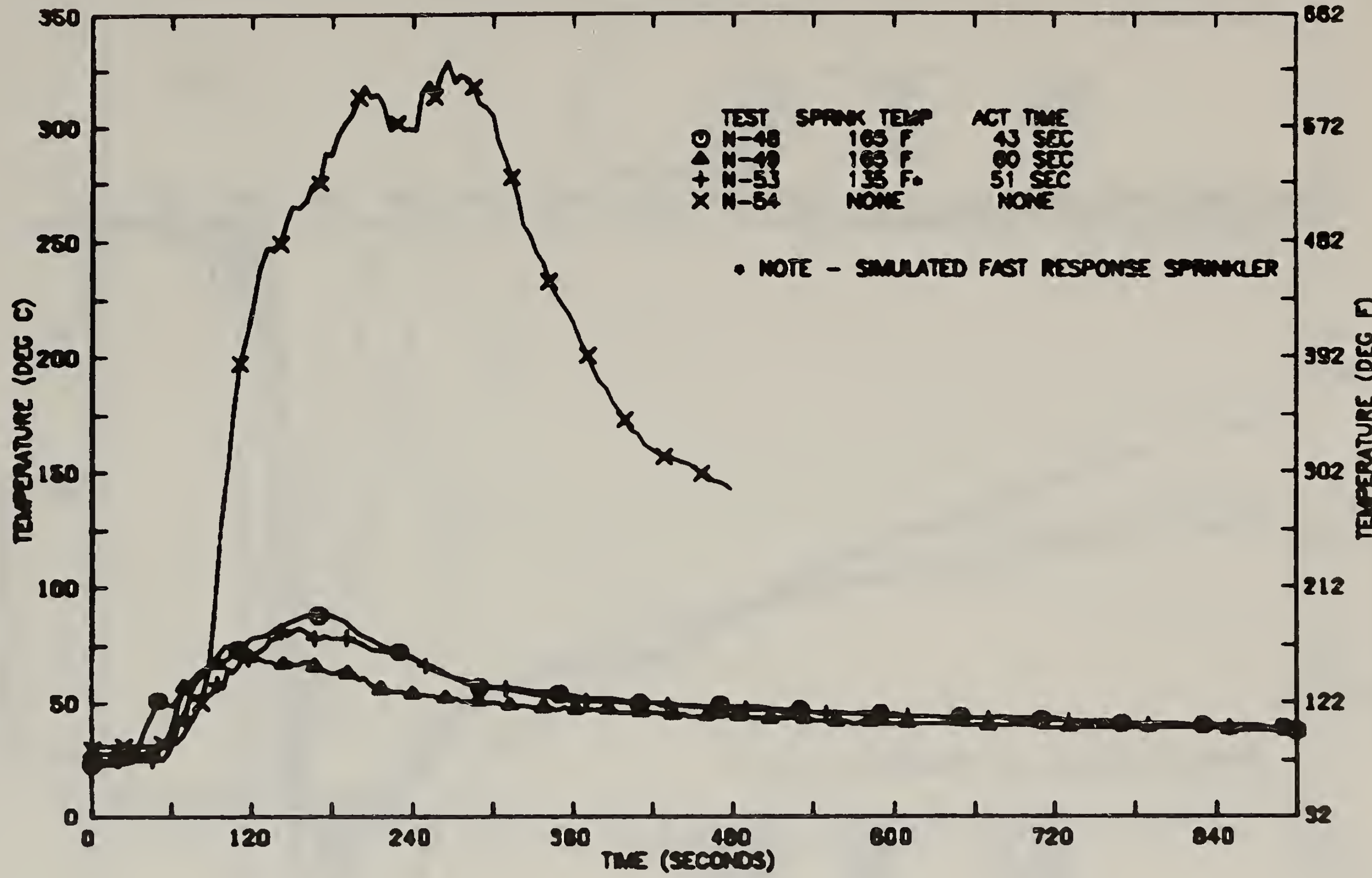



Figure 34. Corridor ceiling temperature 1.5 m (5 ft) west, wardrobe fire tests--center ceiling pendent

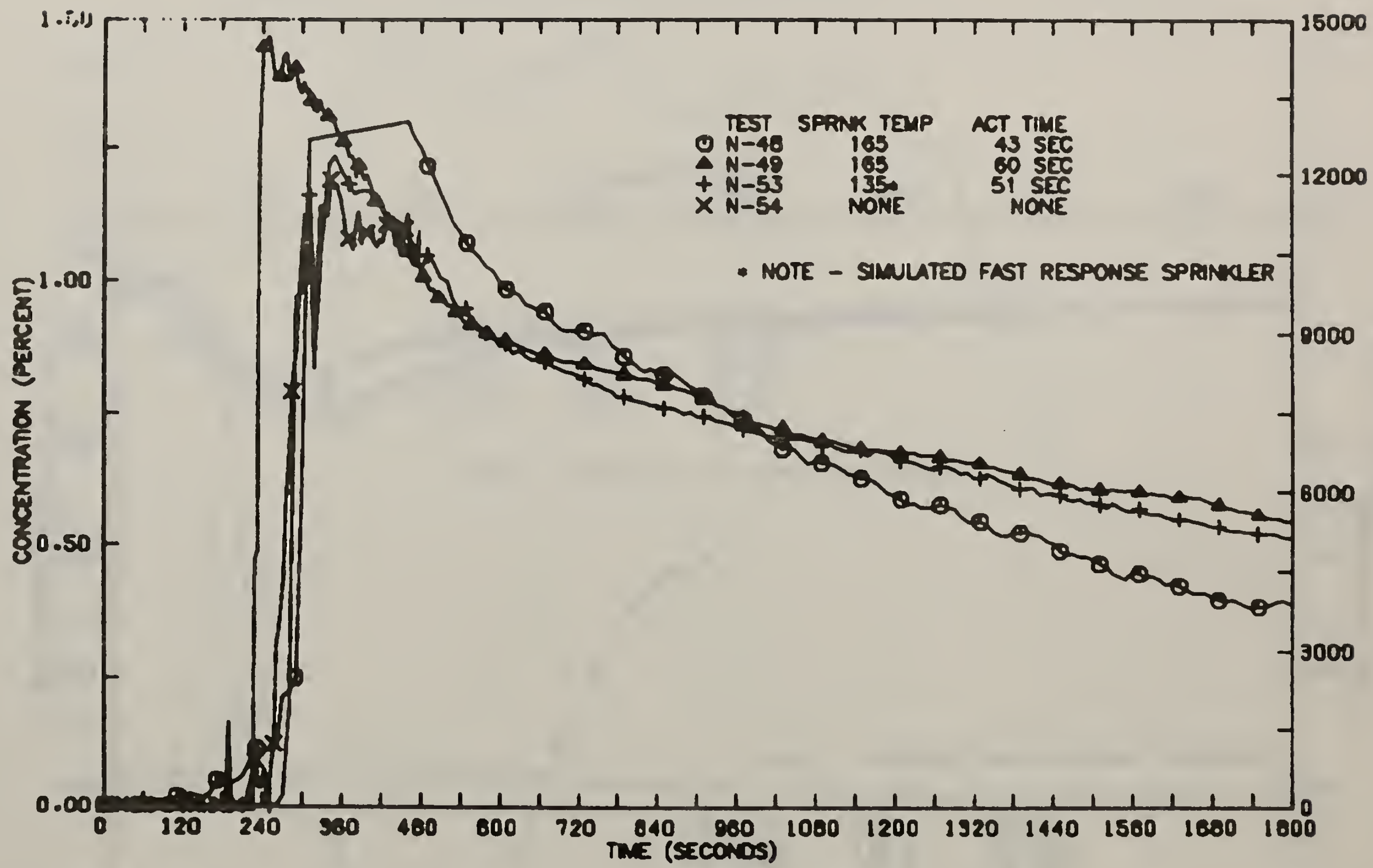



Figure 35. Carbon monoxide concentrations--adjacent patient level, wardrobe fire tests--center ceiling pendent

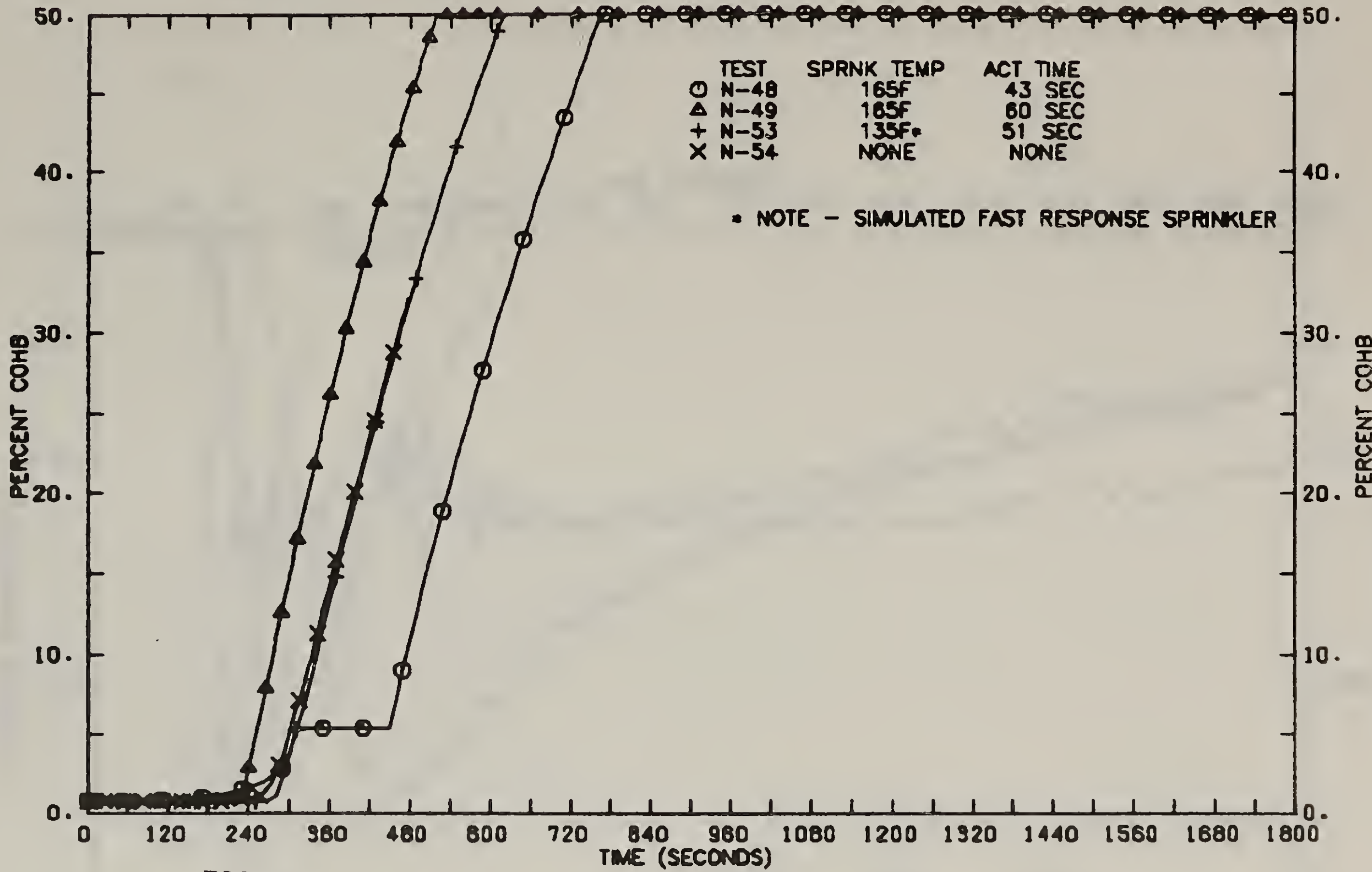



Figure 36. COHB at adjacent patient level, wardrobe fire tests--center ceiling pendent

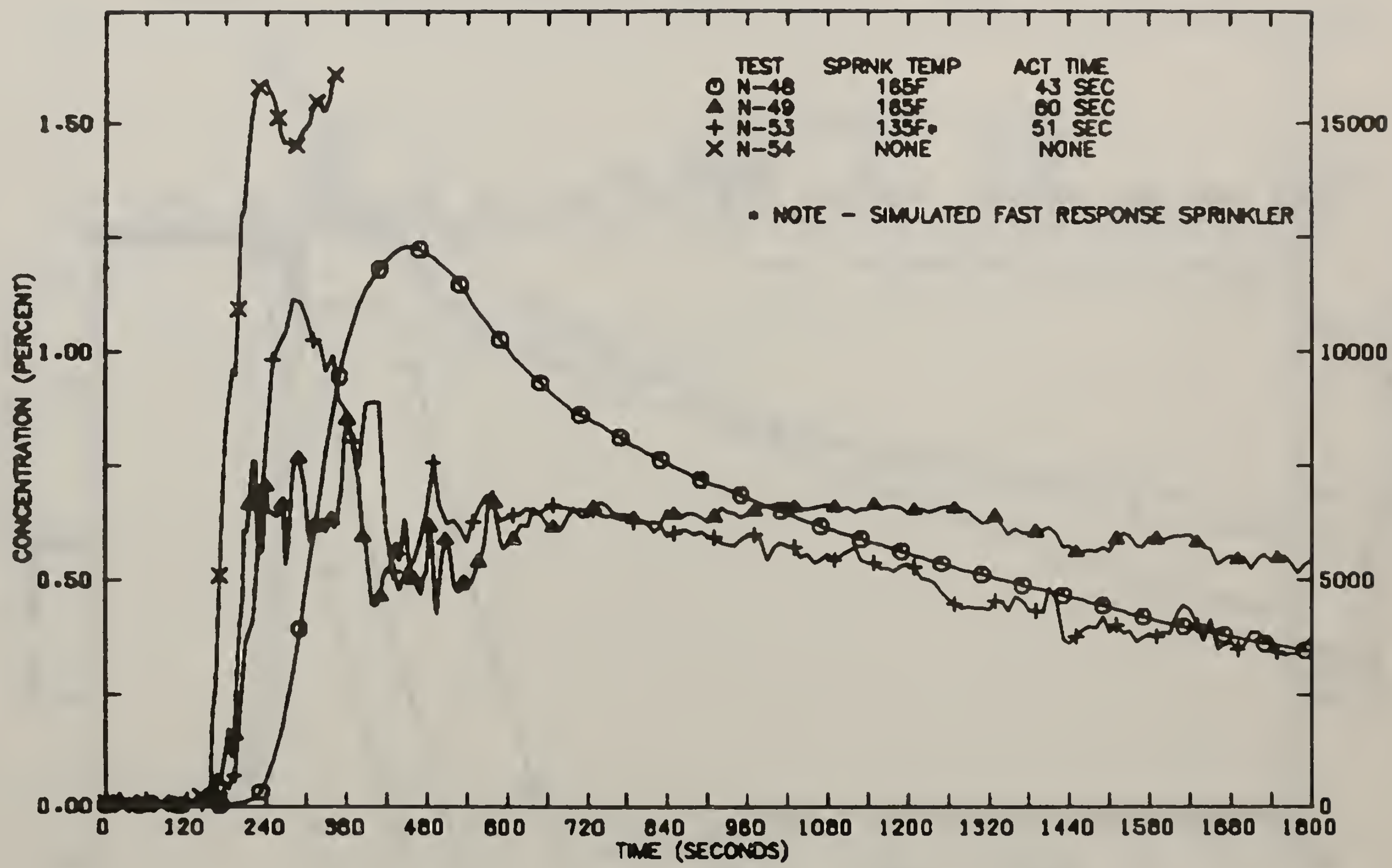



Figure 37. Carbon monoxide concentration in the lobby, wardrobe fire tests--center ceiling pendent

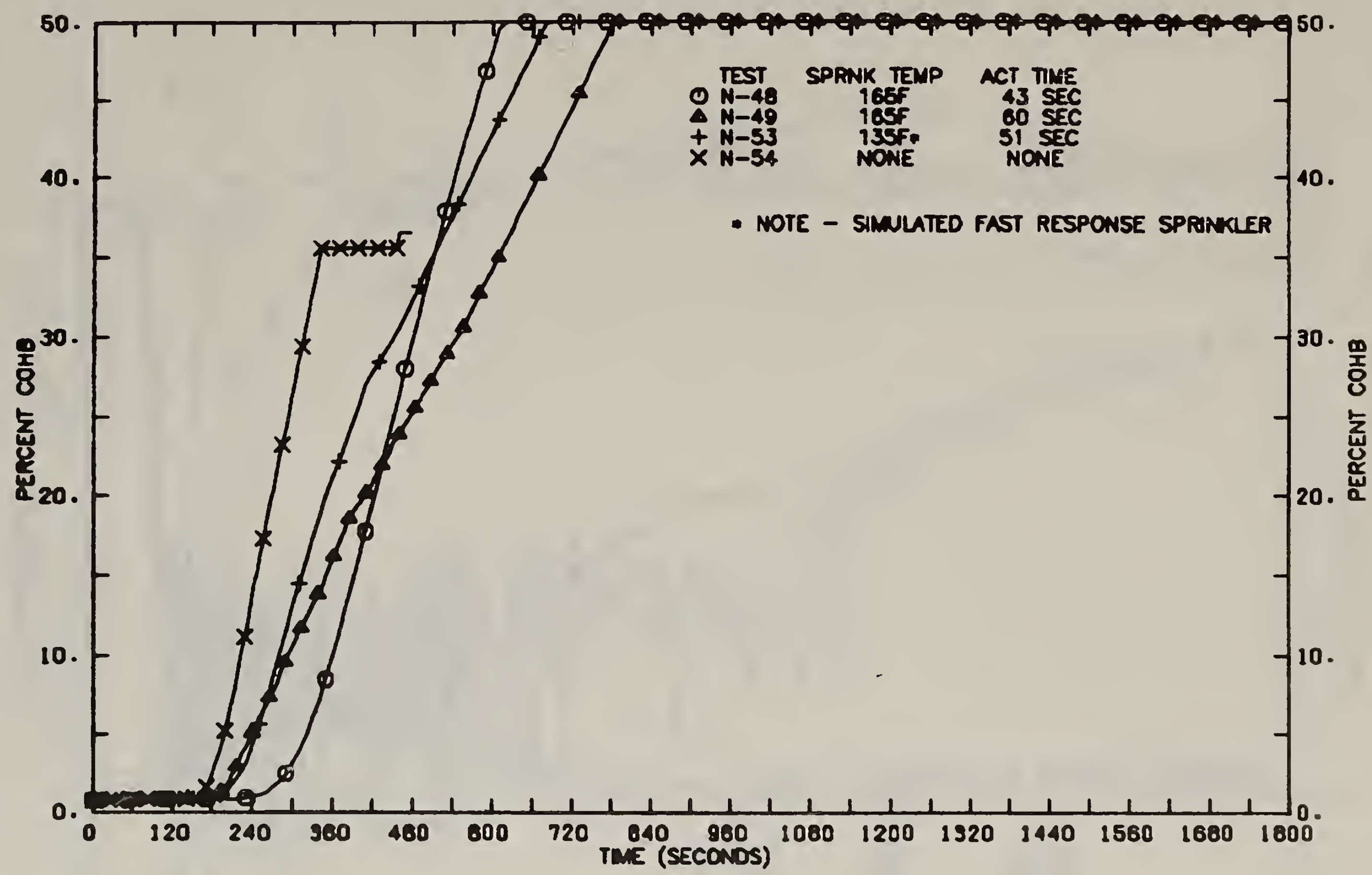



Figure 38. COHB at .92 m (3 ft) level in lobby, wardrobe fire tests--center ceiling pendent

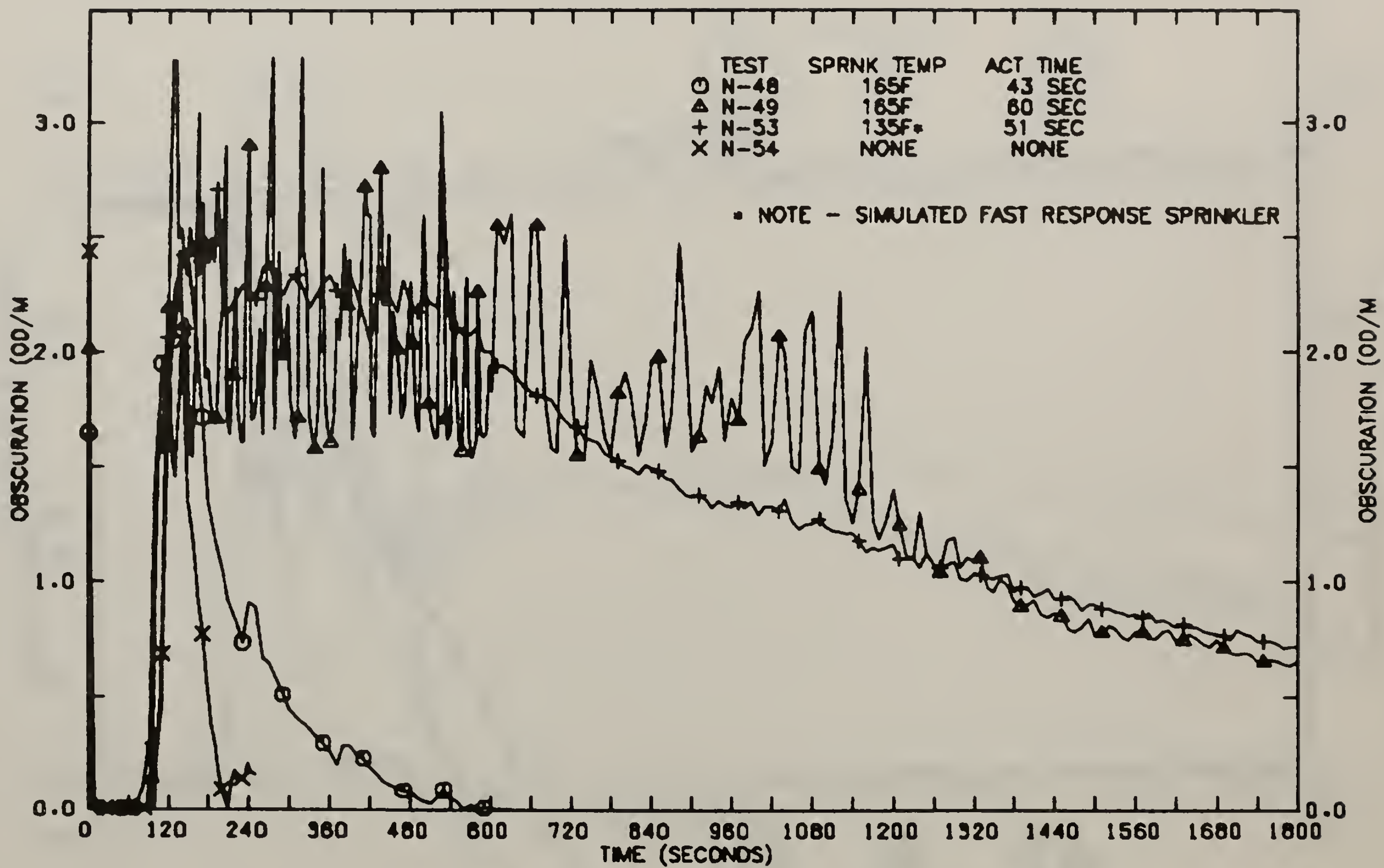



Figure 39. Corridor smoke obscuration 4.6 m (15 ft) west 1.5 m (5 ft) level, wardrobe fire tests--center ceiling pendent

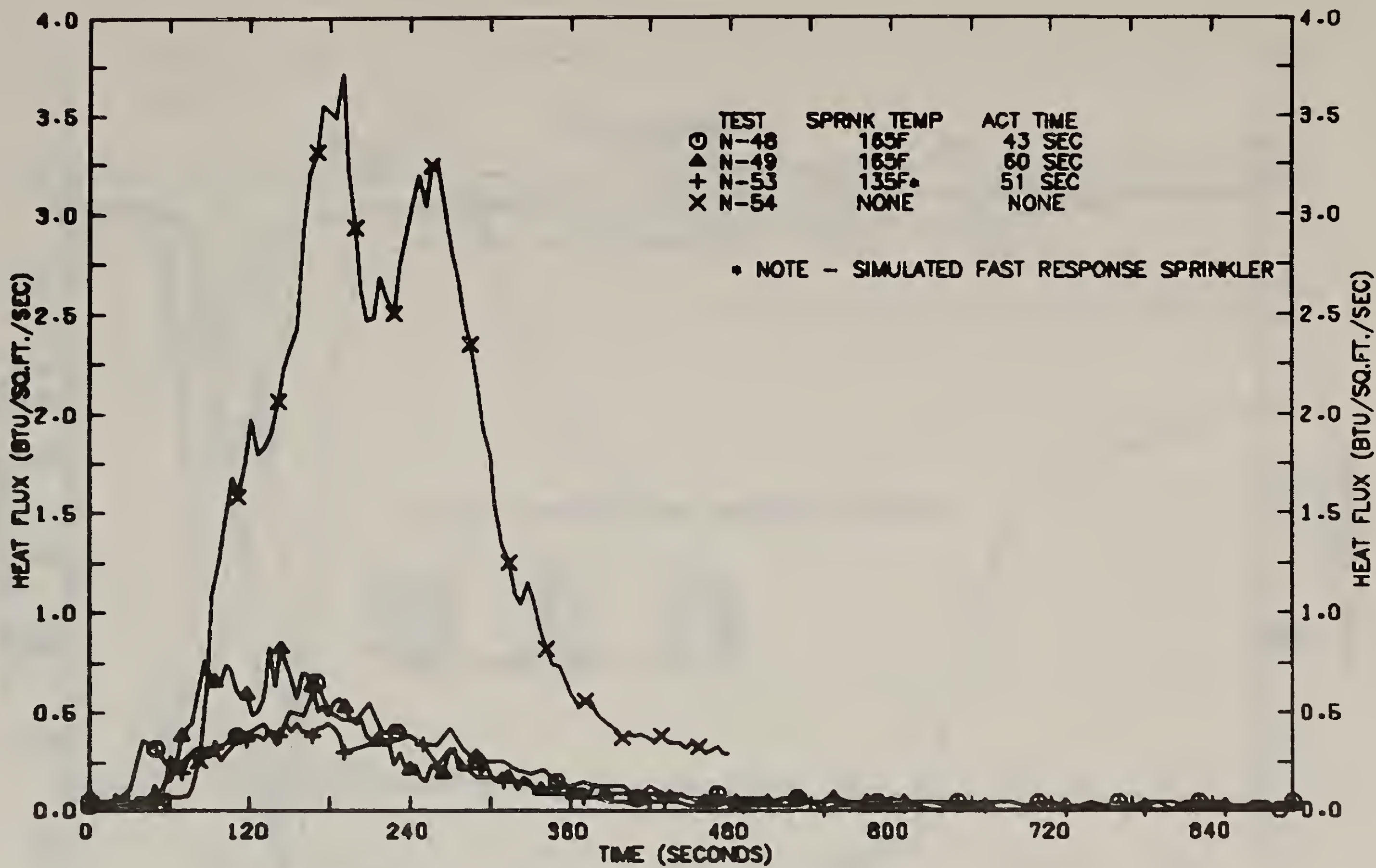



Figure 40. Heat flux--adjacent patient level, wardrobe fire tests--center ceiling pendent

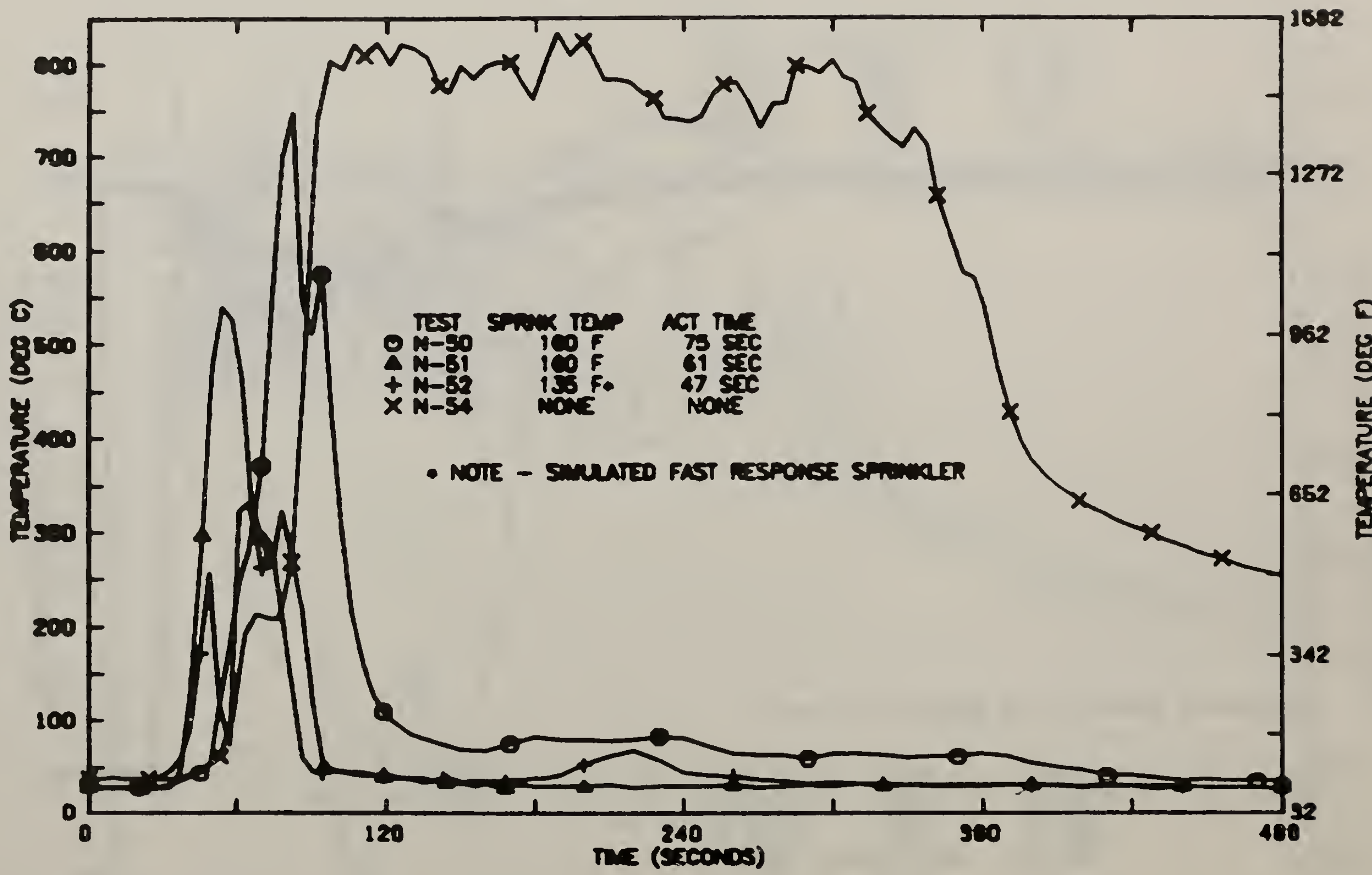



Figure 41. Center of ceiling air temperature, wardrobe fire tests--horizontal sidewall over door

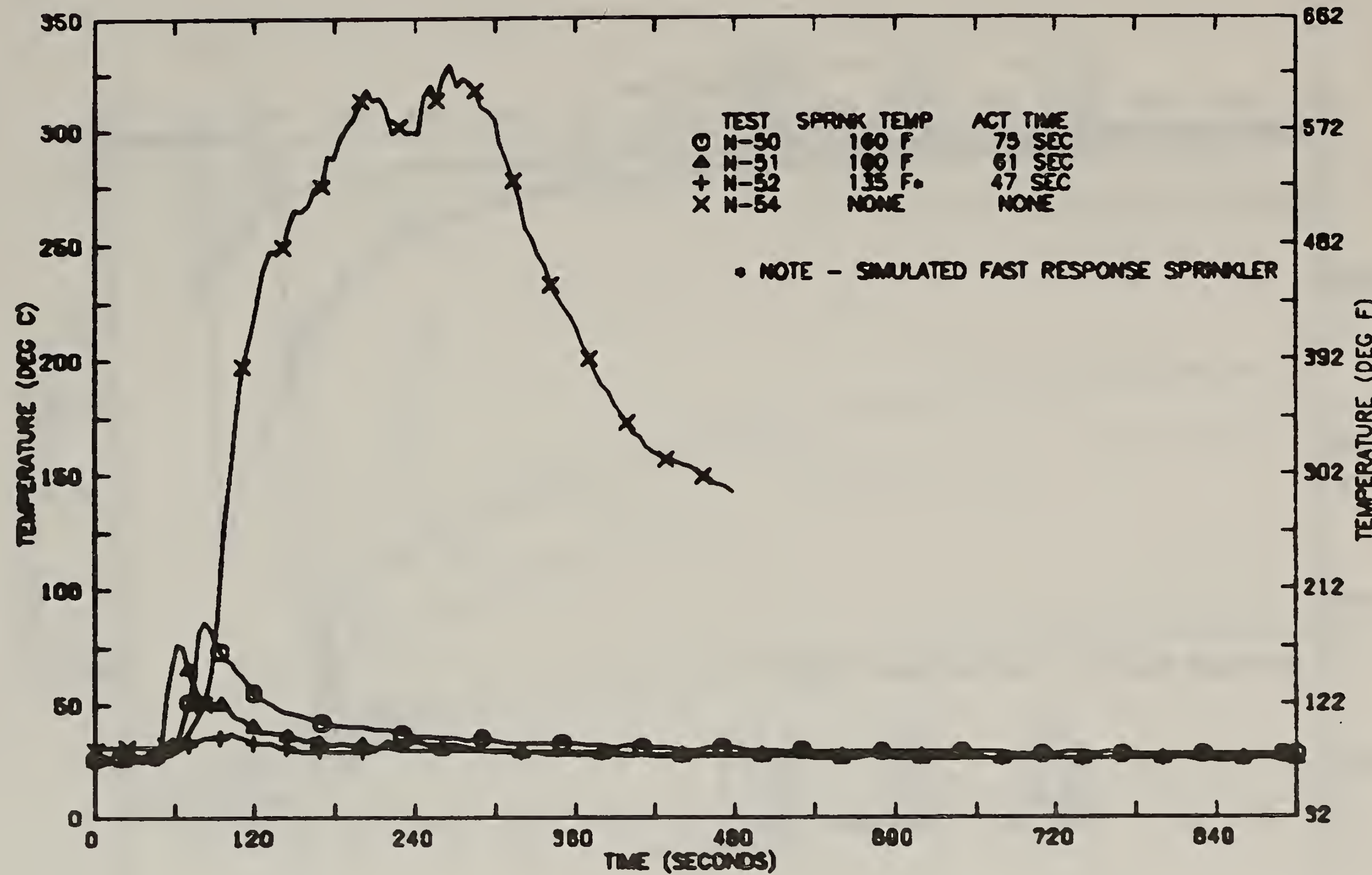



Figure 42. Corridor ceiling temperature 1.5 m (5 ft) west, wardrobe fire tests--horizontal sidewall over door

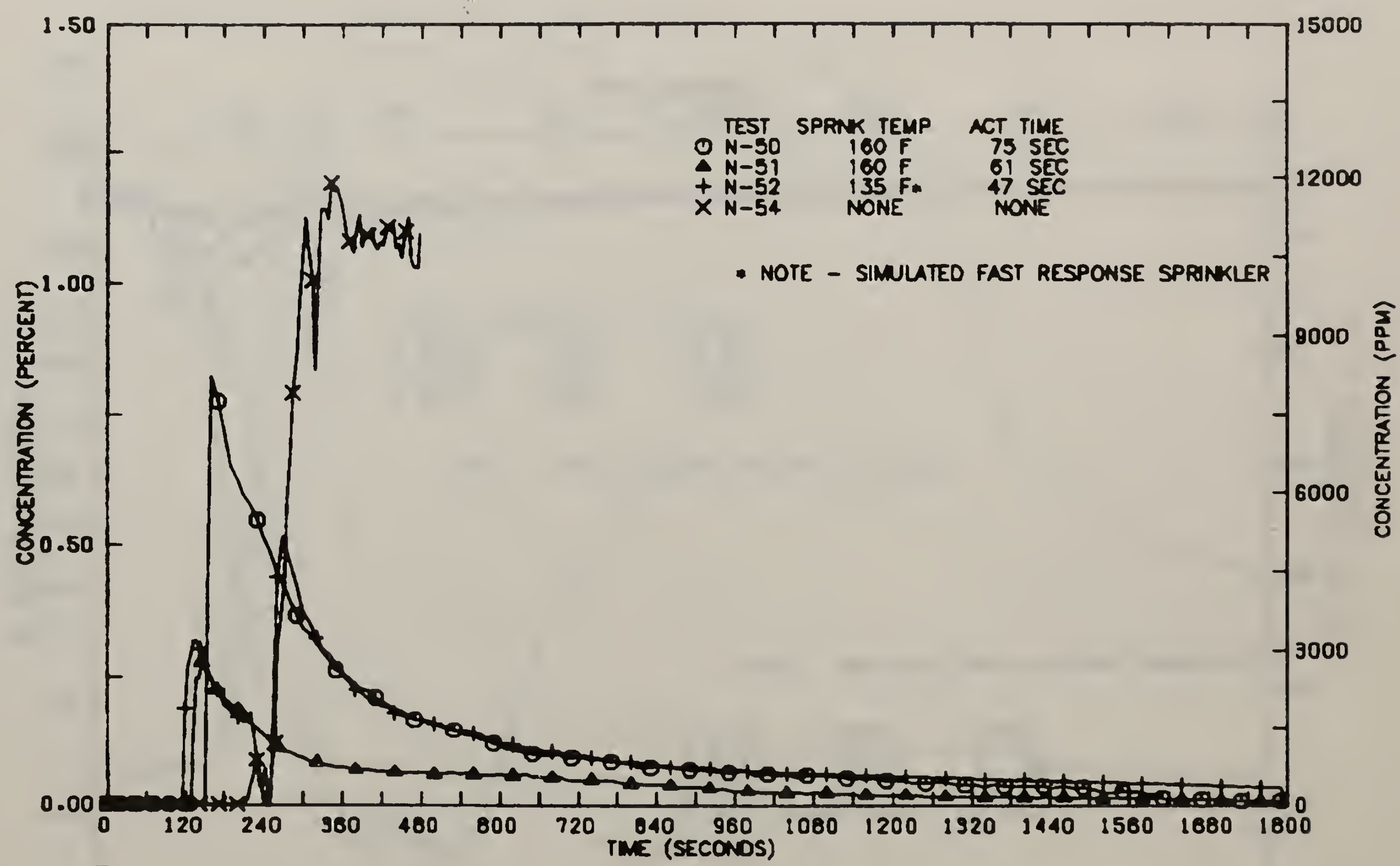



Figure 43. Carbon monoxide concentrations--adjacent patient level, wardrobe fire tests--horizontal sidewall over door

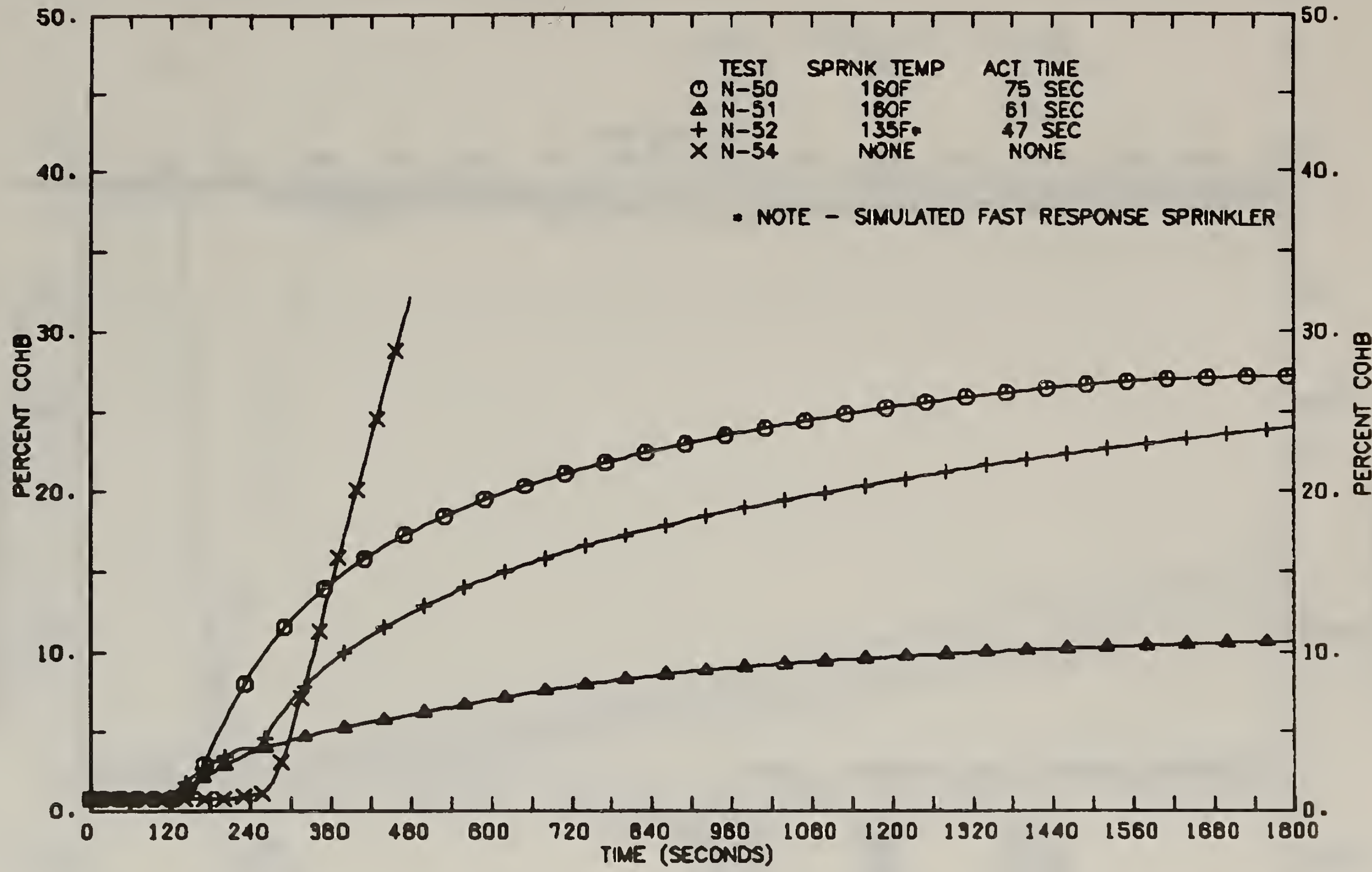



Figure 44. COHB at adjacent patient level, wardrobe fire tests--horizontal sidewall over door

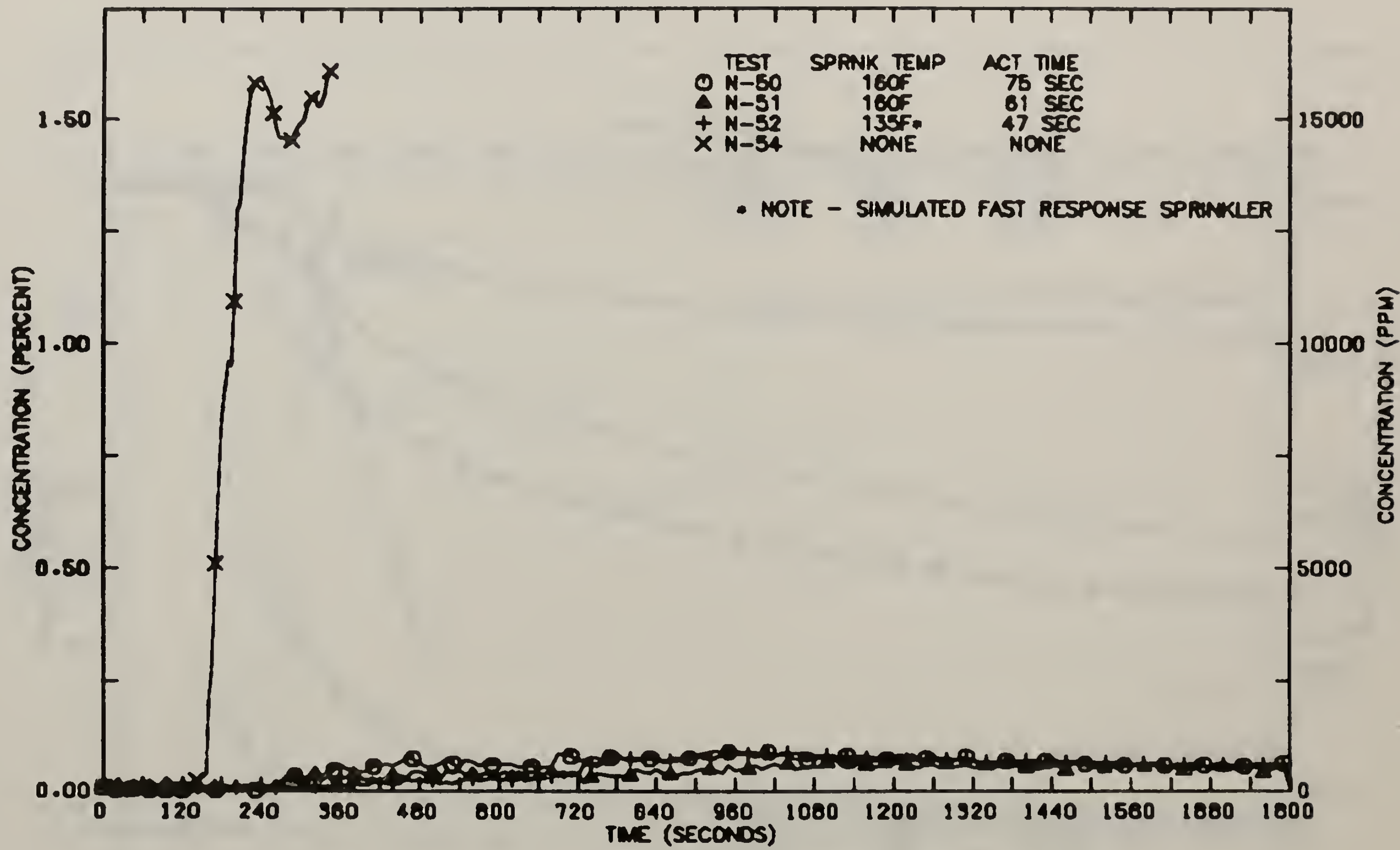



Figure 45. Carbon monoxide concentration in the lobby, wardrobe fire tests--horizontal sidewall over door

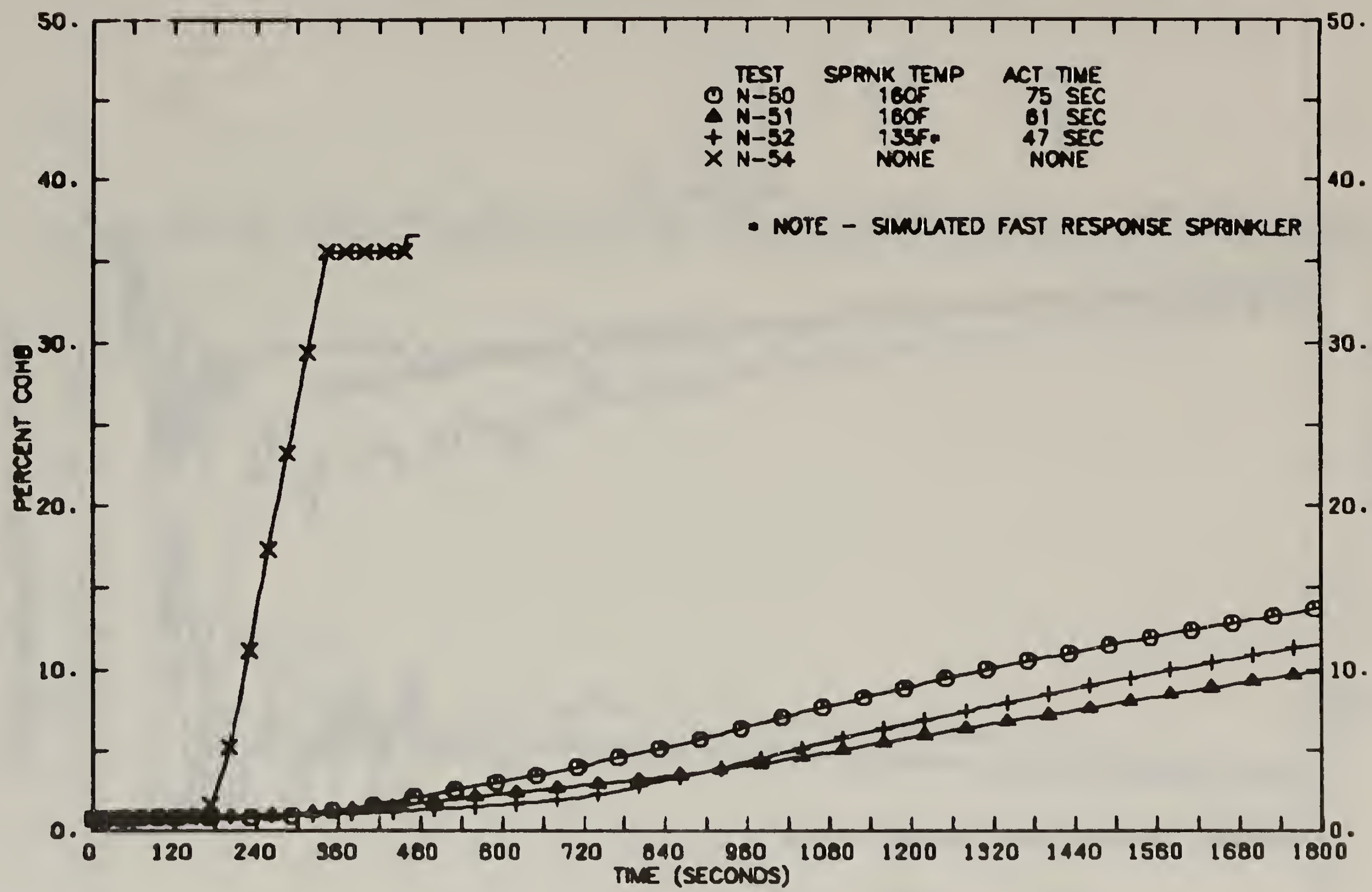



Figure 46. COHB at .92 m (3 ft) level in lobby, wardrobe fire tests--horizontal sidewall over door

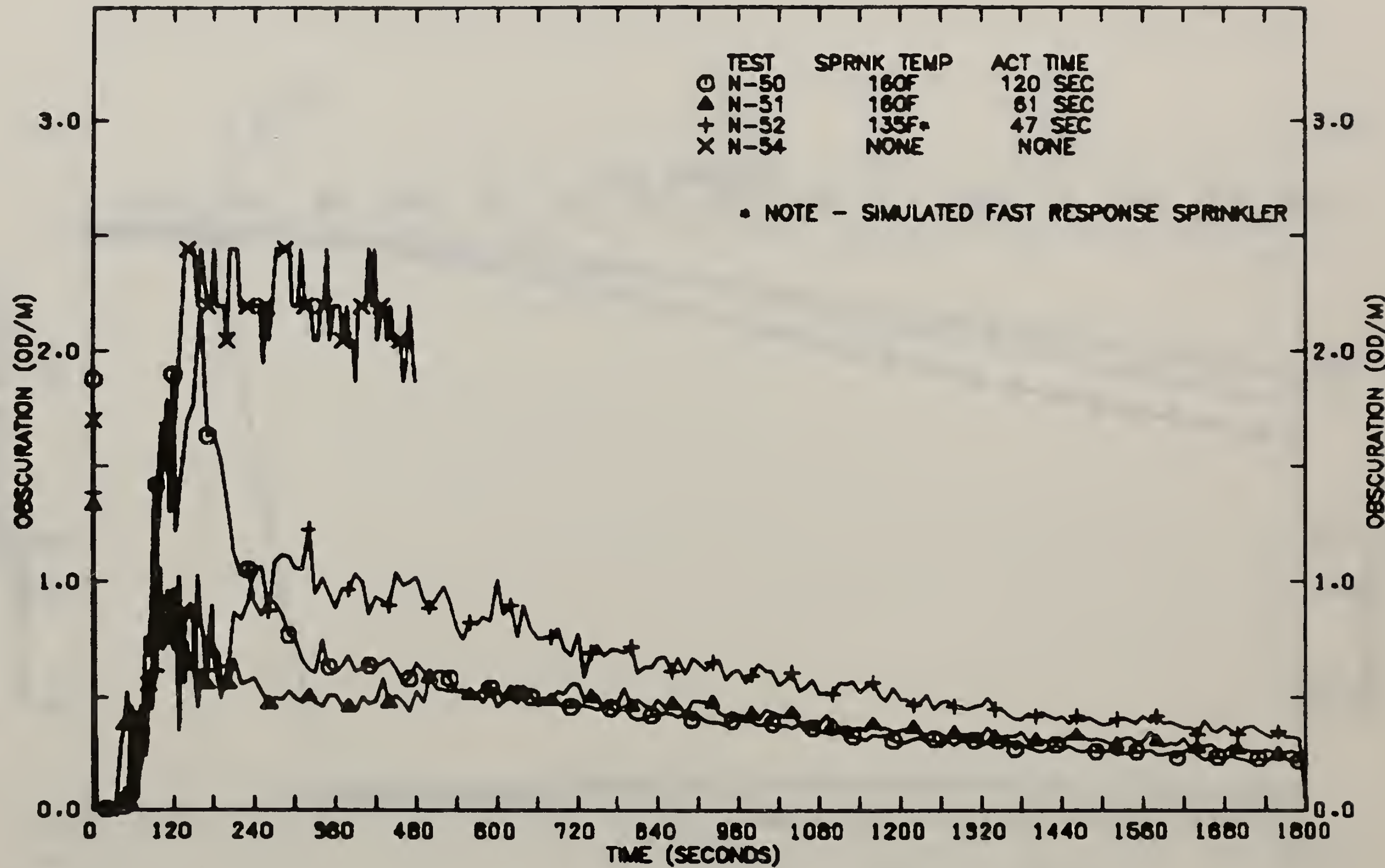



Figure 47. Smoke obscuration at 1.7 m (5 ft 8 in) level in doorway, wardrobe fire tests--horizontal sidewall over door

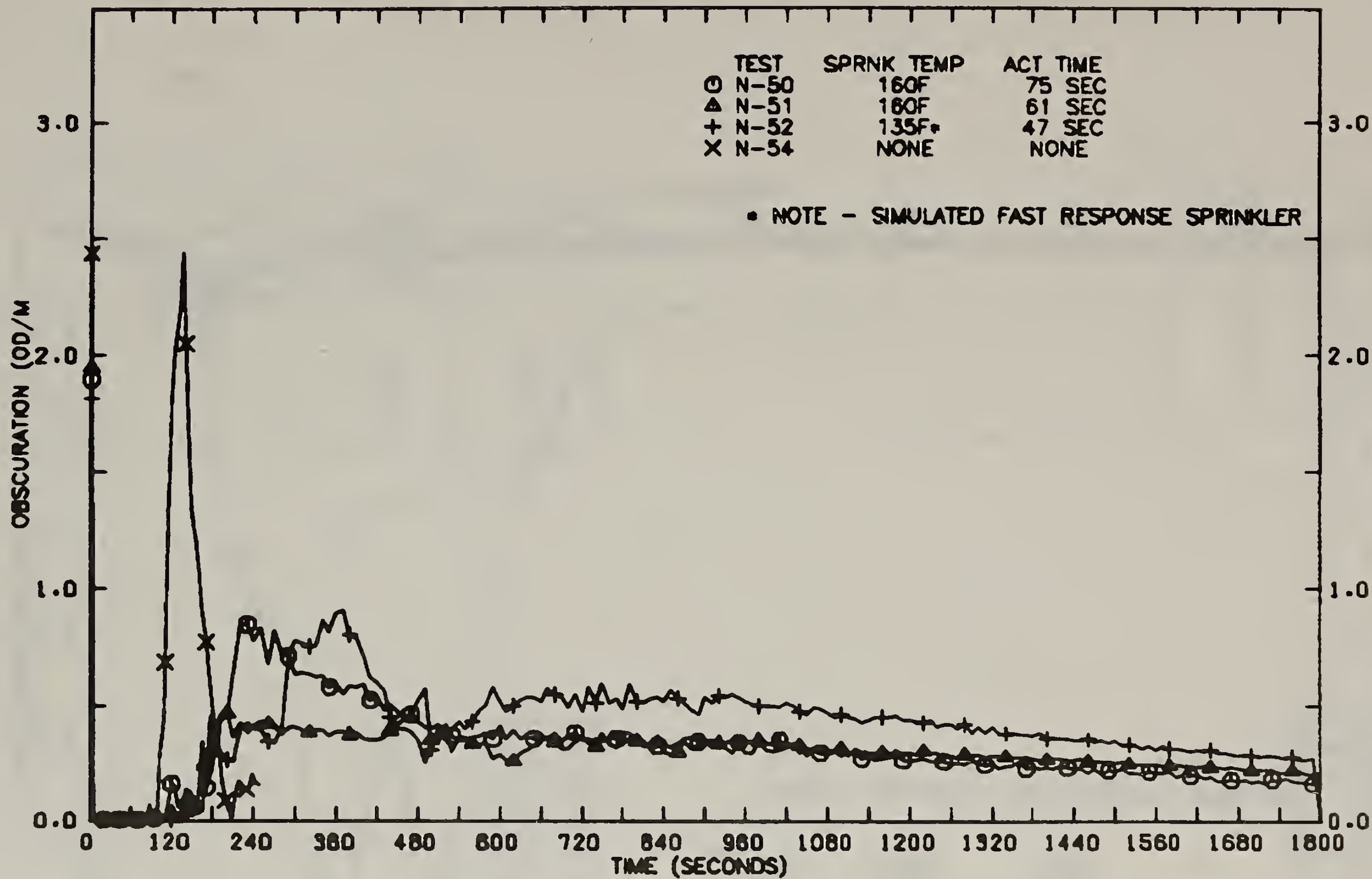



Figure 48. Corridor smoke obscuration 4.6 m (15 ft) west 1.5 m (5 ft) level, wardrobe fire tests--horizontal sidewall over door

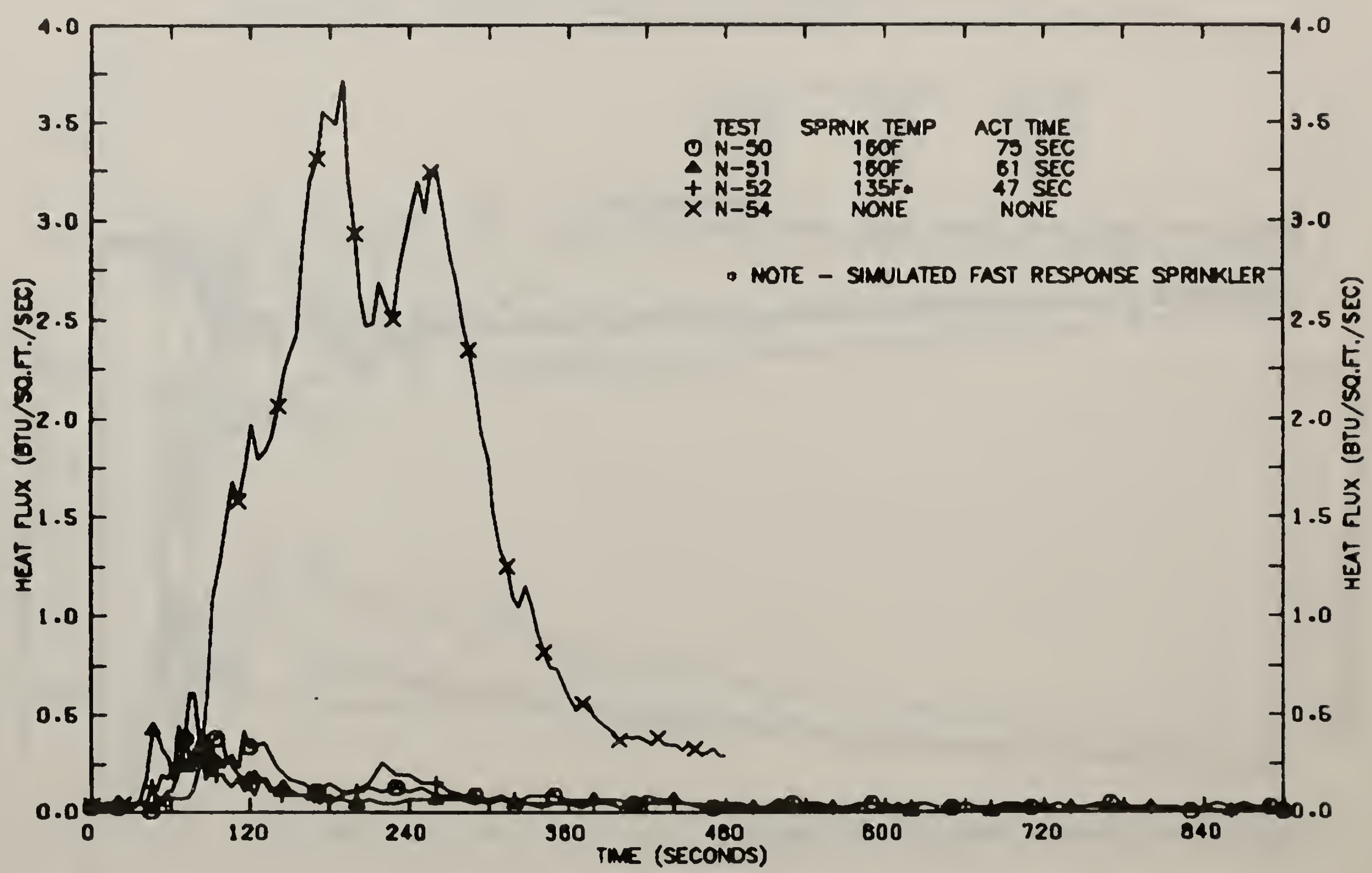



Figure 49. Heat flux--adjacent patient level, wardrobe fire tests--horizontal sidewall over door

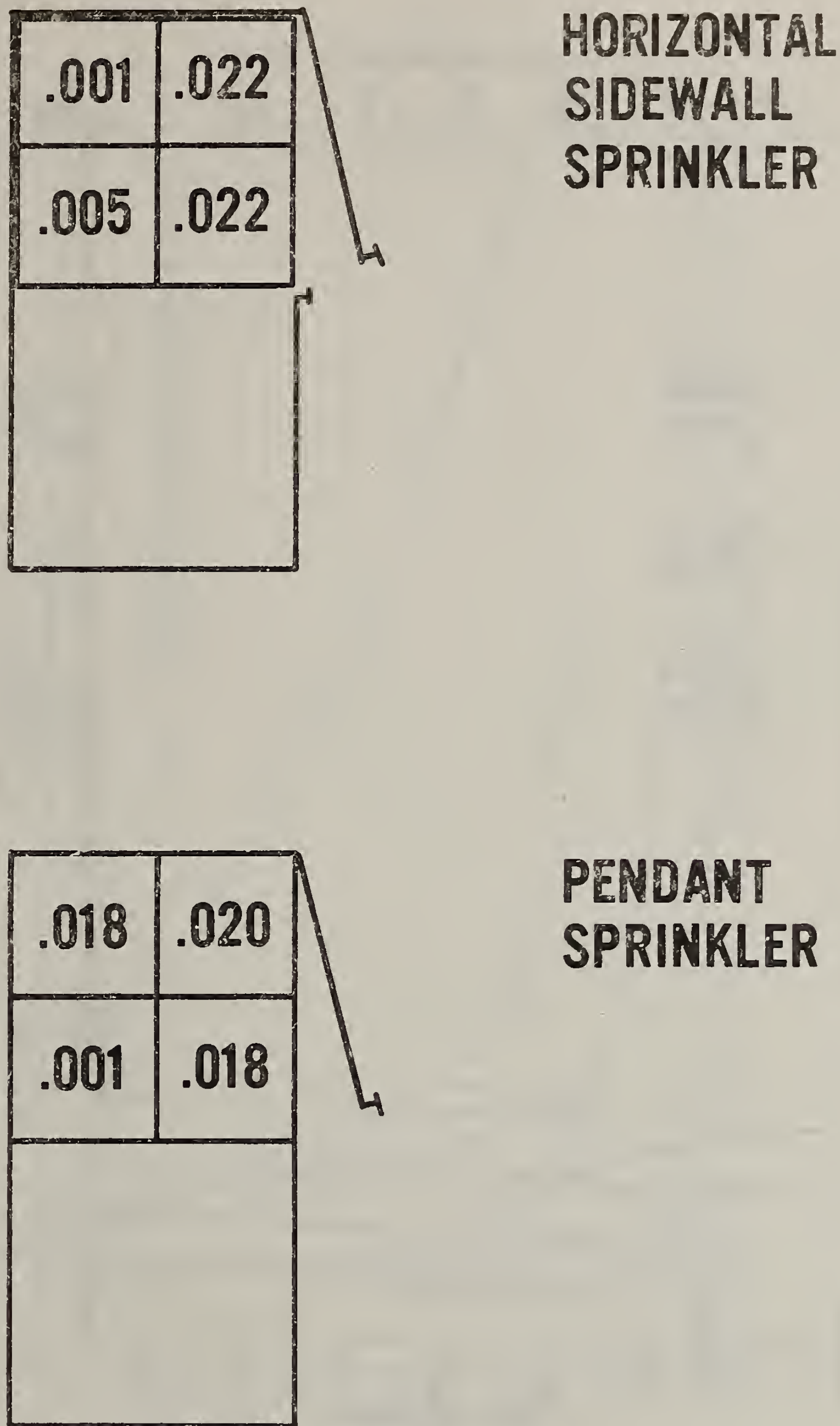



Figure 50. Sprinkler distribution--interior of wardrobes

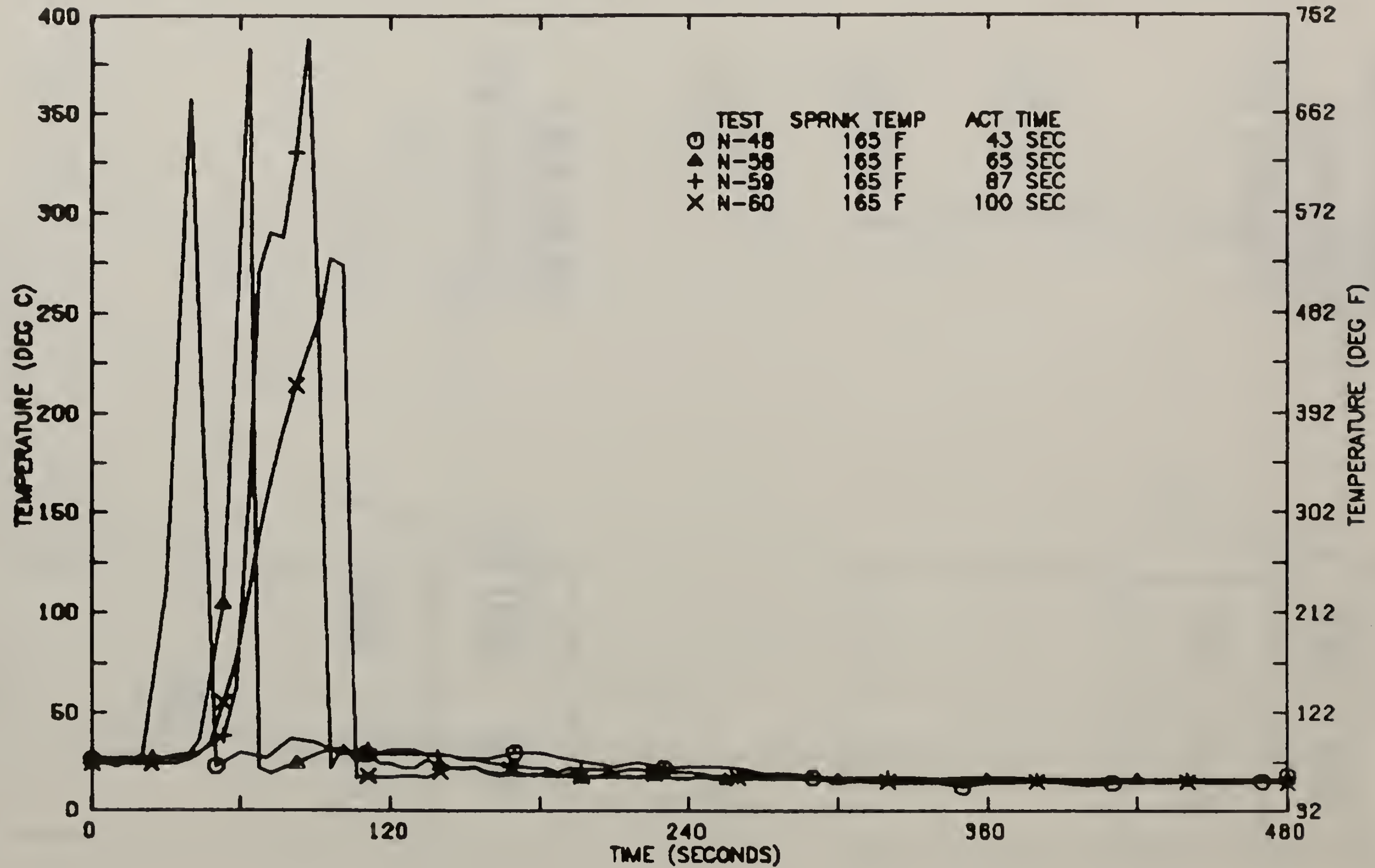



Figure 51. Center of ceiling air temperature, wardrobe fire tests--center ceiling pendent

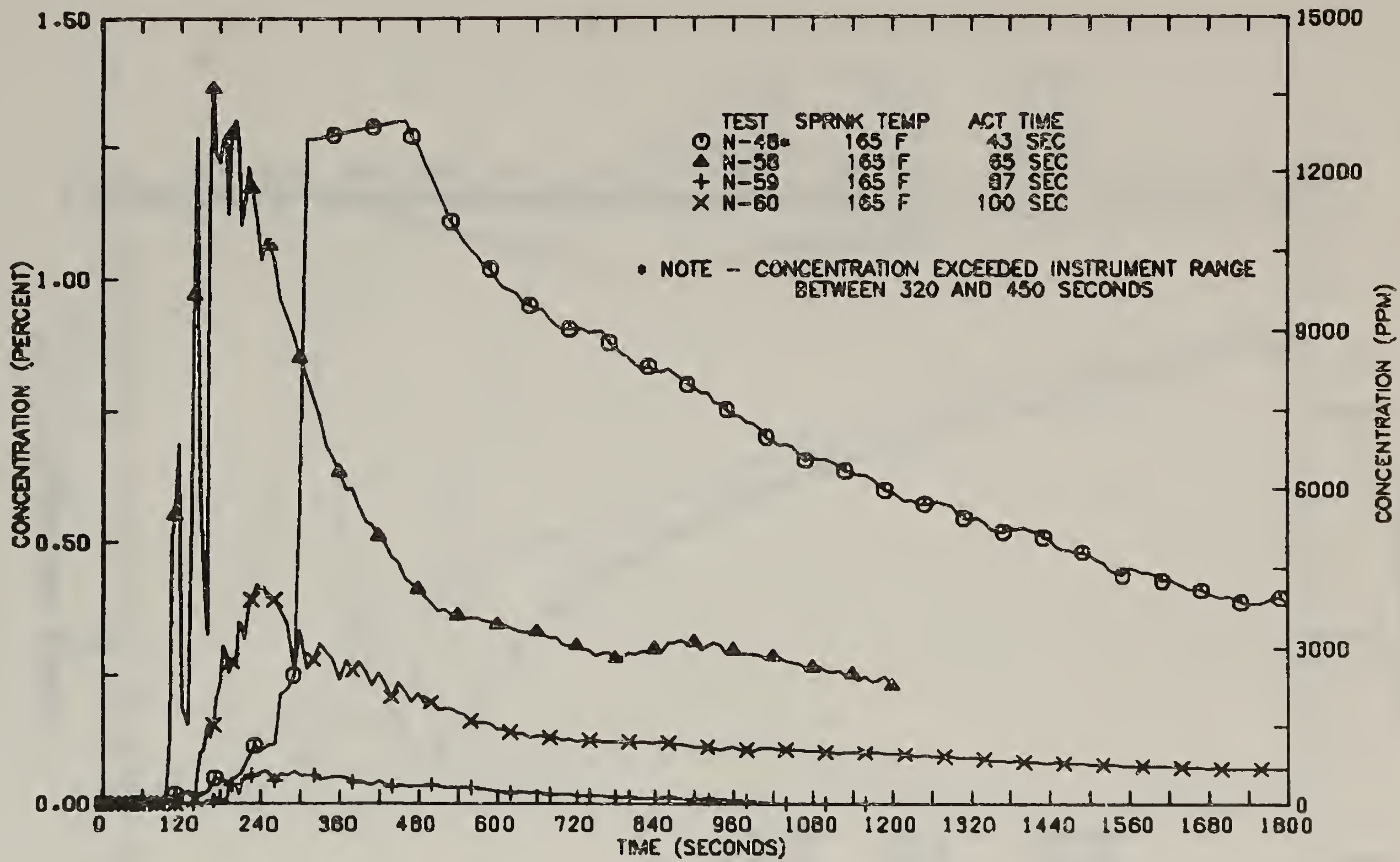



Figure 52. Carbon monoxide concentrations--adjacent patient level, wardrobe fire tests--center ceiling pendent

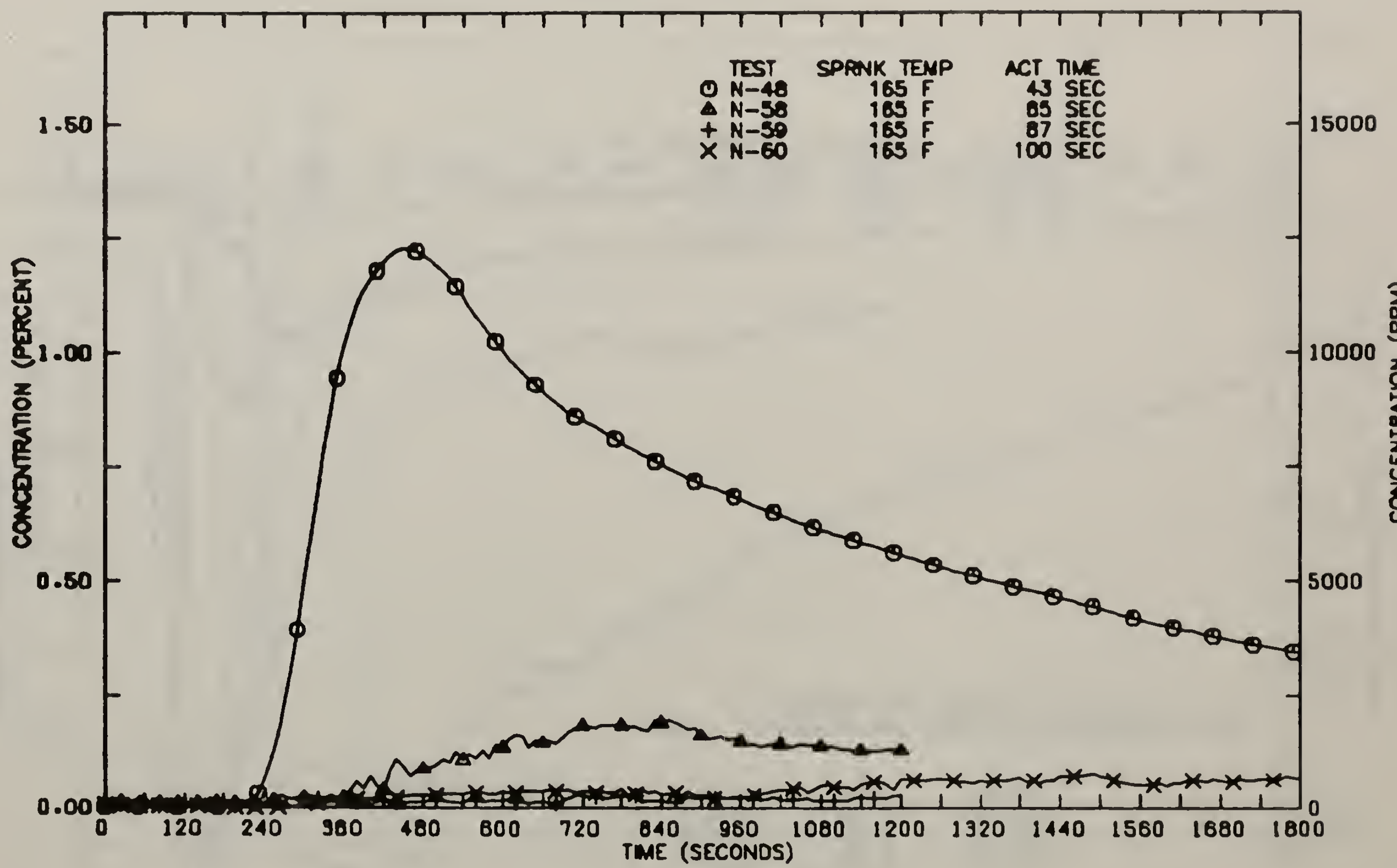



Figure 53. Carbon monoxide concentration in the lobby, wardrobe fire tests--center ceiling pendent

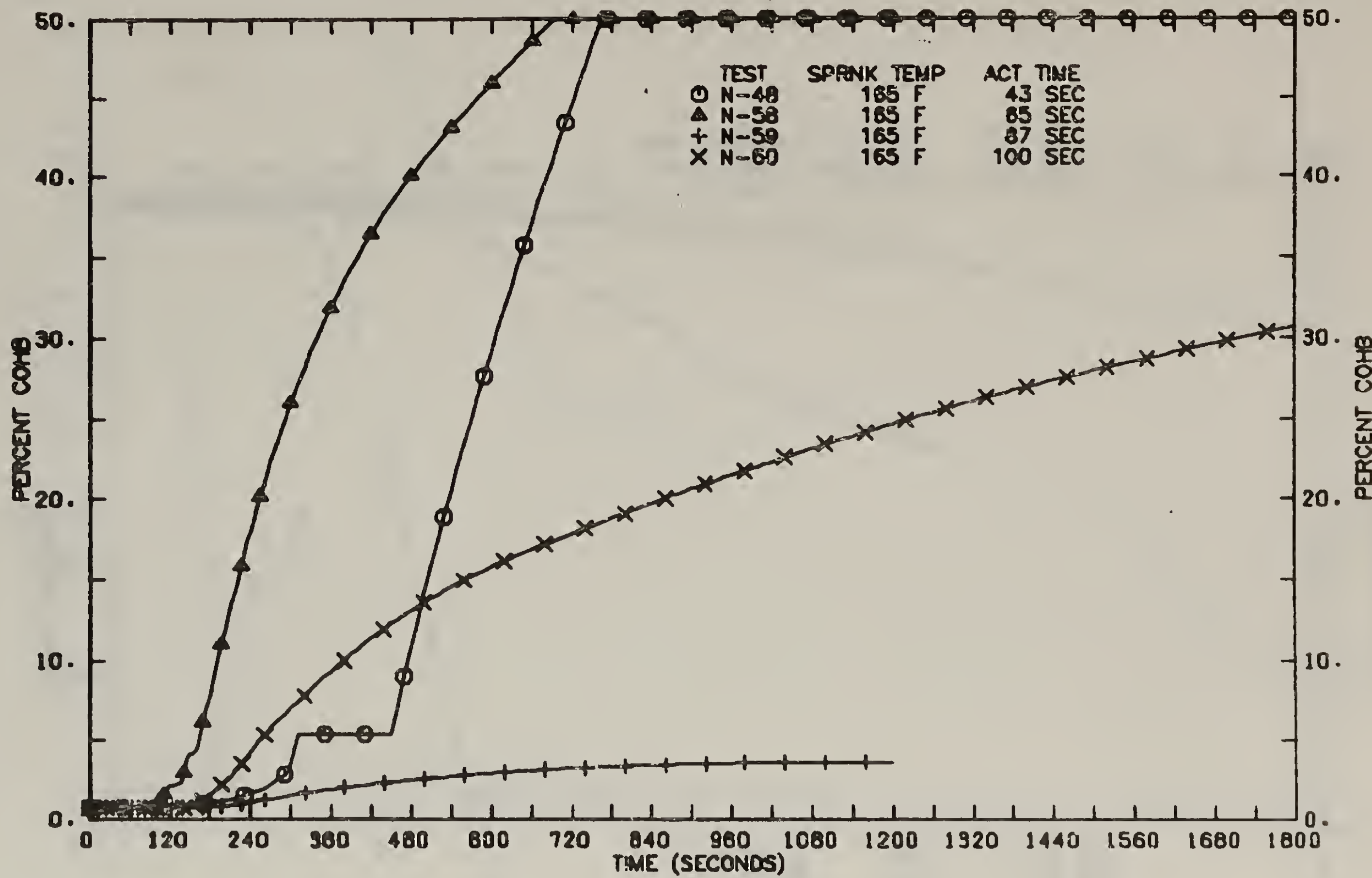



Figure 54. COHB at adjacent patient level, wardrobe fire tests--center ceiling pendent

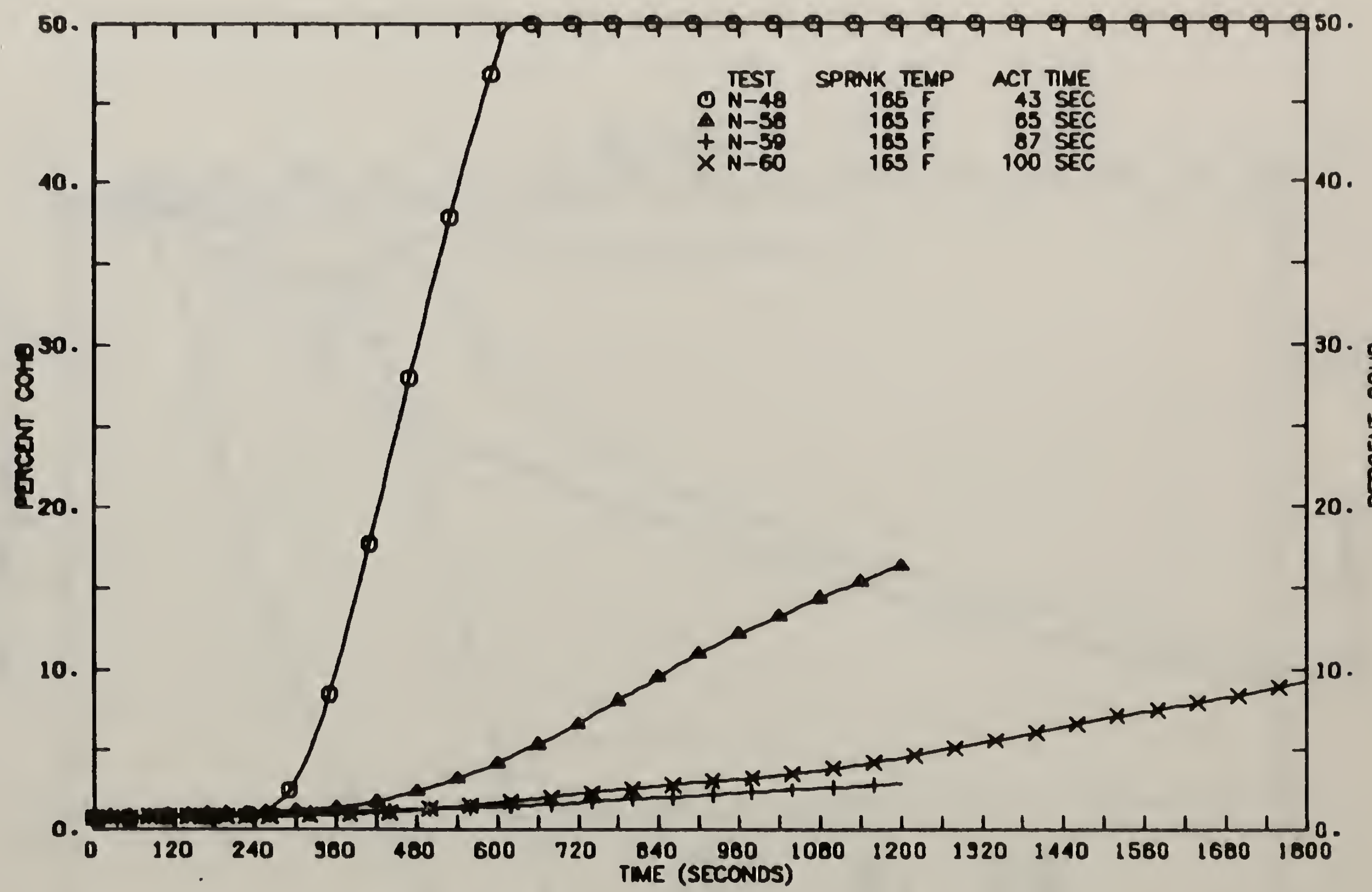



Figure 55. COHB at .92 m (3 ft) level in lobby, wardrobe fire tests--center ceiling pendent

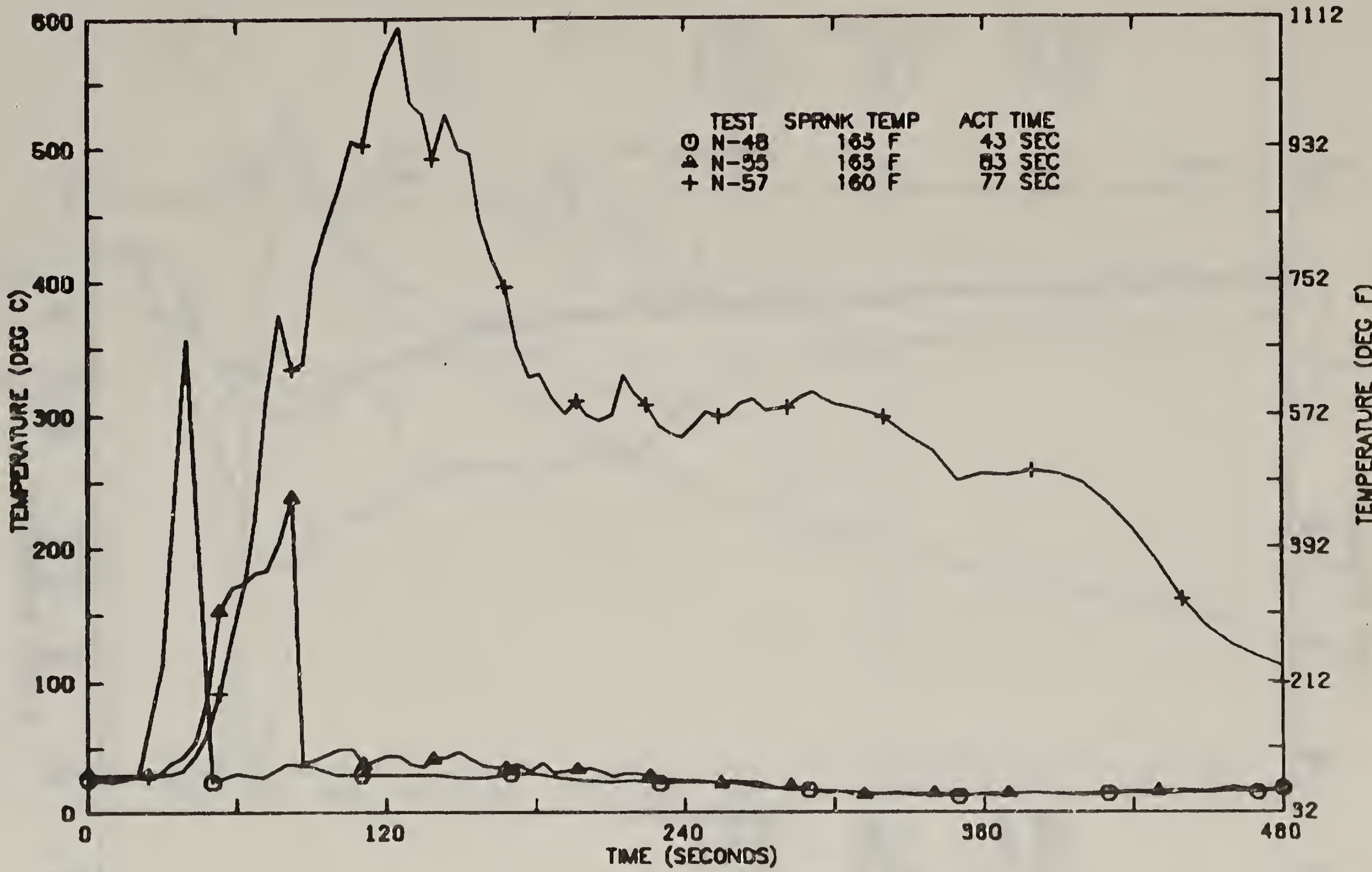



Figure 56. Center of ceiling air temperature, wardrobe fire tests--center ceiling pendent

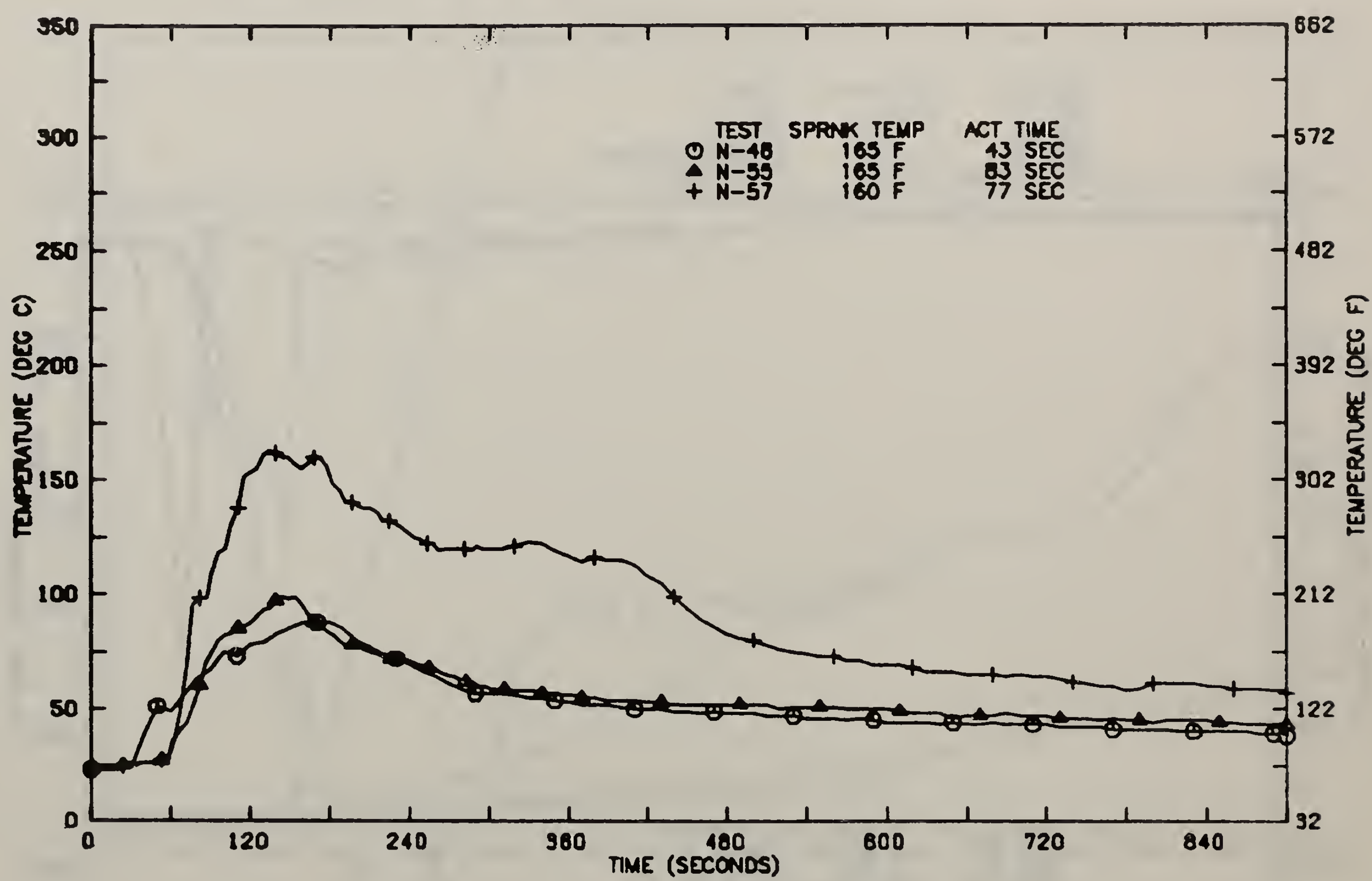



Figure 57. Corridor ceiling temperature 1.5 m (5 ft) west, wardrobe fire tests--center ceiling pendent

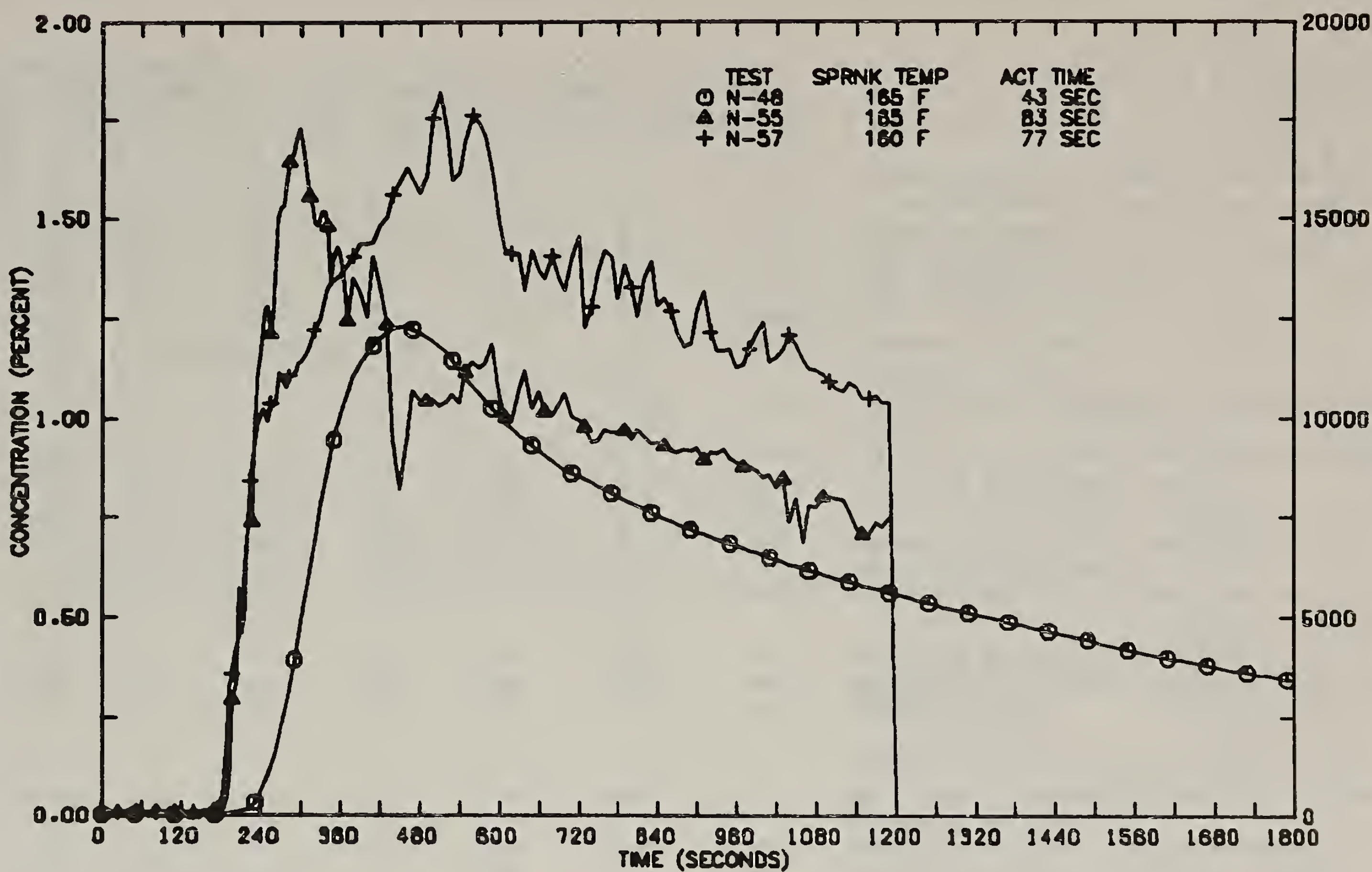



Figure 58. Carbon monoxide concentration in the lobby, wardrobe fire tests--center ceiling pendent

Table 1. Summary of fire tests

| Test No. | Burning Item | Sprinkler Type | Orifice Size (in) | Temp. Rate (°F) | $\dot{G}$ (g/min) | Activation Time (s) | Activation Mode | HVAC System | Comment |
|---|---|---|---|---|---|---|---|---|---|
| N-37 | Bed | SSP | 1/2 | 165 | 27 | 330 | A | No | Repeat of test N-25 [1] "current criteria" |
| N-38 | " | " | 3/8 | --- | 17 | 105 | M | No | Activated at Tc = 57°C (+10 s) Smoke Obscuration Thresholds Not Exceeded |
| N-39 | " | HSW | 1/2 | 160 | 27 | 388 | A | No | "Current criteria" sidewall system |
| N-40 | " | SSP | 3/8 | --- | 17 | 225 | M/HD | Yes | Smoke obscuration briefly exceeded only threshold in corridor |
| N-42 | " | HSW | 1/2 | --- | 27 | 250 | M/HD | No | OD/m briefly exceeded threshold for burn room doorway & exceeded corridor threshold |
| N-44 | " | SSP | 1/2 | 165 | 27 | 345 | A | Yes | Repeat of N-37 |
| N-45 | " | HSW | 1/2 | --- | 27 | 184 | M/HD | Yes | OD/m briefly exceeded only corridor threshold |
| N-47 | " | SSP | 3/8 | --- | 17 | 130 | M/τ = 21 s | Yes | Repeat of N-40 - same result |
| N-48 | C.W | SSP | 1/2 | 160 | 27 | 43 | A | Yes | CO instantaneous threshold exceeded in burn room, corridor, lobby |
| N-49 | " | SSP | 1/2 | 160 | 27 | 60 | A | Yes | Repeat of N-48; same results |
| N-50 | " | HSW | 1/2 | 160 | 27 | 75 | A | Yes | Significantly lower CO concentrations |
| N-51 | " | HSW | 1/2 | 160 | 27 | 61 | A | Yes | Repeat of N-50; same results |
| N-52 | " | HSW | 1/2 | --- | 27 | 47 | M/τ = 21 s | Yes | Simulated fast response; same results as N-50, 51 |
| N-53 | " | SSP | 1/2 | --- | 27 | 51 | M/τ = 21 s | Yes | Simulated fast response; same results as N-48, 49 |
| N-54 | " | --- | NON SPRINKLERED TEST | | | | --- | Yes | Flashover at ≈120 s |
| N-55 | " | SSP | 1/2 | 160 | 27 | 83 | A | Yes | Comb. Ceiling |
| N-56 | " | SSP | 1/2 | 160 | 27 | 48 | A | Yes | Comb. Ceiling |
| N-57 | " | SSP | 1/2 | 160 | 17 | 78 | A | Yes | Comb. Ceiling - Boundary Condition |
| N-58 | " | SSP | 1/2 | 160 | 27 | 65 | A | Yes | PACKED WARDROBE |
| N-59 | NCW | SSP | 1/2 | 160 | 27 | 87 | A | Yes | CO concentrations significant lower |
| N-60 | " | SSP | 1/2 | 160 | 27 | 100 | A | Yes | PACKED WARDROBE - lower CO from N-58 |

Bed: Bedding & Mattress
C.W: Combustible Wardrobe
NCW: Noncombustible Wardrobe

SSP: Standard Pendant Sprinkler
HSW: Horizontal Sidewall Sprinkler

Activation Mode: A - Automatic
M/HD - Manual at time Heat Detector Response
M/τ = 21 s - Manual - at time τ = 21 s disc reached 57°C

Table 2. List of instrumentation

| Number | Thermocouples |
|---|---|
| 00 | Center of room, 0.05 m from ceiling |
| 01 | Ceiling air, average of 8 TC's, 0.05 m from ceiling |
| 02 | Wastebasket plume, average of 9 TC's (0.30 m circle). 0.05 m from ceiling |
| 03 | On E wall, 1.82 m from S wall, 0.31 m from ceiling |
| 04 | On N wall, 2.12 m from W wall, 0.31 m from ceiling |
| 05 | On W wall, 1.82 m from S wall, 0.31 m from ceiling |
| 06 | on S wall, 2.12 m from W wall, 0.31 m from ceiling |
| 07 | Time constant disc (9.0 sec)* |
| 08 | Time constant disc (14.4 sec)* |
| 09 | Time constant disc (21.5 sec)* |
| 10 | At doorway centerline, 0.05 m below top |
| 11 | 3.25 m from E wall, 1.68 m from S wall, 0.05 m from ceiling |
| 12 | 3.25 m from E wall, 1.68 m from S wall, 0.15 m from ceiling |
| 13 | 3.25 m from E wall, 1.68 m from S wall, 0.31 m from ceiling |
| 14 | 3.25 m from E wall, 1.68 m from S wall, 0.61 m from ceiling |
| 15 | 3.25 m from E wall, 1.68 m from S wall, 0.91 m from ceiling |
| 16 | 3.25 m from E wall, 1.68 m from S wall, 1.22 m from ceiling |
| 17 | 3.25 m from E wall, 1.68 m from S wall, 1.53 m from ceiling |
| 18 | At doorway centerline, 1.19 m below top |
| 19 | At doorway centerline, 1.63 m below top |
| 20 | At doorway centerline, 0.13 m below top |
| 21 | At doorway centerline, 0.30 m below top |
| 22 | At doorway centerline, 0.66 m below top |
| 23 | At doorway centerline, 1.02 m below top |
| 25 | At doorway centerline, 1.37 m below top |
| 26 | At doorway centerline, 1.91 m below top |
| 27 | Corridor station B, 0.13 m from ceiling |
| 28 | Corridor station C, 0.13 m from ceiling |
| 29 | Corridor station A, 0.91 m from ceiling |
| 30 | Corridor station D, 0.13 m from ceiling |
| 31 | Corridor station E, 0.13 m from ceiling |
| 32 | Corridor station C, 0.05 m from ceiling |
| 33 | At doorway centerline, 0.48 m below top |
| 34 | Corridor station C, 0.46 m from ceiling |
| 35 | Corridor station C, 0.76 m from ceiling |
| 36 | Corridor station C, 1.07 m from ceiling |
| 37 | Room center, 0.05 m from ceiling |
| 38 | Corridor station E, 0.81 m from ceiling |
| 39 | Corridor station E, 1.42 m from ceiling |
| 40 | Corridor station E, 2.03 m from ceiling |
| 41 | Corridor station D, 0.05 m from ceiling |
| 42 | At doorway centerline, 0.84 m below top |
| 43 | Corridor station D, 0.46 m from ceiling |
| 44 | Corridor station D, 0.76 m from ceiling |
| 45 | Corridor station D, 1.07 m from ceiling |
| 46 | Corridor station D, 1.37 m from ceiling |
| 47 | Corridor station D, 1.68 m from ceiling |

| Number | Thermocouples |
|---|---|
| 48 | Corridor station D, 1.98 m from ceiling |

| Number | Load Cell |
|---|---|
| 50 | Load cell - 500 lb. |

Table 2. List of instrumentation (cont.)

| | |
|---|---|
| | Gas Concentration Probes* |
| 51 | Carbon monoxide, at doorway centerline, 1.95 m below top. Analyzer Range: 0 to 5.0% |
| 52 | Carbon dioxide, at doorway centerline, 1.95 m below top. Analyzer Range: 0 to 5% |
| 53 | Carbon monoxide, 1.12 m from W wall, 0.36 m from S wall, 0.89 m from floor. Analyzer Range: 0 to 5.0% |
| 54 | Carbon dioxide, 1.12 m from W wall, 0.36 m from S wall, 0.89 m from floor. Analyzer Range: 0 to 20% |
| 55 | Carbon monoxide at doorway centerline, 0.51 m below top. Analyzer Range: 0 to 5% |
| 56 | Carbon dioxide, at doorway centerline, 0.51 m below top. Analyzer Range: 0 to 20% |
| 57 | Oxygen, at doorway centerline, 1.95 m below top. Analyzer Range: 0 to 21% |
| 58 | Oxygen, 1.12 m from W wall, 0.36 m from S wall, 0.89 m from floor. Analyzer Range: 0 to 21% |
| 59 | Oxygen, at doorway centerline, 0.51 m below top. Analyzer Range: 0 to 21% |
| 79 | Carbon monoxide, lobby, 1.55 m from E wall, 3.58 m from S wall. Analyzer Range: 0 to 2.0% |
| 85 | Carbon monoxide, corridor station E, 0.05 m from ceiling. Analyzer Range: 0 to 10% |
| 86 | Carbon monoxide, corridor station E, 0.91 m from ceiling. Analyzer Range: 0 to 1.0% |
| 87 | Carbon monoxide, corridor station E, 1.42 m from ceiling. Analyzer Range: 0 to 1.0% |
| 88 | Carbon monoxide, corridor station E, 2.03 m from ceiling. Analyzer Range: 0 to 1.0% |

*Precision: (1.0% of full scale)

| | |
|---|---|
| | Velocity Probes |
| 60 | At doorway centerline, 0.13 m below top |
| 61 | At doorway centerline, 0.30 m below top |
| 62 | At doorway centerline, 0.66 m below top |
| 63 | Room center, 0.13 m from ceiling |
| 64 | At doorway centerline, 1.37 m below top |
| 65 | At doorway centerline, 1.91 m below top |
| 66 | Corridor station E, 2.03 m from ceiling |
| 67 | Corridor station E, 1.42 m from ceiling |
| 68 | Corridor station E, 0.81 m from ceiling |
| 69 | Corridor station E, 0.13 m from ceiling |

| Number | Smoke Meters |
|---|---|
| 70 | Horizontal in doorway, 0.13 m below top (1.219 m light path) |
| 71 | Horizontal in doorway, 0.30 m below top (1.219 m light path) |
| 72 | Horizontal in doorway, 0.66 m below top (1.219 m light path) |
| 73 | Horizontal in doorway, 1.02 m below top (1.219 m light path) |
| 74 | Horizontal, corridor station E, 1.42 m from ceiling (1.219 m light path) |
| 75 | Horizontal, corridor station E, 1.52 m from ceiling (1.219 m light path) |
| 76 | Horizontal, corridor station D, 0.06 m from ceiling (1.219 m light path) |
| 77 | Horizontal, corridor station D, 0.91 m from ceiling (1.219 m light path) |
| 78 | Horizontal, corridor station E, 0.06 m from ceiling (1.219 m light path) |
| 82 | Horizontal, corridor station E, 2.03 m from ceiling (1.219 m light path) |
| 83 | Horizontal, lobby station F, 0.91 m from ceiling (1.219 m light path) |
| 84 | Horizontal, corridor station B, 0.06 m from ceiling (1.219 m light path) |

Table 2. List of instrumentation (cont.)

Heat Flux Meters

| | |
|---|---|
| 80 | Total heat flux meter, facing up, 1.12 m from W wall, 1.19 m from S wall, 0.74 m from floor; range to 23 $W/cm^2$ (20 $BTU/ft^2/sec$) |
| 81 | Total heat flux meter, facing horizontally toward burn-room, on doorway centerline, 2.44 m N from doorway, 1.02 m from floor; range to 5.7 $W/cm^2$ (5 $BTU/ft^2/sec$) |

Detector Board

| | |
|---|---|
| -- | At ceiling, 1.52 m from W wall, 1.80 m from S wall |
| -- | At ceiling, corridor center, 5.10 m E from doorway center |
| -- | At ceiling, corridor center, 5.10 m W from doorway center |

Tell-Tale Sprinklers

| | |
|---|---|
| -- | At ceiling, 1.92 m from W wall, 1.22 m from S wall |

Table 3. Mattress and bedding technical data

| Mattress | Code | Size | | | Total Weight (kg) | Weight Combustibles (kg) | Weight Innerspring (kg) |
|---|---|---|---|---|---|---|---|
| | | Width | Length | Thickness | | | |
| Polyurethane Innerspring | M-02 | 39 in (0.89 m) | 75 in (2.03 m) | 7 in (0.17 m) | 15 | 6 | 9 |

| Bedding Item | Length & Width (m) | Composition | Thickness (mm) | Density ($kg/m^3$) | $\rho\tau$ ($kg/m^2$) | Total Weight (kg) |
|---|---|---|---|---|---|---|
| Drawsheet | 1.07 x 0.69 | Cotton | 0.14 | 775 | 0.108 | 0.40 |
| Sheets | 1.83 x 2.64 | 50% Cotton, 50% Polyester | 0.22 | 570 | 0.125 | 0.60 |
| Spread | 1.93 x 2.79 | 86% Cotton, 14% Polyester | 0.38 | 525 | 0.200 | 1.07 |
| Pillow-filling | | Polyurethane | -- | -- | -- | 0.67 |
| -cover | 0.52 x 0.69 | Cotton | 0.40 | 575 | 0.230 | 0.16 |
| Pillow Protector | 0.53 x 0.69 | Polyvinylchloride | 0.14 | 775 | 0.180 | 0.90 |
| Pillow Case | 0.53 x 0.91 | 50% Cotton | 0.21 | 595 | 0.125 | 0.60 |

Table 4. Simulated clothing technical data

| Item | Length & Width (m) | Fabric Type | Composition (%) | Weight $g/m^2$ |
|---|---|---|---|---|
| Night Shirt | 1.02 x 0.38 | knit jersey | 65 polyester<br>35 cotton | 164.3 |
| T-Shirt | 0.76 x 0.38 | knit jersey | 65 polyester<br>35 cotton | 164.3 |
| Robe | 0.56 x 1.35 | terry cloth | 16 polyester<br>84 cotton | 342.0 |
| Shirt | 0.51 x 1.22 | kettle cloth | 50 polyester<br>50 cotton | 161.8 |
| Dress | 0.61 x 2.03 | kettle cloth | 50 polyester<br>50 cotton | 161.8 |
| Pants | 0.79 x 1.02 | double knit | 100 polyester | 245.1 |

Table 5. Fire load for sprinkler tests

| Test No. | Clothing Load (lbs) | | Wardrobe (lbs) | | | Total Loss |
|---|---|---|---|---|---|---|
| | Before | After | Before | After | Loss | |
| N-48* | 6.22 | 0 | 134 | 102 | 32 | 38.22 |
| N-49* | 7.36 | 0 | 134 | 124 | 10 | 17.36 |
| N-53* | 6.72 | 0 | 145.5 | 115 | 34 | 40.72 |
| N-50** | 6.23 | 0 | 148 | 140 | 8 | 14.23 |
| N-51** | 6.35 | 0 | 148 | 145 | 3 | 9.35 |
| N-52** | 6.68 | 0 | 149.5 | 147 | 2.5 | 9.18 |
| N-54 | 6.77 | 0 | 145 | Total Loss | 145 | 151.77 |
| N-55* | 8.90 | 0 | 134.5 | 99 | 35.5 | 44.40 |
| N-56* | 7.02 | 0 | 131 | 117 | 14 | 21.02 |
| N-57* | 7.15 | 0 | 133.5 | 84 | 49.5 | 56.65 |
| N-58* | 45.14 | 30 | 135 | 129 | 6 | 11.14 |
| N-59*** | 7.19 | 0 | | | | 7.19 |
| N-60*** | 27.66 | 5 | | | | 22.66 |

*Pendant sprinkler

**Horizontal sidewall sprinkler

***Noncombustible wardrobe

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15. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

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.)*


The Center for Fire Research conducted a series of full-scale fire tests in a patient room and corridor arrangement to examine the use of automatic sprinklers in patient rooms of health care facilities. This is a report of twenty-one (21) fire tests in which either mattresses with bedding or clothing wardrobes served as the burning items.

Test results indicated that actuation of both pendant and horizontal sidewall sprinklers in the patient room acted to cool and redistribute the combustion products in the patient room and in the corridor away from the flowing sprinkler. This phenomena resulted in total obscuration throughout the test area. It was demonstrated that the use of a fast response, (low thermal inertia) sprinkler resulted in significantly less smoke obscuration in the mattress and bedding fires.

Sprinkler spray distribution measurements were made to develop criteria for the position of privacy curtains with respect to the automatic sprinklers in the patient room. Recommended installation criteria are provided.

Analysis of the test results indicated that the combustible clothing wardrobe fire resulted in room flashover in a nonsprinklered test. In several tests with sprinklers, flashover did not occur, however, estimated hazardous thresholds for carbon monoxide were still exceeded in the test area. It was determined that the combustible construction of the wardrobe primarily contributed to the high concentrations of carbon monoxide.


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)*

Clothing wardrobes; health care facilities; hospitals; mattresses; smoke movement; sprinkler systems.

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