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EVALUATION OF AN EXTENDED COVERAGE SIDEWALL SPRINKLER AND SMOKE DETECTORS IN A HOTEL OCCUPANCY

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SUMMARY

Twelve fire tests were conducted in a simulated hotel guest room and corridor to evaluate the performance of one model of an extended coverage horizontal sidewall sprinkler equipped with a fast-response link and the performance of smoke detectors. Eight of the tests were flaming-started fire tests using either a chair or a bed as the fire source. In four tests, smoldering combustion was initiated in a bed. Five different ventilation conditions were investigated. In all of the flaming-started tests, the fire was suppressed by the sidewall sprinkler. In the four smoldering-started tests, smoldering was sustained for at least five hours. A tenability criterion based upon the time integrated concentration of carbon monoxide was exceeded in all four smoldering tests. In only one of these tests did the smoldering phase progress to flaming combustion. In that test the fire was extinguished by the sidewall sprinkler. In all twelve tests, guest room smoke detectors responded sufficiently early to increase the escape potential of room occupants. The performance of the corridor smoke detectors was substantially influenced by the ventilation conditions and whether the entry door to the guest room was open or closed.

INTRODUCTION

Hotel fires in the United States remain a significant concern to the public. The National Fire Protection Association (NFPA) estimated that 50 deaths and 300 injuries occurred in hotel fires in 1987[1]. Property damage from the estimated 8000 fires was $80,000,000[1]. As a result of the tragic fire at the San Juan, DuPont Plaza Hotel on December 31, 1986, in which 97 people were killed[2], public hearings on fire safety in hotels were held by the House Subcommittee on Science, Research and Technology (March 1988)[3]. Those hearings resulted in passage by the House of Representatives of legislation (H.R. 3704) to restrict travel by government employees to hotels and motels that are fully protected by sprinkler and alarm systems. The legislation, however, was not passed by the Senate in the 1988 session.

Independent of legislative mandates, the hotel industry has increasingly made use of fire safety technology to reduce the risk of fire deaths and injuries. The American Hotel and Motel Association reports that from 1980 to 1983, the use of sprinkler systems more than doubled and the use of smoke detector equipment increased by a factor of four[4,5]. One attractive solution for sprinkler coverage in guest rooms is the installation of extended coverage sidewall sprinklers. Such sprinklers, when equipped with fast-response links similar to those used in residential sprinklers, have been shown in preliminary demonstration fire tests to provide a level of life safety protection[6,7] similar to that demonstrated by residential sprinklers in the Los Angeles Residential Test Program[8].

The National Fire Protection Research Foundation conducted flaming-started and smoldering-started fire tests in guest rooms of a vacant hotel in Ft. Lauderdale, FL[6]. Prototype extended coverage sidewall sprinklers equipped with fast-response links were installed in the guest rooms. In five flaming-started guest room fire tests, the guest room sprinkler controlled the fire, and critical limits established for survivability were not exceeded. In neither of two smoldering-started tests did smoldering combustion progress to flaming combustion. One test was terminated after two hours with no visible smoke. In the other test, considerable smoke was generated; however, an instrument malfunction prevented measurement of carbon monoxide concentrations and the test was aborted. A single guest room demonstration flaming-started fire test using a similar extended coverage sprinkler was conducted as part of "Operation San Francisco"[7]. Results were similar to those obtained in the Ft. Lauderdale tests.

In both of the demonstration hotel fire test series, photoelectric and ionization detectors were installed. The installation of both sprinklers and smoke detectors parallels the life safety goals of NFPA 13-D, Standard for the Installation of Sprinklers in One- and Two-Family Dwellings and Mobile Homes[9]. This standard assumes that one or more smoke detectors will be installed in accordance with NFPA 74, Standard for the Installation, Maintenance, and Use of Household Fire Warning Equipment[10]. In the Ft. Lauderdale guest room, with flaming-started fire tests[6], detectors responded on average 4 min 4 s prior to sprinkler activation. Thus, the detectors provided an early warning which would improve an occupant's chance for escape.

The present series of fire tests were designed to evaluate the life safety performance of an Underwriters' Laboratory (UL) listed[11] extended coverage horizontal sidewall sprinkler (hereafter designated ECHS sprinkler) and UL listed smoke detectors in a simulated hotel guest room and corridor. The ECHS sprinkler was equipped with a fast response link with a thermal response similar to those used in residential sprinklers. Results of eight flaming-started and four smoldering-started tests are reported. An additional focus of the study was the effect of ventilation on sprinkler actuation, detector response, and the room environment. Five different ventilation conditions were considered through variations in guest room and corridor ventilation, and disposition of the guest room door. The results reported in detail below indicate that the sprinklers employed in these tests, when used in conjunction with smoke detectors, provide a reliable means of enhancing the life safety of hotel occupants, while suppressing the fire.

Life Safety Criteria

Considerable research efforts have been made to quantify the effects of fire products on human health. Some recent reviews of research on causes of deaths in fires are available in[12-15]. Carbon monoxide is generally considered to be the primary contributor to death in fires. Inhalation of carbon monoxide at levels above approximately 100 ppm results in the formation of carboxyhemoglobin causing a decreased supply of oxygen to body tissues[13]. Other causes include narcosis from inhalation of hydrogen cyanide, low levels of oxygen and high levels of carbon dioxide, as well as effects due to heat. Hartzell, however, suggests that "in most real, full-scale, multi-material fires, ... to a good first approximation, tenability limits can be predicted solely on the basis of carbon monoxide produced"[14].

Maximum survivable levels of either gas concentration or temperature levels depend on time duration. A common method of accounting for the role of time in determining physiological effects of toxic gases is Haber's rule[15]. Haber's rule as applied to a single gas suggests that physiological effects for a given time-integrated value of gas concentration are equivalent. For example, Hartzell[14] suggests values of from 35,000 to 45,000 ppm-min of carbon monoxide as limits beyond which incapacitation (escape impairment) would be expected to occur. This range is consistent with the 43,000 ppm-min limit set in the Los Angeles Test Program[8]. If the effects of more than one gas are to be estimated, models expanding this use of Haber's rule to multiple gases are currently available[15].

Haber's rule is a linear approximation which provides a convenient method of evaluating toxic hazards. It is known to lose validity at low gas concentrations[15]. A more accurate model such as the Coburn-Forster-Kane model[15] provides a means of predicting deviations from a linear model of carbon monoxide-uptake. Quintiere, Birky, MacDonald and Smith[16] adopted this method to predict the time for incapacitation due to carbon monoxide in smoldering fires growing as the second power of time. Assuming that the incapacitation is associated with a carboxyhemoglobin level of 20% and that this level occurs in 150 minutes or less, they showed, however, that the criterion for carbon monoxide exposure could still be approximated with Haber's rule, i.e., as a limit on the time-integrated value of the carbon monoxide concentration. Attainment of the 20% carboxyhemoglobin level corresponded to a limit of 45,000 ppm-min. This is consistent with the limits suggested by Hartzell[14] and the time period of 150 minutes is comparable to the critical periods reported in the tests with smoldering combustion in the present study.

For comparison, the lethal limit of carbon monoxide for a 30 minute exposure can be estimated from data cited in Reference 15. An upper limit of 4,000 ppm is cited for an exposure of one-half hour. Using Haber's rule, we estimate a time integrated value of 120,000 ppm-min.

Physiological effects of elevated gas temperatures on humans are also known to depend upon time. For example, data cited in Reference 12 indicates 60 min toleration time at 70°C with decreasing toleration time at higher temperatures. At 140°C, a 5 min toleration time is cited. They note however that very rapid skin burns would be expected to occur at 100°C in humid air. In this context, the tenability limit of 93°C (200°F) at a 1.52 m (5 ft) elevation as used in the Los Angeles Residential Test Program[8] appears reasonable.

As noted by Hartzell[14], visual obscuration per se is not necessarily a dangerous physiological threat to life. However, it is well known that the reduced visibility, disorientation and stress caused by smoke can significantly impair the ability of a person to escape during fire. In a review of critical smoke levels for escape Harpe, Waterman, and Christian[17] judged that an optical density of 0.23 m^{-1} (0.07 ft^{-1}) appears to be a reasonable upper limit. This corresponds to an obscuration of 41% over a 1 meter path length (or 15% over a 1 ft). For comparison, tenability limits for obscuration over a 1 m (3 ft) path were set in the Ft. Lauderdale tests[6] and in "Operation San Francisco"[7] at 45% and 68% (17 and 29%), respectively. No obscuration criterion was set in the Los Angeles Test Program[8], since it was assumed that an occupant could survive to be rescued in the room of fire origin if the tenability criteria for carbon monoxide and gas temperature were satisfied and the occupants were not directly engulfed in flames.

Acknowledging the range and uncertainty of data on fire hazards, we have adopted the life safety tenability criteria of the Los Angeles Test Program: the time-integrated concentration of carbon monoxide is not to exceed 43,000 ppm-min and the maximum gas temperature at the 1.52 m level is to remain below 200°F (93°C). We emphasize that the criteria adapted here are established with the purpose of allowing occupants in the room of fire origin sufficient time to be rescued if necessary.

EXPERIMENTAL FACILITIES

Test Facility

A simulated guest hotel room measuring 4.12 m by 8.99 m was constructed along a corridor 1.83 m by 11.78 m (see Figure 1). The length of the living area of the guest room was 6.10 m. The hotel guest room and corridor were constructed to be typical of hotel/motel occupancies in the United States[18]. The ceiling height of the living area of the guest room was 2.44 m, while the ceiling height in the foyer and bathroom was 2.20 m. The ceiling height above the foyer provided space for the ventilation air supply. In Figure 1, the locations of the air supply register, bathroom exhaust and air return are noted. Ventilation conditions will be discussed in the following section.

The guest room shown in Figure 1 connected through a doorway (2.08 m x 0.79 m) to a hotel corridor. The corridor, 2.44 m high, was connected to an existing one-story test building (see Figure 1) with dimensions of 7.06 m x 11.59 m x 2.44 m. The hotel guest room and corridor were enclosed within a larger test volume (18.29 m (W) x 12.20 m (L) x 10.06 m (H). Fire products were vented through the corridor to the connecting building to provide a simulation of smoke flow through a hotel. The location of the corridor air supply is shown in Figure 1. At that end, the corridor was blocked in order to keep air from being entrained from the surrounding enclosure into the corridor. The total flow supplied by the corridor air supply could then be precisely measured.

Ventilation Systems

Ventilation was furnished to the guest room and corridor to simulate air movement in a hotel environment. Air was supplied from the surrounding enclosure to the guest room and corridor by two independent ventilation systems. In Figure 1, the location of the guest room air supply (a 15.2 cm x 51 cm louvered register) and the corridor air supply (a 76 cm x 36 cm louvered register) are noted. Two exhausts were installed within the guest room: a passive return register (41 cm x 41 cm) attached to a 2.44 m vertical stack on the roof of the hotel test room facility; and a commercial 0.0472 m/s (100 cfm) bathroom exhaust (see Figure 1). Air from the guest room exhausts flowed to the larger enclosure in which the hotel test facility was located. All air was supplied from the surrounding enclosure. As noted in the previous section, air movement in the corridor was exhausted into a previously existing one-story building. During fire tests, products of combustion from the 2.44 cm stack above the passive return were visibly convected to nearly the top of the 9.15 m ceiling of the larger enclosure and did not appear to mix with air supplied to the guest room and corridor by two blowers at a 2.74 m level.

In our study, we supplied 0.0945 m^3/s (200 cfm) of air through the register at the entry of the living area of the guest room. This represented approximately four room changes per hour. Exhaust was then through the passive return and the 0.0472 m^3/s (100 cfm) commercial exhaust in the bathroom. Air flow to the corridor was supplied at a flow rate of 0.680 m^3/s (1440 cfm) which calculates to an average flow speed of 0.15 m/s (30 fpm). Flow rates from the blower to the guest room supply register were set through the standard orifice plate measurements with pressure taps one diameter upstream and one-half diameter downstream of a circular orifice plate[19].

Furnishings

Nominal dimensions, weight and composition of key furnishings used in this study are shown in

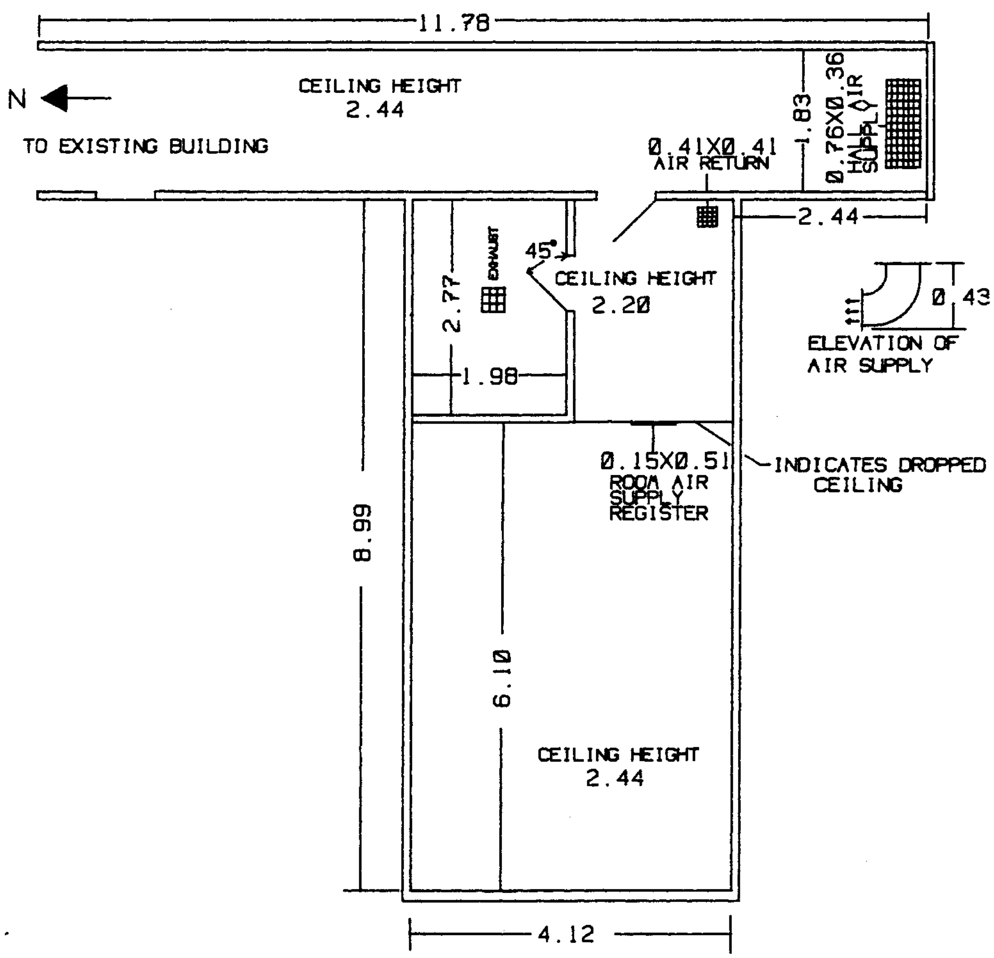

Figure 1. Plan view of guest room and corridor (dimensions in meters).

Table 1. All furnishings (except the table) were supplied by a New England hotel furnishings vendor. The bed mattress and box spring were in compliance with the Consumer Product Safety Commission Mattress Flammability Standard #16, Center for Fire Research (CFR) 1632 and passed the Federal Flammability Standard. The bedspread and drapes were treated with fire retardant chemicals and met U.S. Federal Specification CCC-T-191A. The chair was manufactured to pass Upholstered Furniture Action Council's specification for upholstered furniture, which certifies that the cover and filling material have been modified to reduce ignition by a burning cigarette.

Table 1. Description of furnishings

Item Dimensions (cm), and Weight (kg)	Description of Key Contents
Bed Mattress (135x191; 27 kg)	50% blended cotton felt 50% polyurethane
Box Spring (135x191; 25 kg)	Cellulose fiber pad
Mattress Pad (135x191; 0.6 kg)	Resin treated polyester fiber
Sheets (203x264; 0.6 kg)	Polyester/cotton percale
Bedspread (257x297; 1.9 kg)	Resin treated polyester fiber
Blanket (203x229; 1.3 kg)	Acrylic
Pillows (51x66; 0.6 kg)	Polyester fiber
Chair (66x71x62; 17 kg)	Body: 70% blended cotton batting 30% polyurethane foam Seat: 80% polyurethane foam 20% resin treated polyester fiber
Drapes (183x244; 3.3 kg)	50% cotton 50% polyester
Table (86D;76H; 12 kg)	Top: particle board covered with formica Legs: fir framing lumber

Test Sprinklers and Water Supply System

In each test one ECHS sprinkler equipped with a fast-response link (UL listed as an extended coverage sprinkler[11]) and two pendent sprinklers equipped with fast response links (UL listed as quick response sprinklers[11]) were installed with the deflectors 10 cm below the ceiling at the locations shown in Figure 2. The same model ECHS sprinkler and the same model pendent sprinklers were used throughout the test program. Both types of sprinklers are 1.27 cm (1/2 in.) orifice sprinklers with a temperature rating of 74°C (165°F) and a nominal K factor of 7.9 $dm^3/min/(kPa)^{1/2}$ (5.5 $gpm/psi^{1/2}$). The RTI of the ECHS sprinkler measured in a plunge test[20], with the sprinkler in the horizontal position and the gas flow parallel to the frame arms, was determined to be 29 $(m\text{-}s)^{1/2}$ (53 $(ft\text{-}s)^{1/2}$). The RTI of the pendent sprinkler, measured in the normal position, was 26 $(m\text{-}s)^{1/2}$ (47 $(ft\text{-}s)^{1/2}$). The coverage area for the ECHS sprinkler was the entire living area of the guest room. The pendent sprinklers were installed for coverage of the bathroom and foyer.

Water could be independently supplied during a test to each sprinkler. The flow rates for each sprinkler were independently monitored by rotameters. The flow rate for the ECHS sprinkler was 121 dm^3/min (32 gpm) as specified by the manufacturer. This provided an average water application density of 4.89 mm/min (0.12 gpm/ft^2) for the coverage area of the guest room. The flow rate for each of the pendent sprinklers was set at 94.6 dm^3/min (25 gpm).

Smoke Detectors

The locations of 15 smoke detectors are also shown in Figure 2. Two different model light scattering detectors were used in the test program. One model of ionization detector was used. The alarm threshold for the light scattering detectors was nominally set at an obscuration level of 3%/ft; the ionization detector threshold was nominally 1%/ft. The fifteen smoke detectors were grouped into five stations, each with two light-scattering detectors and one ionization detector. Two of the stations were on sidewalls and corresponded to typical locations in hotel rooms. The sidewall stations were mounted on a panel (see detail of Figure 2 for dimensions) with its top edge placed flush against the ceiling. The ceiling detector station in the center of the room (Detectors 7, 8, 9) provided information at a location fully instrumented for gas sampling, temperature, and smoke obscuration. Two ceiling detector stations were placed in the corridor, one outside the guest room door (Detectors 13, 14, 15); the other (Detectors 10, 11 and 12) was placed nominally 6.4 m (21 ft) away, the maximum distance a detector would be placed from a doorway in a typical corridor installation.

INSTRUMENTATION

Complete details and locations of instrumentation used in this study are given in References[21,22]. The instrumentation relevant to the discussion here includes thermocouples to measure gas and ceiling surface temperature, sampling ports for gas analysis for carbon monoxide, obscuration meters, and event markers to record sprinkler actuation and smoke detector response time. In each test, data from the instrumentation were acquired from 122 channels using an ADAC DISKBASYS 1200 System. The analog signals were digitized using a 12 bit A/D converter. The data were acquired at a rate of 1 scan per second and stored on a 10 Mb removable disk cartridge for subsequent

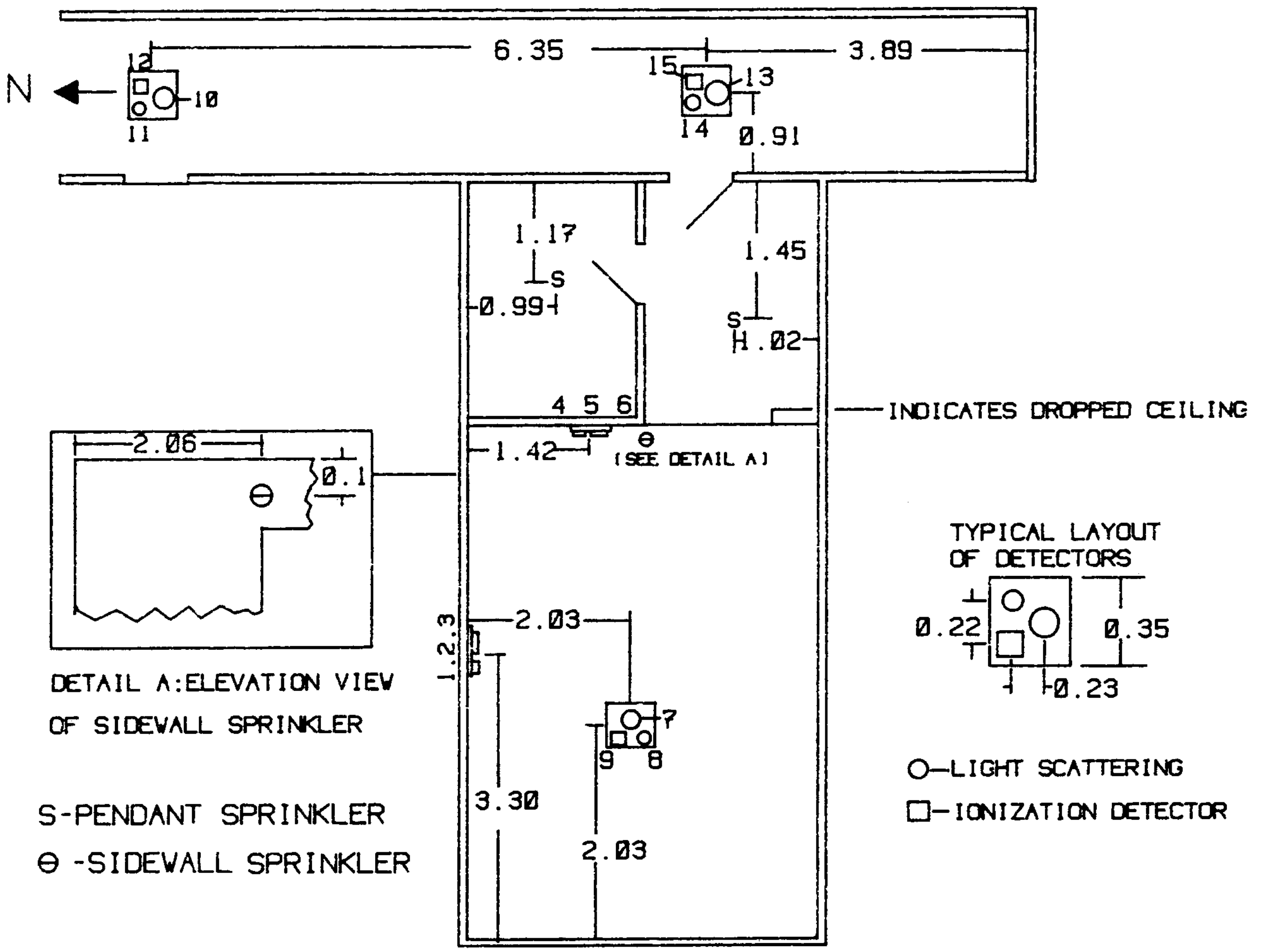

Figure 2. Sprinkler and smoke detector locations (dimensions in meters).

processing on a DEC micro PDP 11/23 computer. As a visual record, video tapes of all tests were recorded.

The thermocouples used in this study were fabricated from inconel-sheathed 30-gage chromel-alumel wire. The locations of thermocouples for gas temperature over ignition (elevation 2.29 m) and at an elevation 1.52 m (5 ft) in the guest room and corridor are shown in Figure 3. The location of the two ceiling surface thermocouples, embedded approximately 0.2 cm in the ceiling, are also shown.

The locations of four gas sampling ports in the guest room and corridor are shown in Figure 4. At all locations, gas sampling occurred at a rate of approximately 10 ℓ/min. The gas samples were drawn to analyzers through 0.6 cm diameter nylon tubing. Gases were passed through a des-

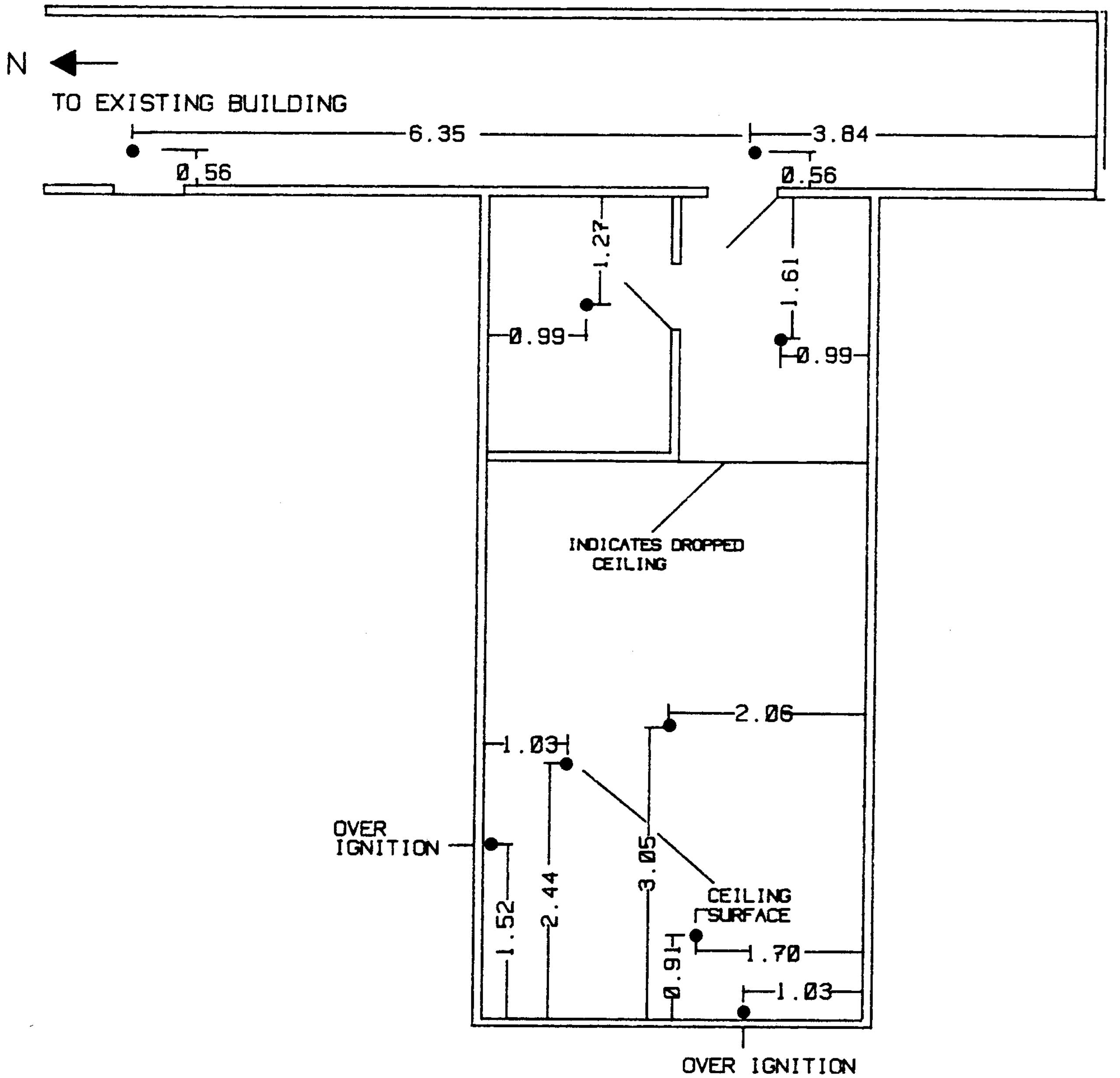

Figure 3. Thermocouple locations (dimensions in meters).

iccant prior to entering the analyzers. Carbon monoxide concentrations were obtained from each of the 1.52 m (5 ft) elevation sampling locations shown in Figure 4, using commercial infrared gas analyzers. In addition, carbon monoxide measurements were obtained from the sampling port in the center of the living area of the guest, 9 cm below the ceiling. As indicated in Figure 4, measurements of oxygen and carbon dioxide concentrations were also obtained.

Obscuration meters were located at four locations within the living area of the guest room (three at the ceiling level near each of the three smoke detector stations shown in Figure 2 and one at the 1.52 m (5 ft) level in the center of the room). The three ceiling-mounted obscuration meters were constructed using the design of Newman and Steciak[23]. The pathlength for these obscuration meters was 0.30 m (1 ft). The obscuration meter at the 1.52 m (5 ft) level was modified from a commercially available projected beam detector. Measurements were over a pathlength of 0.30 m (1 ft) and at a wavelength of 0.94 microns.

Three obscuration meters were installed in the corridor (two at the ceiling level near the smoke detector stations shown in Figure 2 and one at the 1.52 m (5 ft) level outside the guest room doorway). All three meters followed the design of Newman and Steciak[23]. The pathlengths for

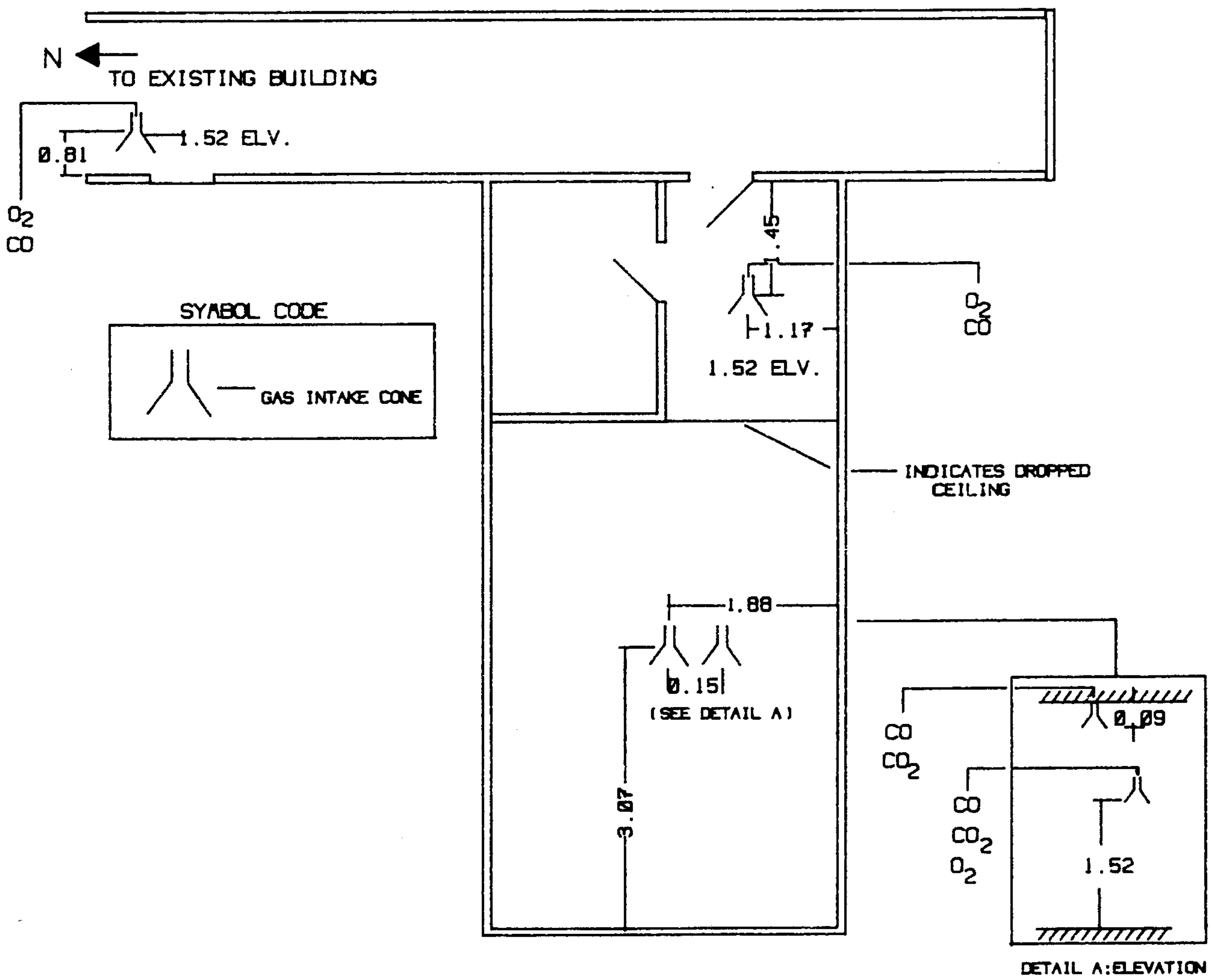

Figure 4. Gas sampling port locations (dimensions in meters).

these meters were 0.30 m (1 ft), and the wavelengths for all three meters were 0.4579 microns.

TEST CONDITIONS AND PROCEDURES

Description of Tests

Twelve different fire tests were conducted in this test series. These twelve tests consisted of four flaming-started fire tests using a chair, drapes and a table; four flaming-started fire tests using a standard bed; and four-smoldering-started fire tests also using a standard bed.

The test scenarios are listed in Table 2 along with the test numbers. The locations of the furnishings for both the flaming-started and smoldering-started tests are shown in Figure 5. (A description of these furnishings is given above in Table 1.) For the flaming-started chair fire tests, the only furnishings in the room were the chair, drapes, table and a metal waste-paper basket (not shown in Figure 5) filled with ten sheets from a newspaper. The metal waste-paper basket was placed on the side of the chair, flush with the corner closest to the table. The detail in Figure 5 illustrates the installation of the drapes with respect to the chair.

The flaming-started bed tests only involved the bed and bed furnishings listed in Table 1, along with a metal waste-paper basket filled with ten sheets of newspaper. Ignition in all of the flaming-started fire tests was by an electric match energized remotely from outside the test room. The electric match was inserted at the bottom of the metal waste-paper basket.

In the smoldering-started fires, the bed scenario was used. The scenario was similar to that used in the CFR 1632 mattress test[24] in that no mattress pad was used. A commercially available cartridge heater was placed adjacent to the folds of the bed sheets and a pillow (see Figure 5 for location of heater). The power output of the heater was approximately 42 watts. Smoke began to be generated in these tests approximately 8 minutes after the cartridge heater was energized. Forty minutes after the beginning of the test, power was turned off. No further external heating was supplied in any of the smoldering-started tests. Self-sustained smoldering was achieved for more than 5 hours in all four tests. Only in Test 11 did flaming combustion spontaneously result from the smoldering combustion induced by the heater. The other tests were aborted after six hours.

Ventilation conditions associated with each test are indicated in Table 2. (The ventilation systems are described above.) In Table 2, tests with "full ventilation" indicate that 0.0945 m^3/s (200 cfm) of air was supplied through the guest room register, the bathroom exhaust was operating (0.0472 m^3/s; 100 cfm), and that 0.680 m^3/s (1440 cfm) was supplied through the corridor register. "Corridor ventilation only" indicates that the guest room register was blocked; the bathroom exhaust was not on, but 0.680 m^3/s (1440 cfm) was supplied to the corridor.

In Test 12, a smoldering-started test, the guest room door was open; however, the door from the corridor to the connecting building was shut as simulation of a fire door. In that test corridor ventilation was reduced to 0.094 m^3/s (200 cfm).

Table 2. Fire test scenarios

Test No.	Description
1.	Flaming-started chair fire test; full ventilation; door open.
2.	Flaming-started chair fire test; full ventilation; door closed.
3.	Flaming-started chair fire test; corridor ventilation only; door open.
4.	Flaming-started chair fire test; corridor ventilation only; door closed.
5.	Flaming-started bed fire test; full ventilation; door open.
6.	Flaming-started bed fire test; full ventilation; door closed.
7.	Flaming-started bed fire test; corridor ventilation only; door open.
8.	Flaming-started bed fire test; corridor ventilation only; door closed.
9.	Smoldering-started bed fire test; corridor ventilation only; door open.
10.	Smoldering-started bed fire test; corridor ventilation only; door closed.
11.	Smoldering-started bed fire test; full ventilation; door closed.
12.	Smoldering-started bed fire test; corridor ventilation (200 cfm); guest room door open; corridor door closed.

In all tests, the bathroom door was ajar at an angle of 45°.

Water Application Rates

In order to estimate the quantity of water applied to the fire sources in our fire tests and variations between sprinklers of the same model type, water application densities (mm/min) under non-fire conditions were measured in the areas covering the two fire test scenarios, i.e., the area covering the chair and the area covering the bed. Water was collected in .30 m x .30 m (1 ft x 1 ft) pans with 10 cm (4 in.) sides. The pans were placed at a height of 46 cm, approximately the height of the bed and the seat of the chair. Results were obtained in the chair area for the ECHS sprinklers used in Tests 1 to 4 and in the bed area for the sprinklers used in Tests 1, 3 and 5.

The average water application density in the chair area for eight distribution tests (four different sprinklers) was 2.65 mm/min (0.065 gpm/ft^2) with the average density varying from 2.00 to 2.97 mm/min (0.049 to 0.073 gpm/ft^2). The design density for the room is 4.89 mm/min (0.12 gpm/ft^2). Each water distribution test in the chair area for a given sprinkler was repeated once. Results were repeatable within 5%. The average water application in the bed area for four distribution tests (four different sprinklers) was 2.08 mm/min (0.051 gpm/ft^2), with the density varying from 1.87 to 2.36 mm/min (0.046 to 0.058 gpm/ft^2). Only one of the water distribution tests was repeated in the bed area. The results agreed within 7%.

RESULTS

Flaming-Started Chair Fire Tests

In all four chair tests (Tests 1 to 4), flaming was first initiated in the waste-paper basket at the side of the chair. Flaming combustion did not occur on the side of the chair until the paper in the basket was nearly consumed and the flame height had subsided to the top of the basket. After initiation of flaming combustion on the side of the chair, the flame spread up the side to the top of the chair and then ignited the curtains. The curtains were completely consumed in all four fire tests; however, sprinkler actuation suppressed the fire in the chair before more than half of the fabric of the chair was involved.

Results within the guest room were not greatly affected by the disposition of the guest room

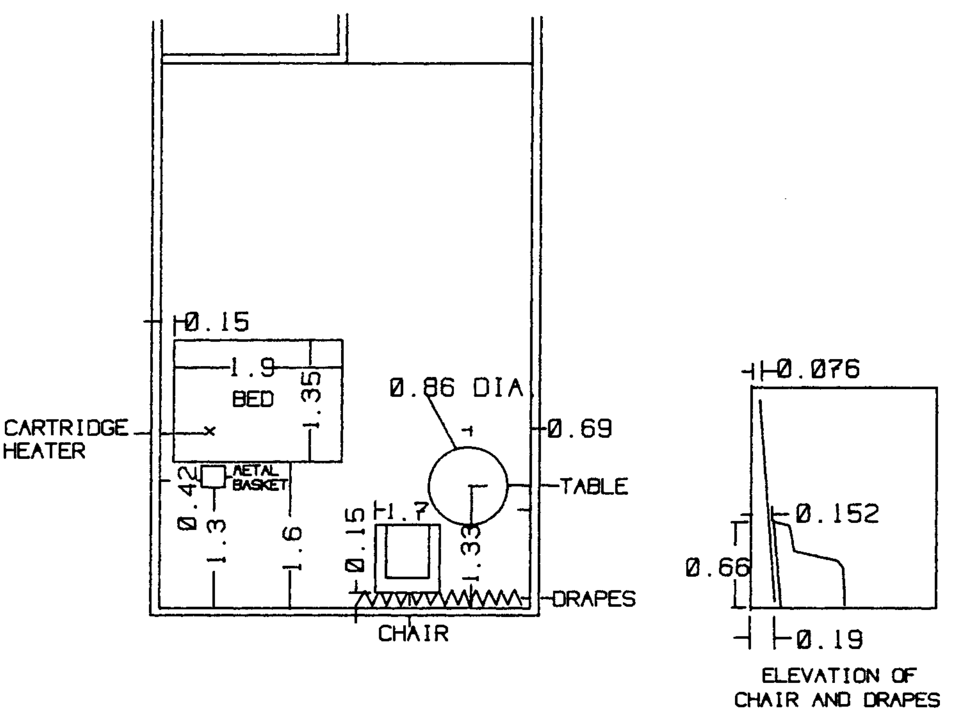

Figure 5. Locations of guest room furnishings (dimensions in meters)

door in Tests 1 to 4. Some typical results will now be reported for Test 1. In Figure 6, gas temperature over the chair at an elevation of 2.29 m (see Figure 3) and at the 1.52 level in the center of the room are shown along with the ceiling surface temperature measured near the chair in Test 1. In this test, both the ECHS sprinkler and the pendent sprinkler in the foyer (Figure 2) actuated at 267 s. (The pendent sprinkler in the bathroom did not actuate in this test nor in any other of the 12 tests.) At 267 s, the gas temperature over the chair achieved its maximum of 791°C. At the same time the gas temperature reached a maximum of 108°C at the 1.52 m level in the center of the room. With sprinkler actuation, gas temperature throughout the room decreased rapidly. A maximum temperature of 81°C was achieved at the ceiling surface near the chair 5 sec after sprinkler actuation.

Table 3 indicates gas temperature maxima at various locations in the guest room and corridor at the 1.52 m level for all flaming-started tests. Maxima at the center of the room, T_{center}, center of foyer, T_{foyer}, and outside the guest room door, T_{door}, were all achieved approximately at the same time as sprinkler actuation. In Test 1 these maxima were 108°C, 63°C and 66°C, respectively. The maximum gas temperature at the end of the corridor (1.52 m elevation) was 29°C. The period of time for which the gas temperature was above 93°C in the center of the room was less than 15 s. Gas temperatures decreased in the direction of the guest room door and the corridor. It should be noted that in all eight flaming-started tests, gas temperatures at the 1.52 m level exceeded the critical value of 93°C for less than 20 s.

In Figure 7, carbon monoxide gas concentration are shown from the four gas sampling locations shown in Figure 4. Results shown in Figure 7 have not been corrected for the lag time due to sampling (approximately 40 s) or instrument response time. A peak concentration of 2254 ppm occurred at the ceiling near the time of sprinkler actuation. Lower peaks occurred at the other 1.52 m locations in the guest room. After sprinkler actuation, carbon monoxide concentration was highest at the 1.52 m level in the center of the guest room, presumably due to mixing and cooling of gases by the sprinkler. A constant concentration of 1433 ppm would produce a time integrated value of 43,000 ppm-min

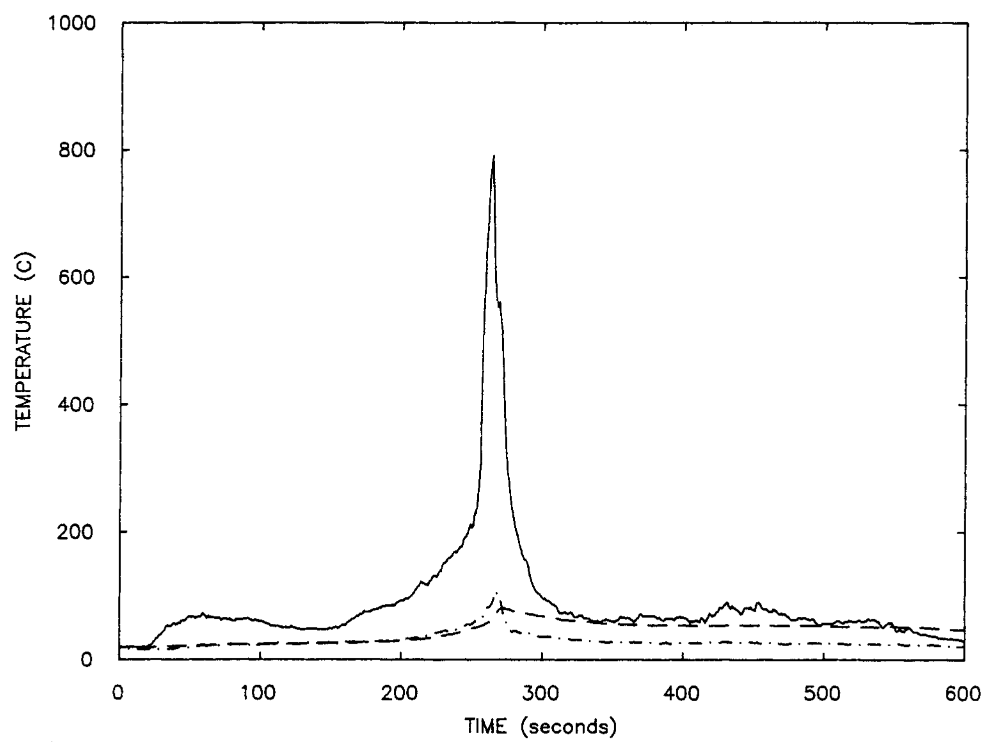

Figure 6. Gas temperatures: over ignition, ——; 1.52 m at the center of room, - . - ; and ceiling surface temperature,— — —; Test 1.

over a thirty minute period. From Figure 7, it is clear that the time integrated carbon monoxide levels are well below this level. With the door open, carbon monoxide concentration levels fell at all locations after sprinkler actuation. The concentration levels decreased in the direction of the guest room door and decreased further into the corridor. The maximum concentration in the corridor was only 237 ppm.

Obscuration measurements are shown at the ceiling and 1.52 m level in the center of the guest room and outside the door in the corridor for Test 1 in Figure 8. The results are typical of the obscuration levels achieved in the guest room in all eight flaming-started tests. Obscuration levels are reported for a 0.30 m (1 ft) pathlength at a wavelength of 0.555 microns, the peak in sensitivity of the human eye. The data has been corrected to this wavelength using the method reported by Newman and Steciak[23]. (This correction technique is discussed in Reference 21, and data are reported from the present study indicating the validity of the correction.)

In Figure 8, it is evident that obscuration approaches 100% in the room at the time of sprinkler actuation (267 s). (Note that due to the electronics, the commercial obscuration meter at the 1.52 m level in the center of the room saturated at slightly below 90% obscuration.) A review of smoke detector response times for Test 1 indicates that even for the slowest responding smoke detector, obscuration at the 1.52 m level did not exceed 15% at the time of response. An occupant alerted by the smoke detectors could easily leave the guest room. By the time of sprinkler actuation, an occupant would have a more difficult time escaping. Based on the criteria selected for this study, the data indicate that tenability was maintained after sprinkler actuation. Presumably an occu-

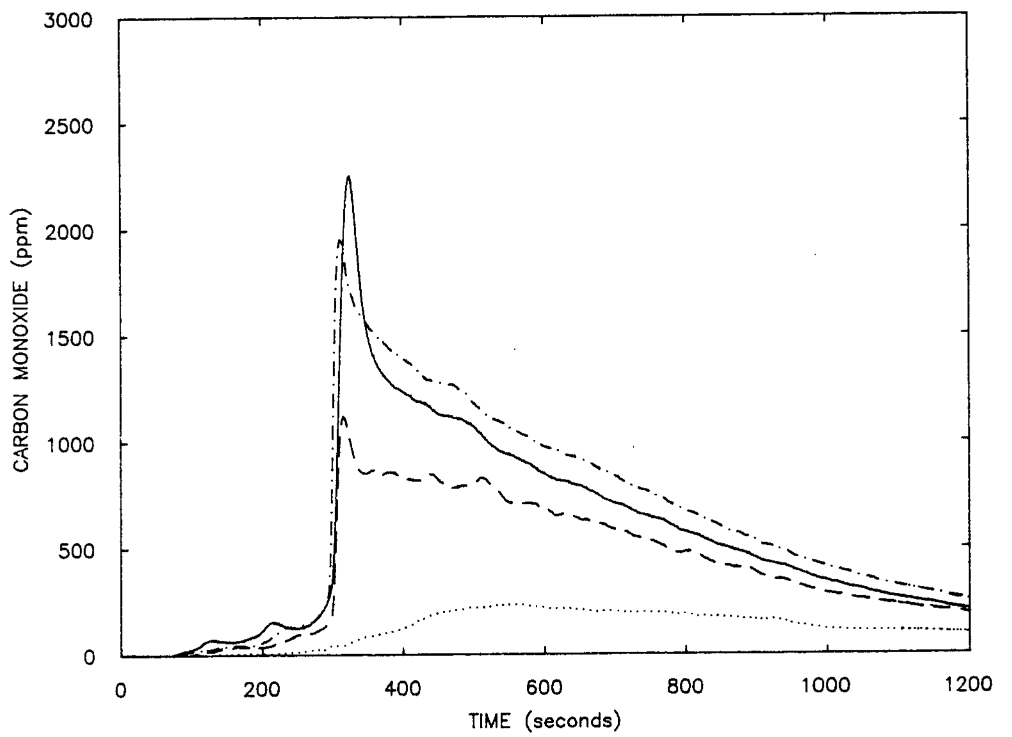

Figure 7. Carbon monoxide concentration: room center at ceiling, —; room center at 1.52 m, —.—; foyer, — — —; end of corridor, ...; Test 1.

pant failing to escape but not in contact with the fire could still be rescued more than 30 minutes after fire initiation.

Obscuration results are also shown in Figure 8 at two levels outside the guest room door. The obscuration levels peak approximately at the time of sprinkler actuation. This was typical of all flaming-started tests in which the door was open. The effect of ventilation in the corridor was to prevent any significant smoke concentration from occurring in the corridor prior to the occurrence of rapid fire growth. Obscuration measured at the end of the corridor at the ceiling (not shown in Figure 8) was essentially the same as that measured outside the door at the ceiling in all 12 tests.

Because the fire was suppressed by the sprinkler and the corridor was ventilated, smoke concentration in the corridor did not significantly increase after sprinkler actuation. A reduction in buoyancy of the gases after sprinkler operation resulted, however, in higher obscuration levels at the 1.52 m level compared to the ceiling. Recalling that tenability limits for obscuration over a 1 ft pathlength have been cited in a range of from 6 to 29%, we conclude that obscuration levels remained near the limit of visibility in the corridor after sprinkler actuation.

The response times for sprinklers and smoke detectors are summarized for all flaming-started fire tests in Table 4. Room detectors responded on average 172 s before sprinkler actuation (Table 4). The gas temperature at an elevation of 1.52 m was never more than 38°C when guest room detectors responded. Thus, early alert by smoke detectors would improve the escape potential of occupants in all flaming-started tests.

Corridor conditions as indicated by "$T_{corridor}$" in Table 3 varied depending upon whether the door was open (odd numbered tests) or closed (even numbered tests). In tests with the door closed (Tests 2 and 4), corridor gas temperatures remained essentially at the initial temperature and smoke obscuration was never more than 5% over a 0.30 m pathlength. No corridor detectors responded in Test 4 in which there was no ventilation in the room and the door was closed. In contrast, with the door open all corridor detectors responded, and the gas temperature at the 1.52 m level outside the doorway (Table 3) was as high as 66°C. The gas temperature at the 1.52 m level, however, decreased to no more than 29°C at the end of the corridor. Obscuration results within the corridor in Test 3 were similar to those reported in Figure 8 for Test 1. Corridor detectors responded 7-35 s before the first sprinkler actuation in these two tests (Table 4).

Ventilation conditions and the disposition of the guest room door were observed to have an effect upon the carbon monoxide concentration levels in the guest room. Figure 9 compares carbon monoxide concentrations at the 1.52 m level in the center of the room from Tests 1 to 4. A clear effect of maintaining the door open in Tests 1 and 3 was the reduction in carbon monoxide concentration levels after sprinkler actuation compared to Tests 2 and 4. Concentrations in Test 1 were less than those in Test 3, probably

Table 3. Summary of results or flaming-started fire tests

	Maximum Temperatures					Maximum Gas Concentration	
Test No.	T_{center} (°C)	T_{foyer} (°C)	T_{bath} (°C)	T_{door} (°C)	$T_{corridor}$ (°C)	CO (ppm)	CO_2 (%)
1	108	63	41	66	29	1953	1.8
2	97	87	42	20	21	1989	1.5
3	101	71	41	53	27	1576	1.5
4	92	91	48	22	23	1431	1.6
5	91	71	47	63	33	1357	1.3
6	93	87	55	20	21	1701	1.3
7	121	97	55	59	34	2426	2.1
8	108	95	61	23	23	1143	1.6

due to the effect of fresh air supplied through the room register. In Test 2 with the door closed, carbon monoxide still decreased as combustion products were vented through the bathroom exhaust and the passive return. In Test 4 in which the room door was closed and no ventilation was supplied to the guest room, carbon monoxide levels remain practically fixed throughout the test at a level of approximately 1100 ppm. At this level the 43,000 ppm-min limit would be achieved in 39 minutes.

Flaming-Started Bed Tests

Sprinkler and detector performance in the flaming-started bed tests (Tests 5 to 8) was similar to that observed in the flaming-started chair tests (see Tables 3 and 4). The fire was suppressed in all four tests, and survivability within the guest room was maintained for at least 30 minutes in all four tests except Test 7 in which the carbon monoxide criterion was exceeded 25 min, 45 s after ignition. Data from the two test scenarios shown in Table 3 indicate the similarity of the eight tests. Note that in Test 7, the maximum gas temperature at the 1.52 m level in the center of the room reached 121°C. However, the temperature was above 93°C for less than 20 s.

The most significant differences between the two test scenarios are related to the production of carbon monoxide and the degree of fire suppression. In contrast to the chair and drape scenario in which carbon monoxide concentration decreased after sprinkler actuation (Figure 9), no decrease in carbon monoxide concentration was observed near the time of sprinkler actuation in the bed tests. At the end of the fire tests, an inspection of the beds showed that while the fire was extinguished on the surface of the bed, smoldering and small flamelets were observed in the box spring. Apparently the bedding materials

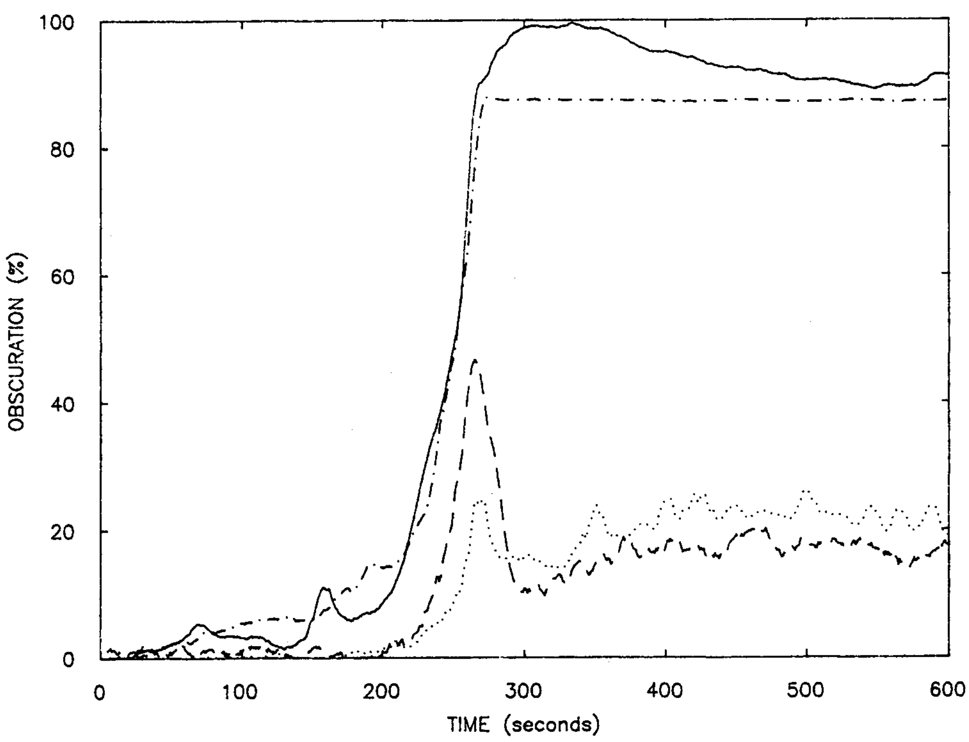

Figure 8. Obscuration over a 0.30 m pathlength at 0.555 microns; center room: 2.35 m, —— ; 1.52 m, — . — ; corridor (outside door): 2.35 m, — — ; 1.52 m, ... ; Test 1.

Table 4. Summary of smoke detector and sprinkler response time for flaming-started fire tests*

Test #	Guest Room Smoke Detector Response Time(s)	Corridor Smoke Detector Response Time(s)	ECHS Response Time(s)	Foyer Sprinkler Response Time(s)
1	36-180	238-255	267	267
2	29-57	455-562[a]	196	no operation
3	32-182	221-249	258	256
4	24-34	no response	248	245
5	27-88	143-176	235	233
6	20-57	624-784[a]	262	no operation
7	22-61	106-195	175	169
8	29-91	no response	197	192

*The pendent sprinkler in the bathroom did not actuate in any test.
[a]Two detectors did not respond.

and top mattress provide some shielding for the fire from sprinkler spray. Thus carbon monoxide continued to be generated after sprinkler actuation. This contrasts with the chair tests in which the fire was extinguished in the chair.

Carbon monoxide concentration levels at the 1.52 m level in the center of the room are shown in Figure 10 for Tests 5 through 8. In Test 5, as in Tests 1 through 4, data acquisition was halted approximately 10 min after sprinkler

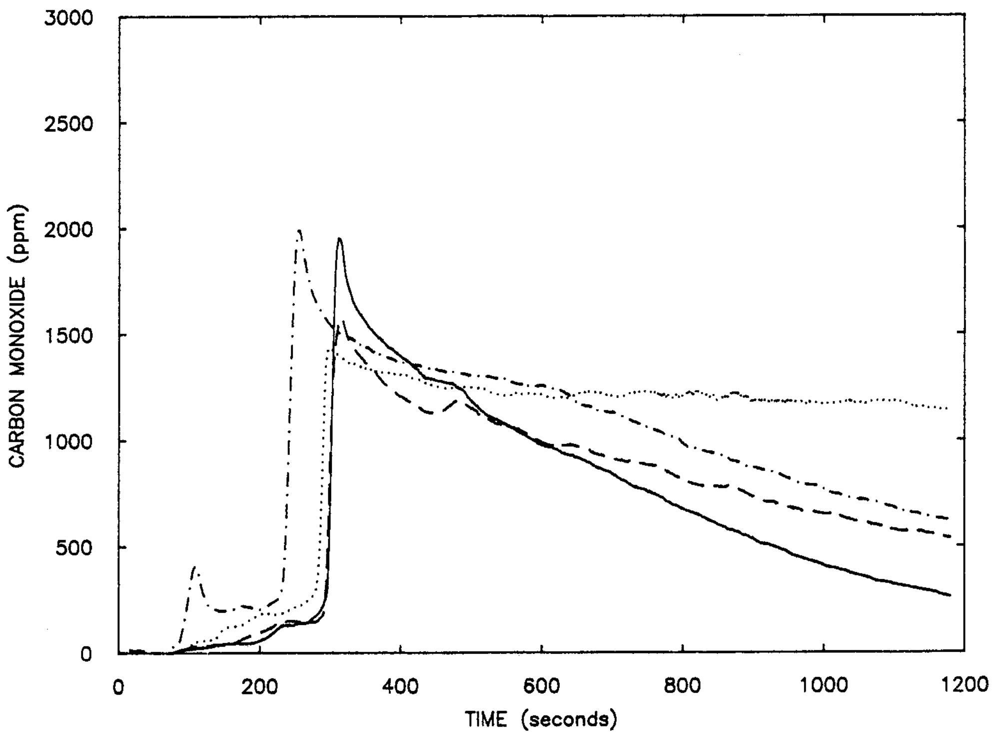

Figure 9. Carbon monoxide concentrations at the 1.52 m level in the room center: Test 1, —; Test 2, — —; Test 3, — . —; Test 4, ...

actuation. At this time, carbon monoxide concentration levels had not significantly decreased. In subsequent tests, data were acquired for 25 min beyond the time of sprinkler actuation. Concentration levels in Test 5, up to 900 s, are comparable to those in Tests 6 and 8. Presumably, the concentration levels in Test 5 (in which the guest room door was open) would have eventually decreased at a more rapid rate than in Test 6 (door closed). In Tests 5, 6, and 8, maximum carbon monoxide levels were such that the time integrated value of carbon monoxide would not exceed 43,000 ppm-min for at least 30 min after sprinkler actuation. Note that in Test 8, as in Test 4, in which the door was closed and the room was unventilated, the carbon monoxide concentration became essentially constant.

In Test 7, the generation of carbon monoxide was significantly increased compared to Tests 5, 6 and 8. The time integrated value of carbon monoxide was exceeded 25 min 45 s into the test (22 min 52 s after sprinkler actuation). No obvious cause for this difference is apparent, particularly in light of the carbon monoxide measurements for Test 3 shown in Figure 9. (Recall that ventilation conditions for Test 3 were the same as those of Test 7.) Observation of the fire spread in these tests suggests that the carbon monoxide generation may have been a function of the particular fire history in each test. We note that in the bed tests, fire spread was less repeatable than in the chair tests. In Test 5, the fire spread primarily across the head of the bed near the pillows, while in Tests 6 and 8, the fire also spread about half way down the side of the bed. In Test 7, the fire spread was primarily down the side of the bed with flames eventually reaching the end of the bed. The fire intensity, also appeared to be greater in this test. Thus, the effect of ventilation on carbon monoxide generation in the flaming-started bed tests is unclear.

Obscuration results were similar in Tests 5 through 8 to those observed in Tests 1 through 4. Results in the guest room and in the corridor with the door open were similar to those shown in Figure 8. In tests in which the guest room door was closed, obscuration in the corridor remained below 5% at either the ceiling or 1.52 m elevation.

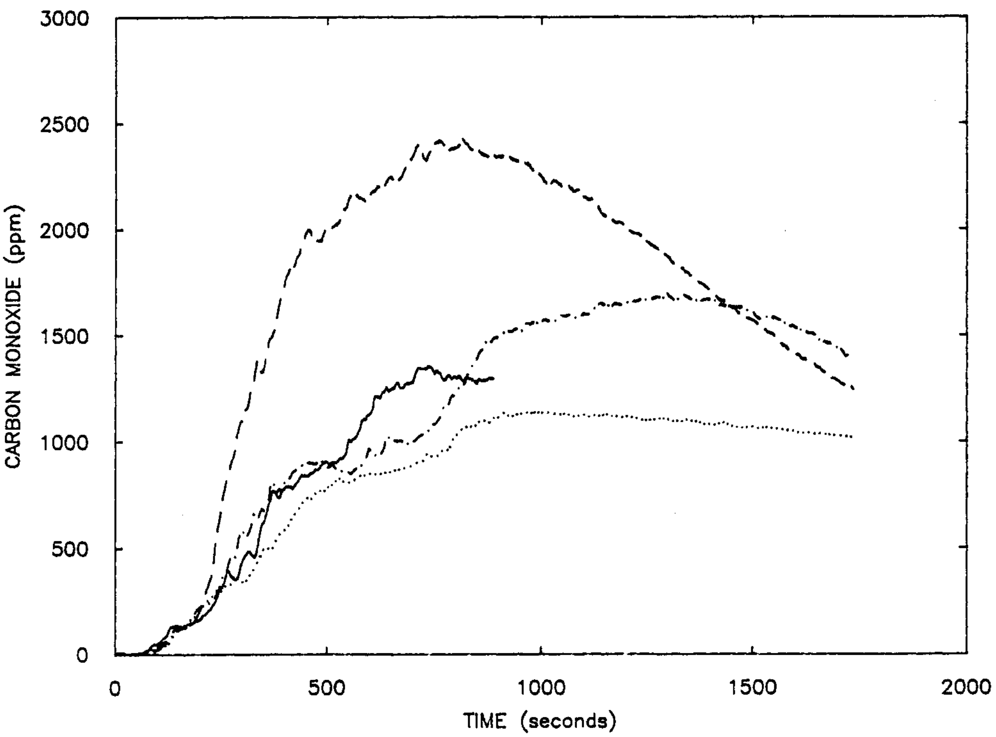

Figure 10. Carbon monoxide concentration at the 1.52 m level in the room center: Test 5, —; Test 6, — . —; Test 7, — —; Test 8, ...

Detector and sprinkler response times for Tests 5 through 8 are summarized in Table 4. Guest room smoke detectors responded while obscuration was less than 15%, carbon monoxide concentration was less than 100 ppm and gas temperature at the 1.52 m level was less than 38°C. The average time between detector response and sprinkler actuation was 166 s.

Corridor-detectors responded in a similar manner to those in the chair fire tests, although in Test 7, two detectors (Nos. 14 and 15) directly outside the guest room door responded 18 and 20 s after sprinkler actuation, in contrast to Test 3 in which all corridor detectors responded before sprinkler actuation.

No significant effect of ventilation on sprinkler or detector response in the guest room was observed in Tests 1 through 8, nor was any significant effect on response due to detector location observed.

Smoldering-Started Tests

Self-sustained smoldering was observed in each of the four tests after the external heat source was disconnected. The propagation of the smoldering combustion, as indicated by discoloration and deformation of the bedding, appeared to be remarkably similar from test to test. Typically smoke was generated by the cartridge heater 8 min into the test. By the time that the power to the heater was disconnected at 40 min into the test, the pillow cover and sheet adjacent to the heater were blackened in an area approximately 15 cm along the length of the pillow and approximately 8 cm high. One hour into the test, an area approximately 30 cm in diameter, centered on the heater, appeared to be discolored. By 2 hours into the test, the smoldering wave had propagated the entire length of the pillow (66 cm) which was adjacent to the heater. An hour later, the pillow adjacent to the heater appeared to be consumed by the smoldering process and discoloration was evident over one-third of the other pillow. At 4 hours into the test, the smoldering wave had propagated about half way down the side of the mattress closest to the heater and the pillow on the opposite side was discolored over approximately two-thirds of its surface. The region of smoldering had the appearance of a quadrant of a circle. At 4-1/2 hours into the test, the smoldering combustion wave had propagated three-fourths of the way across the top of the mattress. Five hours into the test, the combustion wave had propagated almost the entire length of the top of the mattress and two-thirds down the side of the bed. At this time production of smoke began to accelerate. Only in Test 11, however, did transition to flaming occur. By the sixth hour, the bed became totally obscured by smoke to observers viewing outside the test facility (except in Test 9, where the guest room door was open and the corridor vented into the connecting test facility). All tests were aborted after six hours, except for Test 11, in which sprinkler actuation occurred.

The key results for Tests 9 through 12 are summarized in Table 5. These are: 1) detector and sprinkler response times, 2) times to exceed the 43,000 ppm-min limit for CO at two locations (tenability time), 3) total time integrated CO for two locations, $\int CO_{dt}$, 4) maximum CO at three locations, and 5) maximum gas temperature at two locations.

Ventilation conditions (Table 2), as outlined above, significantly affected the levels of carbon monoxide and obscuration in the guest room and corridor. Carbon monoxide concentrations at the 1.52 m level in the room center are shown in Figure 11. (Note that in Test 11, due to an instrumentation problem, carbon monoxide concentration was not recorded prior to 4 hr 20 min.) Carbon monoxide levels were highest in Test 10 in which there was no room ventilation and the door was closed. The instrument maximum of 5000 ppm was reached 5 hr 45 min into the test. At that time, obscuration in the guest room reached a maximum of almost 80% at 1.52 m in the center of the room. With the guest room door open in Test 9, the levels of carbon monoxide were reduced by an order of magnitude, and obscuration in the guest room was reduced to less than 15% over a pathlength of 0.3 m. Test 11, in which the guest room door was closed but ventilation was supplied at a rate of four room changes per hour, produced concentration levels of carbon monoxide intermediate to Tests 9 and 10 in the guest room (see Figure 11). In Tests 9 through 11 the corridor was supplied with fresh air at a rate of 0.680 m^3/s (1440 cfm), which was freely vented to an adjoining test facility. This level of ventilation was sufficient to maintain carbon monoxide concentration levels in the corridor below 106 ppm. Obscuration in the corridor for Tests 9 to 11 was less than 10% over a 0.30 m pathlength. Test 12, in which corridor ventilation was reduced to 0.0945 m^3/s (200 cfm) and the door at the end of the corridor was closed, produced levels of carbon monoxide in the corridor approximately the same as that at the 1.52 m level in the center of the guest room (Figure 11).

Although the levels of carbon monoxide varied appreciably from test to test, the time integrated value of carbon monoxide eventually exceeded 43,000 ppm-min at the 1.52 m level in the foyer in all tests. (In Test 11 carbon monoxide levels at the 1.52 m level prior to 4 hr 20 min were estimated from ceiling data, i.e., the ratio of carbon monoxide at the 1.52 m levels to the ceiling level was fixed at the ratio occurring at 4 hr 20 min.) Furthermore, the lethal limit of 120,000 ppm-min was also exceeded by the end of all smoldering tests except Test 9. The integration time period was 6 hr for all tests except Test 11, in which it was 5.4 hr.

Transition to flaming combustion only occurred in Test 11. In this test, the transition occurred approximately 5 hours into the test. Figure 12 indicates gas temperature as a function of time at the 1.52 m level in the center of the room. The room was ventilated, and perhaps the addition of fresh air caused the transition to occur; however, an uncontrolled test variable, relative humidity, may also have been significant. In Test 11, the relative humidity was 40%. In contrast, in the other three tests, the relative

Table 5. Summary of results for smoldering-started tests

Results	Test 9	Test 10	Test 11	Test 12
Guest room detector response (min)	12-46	15-45	14-81	12-93
Corridor detector response (min)	no response	no response	300-307	102-232
ECHS sprinkler actuation time (min)	no response	no response	307	no response
Room center (1.52 m) Tenability Time (min)**	tenability limit not exceeded	174	300+	228
Foyer (1.52 m) Tenability Time (min)**	226	143	251+	150
$\int CO_{dt}$ (ppm-min) room center (1.52 m)	35,900	375,000	62,000+	268,000
$\int CO_{dt}$ (ppm-min) foyer (1.52 m)	90,300	437,000	127,000+	328,000
CO_{max} **room** (ppm)	387	>5000*	1100	3730
CO_{max} **foyer** (ppm)	589	4820	2290	3620
CO_{max} **corridor** (ppm)	106	56	instrument malfunction	3840
T_{max} 1.52 m room (°C)	36	47	103	59
T_{max} near sprinkler (°C)	35	47	142	61

*Meter off scale.
**Time to reach 43,000 ppm-min of CO.
+Carbon monoxide concentration prior to 4 hr 20 min estimated from ceiling data.

humidity varied from 60% to 100% (raining).

All guest room detectors responded in all four tests while the room was tenable with respect to carbon monoxide and gas temperature. Obscuration was typically 5% or less at the time of response. The average advance warning time provided before the time integrated value of carbon monoxide exceeded 43,000 ppm-min was 2 hr 42 min. The average time in the four tests at which this condition was exceeded was 3 hr 12 min.

No corridor detectors responded in Tests 9 and 10 despite tenability limits being reached in the guest room. In Test 11, in which flaming occurred, the corridor detectors responded on average 3.5 min before the actuation of the sprinkler even though the guest room door was closed. Obscuration in the corridor was no more than 10% over a 0.3 m pathlength throughout Test 11. In Test 12, two corridor detectors responded before the carbon monoxide limit of 43,000 ppm-min had been exceeded in the guest room. The slowest responding corridor detector responded 4 min after the carbon monoxide limit had been reached.

In Test 11, in which transition to flaming occurred, two sprinklers actuated: the extended coverage sidewall sprinkler equipped with a fast response link and the pendent, fast response sprinkler in the foyer. The fire was extinguished. At the time of actuation, however, tenability limits for carbon monoxide were exceeded and obscuration in the guest room was greater than 80%. Sprinkler actuation did not occur in any other test.

CONCLUSIONS

The extended coverage, horizontal sidewall sprinkler equipped with a fast-response link suppressed the fire in all eight flaming-started fire tests in this study. Generally, survivability criteria based upon 1.52 m level gas temperature and time-integrated carbon monoxide concentration levels within the guest room were satisfied. No more than two sprinklers actuated within the guest room under the ventilation conditions of this study, i.e., the extended coverage, sidewall sprinkler and pendent sprinkler in the foyer. Smoke detectors in the guest room responded on average 2 min 50 s before sprin-

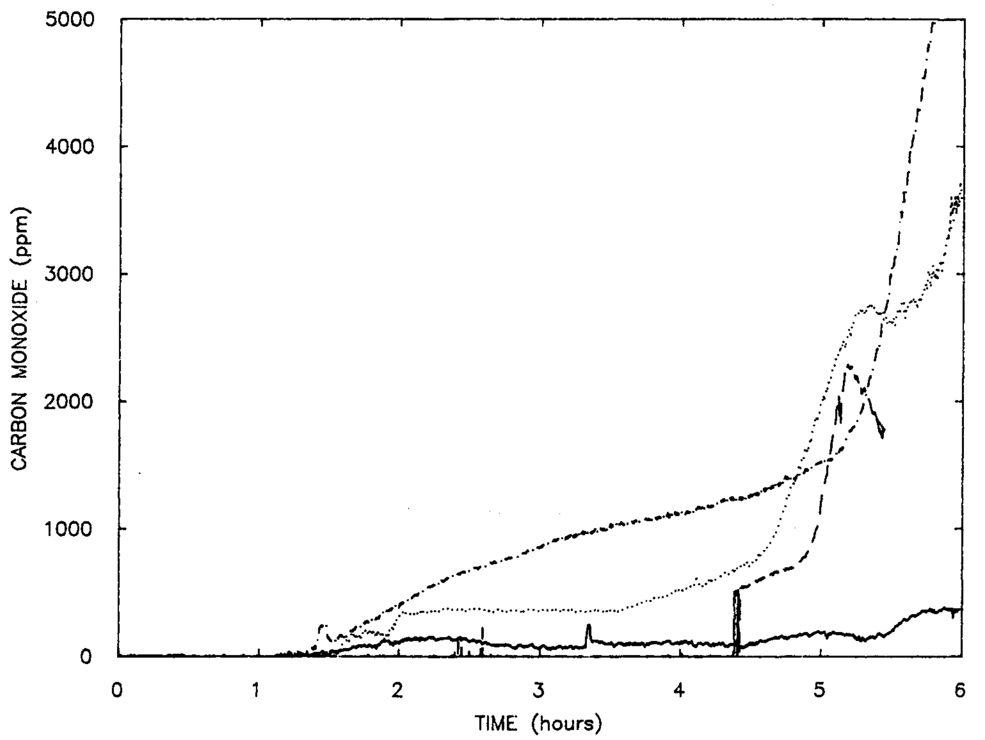

Figure 11. Carbon monoxide concentration at the 1.52 m level in the room center. Test 9, —; Test 10, — . —; Test 11, — —; Test 12, ...

kler actuation. All smoke detectors in the guest room responded in all tests. With gas temperatures at the 1.52 m level within the guest room exceeding 93°C in five tests for up to 20 s, and obscuration approaching 100% at the time of sprinkler actuation, advance warning by smoke detectors would improve chances for escape. Ventilation was not a key factor in the guest room in the flaming-started tests. The response of smoke detectors in the corridor was, however, significantly affected by ventilation. With the door closed and only ventilation in the corridor, no detector responded in the corridor. All detectors in the corridor responded if the guest room door was open.

The series of four smoldering-started tests has shown that tenability conditions can be exceeded in guest rooms when self-sustained smoldering occurs in institutional furnishings. The average advance warning time of 2.7 hours provided by guest room detectors would be more than adequate to allow occupants to leave the guest room or allow time for assistance to incapacitated occupants. It is important to note that untenable conditions were created prior to transition to flaming conditions in one test and without flaming in three other tests.

In the single test in which flaming occurred, the fire was extinguished as in the flaming-started tests. The importance of extinguishing the fire in the room of origin can not be overestimated. Although tenability limits were exceeded before sprinkler actuation, extinguishment of the fire greatly enhances the safety of occupants of other rooms.

The performance of corridor detectors in regard to guest room smoldering-started fires appears to be strongly affected by ventilation conditions. In two of the four smoldering tests, corridor-detectors did not respond despite the carbon monoxide tenability limit being exceeded.

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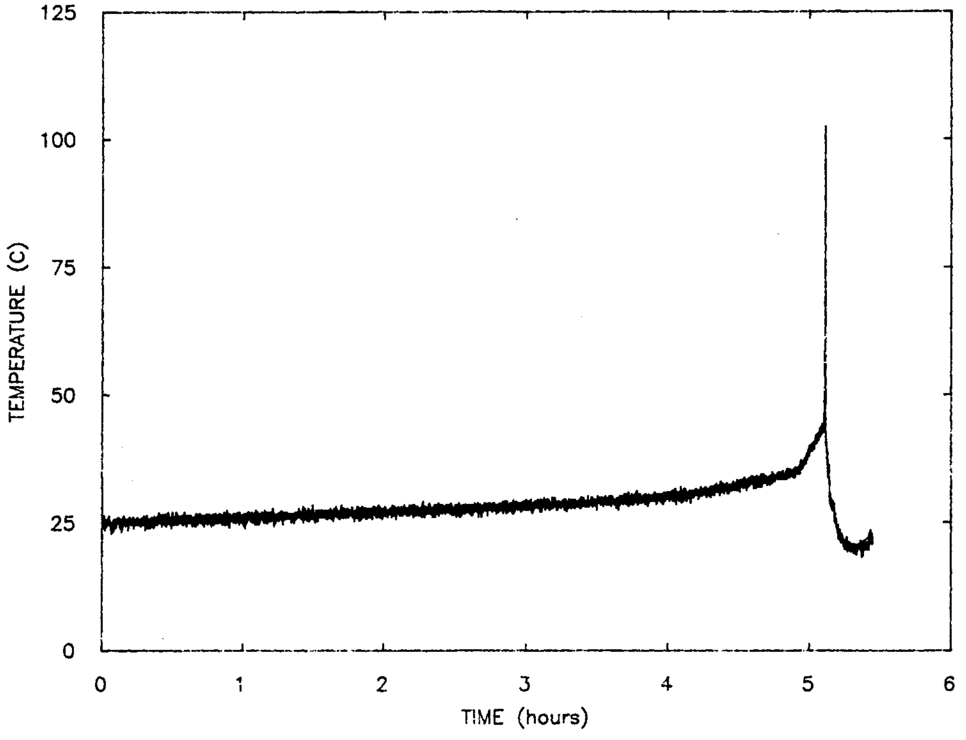

Figure 12. Gas temperatures at the 1.52 m level in the room center. Test 11.

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