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Engineering Analysis of the Fire Development in the Hillhaven Nursing Home Fire, October 5, 1989

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ABSTRACT

This report presents the methods and results of an analysis of the development and spread of fire and smoke during the October 5, 1989 fire in the Hillhaven Rehabilitation and Convalescent Center, Norfolk, Virginia. The analysis uses data gathered from on site visits, reports and information from other investigators, fire tests conducted at the National Institute of Standards & Technology, and fire growth models and similar computations. The report details the procedure and data used, the reasons for those selected, and the results obtained. The analysis addresses mass burning rate; rate of heat release; smoke temperature; smoke layer depth; velocity, depth and temperature of the smoke front; oxygen concentration of smoke layer; carbon monoxide concentrations; and other factors. The areas of building analyzed include the room of fire origin, the corridor system exposed by that room, and other patient rooms on that corridor. The computations used appear to reasonably reproduce the known conditions in the fire. The procedures used, however, involve some assumptions and the results presented in this report must be considered as approximate and indicative rather than exact. This analysis also explores the conditions that might have been expected had various detector and sprinkler systems been present.

1. SCOPE

The analysis in this report relates to the fire that occurred slightly after 10:00 p.m. on October 5, 1989, originating in Room 226 of the Hillhaven Rehabilitation and Convalescent Center, Norfolk, Virginia. Thirteen persons died as a result of this fire. None of the victims were burned; all had high carboxyhemoglobin content in their blood indicating carbon monoxide as the principal cause of death. Initially the investigation was conducted because of the scientific interest of NIST[1] in such fires and the long standing participation of NIST in research related to fire safety in health care facilities. The on site visit was at the invitation of the Fire Marshal of the Commonwealth of Virginia. The subsequent tests and analysis were sponsored by the Health Care Financing Administration of the Department of Health and Human Services.

The report addresses the development and growth of the fire in Room 226 and the impact of the fire products emitting from that room into the second floor corridor and from the corridor into patient

[1] The Fire Prevention and Control Act of 1974 (Public Law 93-489) authorizes NIST to conduct scientific investigations of fires related to its fire research activities.

rooms. Coverage is from the moment of ignition to suppression by the responding fire department, a period of ten to fifteen minutes.

2. PERTINENT DETAILS

2.1 Building Structure

The building is a four-story steel-framed non-sprinklered fire-resistive building constructed in 1968. The flooring system is of bar-joist construction with concrete deck and a time-rated lay-in mineral tile ceiling. The lay-in tile ceiling in Room 226 fell during the fire. There was minor damage to several of the bar joists but no collapse of the floor deck.

2.2 Arrangement of Second Floor

The second floor (See Figure 1) was occupied entirely as a nursing unit and contained bedrooms located on opposite sides of an 2.4 m (8 ft.) wide corridor. The floor also contained a nurses station, a lounge, and several support rooms. The rooms were separated from the corridor by one-hour gypsum wallboard on steel stud partitions. The doors to each room were solid core wood doors equipped with roller latches but not closers.

The floor was divided into two smoke zones by a smoke barrier separating the 14 rooms at the west end of the floor from the rest of the floor. Room 226 was in the west wing one room removed from the smoke barrier.

Figure 2 is an approximate layout of the arrangement of Room 226 at the time of the fire. It was typical of other rooms in the building. The room contained 2 beds, 2 wooden bureaus, 2 chairs each having separate seat and back cushions and wooden frame. Similar chairs that survived the fire were padded with a urethane material. In addition to the material shown in Figure 2, there were curtains on the windows, a privacy curtain between the beds, 2 hospital type bed tables, and a television set mounted towards the ceiling over the position shown for chair one. The east (long) wall of the room was finished with a vinyl fabric wallpaper. The other walls in the room were painted directly on top of the gypsum board. The door to the bathroom was a hollow core wooden door. The door to the corridor was a solid core wooden door.

The smoke doors were held open by magnetic hold-open devices arranged to shut at any time the fire alarm system operated. There were smoke detectors located on each side of the smoke door connected to the fire alarm system. The arrangement of the fire alarm system, however, was such that if the fire alarm system was taken out of service, the electromagnets were not deenergized. The fire alarm did not respond when the fire alarm boxes were pulled during the fire and the main fuse in the fire alarm panel was found blown after the fire.

2.3 Wind

A 4.5 to 6.7 mps (10 to 15 mile an hour) wind was blowing out of the south at the time of the fire. While the exact vector of this wind is not known, it struck the south wall and after the windows in Room 226 failed applied a wind pressure estimated as 12 to 25 Pa (0.05 to 0.1 inches of water).

3. PATIENTS AND STAFF

There were 161 patients in the building at the time of the fire, 54 on the second floor. Of the 54, 23 were in the smoke zone containing Room 226. There were 21 staff members in the building at the time, 7 located on the fire floor.

4. STORY OF THE FIRE

Apparently, a patient sitting in a chair next to his bed lit a cigarette and accidently brought the flaming match in contact with the bedding near the foot of his bed.[2] The fire developed to full room involvement (flashover) in a period possibly as short as 4 to 5 minutes. Early in the fire development (possibly during the first minute of burning) a member of the nursing staff discovered the fire and escorted the patient from his chair out of the room, calling for help and returning to help the other occupant of room 226. This second occupant was bedridden. The staff member attempted to wheel his bed from the room. She was unable to accomplish this alone but help arrived and that bed was removed from the room with the aid of two other staff members. About this time, an emergency call to the fire department was made by using the 911 telephone number. The building fire alarm was also pulled but the alarm system did not respond. The two staff members who came to assist took charge of the bedridden patient and removed him to a location beyond the smoke door. The staff member who initially saw the fire, attempted to close all of the doors to other patient rooms throughout the portion of the floor (west end) containing Room 226. (See Figure 1 for location.) Unfortunately, no one closed the door to the fire room. Also, many of the doors to other patient rooms did not stay closed but ended in a position slightly ajar.

The fire spread through the mattress and bedding. It extended to the wooden head and footboard on the bed, a chair positioned between the bed and the window, the window drapes, and possibly the privacy curtains. This produced more than enough energy to drive the fire into a flashed-over condition. Based on the combination of the recollections of the staff, the tests reported in Appendix A of this report, and the technical analysis covered in section 6, flashover is believed to have occurred about 4 minutes after the fire broke through the side of the mattress into the innerspring area. This penetration, as shown by the tests conducted at NIST, could have taken place as short as thirty seconds from the moment when the match is assumed to have touched the bedding. With the advent of flashover, all of the other materials in the room joined the fire. Initially, this included not only the furniture but the vinyl wall covering on the east wall of the room and the paper on the gypsum board on the other walls. Soon thereafter, additional fuel was provided by the wooden door to Room 226, the bathroom door in Room 226, and the corridor side of the door to Room 225 directly across the corridor. Both panes in the window to Room 226 also broke out. This resulted in temperature conditions within Room 226 estimated at 1000°C (1800°F). The oxygen content in the smoke dropped to close to zero and the carbon monoxide content rose to nearly four percent (40,000 ppm).

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[2] This source of ignition is that suggested as most likely by the Norfolk Fire Department. As shown by the analyses in this report this is a feasible but not proven ignition scenario (See Appendix A for tests to determine the fire initiation sequence from this type of ignition.)

With flashover, the oxygen resident in the room plus that drawn in through the broken windows was not sufficient to provide for combustion of all the fuel gases released from the burning surfaces then involved. As a result, flame extended from the window and from the bedroom door into the corridor. Also in the corridor the sudden change in level of energy following flashover produced a wave front of fire gases that progressed down the corridor with an estimated speed of about 0.6 meters per second (2 ft. per second) and having a depth of approximately 0.8 meters (2.5 ft.). These fire gases contained high concentrations of carbon monoxide and virtually no oxygen. It is expected it took about 2 minutes for this wave to both reach the end of the corridor and then return to the point of origin at Room 226. Some time during this period, the smoke doors closed. Early in the initial post flashover expulsion of flame and hot gases into the corridor, flame extension reached the smoke doors. The hold open device on the corridor doors consisted of electromagnets mounted on the wall at a level near the top of the door, magnetically gripping the steel plate held by an adhesive to an aluminum mounting. Soon after the post flashover surge of fire gases reached the doors the doors closed. After the fire the steel plates were found separated from the aluminum mounting held by the still energized magnets. It is assumed the steel plates separated as the result of the differential in coefficients of expansion between the steel disk and the aluminum mounting. As the assembly was heated the resulting stress sheared the adhesive bond. With the closing of these doors and the filling of the corridor with fire gases containing virtually no oxygen, the flaming in the corridor is believed to have ceased or been greatly reduced.

The carbon monoxide laden smoke in the corridor then penetrated those patient rooms where the door was ajar. The smoke stain above such doors varies from room to room indicating that the doors stood ajar between about 25 and 100 mm (1 and 4 inches). Calculations indicate that the temperatures in the corridor ranged from about 550°C (approximately 1000°F) near Room 226 to about 120°C (about 250°F) at the west end of the corridor. On this basis, the victims would have received lethal doses of carbon monoxide in approximately 2 to 10 minutes after flashover depending upon the location of their bedroom, the amount that the door was ajar, their personal susceptibility, and the impact of the wind on increasing the movement of fire gases into their rooms.

The fire department arrived within 4 minutes of transmittal of the alarm, suppressing the fire within another 2 to 5 minutes. Suppression was accomplished with a hose stream applied from the exterior through the broken windows of Room 226.

Fire fighters advancing through the building interior found the smoke door closed and one of the victims (the patient assigned to the window bed in Room 226) near the nurse's station on the east side of the fire door. This person had been led by the nursing staff to a bedroom in the east side but apparently had returned to this area early enough in the fire to obtain a lethal dose of carbon monoxide. The other victims were found in their beds.

5. POST FIRE TESTING

In November 1990 NIST conducted a series of ignition tests and large scale burn tests using mattresses, bedding, and decubitus pads obtained from the Hillhaven facility. Appendix A provides details of these tests. At the time of the fire, there was concern that the decubitus pads had played an important part in the early stage development of the fire. The tests conducted at NIST, however, indicated that the decubitus pad played only a minor part. The tests did demonstrate, however, a sequence of events that can account for the apparent very rapid development of this fire as discussed later in this report.

6. TECHNICAL ANALYSIS

6.1 Ignition

The Norfolk Fire Department believes that the source of ignition occurred through an accidental contact of a flaming match with the bedding on the bed near the window in Room 226. Tests were made at NIST to evaluate the feasibility and impact of such ignition. In each of the tests, a match was held to the bedding at a position near the foot of the bed and on the vertical portion of the bedding covering the side of the mattress.

a. In the first case, the bed was made with mattress, decubitus pad, flat sheet, fitted sheet, and cotton blanket, tightly made with hospital corner imitating the normal practice in the Hillhaven facility. In this test, it was necessary to hold the match in contact with the exposed surface of the cotton cover for approximately seven seconds to establish a flame. The fire then grew slowly, eventually penetrating into the innerspring portion of the mattress after approximately 5 minutes and 30 seconds. Once penetration had taken place, rapid development occurred.

b. In the second ignition test, the bed was made as above but without the cotton blanket. The top sheet was fitted with a hospital corner and the flame from the match brought in contact with the vertical section of the sheet near the crease formed by the hospital corner. Sustained flaming occurred in about 3 seconds. The fire progressed more rapidly than above taking approximately 2 minutes and 30 seconds to penetrate into the innerspring portion of the mattress.

c. In the third test, the bed was made with both sheet and cover but draped over the sides with the sheet extending lower than the cover. The match was brought in contact with a portion of the sheet hanging below the cover. It took approximately 5 seconds contact to establish a flame. Once established, however, the flame developed very rapidly, penetrated into the innerspring portion of the mattress in approximately 30 seconds.

Each of the above ignition tests was conducted on a quarter section of the mattress. In each case, once the flame penetrated the innerspring section, the burning progressed in an almost identical manner. For each of these scenarios, it is therefore considered that the penetration of the innerspring section is the key event and from that point on, the course of burning would be similar if not identical. In all of the subsequent tests, the third, i.e. most rapid involvement, scenario was used. If conditions were other than that described in this rapid development scenario, it would be reasonable to add the additional 2 to 5 minutes to the time between match contact and the events described in this report.

6.2 Free burn Test of Mattress, Decubitus Pad, and Bedding

An instrumented burn test was conducted under the large hood at the facilities of NIST. The sample burn consisted of one of the mattresses obtained from the Hillhaven facility with a decubitus pad, fitted sheet, draw sheet, cotton cover, and a pillow. The arrangement for ignition was the same as the third scenario in the ignition sequence (free hanging bedding). The fire progressed rapidly, reaching a peak of approximately 775 kW. Figure 3 is a plot of the rate of heat release measured in this test.

In addition to the above free burn test, tests of the same array were conducted in a 2.4 x 3.6 m (8 x 12 foot) test room and in a test facility having a similar size and shape to Room 226 in the Hillhaven facility. The details of these tests are included in Appendix A. The test sample produced flashover in the small room. In the larger room (approximating Room 226), the fire developed fiercely but did not reach the flashover condition. There were two important differences between the two test rooms. First the surface area of the lining (walls, ceiling, and floor) in the large room was slightly more than twice the surface area of the room lining in the smaller room. Second the small room was lined with paper faced gypsum board while the larger room was lined with unfaced calcium silicate board. Both materials have similar heat absorbing properties. It is believed that the increased heat removal resulting from the larger surface area in the larger room and the lack of a second fuel (i.e. the lack of paper facing on the calcium silicate board) were the prime reasons for the lower (sub-flashover) temperatures in the larger room. Both of these results are as predicted by the fire growth model used in this study.

6.3 Estimating the Actual Rate of Heat Release Produced in the Fire

The free burn Test discussed above did not include the wooden head or footboard on the beds in the Hillhaven facility nor did it include the chair shown as chair 2 in Figure 2 located an estimated 6 inches from the side of the bed. The actual fire must have involved all of these. Chair 2 is believed to be virtually identical to a chair previously tested by NIST [1][3]. In that test, a peak burning rate of 285 kW was reached after 130 seconds of exposure. Based on the size, the footboard was estimated as having a maximum rate of heat release of approximately 75 kW. This was based on a footboard approximately 0.3m (12 inches) high by 1m (39 inches) long (approximately 0.3 sq. meters of surface) burning at the rate of approximately 150 kW per square meter. This assumes that both sides of the footboard became involved. A similar calculation for the headboard produces a value of approximately twice this level.

The procedure FREEBURN from the engineering package, FPETOOL [2] was used to combine these burning rates. In using FREEBURN, it was estimated that the footboard became ignited approximately 60 seconds after ignition; that the headboard became ignited in approximately 130 seconds; and that the chair became ignited at approximately the same time as the headboard. The rationale for these times is as follows:

(1) The footboard was near the point of ignition. There was no preheating of the footboard; therefore, some preheat time was necessary after flame contact was made. This is estimated at 60 seconds.

(2) Observation of the free burn tests described in section 6.2 demonstrated that the fire propagated to the head of the bed in approximately 2 minutes and that large flames occurred preheating the material in front of it. A period of 130 seconds was chosen as a reasonable point of ignition and because this would bring the peak rate of heat release from the headboard into play at approximately the same time as the peak from the burning of the mattress. While it cannot be sure that this is exactly the sequence of events, it does produce the maximum rate of heat release.

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[3] Brackets [] indicate a reference in the listing at the end of this report.

(3) Similarly, the chair was assumed to be ignited at 130 seconds. This was based on selecting an ignition time to coordinate the rate of heat release so that the peak rate of heat release of the chair matched that of the bed. Also, the FREEBURN routine indicated that the radiant energy incident on the chair at such time would be approximately 24 kW per square meter, a level of energy appropriate to its ignition and rapid development.

The fire model, FIRE SIMULATOR, contained in FPETOOL [2] was executed using the resulting accumulated fire curve. The purpose of this run was to identify the point at which room temperature would rise sufficiently to impact on the rate of heat release estimated from the NIST tests and the adjustments made using the routine FREEBURN. As pointed out by Parker [3], this enhancement takes place if the ceiling gases become sufficiently hot. The exact temperature for enhancement is not established but is in the neighborhood of 450°C (850°F). This test run indicated that such enhancement would start to occur at about the point where the rate of heat release curve reached 900 kW. To account for this, a new fire input curve was developed progressively increasing the rate of heat release above 900 kW to a point approximately one minute later where the predicted rate of heat release was doubled. This is felt to be a reasonable accommodation for the combination of enhancement and the spread to additional fuels such as the draperies and privacy curtains. Figure 4 shows the relationship of the various rate of heat release curves starting with the NIST test involving only the mattress and bedding and including the adjustment made by the program FREEBURN to include head and footboard and the chair adjacent to the bed. Finally, Figure 4 shows the increased curve reflecting the enhancement produced by the hot smoke and other factors. This final enhanced curve was then used as the source term for modeling fire conditions in Room 226.

6.4 Estimated Conditions in Room 226

The model FIRE SIMULATOR from FPETOOL [2] was then used to produce estimates of the conditions in Room 226. The detailed print out from FIRE SIMULATOR for ROOM 226 is contained in Appendix B. The model estimates that flashover occurred at 267 seconds following ignition. In view of the estimates required for input factors and uncertainties in the model, this should be taken as somewhere between 4 and 5 minutes. Figures 5, 6, and 7 depict results developed by this model. Following flashover the model estimates are based on full involvement of the wall covering materials lasting approximately 2 minutes until the combustible material (vinyl wall covering on the east wall and the paper facing of the gypsum board on the other walls) was consumed. Following that the residual fuel was considered to consist of the furniture in the room and the wood faces of the corridor and bathroom doors.

The model estimates that there was sufficient fuel in the room to continue the fire for about 10 minutes after flashover. This corresponds fairly closely to the estimated time of manual suppression by the fire department. Since there was very little fuel left at the time of suppression, it is likely that the estimate of burnout and suppression at less than 15 minutes after the moment of ignition is reasonable.

Temperatures in the room appeared to have briefly exceeded 1000°C (1800°F). The carbon monoxide concentration of the smoke rose to a level estimated at approximately 3.8% (38,000 ppm)[4] while the oxygen level dropped to close to zero.

6.5 Development of Conditions in the Corridor

Figure 8 depicts the rate of flow of smoke from Room 226 into the corridor and Figure 9 depicts the total enthalpy (i.e. sensible heat of the fire gases plus the potential energy contained in yet unburned fuel) carried in that smoke as calculated by FIRE SIMULATOR as a part of the analysis of conditions in room 226.[5] Prior to flashover the rate of smoke flow grew gradually reaching a level of around 1 cms (2000 cfm) while the total enthalpy rose only slightly. With the advent of flashover, there was a sudden rise to an estimated 6-7 cms (12-13,000 cfm) of smoke flow having a total enthalpy in the range of 13-14 MW. Fortunately, most of that energy was never released. Since the smoke cloud containing the energy was nearly devoid of oxygen only that portion of the unburned fuel in the smoke that could gather air from the corridor space was able to actually burn.

The movement of the smoke in the corridor was calculated using the procedures proposed by Steckler [4] for modeling fire induced flows in corridors. During the initial post flashover stages a wave front such as that diagramed in Figure 10 (abstracted from Steckler's report) flowed to the end or the corridor and back. While the actual physics of smoke flow in corridors is only partially codified, the procedures suggested by Steckler are considered to give a reasonable view of conditions. Figures 11, 12, and 13 depict results obtained from the corridor calculations.

These corridor flow calculations indicate that almost immediately after flashover a wave front flowed through the west wing. As long as the smoke doors remained open smoke also flowed into the east wing. This smoke front traveling initially at a rate of approximately 0.6 meters per second (2 ft. per second) had a depth of approximately 0.8 m (2.5 ft.) from the ceiling. As has been experimentally shown by Zukowski [5], when such a wave reaches the end of a corridor, it develops a return wave of approximately the same thickness at a slightly slower speed that functionally doubles the depth of the smoke in the corridor. By the time the smoke front traversed the length of the west corridor and returned, the smoke doors are assumed to have closed.

Following the initial wave action the west wing was a closed system driven by the fire in room 226. Figure 14 depicts a type of smoke pumping action that is believed to have occurred. The fire draws the corridor gasses into Room 226 through the lower portion of the door to that room and discharges more smoke through the upper portion of the door. The initial rate of flow being (per the calculations of FIRE SIMULATOR) approximately 2.85 cms (6500 cfm).

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[4] The procedure used to estimate carbon monoxide concentration involves an estimate of the carbon monoxide verses carbon dioxide production. In the evaluations used in this report this ratio was estimated at 0.5 for post flashover conditions. This is considered reasonable but not necessarily exact. The rational for this choice is contained in Appendix C of the FPETOOL report [2].

[5] That portion of the curves plotted in Figures 8 and 9 covering the conditions after 6 min. are labeled as estimated. This is to recognize the depletion of oxygen in the corridor, a condition that could not be recognized by the FIRE SIMULATOR evaluation of Room 226.

Based on the above, it would be expected to take slightly less than 1 minute after flashover to fill the west corridor to a depth about 1.7 m (5.5 ft.) above the floor and to about 0.9 m (3 ft.) above the floor within another minute as a result of the return wave. Once the smoke doors closed the carbon monoxide laden smoke and fire gases would extend to near the floor in about another minute. As shown by Figure 13, it would be expected that the temperatures in the immediate area of Room 226 would remain high but would drop rapidly along the length of the corridor. The contents of the smoke would be close to that expelled from Room 226 (i.e carbon monoxide concentrations in the range of 3.8% (38,000ppm) and oxygen depleted to virtually 0.)

6.6 Migration of the Smoke into Remote Patient Rooms

In each room where victims were found, there were smoke marks above the door indicating the door had been ajar. Matching the door to the smoke marks indicated that the degree of openness of these doors varied from about 1 to 4 inches. This is graphically depicted in Figure 15. The locations of the victims are shown in Figure 16. The procedure for estimating smoke flow through an opening contained in FPETOOL [2] was used to evaluate the initial smoke flow into the individual patient rooms as a result of the filling of the corridor. The flow rates range from approximately 0.06 cms (130 cfm) for a situation of a 25 mm (1 inch) crack located where temperatures were in the range of 60° C (140° F) to approximately 0.5 cms (about 1000 cfm) for a door 100 mm (4 inches) ajar with a smoke temperature in the corridor at 540° C (1000° F)[6] Because the smoke and gases entering the patient rooms were at an elevated temperature, it is expected that the incoming smoke formed a descending layer filling the room from the top down, with little dilution of the carbon monoxide concentration. At 0.06 cms (130 cfm) it would take about 9 minutes for the layer to descend to the head height of a patient in bed. At 0.5 cms (1000 cfm) this is reduced to less than 2 minutes.[7] Once the layer reached a patient, that individual would be subjected to the full concentration of the fire product gases. The rate of uptake of carbon monoxide and the resulting increase in caboxihemoglobin (COHb) by humans is variable depending on factors including the weight of the individual, their lung capacity, and their breathing rate. Several researchers have, however, produced procedures for quantifying the relationship between carbon monoxide exposure and COHb accumulation. That

[6] For calculation purposes it was assumed that the smoke actually entering the rooms near the fire was significantly cooled as it passed through the narrow door opening. A working value of 500° F (260° C) for the average temperature of the gasses actually accumulating in the room was used. This lower temperature reasonably coordinates with the very limited fire damage in the patient rooms near Room 226.

[7] These filling times neglect any impact from the wind. It is likely that the wind had an initial impact of increasing the flow into the affected rooms. However, since the windows to the rooms with victims were closed the pressure in those rooms would quickly rise to match the wind pressure. After that point the further movement of smoke into the room would be driven by the smoke temperatures, the pumping action shown in figure 14, the inherent leakage in the walls of the rooms, and any air movement caused by mechanical exhaust from the rooms.

proposed by Peterson and Stewart[6] was used to broadly estimate the increase of carboxyhemoglobin in the blood of the victims in those rooms. The equation used is:

$$COHb=(CO^{0.858}t^{0.63})/197$$

Where: COHb = Percent Carboxyhemoglobin in blood.
CO = Level of Carbon Monoxide Exposure (ppm)
t = Time of Exposure (min.)

Using the above equation it would take less than three minutes for victims to receive a lethal dose of carbon monoxide once the smoke layer reaches their head level.

7. POTENTIAL IMPACT OF FIRE PROTECTION DEVICES

FIRE SIMULATOR was used to estimate the different course that might have occurred had the facility been equipped with automatic sprinklers, smoke detectors, or smoke detector operated door closers. The response of sprinklers and detectors is compared to the temperature conditions in Room 226 in Figure 17.

7.1 Automatic Sprinkler Protection

Three different sprinkler system arrangements were evaluated. Two involved the newer quick response sprinkler heads and one a standard sprinkler head as would have been used if the building had been sprinkler protected when it was built. Print outs of the FIRE SIMULATOR runs are contained in Appendix B. Table 1, below outlines the estimated response that would have occurred had sprinklers been present.

Table 1. Estimated Response Had Sprinkler Protection been Present

Sprinkler Type	Distance to Fire	RTI[8]	Temperature Rating	Response Time	Conditions at Response Temp.	Level	Oxygen
Standard	2.1 m (7 ft.)	166 (300)	74°C (165°F)	177 s	290°C (554°F)	1.6 m (5.1 ft.)	15.9%
Quick Response	2.1 m (7 ft.)	28 (50)	74°C (165°F)	114 s	121°C (249°F)	1.6 m (5.2 ft.)	19.3%
Quick Response Sidewall	4.6 m (15 ft.)	28 (50)	74°C (165°F)	146 s	196°C (385°F)	1.6 m (5.1 ft.)	17.9%

[8] RTI (Response Time Index) is a measurement of the heat sink of the fusible element in the sprinkler head. The lower the RTI the faster the response of the sprinkler head. The values for RTI are expressed in the metric system having the dimension $m^{1/2}s^{1/2}$. The parenthetical value is in the English system with the dimensions $ft.^{1/2}$ $sec.^{1/2}$.

7.2 Smoke Detection

Three different potential smoke detector responses were estimated. One was based on a smoke detector located in Room 226 4.5 m (15 ft.) from the fire; the second on a smoke detector installed in an automatic door closer hypothetically mounted on the bedroom door, 7 m (23 ft.) from the fire; and a corridor detector located 2.4 m (8 ft.) from the door to Room 226. The last installation existed at the time of the fire but is believed to have been inoperative. Print outs of the FIRE SIMULATOR runs are contained in Appendix B. Table 2, below, estimates the response that would have occurred had these smoke detectors been present and operative.

Table 2. Estimated Response Had Smoke Detector Protection been Present and Operative.

Detector Location	Distance to Fire	Response Time	Conditions at Response Temp.	Level	Oxygen	Estimated Time Before Flashover
Room 226	4.6 m (15 ft.)	50 s	35°C (95°F)	2 m (6.5 ft.)	20.7%	217 s(3.6 Min.)
Room 226[9]	7 m (23 ft.)	56 s	99°C (211°F)	1.9 m (6.3 ft.)	20.7%	211 s(3.5 Min.)
Corridor	9.5 m[10] (31 ft.)	100 s	121°C (250°F)	1.6 m (5.2 ft.)	20%	167 s(2.8 Min.)

7.3 Smoke Detector Operated Door Closer

Two additional runs of FIRE SIMULATOR were made to investigate the impact of having the door to Room 226 close at 56 seconds (the estimated time for response of a smoke detector mounted in a door closer for Room 226.) The estimated resulting temperature conditions in Room 226 are shown in Figure 18. Print outs of these runs are contained in Appendix B.

In the first run the door was closed when the detector activated and allowed to remain closed until FIRE SIMULATOR calculations indicated that the oxygen had been consumed and the fire smothered, assuming that the window did not break. Since FIRE SIMULATOR indicates that the resident air in Room 226 would result in a peak temperature of about 525°C (975°F) there is a significant possibility that the window would break out and the fire progress into flashover. In any case FIRE SIMULATOR estimates that the conditions behind the closed door would have become intolerable in about 2 minutes following the closing of the door.

The second run starts the same as the first with the door closed at 56 seconds. In this case, however, the door is reopened one minute later to simulate staff entering for rescue purposes. When the door

[9] As part of an automatic door closer.

[10] 2.4 m (8 feet) from door to Room 226

is reopened the responding staff would have been faced with smoke conditions below their head height but still above bed height. Within about a minute the fire would reestablish itself and as long as the door remained open follow the course that actually occurred.

8. CONCLUSIONS

a. While there is no physical or evidential proof of the ignition scenario suggested by the fire department, the tests and calculations covered in this report indicate that scenario is feasible and could develop into a serious fire in less than one minute from the moment of contact between a match flame and loose bedding.

b. The very rapid development of this fire was due to the fast spread over the bedding and the quick entry of the fire into the innerspring area of the mattress. Tests indicate that the only impact of the decubitus pad obtained from the stock supplies at the Hillhaven facility was to add about one minute to the peak burning period of the fire once the mattress was well involved.

c. There was a brief period during which wall covering material including the paper on the gypsum board as well as the wall covering on the east wall were active contributors to the fire. It appears that during this period the mass burning rate was the highest with resulting oxygen starvation and increased production of carbon monoxide.

d. The deaths were a result of the massively high concentration of carbon monoxide in the fire products produced following flashover and the rapid flow of that smoke to the victims. This production and flow is a natural result of fires that reach flashover and have fuel and ventilation conditions as were present during the fire. Prevention of harm from this phenomena requires either that the fire be prevented from reaching flashover conditions or the combustion products be blocked from reaching persons.

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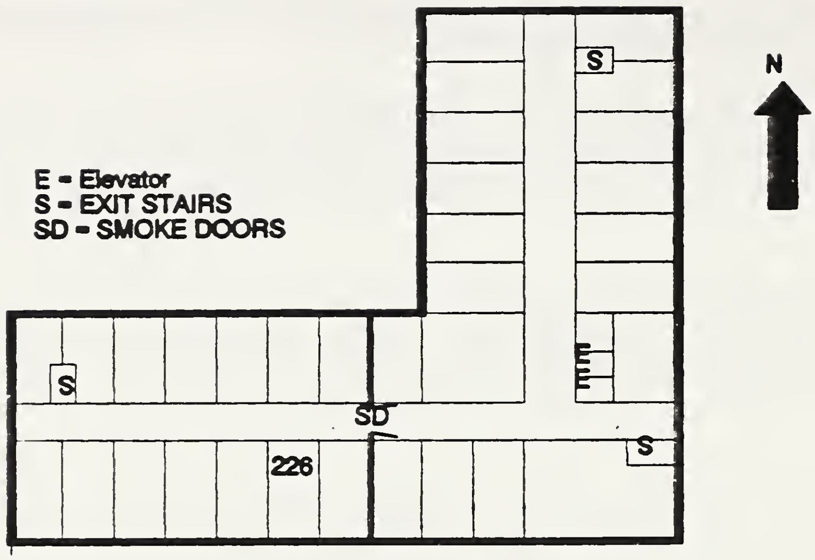

Figure 1. Second Floor Plan

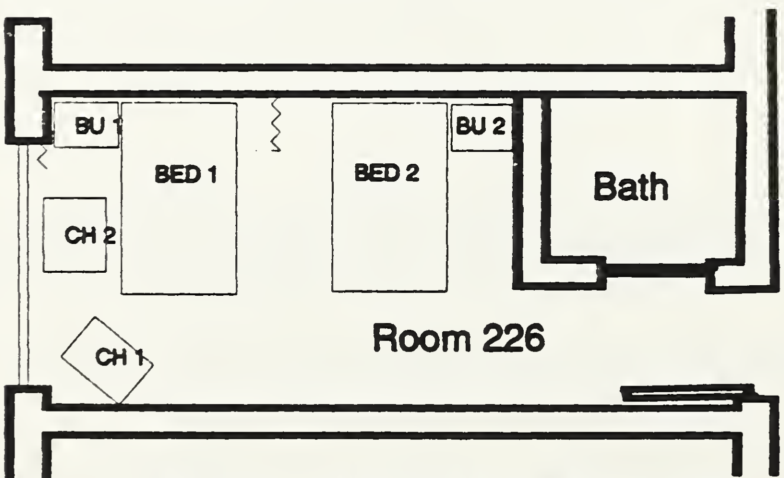

Figure 2. Arrangement of Room 226

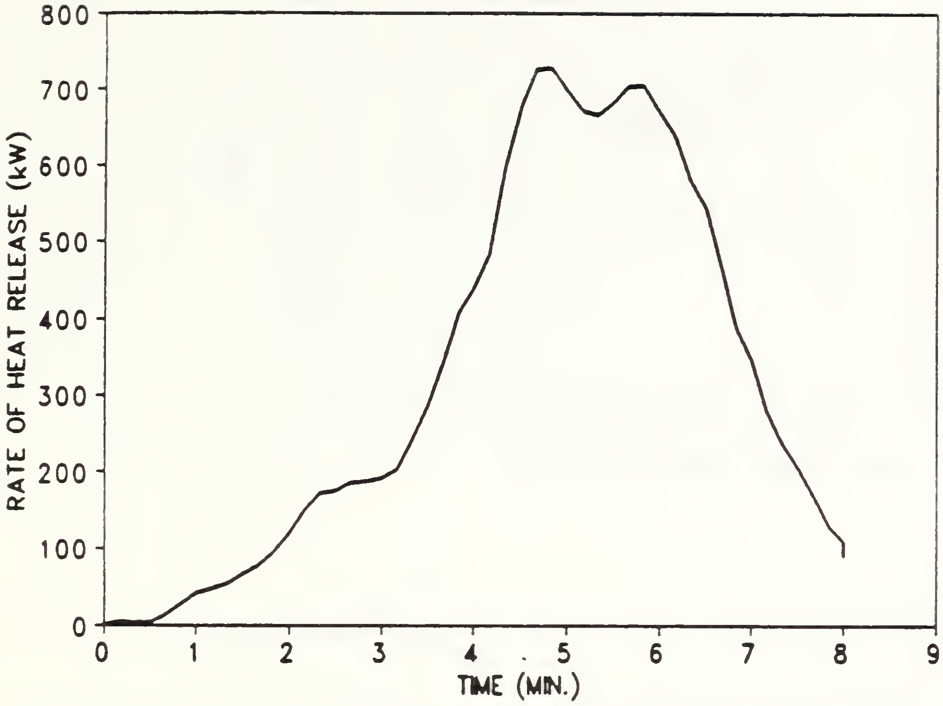

Figure 3. Free Burn Rate of Heat Release

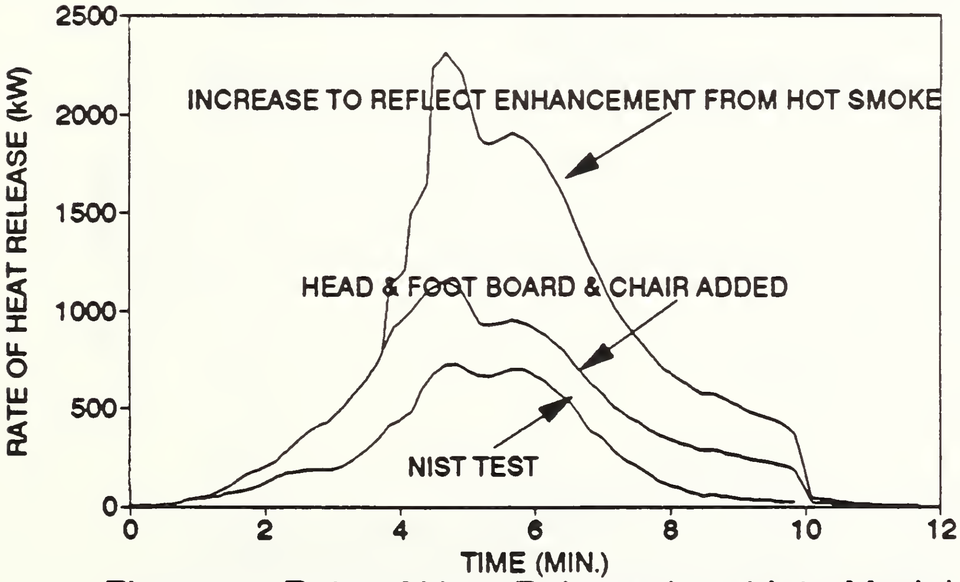

Figure 4. Rate of Heat Release Input into Model

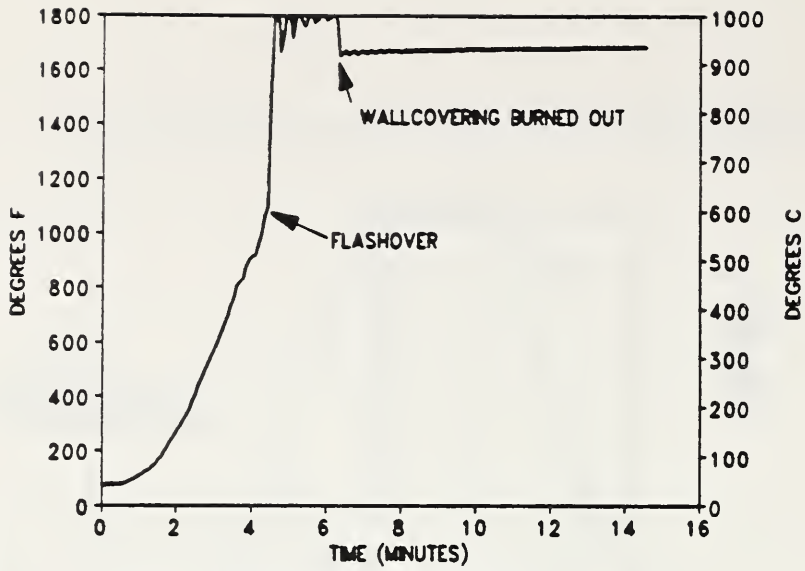

Figure 5. Smoke Temperature in Room 226

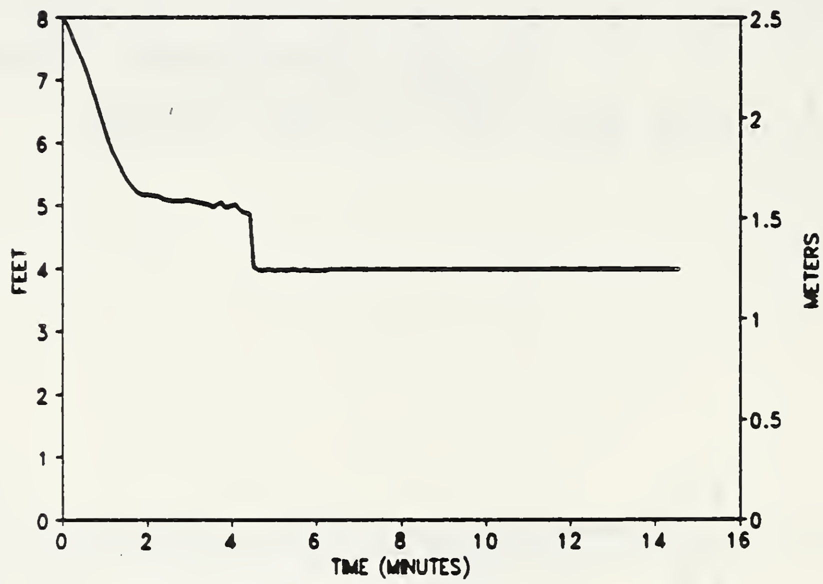

Figure 6. Smoke Layer in Room 226

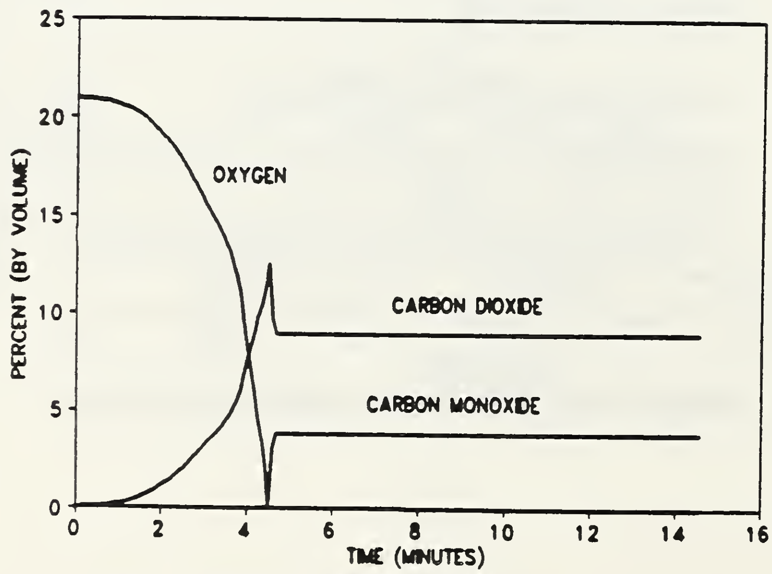

Figure 7. Common Fire Gases in Room 226

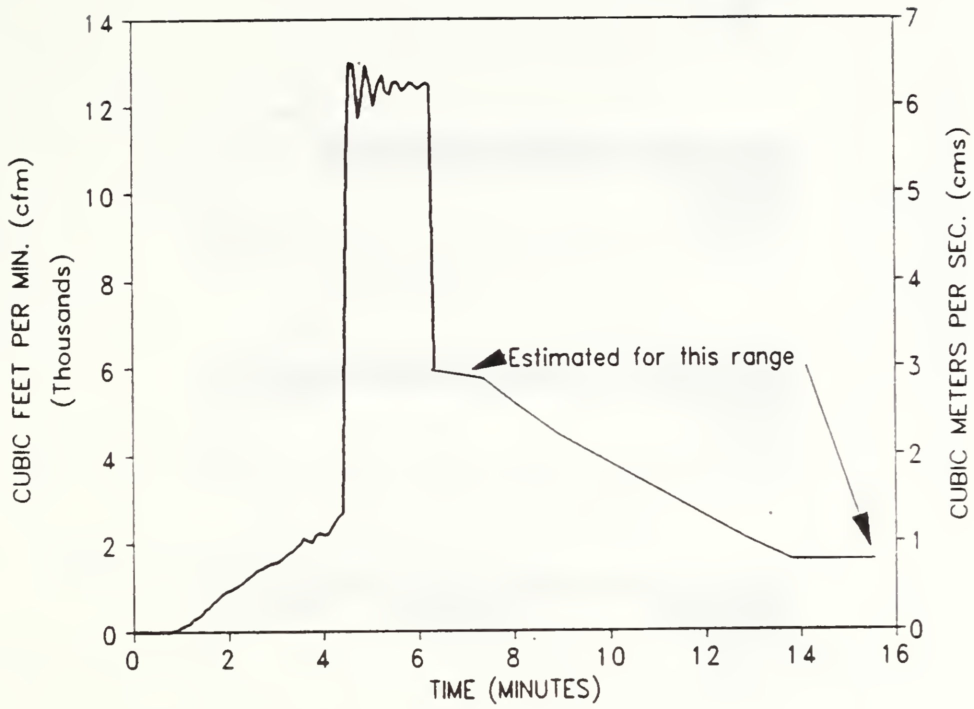

Figure 8. Smoke Flow from Door of Room 226

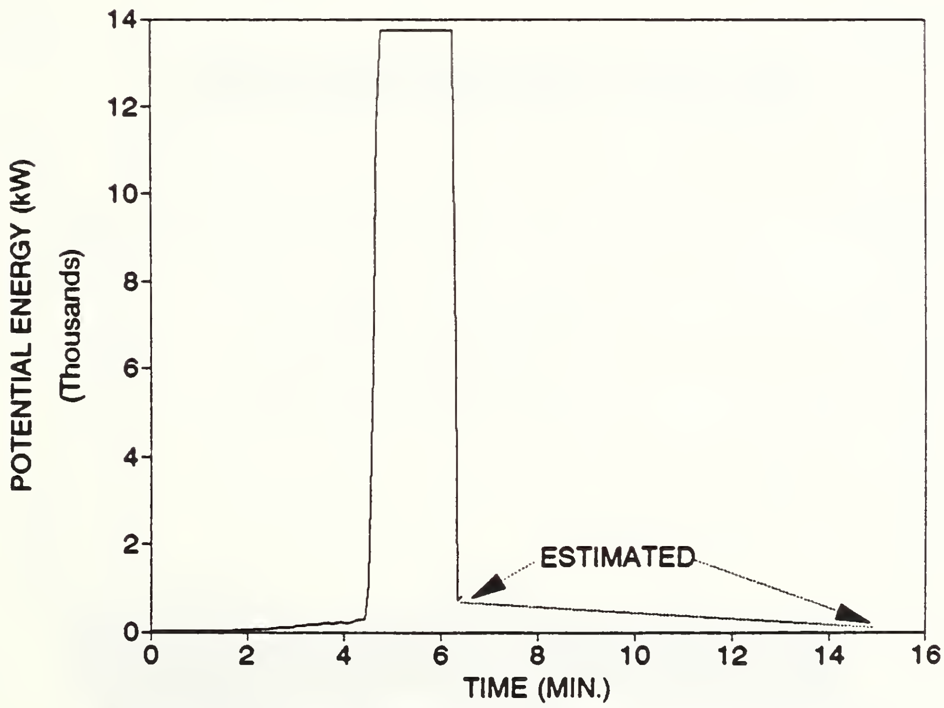

Figure 9. Potential Energy vented from Door of Room 226

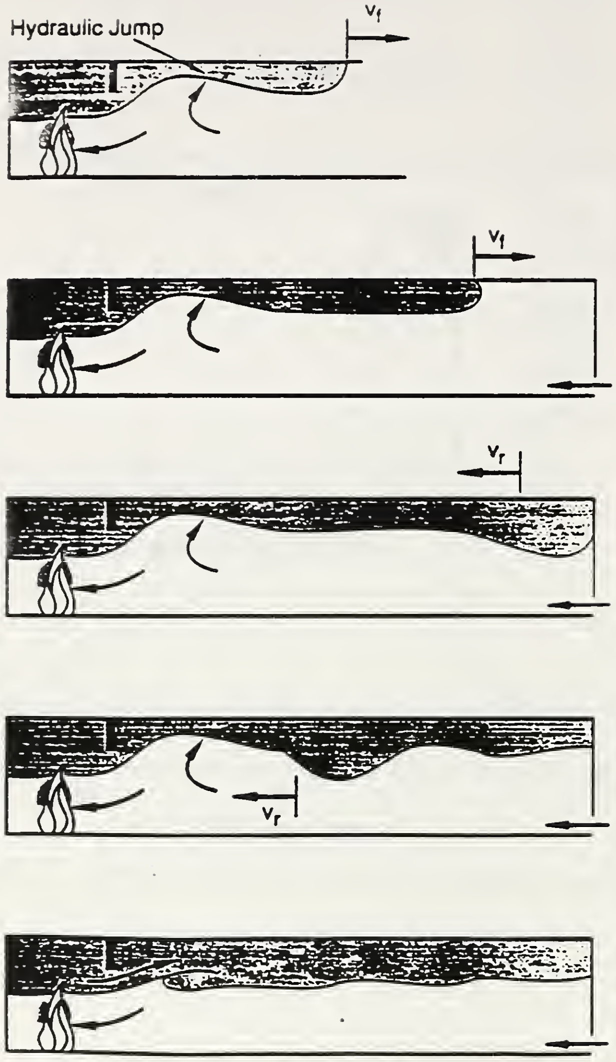

Figure 10. Corridor Wave Flow

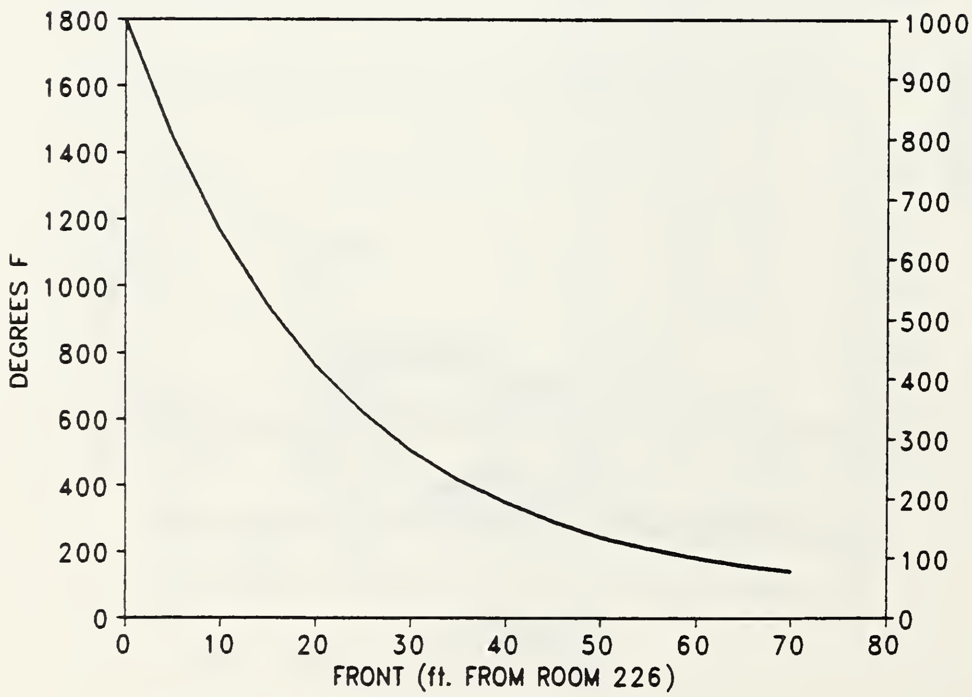

Figure 11. Temperature of Smoke Front

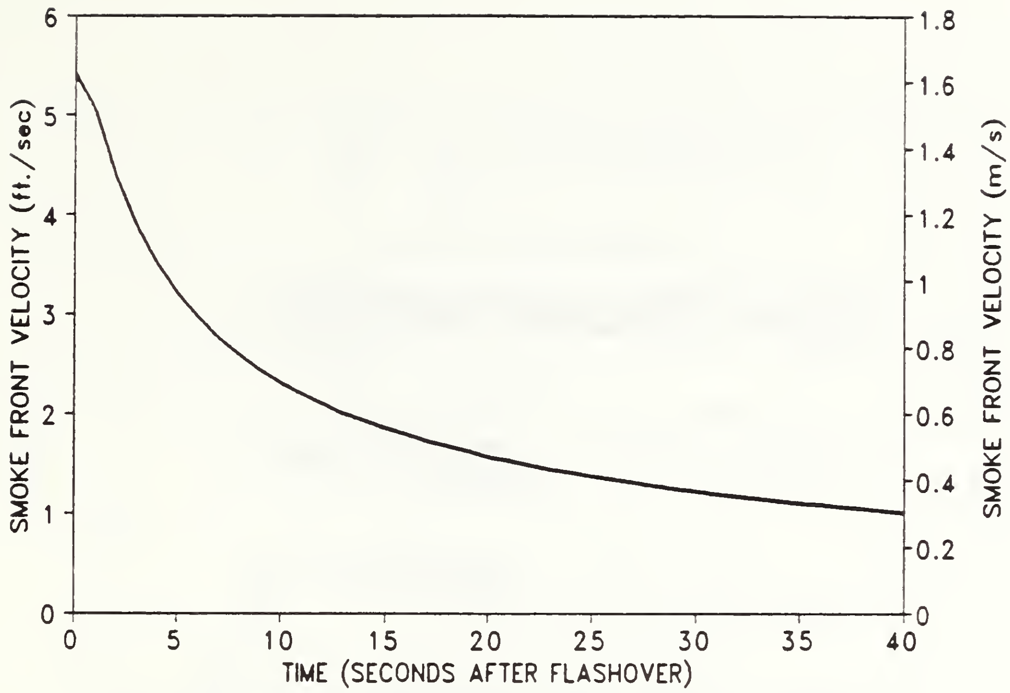

Figure 12. Velocity of Smoke Wave Front

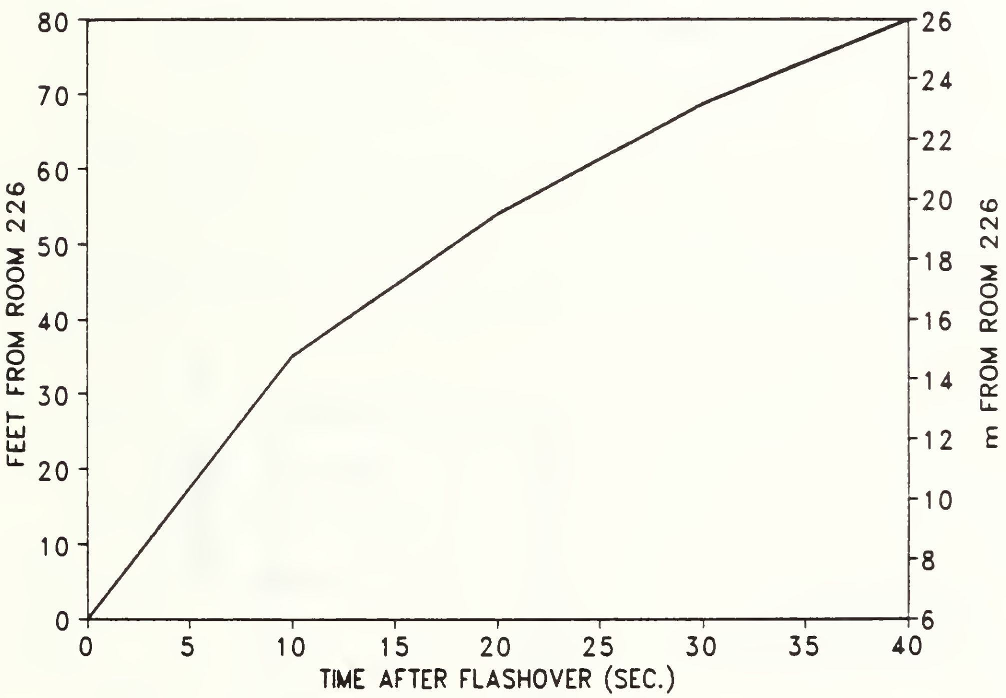

Figure 13. Position of Smoke Wave Front

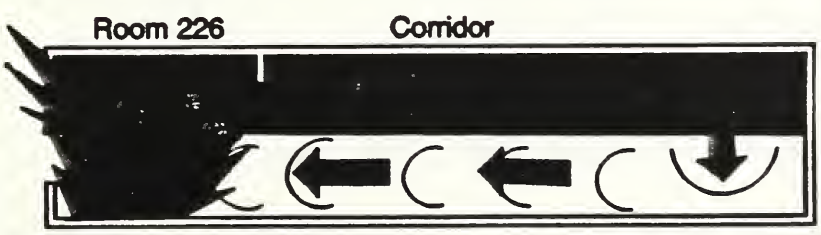

Figure 14. Smoke Flow in Corridor (after traverse of intial wave front)

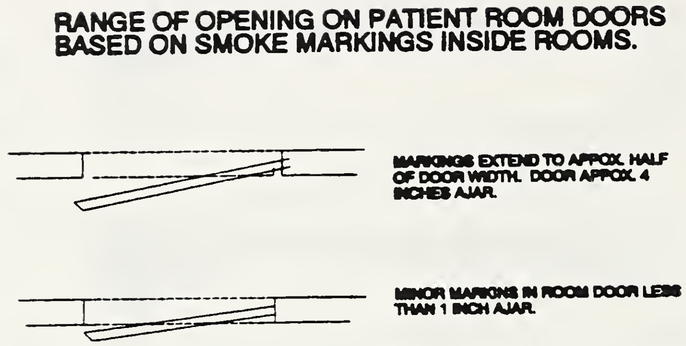

Figure 15. Patient Room Door Openings

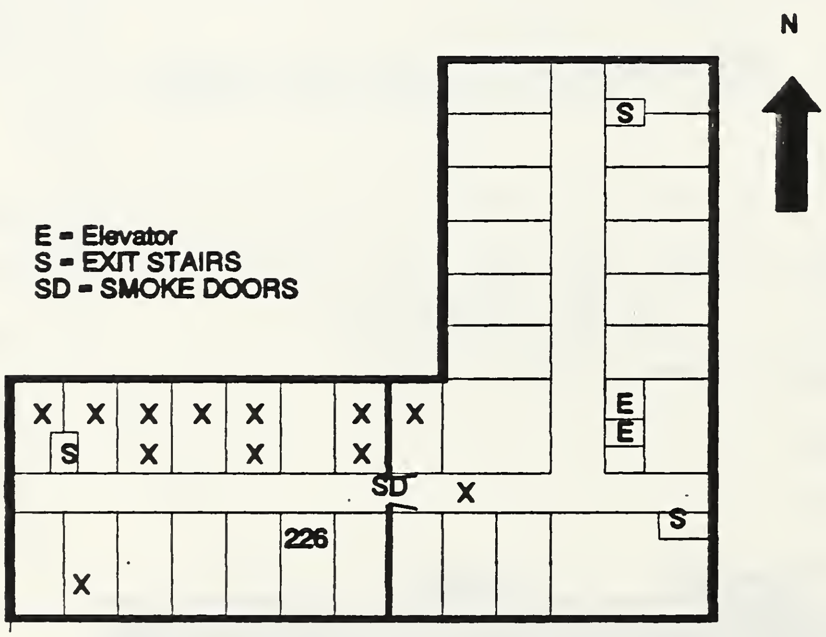

Figure 16. Location of Victims

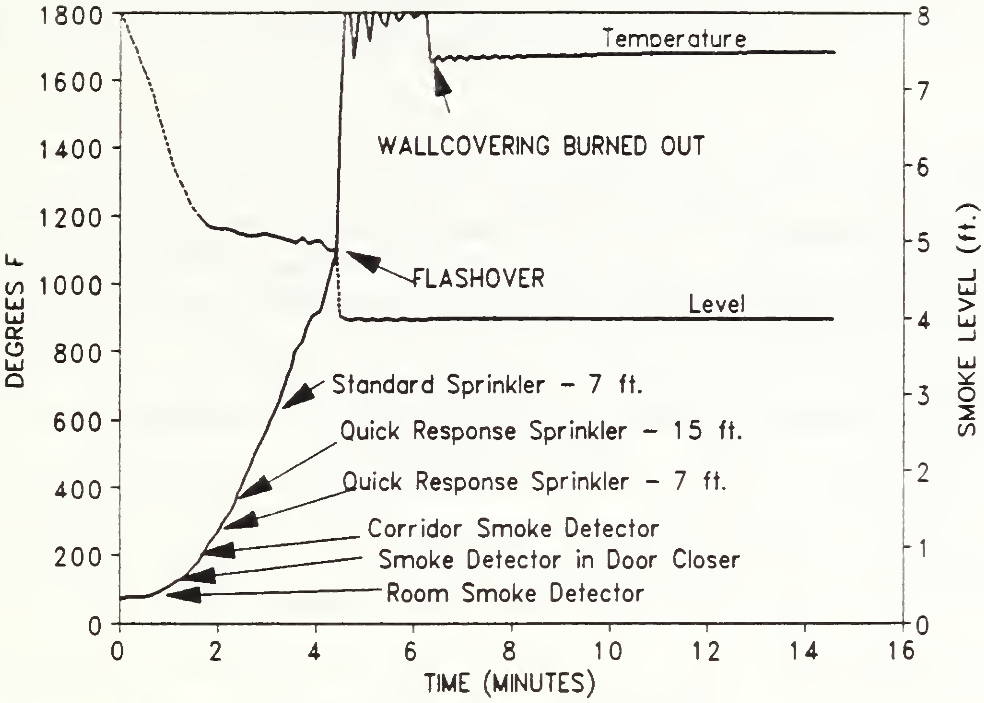

Figure 17. Potential of Sprinklers and Detectors

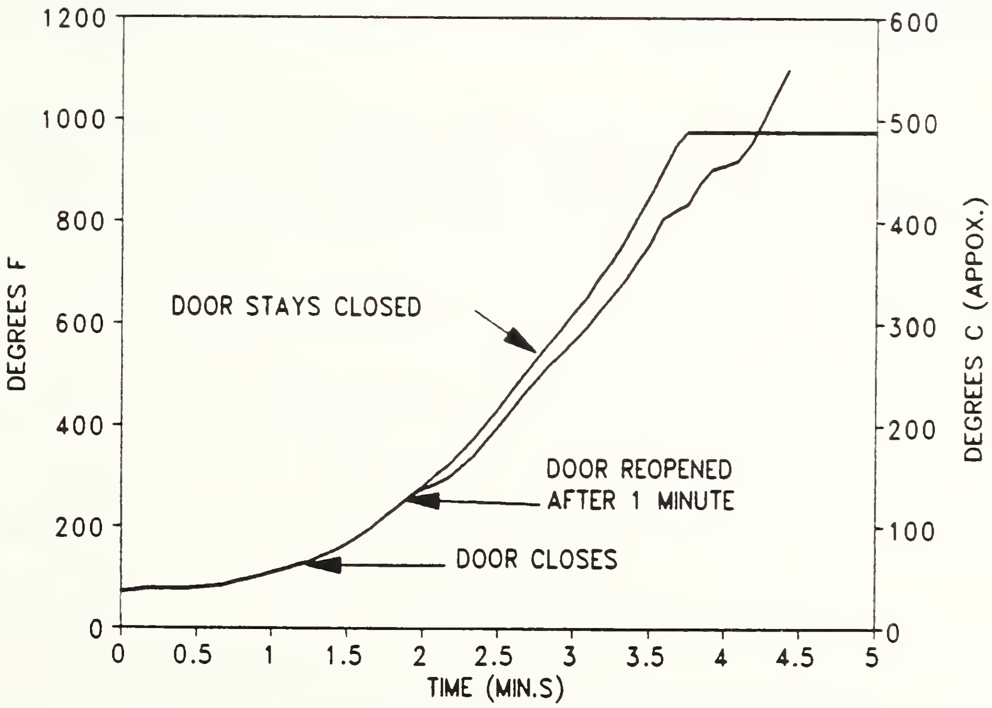

Figure 18. Temperature in Room 226 if Door had been closed

Appendix A
Fire Tests of Mattresses and Bedding

A-1. Background

The apparent rapid development of the fire in Room 226 raised concern regarding the mechanisms involved in this rapid development. As a result, a series of tests was conducted at the facilities of the National Institute of Standards and Technology (NIST) to measure the potential speed of ignition and subsequent fire development in mattress and bedding arrangements. The arrangements tested imitated as nearly as possible the arrangement in Room 226 at the time of fire. The materials used in the test were obtained from the Hillhaven Facility. The actual bedding and mattress involved in Room 226 were destroyed in the fire. It is therefore impossible to be certain that the material used in these tests was identical to that burned. The mattresses, however, were obtained from those that the Hillhaven Facility had removed from the nursing unit of the fire floor and the bedding, pillows and decubitus pads were obtained from their stock. To the best of the knowledge of the Hillhaven staff, the material used is close to, if not identical, to that in Room 226.

A-2. Research Plan Phases.

The test plan was divided into three phases:

a. Ignition Susceptibility - A series of tests to determine the speed at which contact between the flame of a paper match and the bedding could develop into significant fire.

b. Free Burn Tests - A series of tests conducted under the large hood at NIST to determine the inherent rate of heat release. Burns were made with and without the decubitus pad and with and without the mattress.

c. Room Burns - A series of two tests conducted in the standard ASTM room and in a facility having similar shape and arrangement to Room 226 in the Hillhaven facility. These tests were conducted to obtain information on the potential impact of room environment on development of the fire.

A-3. Materials and Bedding Assembly

The bedding materials employed in these tests were obtained from the Hillhaven Rehabilitation and Convalescent Center. The mattresses were selected from those salvaged from various rooms in the west wing of the second floor. None had been damaged by fire. The other materials were obtained from the Hillhaven supply room. The sheets and pillow slips were new; the blankets were not new but freshly laundered. Six sets of each of the following were obtained and used in the tests.

a. Mattress. Each mattress was a 0.9 x 1.9 x 0.15 m (36 x 76 x 6 inch) thick metal innerspring mattresses with urethane foam and cellulose fiber padding and a vinyl ticking. The mattresses were made by Spring Air Mattress Corporation, Greensboro, North Carolina[1].

b. Decubitus Pad. Each decubitus pad was 0.9 x 1.7 x 0.1 m (36 x 66 x 4 inch) thick with the top portion cut to form pyramid shaped supports. The pads were constructed of polyurethane foam labeled as passing the requirements of California Technical Bulletin No. 117.

c. Contour Fitted Sheet. The bottom or fitted sheet was made of a 50% polyester, 50% cotton material.

d. Flat Sheet. The top or flat sheet was also made of a 50% polyester, 50% cotton material.

e. Blanket. The blanket was 100% cotton.

f. Pillow. Each pillow had a 100% polyester fiber for inner material with a 50% cotton, 50% polyester material for ticking.

g. Pillow Cover. The pillow cover was also a 50% polyester, 50% cotton material.

A-4. Ignition Tests

The suspected source of ignition was an accidental contact of a flaming match to a portion of the bedding on the side of the bed rather than on the top. Four tests were conducted to evaluate the feasibility and impact of such ignition. To facilitate these tests, a mattress was cut into four equal sections. Bedding was similarly cut. The beds were then made as described below and for each test a match held at a position near the foot of the bed on a vertical portion of the bedding covering the side of the mattress.

a. Case 1 - Fully made bed

The bed was made with mattress, decubitus pad, flat sheet, fitted sheet, and cotton blanket. The bedding was tucked in under the mattress with tightly made hospital corners imitating the normal practice at the Hillhaven facility. In this test, a flame was established after approximately 7 seconds of contact with the flame from the match. The fire then grew slowly, eventually penetrating into the innerspring portion of the mattress after approximately 5 minutes and 30 seconds. Once penetration took place, rapid development occurred.

---

[1]The salvage storage at the Hillhaven Facility contained two types of mattresses. There were six of the Spring Air mattresses available and five made by Paramount Bedding Corporation that were similar in construction but used polyester padding between the urethane and the springs. The choice of the Spring Air mattress was solely because there were six of these mattresses and only five of the Paramount Bedding Corporation. There is no evidence as to exactly which mattress was used in Room 226 at the time of the fire.

b. Case 2 - Test Without Cotton Cover

The bed was made as in Case 1 except that the cover was omitted. The top sheet was made with tight hospital corners. Sustained flaming of the sheet occurred after approximately 3 seconds contact with the match flame. The fire progressed more rapidly than in Case 1, taking approximately 2 minutes and 30 seconds to penetrate into the innerspring. Once penetration took place, rapid development occurred.

c. Case 3 - Bedding Not Tucked In

In this case, all of the element (mattress, decubitus pad, flat sheet, fitted sheet, and cotton blanket) were present. The sheet and cover were draped over the side; the sheet extending lower than the cover. None of the bedding was tucked under the mattress. Sustained flaming occurred when the match was held in contact for approximately 5 seconds. Once established, the flame developed very rapidly, penetrating into the innerspring in about 30 seconds. Once penetration had taken place, rapid development occurred.

In all subsequent tests, the arrangement in Case 3 (bedding not tucked in and ignition made by contact with the hanging polyester cotton sheet) was used. Since rapid fire development occurred in all cases once the innerspring area had been penetrated, the difference between one bedding arrangement and another is believed to strictly be a time delay leading to essentially the same fire.

Table A-1. Weights of Items of Bedding Used in Tests.

Test No.	1	2	3	4	5	6
Mattress	--------	14528g (32 lb.)	14528g (32 lb.)	14755g (32.5 lb.)	14074g (31 lb.)	14528g (32 lb.)
Decubitus Pad	1953g (4.3 lb.)	--------	1832g (4 lb.)	2054g (4.5 lb.)	1861g (4,1 lb.)	1770g (3.9 lb.)
Contour Sheet	394g (14 oz.)	397g (14 oz.)	408g (14 oz.)	300g (11 oz.)	395g (14 oz.)	305g (11 oz.)
Flat Sheet	534g (19 oz.)	535g (19 oz.)	538g (19 oz.)	555g (20 oz.)	545g (19 oz.)	535g (19 oz.)
Blanket	1796g (4 lb.)	1388g (3 lb.)	1361g (3 lb.)	1238g (2.7 lb.)	1595g (3.5 lb.)	1458g (3.2 lb.)
Pillow	564g (20 oz.)	594g (21 oz.)	610g (21 oz.)	545g (19 oz.)	576g (20 oz.)	594g (21 oz.)
Pillow Cover	111g (4 oz.)	112g (4 oz.)	111g (4 oz.)	111g (4 oz.)	111g (4 oz.)	112g (4 oz.)

A-5. Free Burn Tests.

The term free burn test is used to describe a test conducted away from the influence of the walls and ceilings of a room. Free burn tests were used to obtain data on the intrinsic burning characteristics of the assembled mattresses and bedding. Four such free burn tests were conducted under the calibrated hood at the NIST Fire Test Facility. A load cell platform was employed to acquire the mass loss. Oxygen depletion calorimetry in the hood was used to determine the rate of heat release. In each case, a complete bedding assembly was mounted on a bed frame supported on the load cell. The beds were made as described in Case 3 for the ignition series (bedding hanging loose). Tests 1 and 2 were conducted to determine the impact of the decubitus pad and the impact of the mattress. In test 1, all of the assembly except the mattress was present. In test 2, all of the assembly except the decubitus pad was present. In tests 3 and 4, the entire assembly was present. Table A-1 lists the weights of the items used in both the free burn and the room tests.

In each case, the flame of the match was held in contact with an exposed vertical portion of the free hanging top sheet until a propagating flame occurred. In each case, it occurred within 5 seconds of flame contact. In test 1, no mattress was present. Fire development was slow and the rate of heat release was low as shown in Table A-2. In the other three tests rapid fire development occurred once the fire penetrated the innerspring portion of the mattress.

A-6. Room Burns

Two additional tests were conducted in enclosed rooms. Test 5 was conducted in the standard ASTM test room. This is a room 2.4 m wide by 3.6 m deep and 2.4 m high (8 x 12 x 8 ft.), lined with gypsum wall board. A door is located near the center of one of the 2.4 m (8 ft.) walls; the door is 0.9 m wide by 2 m high (3 ft x 6 ft. 8 in.). The second test was conducted in a test room recently used by Notarianni for extensive testing of response of sprinklers in patient room [1]. A planned view of this room is shown in Figure A-1. In each of these tests, the bed was also located on a load cell. In the ASTM room test, the hot gases vented into the same hood as used in the free burn test and the same oxygen depletion calorimetry was used.

The facility used for test 6 does not have oxygen depletion calorimetry capabilities. A load cell was used to record the rate of burning, extensive temperature measurements were made using thermocouple trees and limited carbon monoxide and carbon dioxide sampling was done.

The facility used for test 5, however, is sufficiently hardened so it was possible to continue the fire to the point where it had consumed all of the combustibles available. In test 6, the building is not of such hardened capabilities and it was necessary to shut the test down when it appeared that flashover was imminent. A later examination of the data from the test, however, indicated that the fire had passed its peak at the time it was extinguished, indicating that it was likely that flashover would not have occurred if the test had not been aborted.

A-7. Experimental Results

In test 6, there was no oxygen depletion calorimetry available and the load cell data became erroneous before the peak burning occurred. Figure A-2 plots the free burn rates of heat release from the first three free burn tests. Figure A-3 shows the rate of heat release for test 3 (free burn of the complete assembly) and 5 (the same arrangement in the ASTM room). In addition, it shows the data from test 5, time shifted about 150 seconds to overlay test 3. In test 5, an obvious and complete flashover occurred. The increased rate of heat release shown in test 5 appears to almost exactly equal the additional energy produced by burning the paper facing off the gypsum board in that room.

Figure A-4 plots a thermocouple tree near the middle of the test room in test 6. While the peak temperatures near the ceiling reached conditions usually indicative of flashover, the average temperature in the upper smoke layer did not reach this level and the fire fell slightly short of triggering a flashover condition. The sudden decrease in temperature at 350 seconds was caused by the application of water from a sprinkler head. This was done to terminate the test.

Table A-2 reports significant data from the first five tests.

Table A-2. Significant Data from First 5 Tests.

Test No.	1	2	3	3	5
Test Duration	900s	480s	480s	480s	480s
Total Mass Loss	5.35 kg (11.8 lb.)	10.25 kg (22.6 lb.)	12.00 kg (26.4 lb.)	12.25 kg (27 lb.)	12.00 kg (26.4 lb.)
Average Mass Loss	0.006 kg/s (0.8 lb./min.)	0.031 kg/s (4.1 lb./min.)	0.025 kg/s (3.3 lb./min.)	0.0255 kg/s (3.4 lb./min.)	0.025 kg/s (3.3 lb./min.)
Average Heat Release Rate	69 kW	325 kW	327 kW	301 kW	454 kW
Average Heat of Combustion	11600 kJ/kg	10500 kJ/kg	13000 kJ/kg	11800 kJ/kg	18500 kJ/kg
Total Heat Release	62060 kJ	107625 kJ	156000 kJ	144600 kJ	218000 kJ
Peak Heat Release Rate	204 kW	751 kW	726 kW	754 kW	2000 kW
Time to Peak Heat Release Rate	648s	330s	350s	410s	468s

A-8. Conclusions

The decubitus pads provided by the Hillhaven Facility (and assumed identical to those involved in the fire) did not significantly contribute to the development of fire. The most important factors in fire development were the total amount of fuel available and the penetration of the innerspring space by the flame. The speed of fire development in its earliest stages was directly a function of the ignition susceptibility of the first item ignited (cotton-polyester sheet vs. cotton blanket) and the extent of draping of that material. In each of the tests, however, once the fire was established inside the innerspring space, the fire development occurred in approximately the same manner.

1. Notarianni, K. A.; Five Small Flaming Fire Tests in a Simulated Hospital Patient Room Protected by Automatic Fire Sprinklers. Report of Test. FR 3982; National Institute of Standards and Technology, Gaithersburg, MD 1990

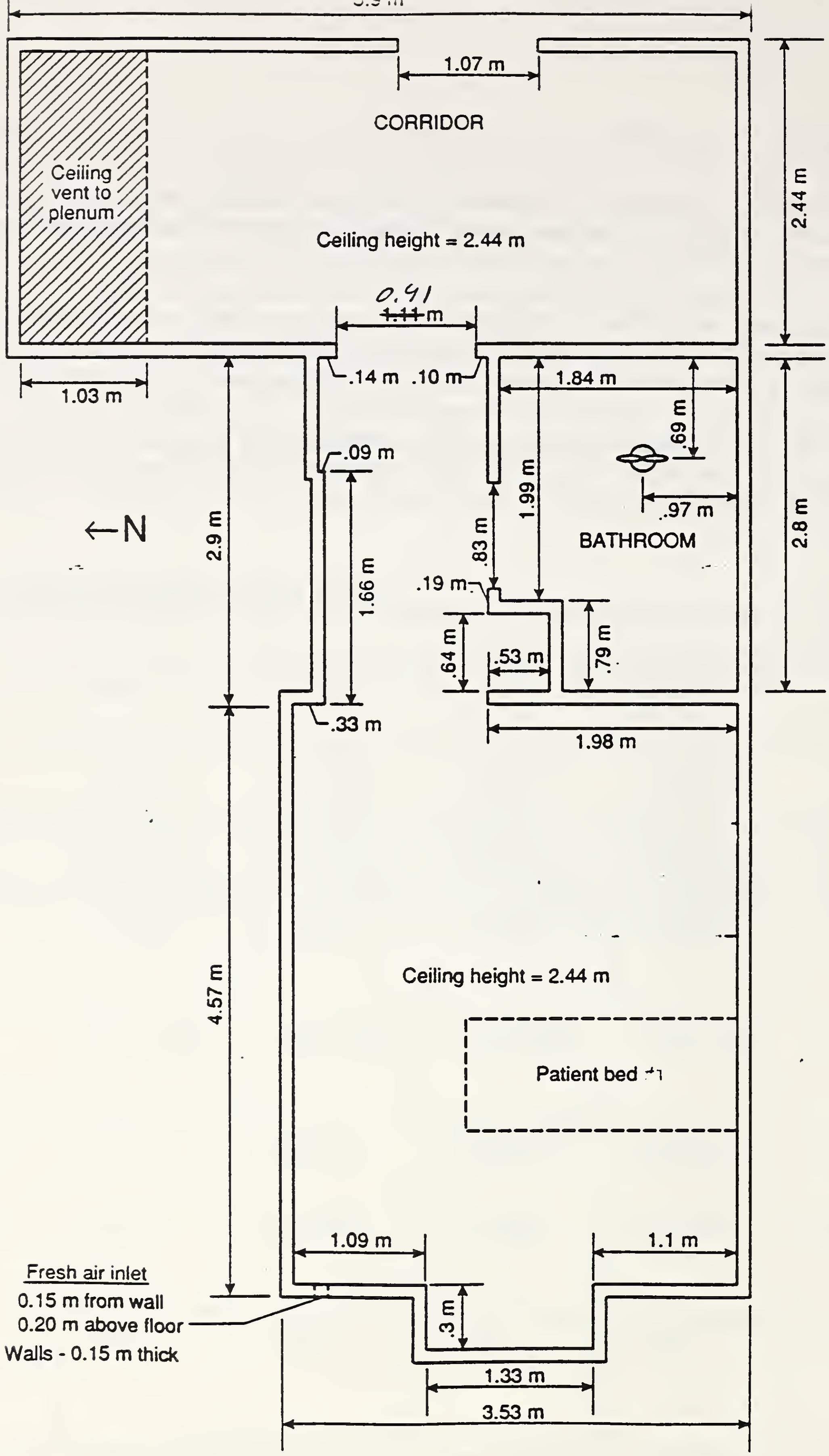

Figure A-1. Plan View of Patient Room Test Facility

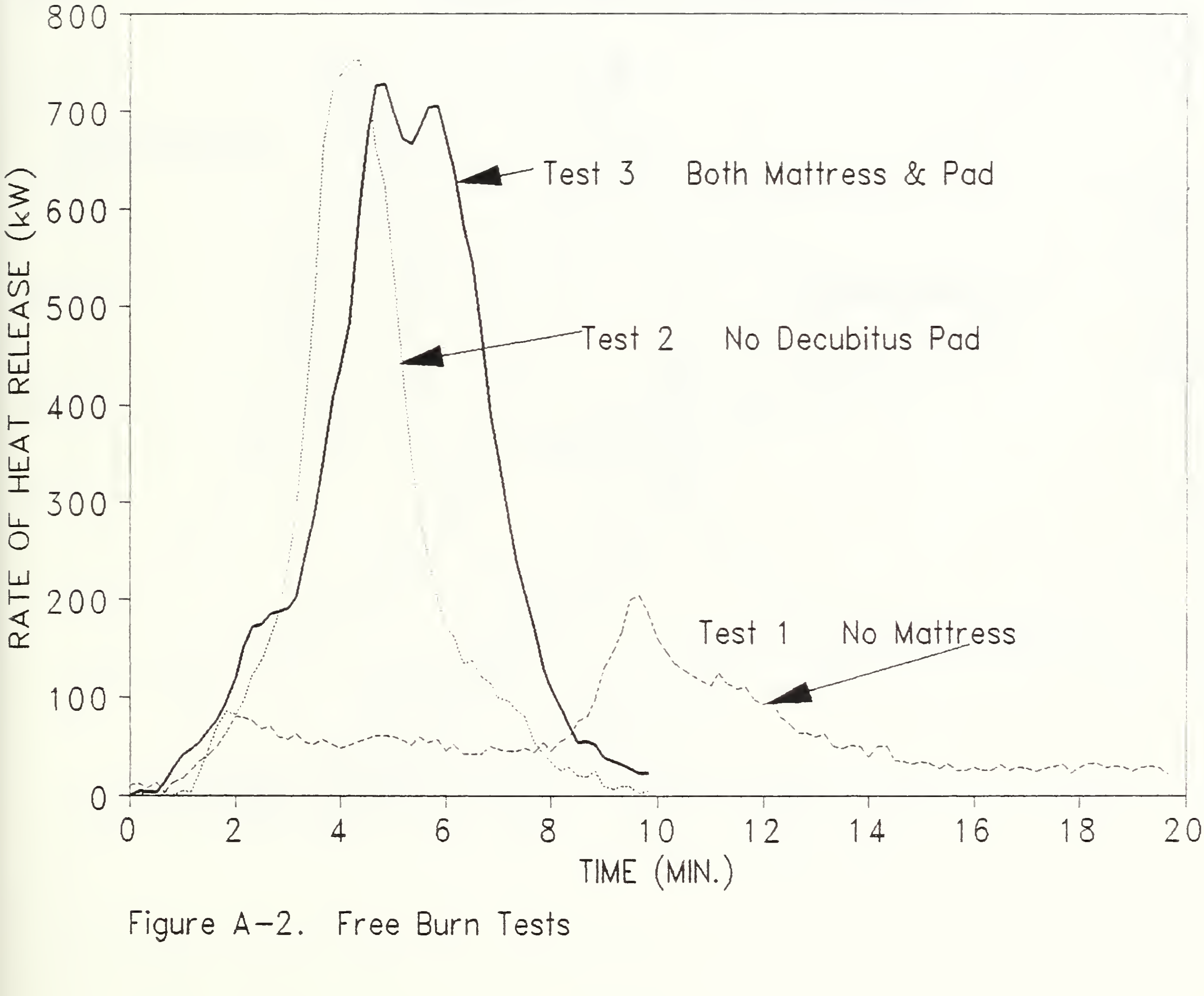

Figure A-2. Free Burn Tests

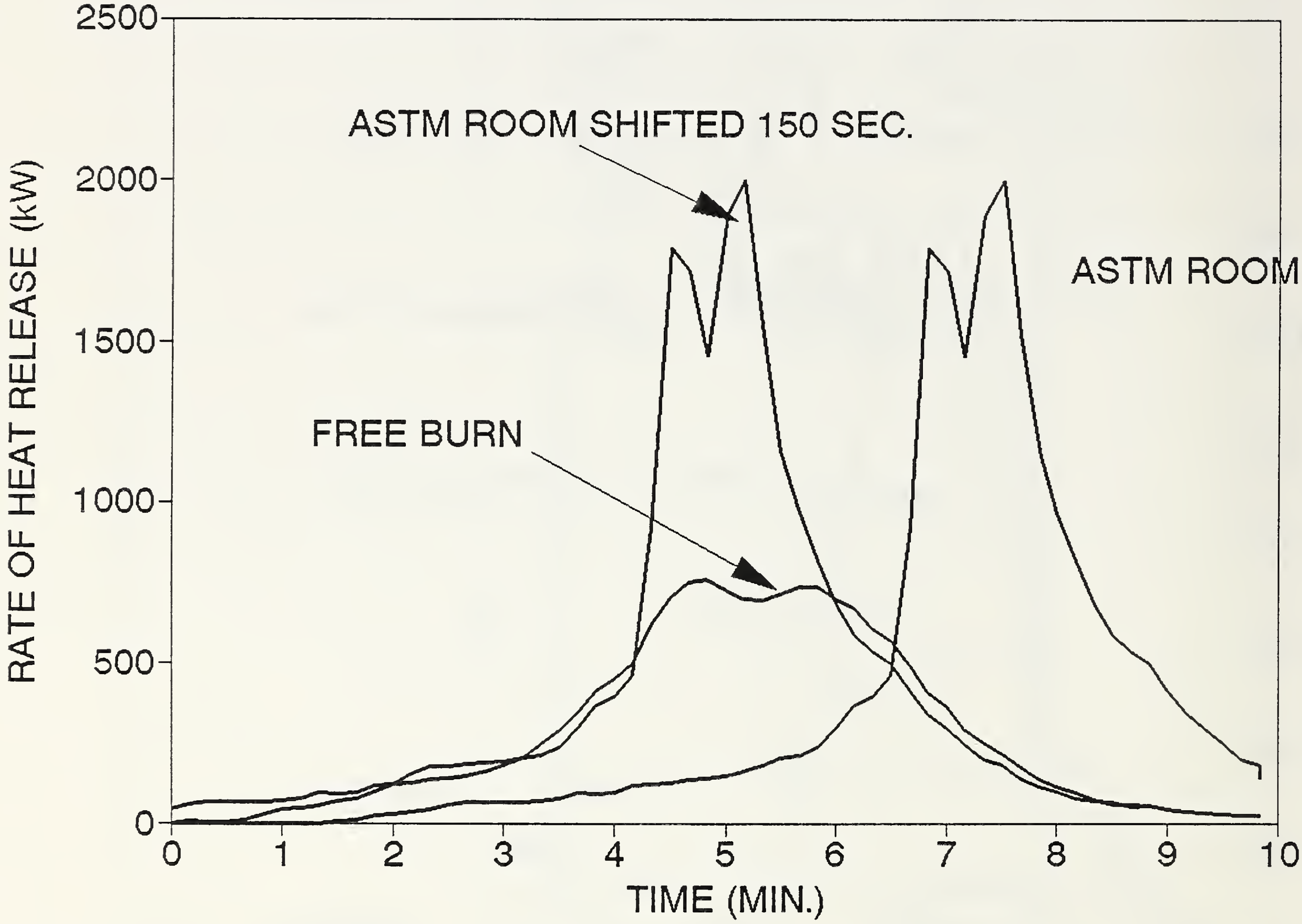

Figure A-3. Rate of Heat Release - Free Burn verses ASTM Room

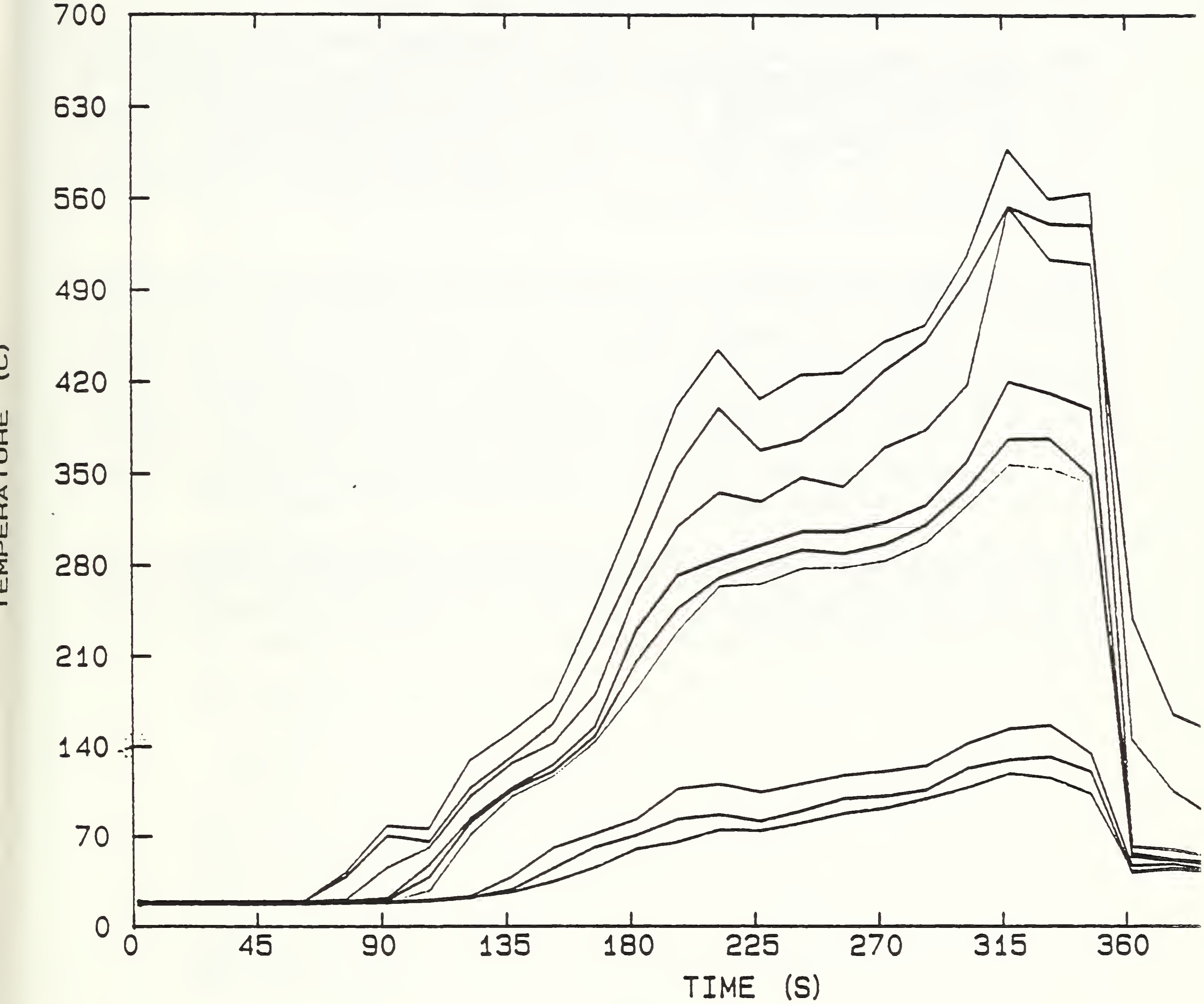

Figure A-4. Temperatures Observed in Patient Room Tests

APPENDIX B
Printouts of FIRE SIMULATOR Runs

Appendix B consists of three multi-part figures containing print outs from FIRE SIMULATOR runs that were used in the evaluation of this fire as follows.

Figure B-1. Fire Simulator Runs Estimating Conditions in Room 226. This figure consists of two runs. Both runs are identical up to the point of flashover. The first run, parts 1 to 3, estimates the impact of the wall covering materials. To do this the post flashover combustible vertical surfaces is set to 100%. The second run estimates the continued impact of the furnishings after the wall covering has burned away. The estimates of conditions in Room 226 contained in this report are a merger of the two runs. The first run covers the conditions from ignition to 2 minutes after flashover; the second the remainder of the fire.

Figure B-2. FIRE SIMULATOR Runs to Estimate Automatic Sprinkler and Smoke Detector Response. This figure consists of four runs. Parts 1 and 2 cover a standard type of sprinkler head having an RTI of 300, and operating temperature of 74°C (165°F) located 2.1 m (7 ft.) from the fire and a smoke detector located 4.6 m (15 ft.) from the fire. Parts 3 and 4 cover a quick response sprinkler having and RTI of 50, and operating temperature of 74°C (165°F) located 2.1 m (7 ft.) from the fire. Parts 5 and 6 cover a quick sprinkler having and RTI of 50 and an operating temperature of 74°C (165°F) located in a sidewall position 4.6 m (15 ft.) from the fire. Part 7 is a special run using the calculated outflow from Room 226 into the corridor to estimate the response of a smoke detector located in the corridor 3.1 m (10 ft.) from the door to Room 226.

Figure B-3. FIRE SIMULATOR Runs Evaluating the Impact of Door Closer. This figure consist of two runs. Parts 1 and 2 cover conditions if the door were closed at the time of smoke detector operation and not reopened during the fire. Part 3 to 5 cover conditions if the door were closed as above but reopened one minute later and kept open.

```
                          FIRE SIMULATOR
                           [VER 2.03]

 Input data used for run of: 04-04-1991 11:25:20

Data file used: ENH-900.IN as of 03/23/91   14:57:44

Run title: HILLHAVEN, EHNANCED BURNING AT 900 kW   03-12-1991

ASCII file name: ENH-900.PRN

Heat of combustion:                       12000.00 BTU/lb    27883.20 KJ/Kg
Specific extinction coefficient:               .10
Flashover temperature:                     1112.00 F           600.00 C
Oxygen starvation threshold:                 10.00 % by volume
Radiant energy fraction (from flame):          .35
Maximum pre flashover energy loss:             .95

There is no Sprinkler/Heat detector defined

There is no Smoke detector defined

Description of initial outside opening:
   Height of opening:             6.75 ft   2.06 m
   Width of opening:              3.60 ft   1.10 m
   Height of sill above floor:    0.00 ft   0.00 m

Spacial dimensions of room:
   Room height:              8.00 ft      2.44 m
   Room floor area:        244.00 ft^2   22.67 m^2
   Room wall perimeter:     74.00 ft     22.56 m
   Room is not rectangular

Description of ceiling materials:
 100%  MINERAL CEILING                      1.000 in     25.400 mm

Description of wall materials:
 100%  GYPSUM BOARD                         0.625 in     15.875 mm

There is no HVAC defined

Fire height:   2.50 ft    0.76 m

1990
Fire description used came from firefile: ENH-900.FIR MAR. 12


    TIME      -----TEMP-----      ------LAYER----      -----FIRE-----
    sec          F         C         ft          m          kW       BTU/sec
     0.0       70.0      21.1       8.0        2.4        0.1        0.1
Vision distance (smoke layer)  =  3000.00  m   9842.52 ft
Smoke gases : Oxygen =  21.0 % : CO =   0.0000 : CO2 =   0.0000 %
Smoke vent rate is        0 cfm    0.00 cms
Enthalpy (Heat content)         0 btu/sec          0 kW
Inside flow of unburned fuel potential          0 BTU/SEC              0 kW

    60.0     108.8      42.7       6.2        1.9       40.8       38.7
Vision distance (smoke layer)  =    14.40  m     47.26 ft
Smoke gases : Oxygen =  20.6 % : CO =   0.0000 : CO2 =   0.2221 %
Smoke vent rate is       80 cfm    0.04 cms
```

Figure B-1. FIRE SIMULATOR Runs Estimating Conditions in Room 226 (Part 1 of 7)

```
Enthalpy (Heat content)          1 btu/sec           1 kW
Inside flow of unburned fuel potential              0 BTU/SEC              0 kW

   120.0      270.4      132.4       5.2        1.6      198.3      188.1
Vision distance (smoke layer)   =     6.34  m     20.80 ft
Smoke gases : Oxygen =  19.1 % : CO =   0.0000 : CO2 =   1.1523 %
Smoke vent rate is     924 cfm    0.44 cms
Enthalpy (Heat content)         39 btu/sec          42 kW
Inside flow of unburned fuel potential              0 BTU/SEC              0 kW

   180.0      568.7      298.2       5.1        1.5      458.5      434.9
Vision distance (smoke layer)   =     5.61  m     18.40 ft
Smoke gases : Oxygen =  15.7 % : CO =   0.0004 : CO2 =   3.1831 %
Smoke vent rate is    1570 cfm    0.74 cms
Enthalpy (Heat content)        118 btu/sec         125 kW
Inside flow of unburned fuel potential              0 BTU/SEC              0 kW

   240.0      911.1      488.4       5.0        1.5     1179.9     1119.1
Vision distance (smoke layer)   =     4.11  m     13.50 ft
Smoke gases : Oxygen =   8.2 % : CO =   0.0040 : CO2 =   7.6026 %
Smoke vent rate is    2196 cfm    1.04 cms
Enthalpy (Heat content)        209 btu/sec         221 kW
Inside flow of unburned fuel potential              0 BTU/SEC              0 kW

   267.0     1122.6      605.9       4.9        1.5     1882.6     1785.6
Vision distance (smoke layer)   =     3.28  m     10.76 ft
Smoke gases : Oxygen =   2.0 % : CO =   0.0125 : CO2 =  11.5159 %
Smoke vent rate is    2706 cfm    1.28 cms
Enthalpy (Heat content)        278 btu/sec         294 kW
Inside flow of unburned fuel potential              0 BTU/SEC              0 kW


UPPER LEVEL TEMP. INDICATES THAT FLASHOVER HAS PROBABLY OCCURRED BY  267  SEC.

   267.0     1122.6      605.9       4.9        1.5     1882.6     1785.6
Vision distance (smoke layer)   =     3.28  m     10.76 ft
Smoke gases : Oxygen =   2.0 % : CO =   0.0125 : CO2 =  11.5159 %
Smoke vent rate is    2706 cfm    1.28 cms
Enthalpy (Heat content)        278 btu/sec         294 kW
Inside flow of unburned fuel potential              0 BTU/SEC              0 kW


Post flashover
Combustion efficiency                100.00
Heat of combustion                    27883.2 kJ/kg      12000 BTU/lb
Base heat of gasification                 2.0 kJ/g         861 BTU/lb
Fuel load                              2.00 lb/ft^2      9.76 kg/m^2
% burnable                           100.00
Horizontal comb. surface (%)          20.00
Vertical comb. surface (%)           100.00
  Horz. comb. surf. > 1/4 in. (%)     20.00
  Vert. comb. surf. > 1/4 in. (%)    100.00
    Horz. comb. surf > 1 in. (%)      20.00
    Vert. comb. surf > 1 in. (%)     100.00
 Duration (Sec)                         119
                  height       width          sill
Inside opening  is    6.75 ft X    3.60 ft X    0.00 ft     2.057 m X  1.097 m X  0.
000 m
Outside opening is    2.50 ft X    7.50 ft X    2.00 ft     0.762 m X  2.286 m X  0.
610 m
```

Figure B-1. FIRE SIMULATOR Runs Estimating Conditions in Room 226 (Part 2 of 7)

```
   300.0    1796.7     980.4       4.0       1.2    7727.8    7329.8
Vision distance (smoke layer)  =     0.09  m      0.30 ft
Smoke gases : Oxygen =   0.0 % : CO =   3.8300 : CO2 =   8.9367 %
Smoke vent rate is   12473 cfm    5.89 cms
Enthalpy (Heat content)      1481 btu/sec       1561 kW
Inside flow of unburned fuel potential      17,386 BTU/SEC        18,325 kW

   360.0    1782.0     972.2       4.0       1.2    7758.8    7359.2
Vision distance (smoke layer)  =     0.03  m      0.11 ft
Smoke gases : Oxygen =   0.0 % : CO =   3.8300 : CO2 =   8.9368 %
Smoke vent rate is   12392 cfm    5.85 cms
Enthalpy (Heat content)      1468 btu/sec       1547 kW
Inside flow of unburned fuel potential      17,386 BTU/SEC        18,325 kW

   387.0    1794.4     979.1       4.0       1.2    7732.7    7334.4
Vision distance (smoke layer)  =     0.03  m      0.08 ft
Smoke gases : Oxygen =   0.0 % : CO =   3.8300 : CO2 =   8.9368 %
Smoke vent rate is   12500 cfm    5.90 cms
Enthalpy (Heat content)      1485 btu/sec       1565 kW
Inside flow of unburned fuel potential      17,386 BTU/SEC        18,325 kW

All available combustibles consumed.  Some individual items may still burn.
 - - - - -   THIS RUN IS OVER   - - - -
   387.0    1794.4     979.1       4.0       1.2    7732.7    7334.4
Vision distance (smoke layer)  =     0.03  m      0.08 ft
Smoke gases : Oxygen =   0.0 % : CO =   3.8300 : CO2 =   8.9368 %
Smoke vent rate is   12500 cfm    5.90 cms
Enthalpy (Heat content)      1485 btu/sec       1565 kW
Inside flow of unburned fuel potential      17,386 BTU/SEC        18,325 kW
```

Figure B-1. FIRE SIMULATOR Runs Estimating Conditions in Room 226 (Part 3 of 7)

```
                                  FIRE SIMULATOR
                                    [VER 2.03]

 Input data used for run of: 03-24-1991 09:07:55

Data file used: ENH-900.IN as of 03/23/91    14:57:44

Run title: HILLHAVEN, EHNANCED BURNING AT 900 kW    03-12-1991

ASCII file name: ENH-900.PRN

Heat of combustion:                          12000.00 BTU/lb    27883.20 KJ/Kg
Specific extinction coefficient:                  .10
Flashover temperature:                        1112.00 F            600.00 C
Oxygen starvation threshold:                    10.00 % by volume
Radiant energy fraction (from flame):             .35
Maximum pre flashover energy loss:                .95

There is no Sprinkler/Heat detector defined

There is no Smoke detector defined

Description of initial outside opening:
   Height of opening:            6.75 ft    2.06 m
   Width of opening:             3.60 ft    1.10 m
   Height of sill above floor:   0.00 ft    0.00 m

Spacial dimensions of room:
   Room height:             8.00 ft       2.44 m
   Room floor area:       244.00 ft^2    22.67 m^2
   Room wall perimeter:    74.00 ft      22.56 m
   Room is not rectangular

Description of ceiling materials:
 100%  MINERAL CEILING                        1.000 in      25.400 mm

Description of wall materials:
 100%  GYPSUM BOARD                           0.625 in      15.875 mm

There is no HVAC defined

Fire height:   2.50 ft    0.76 m

1990
Fire description used came from firefile: ENH-900.FIR MAR. 12


    TIME       -----TEMP-----       ------LAYER----       -----FIRE-----
    sec          F          C          ft         m          kW      BTU/sec
     0.0       70.0       21.1        8.0        2.4        0.1        0.1
Vision distance (smoke layer)  =  3000.00  m   9842.52 ft
Smoke gases : Oxygen =  21.0 % : Co =   0.0000 : Co2 =   0.0000 %
Smoke vent rate is       0 cfm    0.00 cms
Enthalpy (Heat content)         0 btu/sec          0 kW
Inside flow of unburned fuel potential          0 BTU/SEC              0 kW

    60.0      108.8       42.7        6.2        1.9       40.8       38.7
Vision distance (smoke layer)  =    14.40  m     47.26 ft
Smoke gases : Oxygen =  20.6 % : Co =   0.0000 : Co2 =   0.2221 %
Smoke vent rate is      80 cfm    0.04 cms
Enthalpy (Heat content)         1 btu/sec          1 kW
Inside flow of unburned fuel potential          0 BTU/SEC              0 kW
```

Figure B-1. FIRE SIMULATOR Runs Estimating Conditions in Room 226 (Part 4 of 7)

```
   120.0     270.4     132.4       5.2        1.6     198.3     188.1
Vision distance (smoke layer)  =     6.34  m     20.80 ft
Smoke gases : Oxygen =  19.1 % : Co =   0.0000 : Co2 =   1.1523 %
Smoke vent rate is     924 cfm    0.44 cms
Enthalpy (Heat content)       39 btu/sec         42 kW
Inside flow of unburned fuel potential          0 BTU/SEC              0 kW

   180.0     568.7     298.2       5.1        1.5     458.5     434.9
Vision distance (smoke layer)  =     5.61  m     18.40 ft
Smoke gases : Oxygen =  15.7 % : Co =   0.0004 : Co2 =   3.1831 %
Smoke vent rate is    1570 cfm    0.74 cms
Enthalpy (Heat content)      118 btu/sec        125 kW
Inside flow of unburned fuel potential          0 BTU/SEC              0 kW

   240.0     911.1     488.4       5.0        1.5    1179.9    1119.1
Vision distance (smoke layer)  =     4.11  m     13.50 ft
Smoke gases : Oxygen =   8.2 % : Co =   0.0040 : Co2 =   7.6026 %
Smoke vent rate is    2196 cfm    1.04 cms
Enthalpy (Heat content)      209 btu/sec        221 kW
Inside flow of unburned fuel potential          0 BTU/SEC              0 kW

   267.0    1122.6     605.9       4.9        1.5    1882.6    1785.6
Vision distance (smoke layer)  =     3.28  m     10.76 ft
Smoke gases : Oxygen =   2.0 % : Co =   0.0125 : Co2 =  11.5159 %
Smoke vent rate is    2706 cfm    1.28 cms
Enthalpy (Heat content)      278 btu/sec        294 kW
Inside flow of unburned fuel potential          0 BTU/SEC              0 kW


UPPER LEVEL TEMP. INDICATES THAT FLASHOV
ER HAS PROBABLY OCCURRED BY  267  SEC.

   267.0    1122.6     605.9       4.9        1.5    1882.6    1785.6
Vision distance (smoke layer)  =     3.28  m     10.76 ft
Smoke gases : Oxygen =   2.0 % : Co =   0.0125 : Co2 =  11.5159 %
Smoke vent rate is    2706 cfm    1.28 cms
Enthalpy (Heat content)      278 btu/sec        294 kW
Inside flow of unburned fuel potential          0 BTU/SEC              0 kW


Post flashover
Combustion efficiency               100.00
Heat of combustion                   27883.2 kJ/kg     12000 BTU/lb
Base heat of gasification                2.0 kJ/g        861 BTU/lb
Fuel load                              2.00 lb/ft^2     9.76 kg/m^2
% burnable                          100.00
Horizontal comb. surface (%)         15.00
Vertical comb. surface (%)           15.00
  Horz. comb. surf. > 1/4 in. (%)    15.00
  Vert. comb. surf. > 1/4 in. (%)    15.00
    Horz. comb. surf > 1 in. (%)     15.00
    Vert. comb. surf > 1 in. (%)     15.00
 Duration (Sec)                        608
                  height      width        sill
Inside opening  is    6.75 ft X    3.60 ft X    0.00 ft     2.057 m X   1.097 m X   0.
000 m
Outside opening is    2.50 ft X    7.50 ft X    2.00 ft     0.762 m X   2.286 m X   0.
610 m

   300.0    1624.9     884.9       4.0        1.2    7223.2    6851.2
Vision distance (smoke layer)  =     0.11  m      0.37 ft
Smoke gases : Oxygen =   0.0 % : Co =   3.8233 : Co2 =   8.9211 %
Smoke vent rate is    5924 cfm    2.80 cms
Enthalpy (Heat content)      687 btu/sec        724 kW
```

Figure B-1. FIRE SIMULATOR Runs Estimating Conditions in Room 226 (Part 5 of 7)

```
Inside flow of unburned fuel potential          0 BTU/SEC              0 kW

   360.0     1668.0     908.9        4.0        1.2     7142.2     6774.3
Vision distance (smoke layer)  =     0.04  m      0.12 ft
Smoke gases : Oxygen =    0.0 % : Co =    3.8300 : Co2 =    8.9368 %
Smoke vent rate is    6002 cfm    2.83 cms
Enthalpy (Heat content)       700 btu/sec        738 kW
Inside flow of unburned fuel potential          0 BTU/SEC              0 kW

   420.0     1664.6     907.0        4.0        1.2     7148.5     6780.4
Vision distance (smoke layer)  =     0.02  m      0.07 ft
Smoke gases : Oxygen =    0.0 % : Co =    3.8300 : Co2 =    8.9368 %
Smoke vent rate is    6001 cfm    2.83 cms
Enthalpy (Heat content)       700 btu/sec        738 kW
Inside flow of unburned fuel potential          0 BTU/SEC              0 kW

   480.0     1664.2     906.8        4.0        1.2     7149.3     6781.1
Vision distance (smoke layer)  =     0.02  m      0.05 ft
Smoke gases : Oxygen =    0.0 % : Co =    3.8300 : Co2 =    8.9368 %
Smoke vent rate is    6004 cfm    2.83 cms
Enthalpy (Heat content)       700 btu/sec        738 kW
Inside flow of unburned fuel potential          0 BTU/SEC              0 kW

   540.0     1672.2     911.2        4.0        1.2     7134.2     6766.8
Vision distance (smoke layer)  =     0.01  m      0.04 ft
Smoke gases : Oxygen =    0.0 % : Co =    3.8300 : Co2 =    8.9368 %
Smoke vent rate is    6019 cfm    2.84 cms
Enthalpy (Heat content)       703 btu/sec        741 kW
Inside flow of unburned fuel potential          0 BTU/SEC              0 kW

   600.0     1675.6     913.1        4.0        1.2     7127.9     6760.8
Vision distance (smoke layer)  =     0.01  m      0.03 ft
Smoke gases : Oxygen =    0.0 % : Co =    3.8300 : Co2 =    8.9368 %
Smoke vent rate is    6026 cfm    2.84 cms
Enthalpy (Heat content)       704 btu/sec        742 kW
Inside flow of unburned fuel potential          0 BTU/SEC              0 kW

   660.0     1677.2     914.0        4.0        1.2     7125.0     6758.0
Vision distance (smoke layer)  =     0.01  m      0.03 ft
Smoke gases : Oxygen =    0.0 % : Co =    3.8300 : Co2 =    8.9368 %
Smoke vent rate is    6030 cfm    2.85 cms
Enthalpy (Heat content)       705 btu/sec        743 kW
Inside flow of unburned fuel potential          0 BTU/SEC              0 kW

   720.0     1679.0     915.0        4.0        1.2     7121.6     6754.8
Vision distance (smoke layer)  =     0.01  m      0.02 ft
Smoke gases : Oxygen =    0.0 % : Co =    3.8300 : Co2 =    8.9368 %
Smoke vent rate is    6034 cfm    2.85 cms
Enthalpy (Heat content)       705 btu/sec        743 kW
Inside flow of unburned fuel potential          0 BTU/SEC              0 kW

   780.0     1680.8     916.0        4.0        1.2     7118.2     6751.6
Vision distance (smoke layer)  =     0.01  m      0.02 ft
Smoke gases : Oxygen =    0.0 % : Co =    3.8300 : Co2 =    8.9368 %
Smoke vent rate is    6038 cfm    2.85 cms
Enthalpy (Heat content)       706 btu/sec        744 kW
Inside flow of unburned fuel potential          0 BTU/SEC              0 kW

   840.0     1682.4     916.9        4.0        1.2     7115.1     6748.6
Vision distance (smoke layer)  =     0.01  m      0.02 ft
Smoke gases : Oxygen =    0.0 % : Co =    3.8300 : Co2 =    8.9368 %
Smoke vent rate is    6042 cfm    2.85 cms
Enthalpy (Heat content)       707 btu/sec        745 kW
```

Figure B-1. FIRE SIMULATOR Runs Estimating Conditions in Room 226 (Part 6 of 7)

```
Inside flow of unburned fuel potential          0 BTU/SEC          0 kW

   876.0    1683.8     917.7        4.0        1.2     7112.5    6746.2
Vision distance (smoke layer)  =     0.01  m       0.02 ft
Smoke gases : Oxygen =   0.0 % : Co =   3.8300 : Co2 =   8.9368 %
Smoke vent rate is    6044 cfm    2.85 cms
Enthalpy (Heat content)       707 btu/sec        745 kW
Inside flow of unburned fuel potential          0 BTU/SEC          0 kW

All available combustibles consumed.  Some individual items may still burn.
 - - - - -   THIS RUN IS OVER  - - - -
   876.0    1683.8     917.7        4.0        1.2     7112.5    6746.2
Vision distance (smoke layer)  =     0.01  m       0.02 ft
Smoke gases : Oxygen =   0.0 % : Co =   3.8300 : Co2 =   8.9368 %
Smoke vent rate is    6044 cfm    2.85 cms
Enthalpy (Heat content)       707 btu/sec        745 kW
Inside flow of unburned fuel potential          0 BTU/SEC          0 kW
```

Figure B-1. FIRE SIMULATOR Runs Estimating Conditions in Room 226 (Part 7 of 7)

```
                    FIRE SIMULATOR
                      [VER 2.03]

 Input data used for run of: 03-24-1991 11:10:58

Data file used: ENH-900S.IN as of 03/24/91   11:10:18

Run title: HILLHAVEN, EHNANCED BURNING AT 900 kW   03-12-1991

ASCII file name: ENH-99S.PRN

Heat of combustion:                      12000.00 BTU/lb    27883.20 KJ/Kg
Specific extinction coefficient:              .10
Flashover temperature:                    1112.00 F            600.00 C
Oxygen starvation threshold:                10.00 % by volume
Radiant energy fraction (from flame):         .35
Maximum pre flashover energy loss:            .95

Sprinkler/Heat detector description:
   Radial distance     7.00    ft          2.13 m
   RTI:               300.00 (Ft-Sec)^.5 165.63 (m-Sec)^.5
   Sprinkler rating: 165.00 F            73.89 C
   Sprinkler is not sidewall mounted

Smoke detector description:
   Radial distance    15.00    ft          4.57 m
   Smoke temperature at detection:  93  F      33.88889  C
   Smoke detector is not sidewall mounted

Description of initial outside opening:
   Height of opening:           6.75 ft   2.06 m
   Width of opening:            3.60 ft   1.10 m
   Height of sill above floor:  0.00 ft   0.00 m

Spacial dimensions of room:
   Room height:            8.00 ft      2.44 m
   Room floor area:     244.00 ft^2   22.67 m^2
   Room wall perimeter:  74.00 ft     22.56 m
   Room is not rectangular

Description of ceiling materials:
 100%  MINERAL CEILING                     1.000 in     25.400 mm

Description of wall materials:
 100%  GYPSUM BOARD                        0.625 in     15.875 mm

There is no HVAC defined

Fire height:   2.50 ft    0.76 m

1990
Fire description used came from firefile: ENH-900.FIR MAR. 12

A halt flag is set for Smoke detector activation

A halt flag is set for Sprinkler activation


    TIME      -----TEMP-----      ------LAYER----      -----FIRE-----
    sec        F         C         ft         m          kW       BTU/sec
    0.0      70.0      21.1        8.0        2.4        0.1         0.1
Smoke at Smoke detector =    0 % of detectable concentration.
Link temperature        =     70.0 F       21.1  C
Ceiling Jet Temperature (at link) =     71.0 F      21.6  C
```

Figure B-2 FIRE SIMULATOR Runs to Estimate Automatic Sprinkler and Smoke Detector Response (Part 1 of 7)

```
Ceiling Jet Velocity (at link)  =     0.20 ft/sec      0.06  m/sec
Vision distance (smoke layer)  =  3000.00  m   9842.52 ft
Smoke gases : Oxygen =  21.0 % : Co =   0.0000 : Co2 =   0.0000 %
Smoke vent rate is       0 cfm    0.00 cms
Enthalpy (Heat content)         0 btu/sec          0 kW
Inside flow of unburned fuel potential           0 BTU/SEC             0 kW
```

Smoke detector activated at 50 seconds .

```
    50.0      95.2      35.1       6.5       2.0      27.4      26.0
Link temperature          =     72.4 F      22.4  C
Ceiling Jet Temperature (at link) =    106.9 F      41.6  C
Ceiling Jet Velocity (at link)  =     1.31 ft/sec      0.40  m/sec
Vision distance (smoke layer)  =    20.21  m     66.30 ft
Smoke gases : Oxygen =  20.7 % : Co =   0.0000 : Co2 =   0.1530 %
Smoke vent rate is      11 cfm    0.01 cms
Enthalpy (Heat content)         0 btu/sec          0 kW
Inside flow of unburned fuel potential           0 BTU/SEC             0 kW

    50.0      95.2      35.1       6.5       2.0      27.4      26.0
Link temperature          =     72.5 F      22.5  C
Ceiling Jet Temperature (at link) =    108.2 F      42.4  C
Ceiling Jet Velocity (at link)  =     1.33 ft/sec      0.41  m/sec
Vision distance (smoke layer)  =    20.21  m     66.30 ft
Smoke gases : Oxygen =  20.7 % : Co =   0.0000 : Co2 =   0.1593 %
Smoke vent rate is      11 cfm    0.01 cms
Enthalpy (Heat content)         0 btu/sec          0 kW
Inside flow of unburned fuel potential           0 BTU/SEC             0 kW
```

Sprinkler/Heat detector activated at 177 seconds.

```
   177.0     553.9     289.9       5.1       1.5     442.2     419.4
Vision distance (smoke layer)  =     5.62  m     18.45 ft
Smoke gases : Oxygen =  15.9 % : Co =   0.0004 : Co2 =   3.0643 %
Smoke vent rate is    1546 cfm    0.73 cms
Enthalpy (Heat content)       115 btu/sec        121 kW
Inside flow of unburned fuel potential           0 BTU/SEC             0 kW
```

Figure B-2 FIRE SIMULATOR Runs to Estimate Automatic Sprinkler and Smoke Detector Response (Part 2 of 7)

```
_______________________________FIRE SIMULATOR___________________________
                                 [VER 2.03]

 Input data used for run of: 03-24-1991 11:14:18

Data file used: ENH-900S.IN as of 03/24/91   11:14:06

Run title: HILLHAVEN, EHNANCED BURNING AT 900 kW   03-12-1991

ASCII file name: ENH-99S.PRN

Heat of combustion:                       12000.00 BTU/lb    27883.20 KJ/Kg
Specific extinction coefficient:               .10
Flashover temperature:                     1112.00 F            600.00 C
Oxygen starvation threshold:                 10.00 % by volume
Radiant energy fraction (from flame):          .35
Maximum pre flashover energy loss:             .95

Sprinkler/Heat detector description:
   Radial distance      7.00    ft           2.13 m
   RTI:              50.00 (Ft-Sec)^.5  27.60 (m-Sec)^.5
   Sprinkler rating: 165.00 F           73.89 C
   Sprinkler is not sidewall mounted

There is no Smoke detector defined

Description of initial outside opening:
   Height of opening:           6.75 ft   2.06 m
   Width of opening:            3.60 ft   1.10 m
   Height of sill above floor:  0.00 ft   0.00 m

Spacial dimensions of room:
   Room height:            8.00 ft      2.44 m
   Room floor area:      244.00 ft^2   22.67 m^2
   Room wall perimeter:   74.00 ft     22.56 m
   Room is not rectangular

Description of ceiling materials:
 100%  MINERAL CEILING                       1.000 in      25.400 mm

Description of wall materials:
 100%  GYPSUM BOARD                          0.625 in      15.875 mm

There is no HVAC defined

Fire height:   2.50 ft    0.76 m

1990
Fire description used came from firefile: ENH-900.FIR MAR. 12

A halt flag is set for Smoke detector activation

A halt flag is set for Sprinkler activation


    TIME      -----TEMP-----      ------LAYER----       -----FIRE-----
    sec          F        C          ft        m          kW      BTU/sec
     0.0       70.0      21.1        8.0      2.4         0.1       0.1
Link temperature             =       70.0 F       21.1  C
Ceiling Jet Temperature (at link) =      71.0 F       21.6  C
Ceiling Jet Velocity (at link)  =     0.20 ft/sec      0.06  m/sec
Vision distance (smoke layer)  =  3000.00  m   9842.52 ft
Smoke gases : Oxygen =   21.0 % : Co =    0.0000 : Co2 =    0.0000 %
Smoke vent rate is        0 cfm     0.00 cms
```

Figure B-2 FIRE SIMULATOR Runs to Estimate Automatic Sprinkler and Smoke Detector Response (Part 3 of 7)

```
Enthalpy (Heat content)          0 btu/sec          0 kW
Inside flow of unburned fuel potential          0 BTU/SEC          0 kW
```

Sprinkler/Heat detector activated at 114 seconds.

```
   114.0     249.2     120.7       5.2       1.6     185.2     175.7
Vision distance (smoke layer)  =     6.41  m     21.02 ft
Smoke gases : Oxygen =  19.3 % : Co =   0.0000 : Co2 =   1.0116 %
Smoke vent rate is     864 cfm    0.41 cms
Enthalpy (Heat content)        34 btu/sec         36 kW
Inside flow of unburned fuel potential          0 BTU/SEC          0 kW
```

Figure B-2 FIRE SIMULATOR Runs to Estimate Automatic Sprinkler and Smoke Detector Response (Part 4 of 7)

```
                         FIRE SIMULATOR
                           [VER 2.03]

 Input data used for run of: 03-25-1991 04:19:08

Data file used: ENH-900S.IN as of 03/25/91   04:18:22

Run title: HILLHAVEN, EHNANCED BURNING AT 900 kW   03-12-1991

ASCII file name: ENH-99S.PRN

Heat of combustion:                       12000.00 BTU/lb    27883.20 KJ/Kg
Specific extinction coefficient:               .10
Flashover temperature:                     1112.00 F           600.00 C
Oxygen starvation threshold:                 10.00 % by volume
Radiant energy fraction (from flame):          .35
Maximum pre flashover energy loss:             .95

Sprinkler/Heat detector description:
   Radial distance    15.00    ft           4.57 m
   RTI:               50.00 (Ft-Sec)^.5  27.60 (m-Sec)^.5
   Sprinkler rating: 165.00 F            73.89 C
   Sprinkler is sidewall mounted with a  25 % flow reduction

There is no Smoke detector defined

Description of initial outside opening:
   Height of opening:          6.75 ft   2.06 m
   Width of opening:           3.60 ft   1.10 m
   Height of sill above floor:  0.00 ft   0.00 m

Spacial dimensions of room:
   Room height:             8.00 ft      2.44 m
   Room floor area:       244.00 ft^2   22.67 m^2
   Room wall perimeter:   74.00 ft      22.56 m
   Room is not rectangular

Description of ceiling materials:
 100%  MINERAL CEILING                      1.000 in     25.400 mm

Description of wall materials:
 100%  GYPSUM BOARD                         0.625 in     15.875 mm

There is no HVAC defined

Fire height:   2.50 ft    0.76 m

1990
Fire description used came from firefile: ENH-900.FIR MAR. 12

A halt flag is set for Smoke detector activation

A halt flag is set for Sprinkler activation


    TIME      -----TEMP-----     ------LAYER----      -----FIRE-----
    sec          F         C          ft         m         kW       BTU/sec
     0.0      70.0      21.1         8.0       2.4        0.1         0.1
Link temperature         =      70.0 F      21.1  C
Ceiling Jet Temperature (at link) =     70.7 F       21.5  C
Ceiling Jet Velocity (at link)  =     0.11 ft/sec      0.03  m/sec
Vision distance (smoke layer)  =  3000.00  m   9842.52 ft
Smoke gases : Oxygen =  21.0 % : Co =   0.0000 : Co2 =   0.0000 %
```

Figure B-2 FIRE SIMULATOR Runs to Estimate Automatic Sprinkler and Smoke Detector Response (Part 5 of 7)

```
Smoke vent rate is        0 cfm    0.00 cms
Enthalpy (Heat content)          0 btu/sec         0 kW
Inside flow of unburned fuel potential          0 BTU/SEC              0 kW
```

Sprinkler/Heat detector activated at 146 seconds.

```
   146.0     385.2     196.2       5.1       1.6     321.8     305.2
Vision distance (smoke layer)  =     5.89  m     19.32 ft
Smoke gases : Oxygen =  17.9 % : Co =   0.0001 : Co2 =   1.8780 %
Smoke vent rate is    1229 cfm    0.58 cms
Enthalpy (Heat content)        71 btu/sec         75 kW
Inside flow of unburned fuel potential          0 BTU/SEC              0 kW
```

Figure B-2 FIRE SIMULATOR Runs to Estimate Automatic Sprinkler and Smoke Detector Response (Part 6 of 7)

```
___________________________________FIRE SIMULATOR___________________________________
                                   [VER 2.03]

 Input data used for run of: 03-24-1991 11:25:09

Data file used: NORCOR-S.IN as of 03/24/91   11:25:00

Run title: NORCORR2   10-08-1989

ASCII file name: NORCOR-S.PRN

Heat of combustion:                         15370.24 BTU/lb    35714.29 KJ/Kg
Specific extinction coefficient:                 .10
Flashover temperature:                       1112.00 F            600.00 C
Oxygen starvation threshold:                   10.00 % by volume
Radiant energy fraction (from flame):            .35
Maximum pre flashover energy loss:               .94

There is no Sprinkler/Heat detector defined

Smoke detector description:
   Radial distance    10.00   ft          3.05 m
   Smoke temperature at detection:  93  F     33.88889  C
   Smoke detector is not sidewall mounted

There is no initial outside opening defined

Spacial dimensions of room:
   Room height:             8.00 ft      2.44 m
   Room floor area:       639.98 ft^2   59.46 m^2
   Room wall perimeter:   176.00 ft     53.64 m
   Room is rectangular:    80.00 ft   by     8.00 ft     24.38 m   by    2.44 m

Description of ceiling materials:
 100%  MINERAL CEILING                        1.000 in     25.400 mm

Description of wall materials:
 100%  GYPSUM BOARD                           0.625 in     15.875 mm

There is no HVAC defined

Fire height:   2.50 ft    0.76 m

Output fire from RNTOOL running ENH-900.IN as input
Fire description used came from firefile: FIRE.FIR 03-24-1991

A halt flag is set for Smoke detector activation


    TIME       -----TEMP-----      ------LAYER----      -----FIRE-----
    sec          F         C          ft         m         kW      BTU/sec
     0.0       70.0      21.1        8.0        2.4       0.1       0.1
Smoke at Smoke detector =    0 % of detectable concentration.
Vision distance (smoke layer)  =  3000.00  m    9842.52 ft
Smoke gases : Oxygen =  21.0 % : Co =   0.0000 : Co2 =   0.0000 %

Smoke detector activated at 100 second
s.

   100.0       84.1      28.9        7.4        2.2      20.6      19.5
Vision distance (smoke layer)  =    39.74  m    130.38 ft
Smoke gases : Oxygen =  20.8 % : Co =   0.0000 : Co2 =   0.0834 %
```

Figure B-2 FIRE SIMULATOR Runs to Estimate Automatic Sprinkler and Smoke Detector Response (Part 7 of 7)

```
_______________________________FIRE SIMULATOR_______________________________
                              [VER 2.03]

 Input data used for run of: 03-24-1991 15:18:35

Data file used: ENH900-D.IN as of 03/24/91   15:16:20

Run title: HILLHAVEN, EHNANCED BURNING AT 900 kW   03-12-1991

ASCII file name: ENH900-D.PRN

Heat of combustion:                        12000.00 BTU/lb    27883.20 KJ/Kg
Specific extinction coefficient:                .10
Flashover temperature:                      1112.00 F           600.00 C
Oxygen starvation threshold:                  10.00 % by volume
Radiant energy fraction (from flame):           .35
Maximum pre flashover energy loss:              .95

There is no Sprinkler/Heat detector defined

Smoke detector description:
   Radial distance    23.00    ft          7.01 m
   Smoke temperature at detection:  93  F     33.88889  C
   Smoke detector is not sidewall mounted

Description of initial outside opening:
   Height of opening:          6.75 ft   2.06 m
   Width of opening:           3.60 ft   1.10 m
   Height of sill above floor: 0.00 ft   0.00 m

Spacial dimensions of room:
   Room height:            8.00 ft     2.44 m
   Room floor area:      244.00 ft^2   22.67 m^2
   Room wall perimeter:   74.00 ft     22.56 m
   Room is not rectangular

Description of ceiling materials:
 100%  MINERAL CEILING                      1.000 in     25.400 mm

Description of wall materials:
 100%  GYPSUM BOARD                         0.625 in     15.875 mm

There is no HVAC defined

Fire height:   2.50 ft    0.76 m

1990
Fire description used came from firefile: ENH-900.FIR MAR. 12

A halt flag is set for Smoke detector activation


    TIME       -----TEMP-----      ------LAYER----       -----FIRE-----
    sec          F         C         ft         m          kW       BTU/sec
     0.0       70.0      21.1       8.0        2.4        0.1        0.1
Smoke at Smoke detector =    0 % of detectable concentration.
Vision distance (smoke layer)  =  3000.00  m   9842.52 ft
Smoke gases : Oxygen =  21.0 % : Co =   0.0000 : Co2 =   0.0000 %
Smoke vent rate is        0 cfm    0.00 cms
Enthalpy (Heat content)        0 btu/sec          0 kW
Inside flow of unburned fuel potential          0 BTU/SEC            0 kW

Smoke  detector  activated  at   56   seconds
```

Figure B-3 FIRE SIMULATOR Runs Evaluating the Impact of Door Closers (Part 1 of 5)

```
    56.0      103.2      39.6       6.3       1.9      35.4      33.6
Vision distance (smoke layer)  =    16.31  m     53.52 ft
Smoke gases : Oxygen =  20.7 % : Co =   0.0000 : Co2 =   0.1928 %
Smoke vent rate is      46 cfm    0.02 cms
Enthalpy (Heat content)        0 btu/sec          0 kW
Inside flow of unburned fuel potential           0 BTU/SEC             0 kW


There is no inside opening in the room.


Currently there is no outside opening in the room.


Air from an operating HVAC system is not currently being considered.
    56.0      103.2      39.6       6.3       1.9      35.4      33.6
Vision distance (smoke layer)  =    16.31  m     53.52 ft
Smoke gases : Oxygen =  20.7 % : Co =   0.0000 : Co2 =   0.1999 %

    60.0      108.9      42.7       6.2       1.9      40.8      38.7
Vision distance (smoke layer)  =    14.58  m     47.85 ft
Smoke gases : Oxygen =  20.6 % : Co =   0.0000 : Co2 =   0.2221 %

   120.0      279.2     137.3       3.7       1.1     198.3     188.1
Vision distance (smoke layer)  =     3.30  m     10.82 ft
Smoke gases : Oxygen =  19.1 % : Co =   0.0002 : Co2 =   1.1283 %

   180.0      619.6     326.4       1.5       0.5     458.5     434.9
Vision distance (smoke layer)  =     1.38  m      4.51 ft
Smoke gases : Oxygen =  15.1 % : Co =   0.0044 : Co2 =   3.5111 %

   240.0      975.9     524.4       0.0       0.0       0.0       0.0
Vision distance (smoke layer)  =     0.88  m      2.88 ft
Smoke gases : Oxygen =   9.9 % : Co =   0.0240 : Co2 =   6.7460 %

   300.0      975.9     524.4       0.0       0.0       0.0       0.0
Vision distance (smoke layer)  =     0.88  m      2.88 ft
Smoke gases : Oxygen =   9.9 % : Co =   0.0240 : Co2 =   6.7461 %

   305.0      975.9     524.4       0.0       0.0    1996.6    1893.8
Vision distance (smoke layer)  =     0.88  m      2.88 ft
Smoke gases : Oxygen =   9.9 % : Co =   0.0240 : Co2 =   6.7461 %

At  305  Sec. all available oxygen has been consumed.  Since no
openings or HVAC were specified, it is expected that the fire will
quickly go into a smoldering state, leakage of air through small
openings may sustain some fire.
```

Figure B-3 FIRE SIMULATOR Runs Evaluating the Impact of Door Closers
(Part 2 of 5)

```
FIRE SIMULATOR
[VER 2.03]

 Input data used for run of: 03-24-1991 15:29:34

Data file used: ENH900-D.IN as of 03/24/91   15:29:08

Run title: HILLHAVEN, EHNANCED BURNING AT 900 kW   03-12-1991

ASCII file name: ENH900-D.PRN

Heat of combustion:                        12000.00 BTU/lb    27883.20 KJ/Kg
Specific extinction coefficient:                .10
Flashover temperature:                      1112.00 F          600.00 C
Oxygen starvation threshold:                  10.00 % by volume
Radiant energy fraction (from flame):           .35
Maximum pre flashover energy loss:              .95

There is no Sprinkler/Heat detector defined

Smoke detector description:
   Radial distance    23.00   ft          7.01 m
   Smoke temperature at detection:  93  F     33.88889  C
   Smoke detector is not sidewall mounted

Description of initial outside opening:
   Height of opening:            6.75 ft   2.06 m
   Width of opening:             3.60 ft   1.10 m
   Height of sill above floor:   0.00 ft   0.00 m

Spacial dimensions of room:
   Room height:             8.00 ft      2.44 m
   Room floor area:       244.00 ft^2   22.67 m^2
   Room wall perimeter:    74.00 ft     22.56 m
   Room is not rectangular

Description of ceiling materials:
 100%  MINERAL CEILING                      1.000 in     25.400 mm

Description of wall materials:
 100%  GYPSUM BOARD                         0.625 in     15.875 mm

There is no HVAC defined

Fire height:   2.50 ft    0.76 m

1990
Fire description used came from firefile: ENH-900.FIR MAR. 12

A halt flag is set for time =  116  Sec

A halt flag is set for Smoke detector activation


    TIME      -----TEMP-----      ------LAYER----       -----FIRE-----
    sec         F         C         ft          m         kW       BTU/sec
     0.0       70.0      21.1       8.0        2.4        0.1        0.1
Smoke at Smoke detector =    0 % of detectable concentration.
Vision distance (smoke layer)  =  3000.00  m   9842.52 ft
Smoke gases : Oxygen =  21.0 % : Co =    0.0000 : Co2 =   0.0000 %
Smoke vent rate is        0 cfm    0.00 cms
Enthalpy (Heat content)        0 btu/sec         0 kW
Inside flow of unburned fuel potential         0 BTU/SEC              0 kW
```

Figure B-3 FIRE SIMULATOR Runs Evaluating the Impact of Door Closers (Part 3 of 5)

```
Smoke detector activated at 56 seconds
-

    56.0      103.2      39.6       6.3       1.9       35.4      33.6
Vision distance (smoke layer)  =    16.31  m      53.52 ft
Smoke gases : Oxygen =  20.7 % : Co =   0.0000 : Co2 =   0.1928 %
Smoke vent rate is      46 cfm    0.02 cms
Enthalpy (Heat content)        0 btu/sec          0 kW
Inside flow of unburned fuel potential          0 BTU/SEC             0 kW


There is no inside opening in the room.


Currently there is no outside opening in the room.


Air from an operating HVAC system is not currently being considered.
    56.0      103.2      39.6       6.3       1.9       35.4      33.6
Vision distance (smoke layer)  =    16.31  m      53.52 ft
Smoke gases : Oxygen =  20.7 % : Co =   0.0000 : Co2 =   0.1999 %

    60.0      108.9      42.7       6.2       1.9       40.8      38.7
Vision distance (smoke layer)  =    14.58  m      47.85 ft
Smoke gases : Oxygen =  20.6 % : Co =   0.0000 : Co2 =   0.2221 %



The top of the current inside opening is   0.68 Ft     0.206m above the floor.
                            The width is   3.60 FT     1.097m
                             And the sill is at the floor.


Currently there is no outside opening in the room.


Air from an operating HVAC system is not currently being considered.
   116.0      263.3     128.5       3.9       1.2      189.6     179.8
Vision distance (smoke layer)  =     3.55  m      11.66 ft
Smoke gases : Oxygen =  19.3 % : Co =   0.0002 : Co2 =   1.0566 %
Smoke vent rate is       0 cfm    0.00 cms
Enthalpy (Heat content)        0 btu/sec          0 kW
Inside flow of unburned fuel potential          0 BTU/SEC             0 kW

   120.0      274.2     134.6       3.8       1.2      198.3     188.1
Vision distance (smoke layer)  =     3.56  m      11.68 ft
Smoke gases : Oxygen =  19.1 % : Co =   0.0002 : Co2 =   1.1268 %
Smoke vent rate is    2568 cfm    1.21 cms
Enthalpy (Heat content)      111 btu/sec        117 kW
Inside flow of unburned fuel potential          0 BTU/SEC             0 kW

   180.0      566.0     296.7       5.1       1.5      458.5     434.9
Vision distance (smoke layer)  =     2.39  m       7.83 ft
Smoke gases : Oxygen =  15.7 % : Co =   0.0005 : Co2 =   3.1536 %
Smoke vent rate is    1580 cfm    0.75 cms
Enthalpy (Heat content)      119 btu/sec        125 kW
Inside flow of unburned fuel potential          0 BTU/SEC             0 kW

   240.0      911.1     488.4       5.0       1.5     1179.9    1119.1
Vision distance (smoke layer)  =     2.10  m       6.89 ft
Smoke gases : Oxygen =   8.2 % : Co =   0.0040 : Co2 =   7.5991 %
Smoke vent rate is    2196 cfm    1.04 cms
Enthalpy (Heat content)      209 btu/sec        221 kW
```

Figure B-3 FIRE SIMULATOR Runs Evaluating the Impact of Door Closers (Part 4 of 5)

```
Inside flow of unburned fuel potential          0 BTU/SEC          0 kW

   267.0    1122.6     605.9       4.9       1.5     1882.6    1785.6
Vision distance (smoke layer)  =     1.89  m      6.21 ft
Smoke gases : Oxygen =   2.0 % : Co =   0.0125 : Co2 =  11.5151 %
Smoke vent rate is    2706 cfm    1.28 cms
Enthalpy (Heat content)       278 btu/sec        294 kW
Inside flow of unburned fuel potential          0 BTU/SEC          0 kW
```

<u>UPPER LEVEL TEMP. INDICATES THAT FLASHOV ER HAS PROBABLY OCCURRED BY 267 SEC.</u>

Figure B-3 FIRE SIMULATOR Runs Evaluating the Impact of Door Closers (Part 5 of 5)

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This report presents the methods and results of an analysis of the development and spread of fire and smoke during the October 5, 1989 fire in the Hillhaven Rehabilitation and Convalescent Center, Norfolk, Virginia. The analysis uses data gathered from onsite visits, reports and information for other investigators, fire tests conducted at the National Institute of Standards & Technology, and fire growth models and similar computations. The report details the procedure and data used, the reasons for those selected, and the results obtained. The analysis addresses mass burning rate; rate of heat release; smoke temperature; smoke layer depth; velocity, depth and temperature of the smoke front; oxygen concentration of smoke layer; carbon monoxide concentrations: and other factors. The areas of building analyzed include the room of fire origin, the corridor system exposed by that room, and other patient rooms on that corridor.

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