NISTIR 90-4253

NEW NIST PUBLICATION

July 1990

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John H. Klote

U.S. DEPARTMENT OF COMMERCE
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Fire Experiments of Zoned Smoke Control at the Plaza Hotel in Washington DC

John H. Klote

Abstract

A series of full-scale tests were conducted to evaluate the current approach to zoned smoke control systems with and without stairwell pressurization. Smoke movement and the performance of smoke control systems were studied with smoke generated from unsprinklered wood fires, sprinklered wood fires, and smoke bombs. As expected, the zoned smoke control system prevented smoke migration beyond the fire floor. The minimum pressure difference approach to achieve smoke control for zoned smoke control systems was evaluated. This minimum pressure difference approach is based on a tacit assumption of a constant mass flow rate into the zone where the fire is located. To evaluate this assumption, a model was developed for mass flow in the smoke zone. Agreement between experimental results and calculations based on the model was good. Concerns about expansion of combustion gases and fan temperatures were identified. Approaches to deal with these problems were developed. The experiments showed that chemical smoke from smoke bombs is very different from hot smoke from flaming fires. With few exceptions, smoke bombs should not be used for acceptance tests. Additional research is needed concerning smoke generation of sprinklered fires and concerning the interaction of fires and smoke control.

1. INTRODUCTION

Smoke is recognized as the major killer in building fires. Smoke often migrates to building locations remote from the fire space, threatening life and damaging property. Stairwells and elevator shafts frequently become smoke-logged, thereby blocking evacuation and inhibiting rescue and fire fighting. The MGM Grand Hotel fire (Best and Demers 1982) is an example of the smoke problem. The fire was limited to the first floor, but smoke spread throughout the building. Some occupants on upper floors were exposed to smoke for hours before rescue. The death toll was 85, and the majority of the deaths were on floors far above the fire.[1] The MGM Grand fire is not unique in this respect as is illustrated by the fires at the Roosevelt Hotel (Juillerant 1964) and Johnson City Retirement Center (Steckler 1990). All these fires were located on the first floor, but the majority of deaths were on upper floors, as is shown in Figure 1. As a solution to the smoke problem, the concept of smoke control was developed.

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[1] It is a credit to the Clark County Fire Department that during such a complex fire-fighting operation, the location of exposure is known for all but six of the fatalities.

In the spring of 1989, a series of full-scale fire experiments of zoned smoke control were conducted at the seven-story Plaza Hotel in Washington, DC. A zoned smoke control system is a system that uses pressurization produced by fans to restrict smoke migration to the zone of fire origin. The benefit of these systems is that other zones in the building remain essentially "smoke free," reducing property loss and hazard to life. Prior to this project, no zoned smoke control system had been tested under real fire conditions, either in a research effort or an accidental fire. However, fire experiments of smoke control systems for stairwells and elevators have been conducted.

The objective of this project was to evaluate the current approach concerning minimum pressure difference to achieve smoke control for zoned smoke control systems with and without stairwell pressurization. This minimum pressure difference approach is based on a tacit assumption of a constant mass flow rate into the zone where the fire is located. The results of the experiments of this project provide insight about this assumption. Further, the interaction between smoke control and the fire was studied.

Wood was selected as the fuel for these fires. The behavior of wood fires in depleted oxygen is believed to be somewhat representative of that of actual building fires. Air pollution was also a concern for these urban area experiments. While a mixture of wood and polymers might have produced smoke more representative of that from many building fires, burning wood alone produced relatively light smoke.

The experimental fires had peak energy release from 900 to 2800 Btu/s (1 to 3 MW) for a durations of about 10 minutes. This intensity and duration are considerable. However, it is believed that many fire accidents with multiple deaths due to smoke inhalation have had fires of even higher intensity for longer durations. Even with extensive precautions, larger fires were avoided because of the possibility of structural damage that could result in a premature end to the project. It is not surprising that the smoke obscuration and toxicity away from the fire floor were not at extremely hazardous levels, and any discussion of the hazards of this smoke would be misleading. The levels of smoke away from the fire floor should be thought of as tracers, indicating relative smoke spread. An analysis is presented allowing an approximate evaluation of the hazards of smoke spread in high-rise buildings.

2. EXPERIMENTAL FACILITY

2.1 Plaza Hotel Building

The Plaza Hotel building was a masonry structure consisting of two wings, one three stories and the other seven stories tall. The two wings were built at different times. It appeared that the building was constructed a few years after the turn of the century. The wings were connected to each other at only one location on each floor, as can be seen from the floor plans of Figures 2 through 7. The connections between the wings at each floor were sealed off, and the fires were set on the second floor of the seven-story wing, using the shorter wing as an instrumentation area. The areas of the second floor indicated on Figure 3 were fire hardened to minimize structural damage to the building. The walls were covered by a 1/2 in. (12.7 mm) layer of calcium silicate board over a 1/2 in. (12.7 mm) layer of type X gypsum board attached to wood furring strips. The ceilings were protected by similar layers of calcium silicate and gypsum attached to the bottom of ceiling joists made of commercial steel studs. The floors were protected by calcium silicate board within about 10 ft (3 m) of the fire and by type X gypsum board for the rest of the fire-hardened areas. The ceiling heights and window dimensions are listed in Table 1.

2.1 Smoke Control Systems

The smoke control systems were designed using the methods presented in the ASHRAE smoke control manual (Klote and Fothergill 1983), and the design analysis is discussed in detail by Klote (1988a). The minimum design pressure difference was 0.10 in H_2O (25 Pa), meaning that the system should be able to maintain at least this value without a fire. The intent was that the system should function satisfactorily under the most challenging conditions likely to occur during a fire. This level of pressurization is recommended by the National Fire Protection Association (NFPA 92A, 1988) for smoke control in unsprinklered buildings. This design pressure difference incorporates the effects of fire in the form of a buoyancy term plus a safety factor, as explained in the appendix of NFPA 92A. A general discussion of design pressure differences is provided by Klote (1988b).

In general, the design analysis should be based on likely conditions of open doors and windows; also, the direct effects of the fire must be included in the selection of the minimum design pressure difference. This is the approach evaluated by this project. The design analysis did not include a broken fire room window as one of the likely fire conditions. The importance of this open window was not apparent at the start of the project, and this topic is addressed later in this paper.

In zoned smoke control, the building is divided into a number of zones. These zones may be separate floors, parts of floors, or even a number of floors together. The zone in which the fire occurs is called the smoke zone. For the experiments of this project, each floor of the building was a zone.

Exhausting air from the smoke zone results in air from the outside and from other zones being pulled into the smoke zone. This air flowing into the smoke zone can provide oxygen to the fire. Smoke control systems frequently are designed to exhaust and supply air at six air changes per hour. Most commercial air-conditioning systems are capable of moving about four to six air changes per hour, which probably accounts for the popularity of six air changes in smoke control applications. Current designs are based on the assumption that the adverse effect of supplying oxygen at six air changes per hour is not significant in comparison with the benefit of smoke control. For these reasons, the tests described in this report were conducted at six air changes.

The Plaza building had no central forced-air heating, ventilating, and air-conditioning (HVAC) system, so a dedicated system of fans and ducts was installed for zoned smoke control and stairwell pressurization. The smoke control system consisted of the three 2000 cfm (0.944 m^3/s) centrifugal fans shown in Figures 2, 3 and 4 plus another centrifugal fan (not shown) located outside and supplying 9000 cfm (4.25 m^3/s) of pressurization air to the stairwell at the first floor. The smoke control system is illustrated in Figure 8. All the test fires were located in the second floor smoke zone. This smoke zone was exhausted at about six air changes per hour. The first and second floors were pressurized at about six air changes per hour. When the stairwell pressurization system was activated, the exterior stairwell door was open. This approach, first used in Canada, is intended to minimize pressure fluctuations due to opening and closing doors.

3. EXPERIMENTAL DETAILS

3.1 Instrumentation

To measure temperatures, pressure differences, gas concentration, smoke obscuration, and wind speed and direction, over 2 ½ miles (4 km) of wire were installed between the instruments and a data acquisition system. The instruments used in this test series are shown in Figures 2 to 7 and are listed in Table 2. All tests were recorded on video tape by cameras (not shown in Figures) located in the corridor on floors 2, 3, 4, 5, 6, and 7 and in the stairwell on floors 2, 4 and 7. All instrumentation channels were recorded at 20-second intervals, and the data acquisition system was located in the instrumentation room on the first floor (Figure 2). More instrumentation was used than was necessary for evaluation of the effectiveness of smoke control system with the view that it would be valuable for later computer simulation of the experimental fires.

Temperatures were measured on the fire floor and the other floors at locations shown in Figures 2 through 7. Additionally, outside air temperature, second floor exhaust fan outlet air temperature, and inlet air temperature of second floor exhaust duct were measured. These temperatures were measured by bare beaded chromel-alumel (type K) thermocouples made from 24-gauge (0.51 mm) diameter wire. The wind speed and direction were measured by a propeller-type transducer located 10 ft (3 m) above the roof of the seven-story wing.

Smoke meters developed by Bukowski (1978) were used to measure light obscuration in the corridors of floors 2, 3, and 7 (figs. 3, 4, and 7) 5 ft (1.52 m) above floor level. This type of meter is an extinction beam consisting of a collimated light source and a detector separated by a path through the smoke. In this paper, smoke obscuration is expressed in terms of optical density per unit distance, which is defined as

$$\delta = - \frac{\log_{10} (I_x/I_o)}{x}$$

where I_0 is the intensity of light at the beginning of the pathlength, I_x is the intensity of light remaining after it has passed through the pathlength, and x is the distance of light travel or the pathlength.

Carbon monoxide (CO), carbon dioxide (CO_2), and oxygen (O_2) were continuously measured at three locations. On floors 2, 3, and 7, gas probes were located 5 ft (1.52 m) above the floor in the center of the corridor (figs. 3, 4, and 7). Pressure differences were measured by variable reluctance differential pressure transducers.

Not all the instruments operated for every test. The gas measurements were inappropriate for the smoke bomb tests. Some instruments were installed late in the series based on the findings of earlier tests, and technical problems rendered some instruments inoperative during experiments. Table 2 includes the operating status of all instruments for all the tests.

3.2 Test Program

Smoke movement and the performance of smoke control systems were studied with smoke generated from unsprinklered wood fires, sprinklered wood fires, and smoke bombs. All the windows were closed except for the window of the fire-hardened room during test 12, which was left open to simulate the effect of a broken window. For many of the tests, the second floor stairwell door was cracked open ½ in. (13 mm), simulating the gap of a door warped due to high differential temperatures. The specific doors open and other test conditions are listed in Table 3.

3.3 Test Procedures

3.3.1 Unsprinklered Fires

Wood sticks were arranged in geometric piles called cribs, because these crib fires are repeatable and fairly well understood (Gross 1962, Block 1971). The cribs were constructed of fir sticks 1.5 in. (38 mm) by 1.5 in. (38 mm) by 2 ft (0.61 m) long. The sticks were fastened together with 8d common nails. The crib illustrated in Figure 9 was 24 layers high and weighed about 150 lb (68 kg). The 24-layer crib was used for most of the tests. The exception was test 3 for which smaller cribs of 18 layers were used because of concern about possible damage to the building's structural system.

All of the fires used two cribs located in the second floor corridor (Figure 3), except for test 12 for which four 24-layer cribs were located in the fire-hardened room on the second floor (Figure 3). The cribs were stored in a room in the Plaza Hotel without humidity control. However, the moisture content of the cribs was measured at less than 6 percent for all the cribs. By extrapolation of data for similar cribs burning in free air (Walton 1988), it is estimated that two 24-layer cribs would have a peak energy release rate of 1400 Btu/s (1.5 MW), and two 18-layer cribs would have a peak energy release rate of 950 Btu/s (1.0 MW). Four 24-layer cribs would have an energy release rate of 2800 Btu/s (3.0 MW).

A 5.0 in. (0.13 m) diameter metal pan with one liter of heptane was centered under each crib as an ignition source. After a technician ignited the heptane with a propane torch, he left the fire floor by way of the stairwell.

3.3.2 Sprinklered Fires

The sprinklered fire were set in the corridor, as illustrated in Figure 3, and two 24-layer cribs as described above were used. Test 10 was with a listed quick-response pendant sprinkler with a 160°F (71°C) operating temperature. Test 11 was with a pendent sprinkler with a fusible element operating at 145°F (63°C) and a bimetallic disk for on-off operation opening at 165°F (74°C) and closing at 95°F (35°C). The sprinklers were located above the cribs about 25 in. (0.64 m) from the center of the two cribs. The deflector of the quick response sprinkler was 4 in. (0.10 m) below the ceiling, and the deflector of the on-off sprinkler was 6 in. (0.15 m) below the ceiling. The density of spray was measured by collecting water from the sprinklers in pans located so that the pan top was at the elevation of the top of the cribs. The quick-response sprinkler produced an average density of 0.31 gpm/ft^2 (0.21 L/s m^2), and the on-off head produced an average density of 0.41 gpm/ft^2 (0.28 L/s m^2).

3.3.3 Smoke Bomb Tests

The smoke bombs were ignited at the same corridor location as most of the other tests (Figure 3). Three smoke bombs rated by the manufacturer for a three minute duration were wired together, placed in a metal container, and ignited. After ignition, the technician left the fire floor by way of the stairwell.

3.3.4 Smoke Control Activation Time

Because so many complicated detection and activation schemes are in common use, simulation of one particular activation approach would have been of limited value. Thus, it was decided to simulate the extreme conditions of very fast activation and delayed activation. For very fast activation, the smoke control system was activated before ignition for tests 2, 3, 6, 7, and 12. This is considered to be similar to what would happen if the smoke control system were activated rapidly enough so that very little smoke would reach the horizontal barriers of the smoke control system before ignition. A four-minute time was arbitrarily selected for the delayed activation for tests 8 and 9.

4. RESULTS AND DISCUSSION

4.1 Unsprinklered Fires with Smoke Control

Tests 3, 7, 9, and 12 were unsprinklered fires with zoned smoke control. Tests 7 and 9 were with stair pressurization, and test 3 was without. Without the fire, the smoke control system was able to maintain the following pressure differences from the stairwell to the fire floor:

Test	Pressure Difference in. H_2O (Pa)
3	0.14 (35)
7	0.11 (27)
9	0.11 (27)
12	0.06 (15)

The pressure differences from the adjacent floors to the fire floor were much greater (0.19 to 0.15 in. H_2O [47 to 37 Pa]), and so attention was focused on the pressure differences at the fire floor stairwell. For tests 3, 7 and 9, the system produced pressures above the design value. With the burn room window open in test 12, the pressure difference dropped significantly. Even though the effect of broken windows is addressed in design literature, more comprehensive treatment of this subject is appropriate.

During tests 7 and 9, the fire floor stairwell door was cracked open, and the seventh floor stairwell door was completely open. The relative shapes of the temperature curves at the center of corridor (Figure 10) are typical of all of the unsprinklered fire tests. Figure 11 shows the temperature of the second from the top thermocouple of each thermocouple tree on the second floor for test 7. Temperature variations over the length of the corridor are relatively small, and the fire-hardened room has a much lower temperature. This trend is the same for all of the unsprinklered fires located in the corridor.

The corridor temperatures for test 7 was about 200°F (100°C) higher than that for test 9 (Figure 12). The only significant difference between the tests was the delayed activation time of test 9. It seems doubtful that delayed activation could have caused such a difference. The cause of the temperature difference is unknown, but it could be thought of as an indication of the extent to which these experiments are repeatable. The temperature for test 3 started to decline sooner than for tests 7 and 9 (Figure 12), which was expected because test 3 had only two-thirds as much wood as the other two tests.

As shown in Figure 12, the corridor temperature of test 12 is considerably different from all the others, because the fire was in the fire-hardened room off the corridor. Figure 13 shows the temperature from the second from the top thermocouple of each thermocouple tree in the second floor corridor for test 12. The corridor temperatures are rather close to each other. The burn room (fire-hardened room) has a much higher temperature, as is apparent from Figure 14. Because of the intensity of this fire, it was conducted at the end of the project. Much of the fire hardening in the burn room was damaged, justifying the concern about structural damage.

For the tests 3, 7, and 9, the O_2 levels on the fire floor decrease during the first half of the test and then increase, as illustrated in Figure 15. As expected, the fire floor CO_2 levels follow the opposite trend (Figure 16). The increase in CO (Figure 17) during the first half of each of these fires seems to be due to increasing O_2 consumed during a period of fire growth. This is followed by a decrease in CO concentration, which probably corresponds to decreasing energy release while fresh air pulled into the fire floor by the smoke control system purges fire gases from the second floor. The higher O_2 and lower CO_2 and CO during test 3 were expected because this fire had only two-thirds of the fuel of the other two fires (tests 7 and 9).

The CO concentrations on the fire floor are much greater for test 12 than for the other unsprinklered fires with smoke control (Figure 17). Test 12 had at least twice the fuel of the other fires, and the burn room window was open. The very high temperatures of the burn room (Figure 14) indicate that the room was completely or almost completely involved in fire. The energy release rate was probably controlled by the amount of O_2 that could flow through the open window. At 14 minutes into test 12, the electronic control system for the smoke control fans failed, and the fans shut off. This was followed by a sharp rise in CO concentration. The following is a possible explanation: When the fan was working, the air entering the burn room was near stoichiometric requirements. This air was primarily from the outside through the open window due to buoyancy of fire gases and due to the exhaust fan. After the fan stopped, less air was available to the fire. As the fire became oxygen starved, CO production increased significantly. This effect is highly dependant on the size of the open window and the amount of fuel available. Differences in either would greatly change the CO production.

During all of the unsprinklered fire tests with smoke control, no smoke was evident in the video recordings on the floors away from the fire or in the stairwell. This was particularly interesting for test 12, because of the low level of pressurization when the window was open. Figure 18 shows that for test 9 there was essentially no smoke obscuration on floors three and seven but significant obscuration on the fire floor (second floor). For the conditions of these tests, the four-minute activation time did not result in any increase in visible smoke away from the fire. The effects of the activation delay on seventh floor gas concentrations are discussed later.

4.2 Unsprinklered Fires without Smoke Control

Tests 1 and 5 were unsprinklered fires without zoned smoke control or stairwell pressurization. For these tests, the O_2 on the fire floor decreases for about the first 10 minutes and then remains relatively constant (Figure 19). The CO_2 levels on the fire floor increased and then remained at a high level for the rest of each test (Figure 20). The levels of CO on the fire floor were much greater than those of the fires with smoke control operation and the windows closed (figs. 17 and 21). At the reduced O_2, the energy release of the fire dropped off, as is apparent from the corridor temperature of test 5 (Figure 12). It is believed that CO production is more dependant on the overall availability of oxygen than the percent of oxygen.

Caution should be exercised in attempting to extend these results to building fires in general. Real building fires are not so likely to have such limited quantities of fuel available. If there had been more fuel, the gas concentrations for the tests with smoke control might have looked much like those of the tests without it. Further, such increased fuel fires could result in as much or possibly more CO production than fires without smoke control. It is apparent that there are some complex relationships between smoke control and fire behavior, and further research is needed in this area. Scale model experiments would probably be appropriate for such an effort.

The CO_2 and CO levels (Figure 22 and 23) on the seventh floor are much greater for test 5 without smoke control than they are for the tests with smoke control. The peaks on the seventh floor for test 5 were about 0.15% and 0.015% for CO_2 and CO. Test 7 had only slight amounts (0.002% and 0.001% CO_2 and CO) for short durations. These can be thought of as small puffs of fire gases. The concentrations of CO_2 and CO for test 9 start to increase at 12 minutes and at 15 minutes level off at about 0.04 and 0.004% CO_2 and CO. The concentrations of test 7 are believed to be due to the delayed activation time of this test. During the first four minutes of this fire, the smoke control system was off, and some fire gases flowed into the stairwell. During these first few minutes, the wood fire was relatively clean burning and the smoke was not visible on the video and did not register on the smoke meter (Figure 18). However, this indicates that there should be concern about delays before activation.

During test 1, only slight smoke was evident in the video recordings on the floors away from the fire and in the stairwell. However, considerable smoke was observed in the stair and on floors during test 5. The difference was that all stair doors were closed for test 1, while the second floor stair door was cracked and the seventh floor stair door open during test 5. It seems that smoke reached the seventh floor by way of the stairwell during test 5. Smoke obscuration for these tests is shown in Figure 24. By comparison with the tests with smoke control, it is obvious that smoke control can significantly reduce smoke spread to locations remote from the fire.

With all the stairwell doors closed (test 1), there was little smoke flow beyond the fire floor, as is apparent from the video recordings and the smoke obscuration data. For the tests with the second floor stair door cracked open and the seventh floor stairwell door open, there was a lot of smoke movement beyond the fire floor without smoke control and very little with smoke control. This is apparent from the video recordings, smoke obscuration and gas analysis data for tests 5, 7, and 9. Further, it is apparent that research is needed concerning the generation gases during fire with and without smoke control.

4.3 Sprinklered Fires

Large unsprinklered fires are the greatest challenge, because the smoke control system must produce sufficient pressures to contain the hot and buoyant fire gases. Many buildings with smoke control systems are sprinklered, and two tests were initially included to obtain an idea of how these systems operate against sprinklered fires. However, the sprinklered fires produce such small pressure differences that they were not much of a challenge for a smoke control system. There is no question that the smoke control system that worked so well for the large flaming unsprinklered fire would have no difficulty in preforming as well against smoke from sprinklered fires. The sprinklered fires were conducted without smoke control operation so that an idea of smoke spread beyond the fire floor could be studied. Additionally, this provided some information about the concept of using sprinklers for smoke protection by limiting the production of smoke. The smoke bomb tests were included in an attempt to evaluate the extent to which smoke bombs are appropriate for acceptance testing of smoke control systems.

The quick-response sprinkler that was used for test 10 activated about two minutes after ignition. From the video, it was observed that the flames were reduced significantly when the water spray started. The fire was out about seven minutes after the sprinkler started. The CO concentrations on the fire floor were relatively low (Figure 21) and on the seventh floor were insignificant (Figure 23). The smoke control system was not operating during this test, but no smoke was observed on the video of the stairs and of the nonfire floors. Relatively small amounts of smoke were observed on the fire floor. The smoke obscuration was negligible on floors 3 and 7, and it was slight on the fire floor (Figure 25). It can be concluded that such rapid fire extinction significantly reduces smoke production and that this can be considered a form of smoke protection.

The on-off sprinkler used in test 11 activated at about two and half minutes after ignition, but it failed to extinguish the fire. The flames were reduced significantly when water spray started. After a few minutes, the spray stopped, and the fire started to grow again. This cycling of water spray following by fire growth lasted for almost an hour until the fire was extinguished manually by a hose stream.

This resulted in considerable smoke on the fire floor, stairs, and nonfire floors as was seen on the video and is apparent from the smoke obscuration measurements (Figure 25). For sprinklered fires that are not rapidly extinguished, smoke production can be significant and smoke control could be useful. However, there was less smoke production with the on-off sprinklers than there was without sprinklers. Smoke obscuration on the fire floor, third floor, and seventh floors was greater for tests 1 and 5 without sprinklers (figs. 24 and 25). The CO levels on the fire floor were only a small fraction of those for the unsprinklered fires (Figure 21). However, there is insufficient information to support general conclusions about the relative toxicity of smoke from sprinklered fires. Further study is needed concerning the effect of sprinklers on smoke generation. Any evaluation of smoke generation from sprinklered fires should address fires that are shielded from the water spray.

4.4 Smoke Bombs Tests

Test 4 was a smoke bomb test without operation of the zoned smoke control system and the pressurized stairwell. During this test, the video showed considerable smoke on the fire floor, lighter smoke in the stairwell, and only very light smoke on the seventh floor. This was qualitatively similar to what was observed for the unsprinklered wood fire (test 5) with similar conditions, except that smoke obscuration was greater for the wood fire. The smoke bombs generated most of their chemical smoke during the first three minutes after ignition. From the video, heavy smoke was observed near the smoke bombs during the first three minutes of the test, and then this smoke dispersed and filled the corridor. There is a smoke obscuration spike at about three minutes (Figure 26), corresponding to the smoke generation, then the obscuration levels off for the rest of the test.

For smoke bomb tests 2, 6, and 8 with smoke control, the video showed smoke on the second floor but none or very light smoke in the stairwell and on the nonfire floors. While the chemical smoke was being generated, it was being pulled down the corridor by the smoke exhaust fan (Figure 3). Five or six minutes after ignition, the smoke level on the fire floor had dropped off significantly. This was probably due to the purging action of the smoke control system. The smoke obscuration data for these tests are shown in Figure 27. As expected, smoke obscuration on the fire floor consisted of an initial peak followed low value that generally declined with time.

The smoke concentrations from the smoke bomb tests are considerably different from those from the unsprinklered fires. The chemical smoke is produced over a short time, and it results in lower obscuration. With smoke control, obscuration decreases rapidly at about five minutes or so after ignition. This decrease is the result of the smoke control system purging the chemical smoke. Smoke from a real fire continues to be generated, and thus there is no corresponding decrease. Further, this chemical smoke does not have the buoyancy of the hot fire gases from the wood fires.

Before this series of tests, this author and many other professionals involved with smoke control were concerned that the results of smoke bomb tests were giving some people unrealistic expectations of what smoke control can accomplish. Usually when smoke bombs are used for acceptance tests, the smoke is generated for a few minutes, and it is purged out of the fire floor a few minutes later. People who do not have an understanding of fire science could easily believe that a smoke control system would result in similar performance for a large flaming fire. The test results indicate that this is not so. Even with smoke control, the levels of smoke on the fire floor were significant for the unsprinklered fires of this series (tests 3, 7, and 9). With few exceptions, smoke bombs should not be used for acceptance tests. These exceptions include testing for smoke feedback into supply air and locating leakage paths in construction (Klote 1988b). Readers are referred to the recommendations of NFPA 92A concerning acceptance testing.

5. REEVALUATION OF THE HYDROSTATIC ASSUMPTION

In fire modeling it is commonly assumed that the pressures in compartments are described by the hydrostatic equation:

$$dp = -\rho g\, dz \tag{1}$$

Combining this with the ideal gas law ($\rho = p/RT$) and integrating yields an expression for the pressure

$$p_h = p_o - \int_0^h \frac{g\,p}{R\,T}\, dz \tag{2}$$

where the subscripts o and h are a datum elevation and elevation h above the datum, respectively. The pressure difference from the stairwell to the fire floor is considered at two elevations: a datum level near the floor and a higher level near the ceiling. These pressure differences are defined as

$$\Delta p_o = p_{so} - p_{fo} \tag{3}$$

and

$$\Delta p_h = p_{sh} - p_{fh} \tag{4}$$

where the subscripts s and f are for stairwell and fire floor, respectively. Subtracting Equations (4) from Equation (3), rearranging, and expressing in the integral form of Equation (2) yields

$$\Delta p_o - \Delta p_h = \frac{g\,p}{R} \left(\int_0^h \frac{dz}{T_s} - \int_0^h \frac{dz}{T_f} \right) \tag{5}$$

This assumes that the pressure, p, can be considered constant for purposes of integration. The pressure, p, has a value of about 407 in. H_2O (101,000 Pa) and Δp terms are on the order of 0.1 in. H_2O (25 Pa). Thus p changes by less than 0.03% during a fire. The two sides of Equation (5) were evaluated from different measurements. The left-hand term was calculated from the pressure differences measurements across the second floor stairwell door near the floor and near the ceiling (Figure 3 and Table 2). The right-hand term was calculated from temperature measurements in the stairwell and in the fire floor corridor by the stairwell. The integral was evaluated by the extended trapezoidal rule (Press et al. 1986, p. 107). These terms are plotted in Figure 28 for the fires for which the necessary data were available. For the fires with smoke control (tests 3, 7, and 9), the two terms are no more than about 0.005 in. H_2O (1.2 Pa) apart. This is very good agreement, especially considering that there was no radiation correction for the thermocouple readings.

For test 5, without smoke control, the two terms were not much further apart than 0.01 in. H_2O (2.5 Pa), but this is still a good correlation. The term calculated from temperatures is consistently larger than that from pressure difference measurements beyond five minutes into test 5. While such a difference could be due to radiation errors in thermocouple readings, the complexity of the process makes it difficult to envision how this could occur. The processes are further complicated because the fire occurred during a period of normal stack effect, which would have been causing airflow into the stairwell on the fire floor. Before the fire, the average inside temperature was 61°F (16°C) and the outside temperature was 46°F (8°C). The above discussion tends to confirm the use of the hydrostatic equation concerning fire modeling and smoke control analysis.

6. ANALYSIS OF PRESSURE DIFFERENCES

In this section, an analysis of pressure differences and mass flows during smoke control operation is presented. This analysis does not assume that the mass flow into the smoke zone is constant. However, the analysis leads to insight regarding the extent to which the constant mass flow rate assumption is appropriate. This analysis was specifically developed for the data from the fire tests of the zoned smoke control system at the Plaza Hotel. For reasons of simplicity, the accompanying discussion refers to the fire floor and the other floors in a direct manner. This is consistent with the experiments. However, a smoke control system can consist of zones that are only a part of a floor or even made of a number of floors. If the reader wishes to generalize the analysis, the term "fire floor" should be thought of as the smoke zone.

The fire floor is made up of a number of rooms, each of which has an average temperature that can be determined by Equation (6). The law of conservation of mass can be expressed for the volume of the fire floor, V_f:

$$\left\{ \begin{array}{l} \text{Net mass flow} \\ \text{into volume, } V_f \end{array} \right\} = \left\{ \begin{array}{l} \text{Rate of mass change} \\ \text{within volume, } V_f \end{array} \right\}$$

$$\dot{m}_i - \dot{m}_e = \frac{dm}{dt}$$

or (6)

$$\dot{m}_i - \dot{m}_e = \frac{d}{dt} (\bar{\rho}_f \; V_f)$$

where the subscripts i and e are for into and exiting to volume. The average density, ρ_f, inside the volume, V_f, is determined by a weighted average of the temperatures for all the rooms on the fire floor. During idealized smoke control operation, the only mass leaving V_f is through the exhaust fan. Consideration of a fan as a constant volumetric flow device is a good first order assumption, so the mass flow rate from the V_f can be expressed as

$$\dot{m}_e = \rho_{fan} \dot{V}_{fan} \tag{7}$$

The mass flow, $\dot{m}_i$, into the volume consists of flows through numerous paths into all of the rooms and the corridor of the fire floor. The temperature in each room is different from the others and varies with elevation. For each flow path, k, between space n and V_f, the mass flow rate can be expressed as

$$d\dot{m}_{ki} = C\ w_k\ (2\ \rho_n\ \Delta p_k)^{\frac{1}{2}}\ dz \tag{8}$$

The pressure difference, Δp_k, can be expressed as

$$\Delta p_k = \Delta p_{ko} - (\rho_n - \bar{\rho}_{kf})gz \tag{9}$$

where $\bar{\rho}_{kf}$ is the average density within V_f in the vicinity of path k. Assuming C, w_k and ρ_n constant, substituting Equation (9) into Equation (8), and integrating from z=0 to z=h to yields

$$\dot{m}_{ki} = \frac{2}{3}\ C\ w_k\ (2\ \rho_n)^{\frac{1}{2}} \left(\frac{\Delta p_{kh}^{3/2} - \Delta p_{ko}^{3/2}}{\Delta p_{kh} - \Delta p_{ko}} \right) \tag{10}$$

The mass flow into V_f equals the sum of the mass flows through each path. For N paths this is

$$\dot{m}_i = \sum_{k=1}^{N} \dot{m}_{ki} \tag{11}$$

The greatest flow into the fire floor during the experiments of this project was probably at the stairwell door. Thus the model can be simplified by considering only one opening at the stair door. This simplification facilitates analysis, and the resulting mass flow into the fire floor is expressed as

$$\dot{m}_i = C\ A\ (\ 2\ \rho_s\ \overline{\Delta p})^{\frac{1}{2}} \tag{12}$$

where

$$\overline{\Delta p} = \frac{4}{9} \left[\frac{\Delta p_h^{3/2} - [\Delta p_h + (\rho_s - \bar{\rho}_{sf})gh]^{3/2}}{2\Delta p_h + (\rho_s - \rho_{sf})gh} \right]^2 \quad (13)$$

The average density, $\bar{\rho}_{sf}$, is on the fire floor in the vicinity of the stairwell door. Equations (7) and (12) can be substituted into Equation (6) to get the following solution for the average pressure difference from the stairwell to the fire floor:

$$\overline{\Delta p} = \frac{1}{2\ \rho_s\ (CA)^2} \left[\frac{d}{dt} (\bar{\rho}_f\ V_f) + \dot{V}_{fan}\ \rho_{fan}\right]^2 \quad (14)$$

The pressure difference, Δp_o, can be expressed as

$$\Delta p_o = \Delta p_h + (\rho_s - \bar{\rho}_{sf})gh \quad (15)$$

To gain insight into the test results, the above model was used to calculate mass flows and pressure differences using the test data. For each data scan of tests 3, 7 and 9, $\overline{\Delta p}$ was calculated from Equation (15) using ρ_s and ρ_{fan} from the appropriate temperature measurements. The product C A was evaluated by solving Equation (15) when there was no fire (derivative term is zero), and using the measured value of $\overline{\Delta p}$. To determine the average density, $\bar{\rho}_f$, of the fire floor, the average temperatures in the corridor and fire-hardened room were evaluated from measurements by the extended trapezoidal rule. The average density was estimated using a weighted average temperature based on the volume of the corridor, the fire-hardened room, and of the other rooms. Because measurements were not available for the other rooms, all of the other rooms but one were taken to remain at ambient temperature throughout the fire; the other room was considered to be at the temperature of the fire-hardened room. The derivative in Equation (14) was evaluated using the forward-difference formula (Burden et al. 1981, pp 125-26). Using $\overline{\Delta p}$ from Equation (14), Δp_h was calculated by the method of bisection (Press et al. 1986, pp. 246-47) from Equation (13). The pressure difference, Δp_o, near the floor was calculated from Equation (15).

Figure 29 shows the measured and calculated values of Δp_o. In general, the calculations are a little lower than the measurements. The calculated values are generally within 0.02 in. H_2O (5 Pa) of the measurements, and the largest difference is 0.04 in. H_2O (10 Pa). The agreement between measured and calculated pressure differences, Δp_h, near the ceiling is nearly as good as that of as those near the floor (figs. 29 and 30).

Figure 31 is a graphical representation of the conservation of mass equation for test 7. The mass flow, $\dot{m}_e$, was calculated from Equation (7), and the change in mass within V_f was calculated by numerical integration, as discussed above. The mass flow, $\dot{m}_i$, was calculated from the conservation of mass equation. The calculated values of Δp_o and Δp_h were low because the calculated $\dot{m}_i$ is too small. Some of the error could be due to numerical differentiation, which is frequently an ill-conditioned problem (small errors in data result in large errors in the derivative). Deviations from the constant volumetric flow fan model were probably not the cause of significant errors. The pressure across the fan increased by only about 0.05 in. H_2O (12 Pa), which, based on the manufacturer's data, would decrease the fan flow by less than 1%. The simple first-order model does not include the effect of the pressurization fans on the adjacent floors and in the stairwell. A possible explanation of the systematic error is that the balance of the flows from the stairwell, from the other floors, and from the outside is altered such that the flow from the stairwell did not decrease as much as some of the others. However, it can be concluded that the correlation between measurements and calculations was good.

7. EXPANSION OF GASES

As a fire develops, gases on the fire floor are heated and expand. The increased volume of gases due to expansion flow out of the fire floor with the rest of the gases exhausted by the fan. Accordingly, the mass flow rate into the fire floor is decreased by the same amount. The decrease in flow into the fire floor is accompanied by a decrease in pressure difference across the boundaries of the fire floor. This is illustrated graphically by Figure 31. The expansion results in a decrease in the mass on the fire floor and in a negative dm/dt. Rapidly growing fires result in smaller dm/dt than do slower growing fires. Smaller values of dm/dt result in greater reductions in $\dot{m}_i$ and greater reductions in the pressure differences at the smoke zone boundaries.

This section develops a method to evaluate the effect of expansion on zoned smoke control. For the unsprinklered fire tests with zoned smoke control, the dm/dt term reached a minimum of about -1 lb/s (-0.5 kg/s). This directly decreases the mass flow, $\dot{m}_i$, into the fire floor by about 800 cfm (0.38 m^3/s). For the smoke control system of these tests, this amounted to a 40% decrease in mass flow rate. The effect of this change in $\dot{m}_i$ on pressurization can be expressed as

$$\overline{\Delta p} = \overline{\Delta p}_r \; (\dot{m}_i/\dot{m}_{ir}) \tag{16}$$

or it can be expressed in terms of volumetric flow as

$$\overline{\Delta p} = \overline{\Delta p}_r \; (\dot{V}_i/\dot{V}_{ir}) \tag{17}$$

where the subscript r refers to normal operating conditions without a fire. Equation (17) can be used to design systems such that the pressurization decrease due to expansion is small. Based on a knowledge of fire science, the dm/dt term can be evaluated, and $\dot{V}_i = \dot{V}_{ir} - (dm/dt)/\rho$. For example, $\dot{V}_{ir}$ = 2000 cfm (0.94 m^3/s), $(dm/dt)/\rho$ = 800 cfm (0.38 m^3/s), and $\overline{\Delta p}_r$ = 0.11 in. H_2O (27 Pa), result in $\dot{V}_i$ of 1200 cfm (0.57 m^3/s) and $\overline{\Delta p}$ of 0.04 in. H_2O (10 Pa).

If the exhaust rate were larger, dm/dt has a smaller effect. Consider $\dot{V}_{ir}$ = 10,000 cfm (4.72 m^3/s); then the average pressure difference would decrease to 0.09 in. H_2O (22 Pa). This is a considerable improvement and indicates that if the exhaust rate is large enough, reductions in pressure difference due to dm/dt can be insignificant. The larger exhaust air rate can be accomplished at six air changes per hour with a larger smoke control zone. For this example, the zone would need to be increased from 20,000 ft^3 (566 m^3) to 100,000 ft^3 (2830 m^3). However, using more than six air changes per hour is not recommended because of concerns about increased fire growth from air supplied at the higher air change rate.

An alternative approach is to allow some smoke leakage from the smoke zone for a short period of time. Expansion depends on the growth rate of the fire, but, by nature, the expansion effect is relatively short lived. In Figure 31, a negative peak in dm/dt occurs for a few minutes.

8. EXHAUST FAN TEMPERATURE

Concern is frequently expressed about problems of fan reliability at elevated operating temperatures. However, this should not be the major concern about fan temperature. It is apparent from the above analysis that increased fan temperature decreases smoke control system pressurization by decreasing the mass flow rate of the exhaust fan. The maximum operating temperatures of the exhaust fan during tests 3, 7, and 12 were 156°F (69°C), 315°F (157°C), and 207°F (97°C). These temperatures are low compared to the temperatures in the upper portion of the corridor for these tests, because the fan intake duct was located at the floor level in the corridor.

Calculations were made with the fan temperature set at the temperature near the corridor ceiling to see what the effect would be on pressurization. At four minutes after ignition, the calculation indicated that positive pressurization was lost at the stairwell (Δp_h became negative) for tests 3, 7, and 9. The pressure loss lasted 12 minutes or more for each test. The temperature of the gases going through the exhaust fan is of critical importance. When many HVAC systems are used for smoke control, they exhaust air from all or most of the rooms on a floor. Thus, hot fire gases and lower temperature air from remote rooms are mixed, and the fan temperature is much lower than that of the fire gases. Also, heat transfer from the exhaust duct lowers the fan temperature.

If an allowable reduction in $\dot{m}_e$ is established, then the maximum allowable fan temperature can be calculated as

$$T_{fan} = T_r/(1 - \phi) \qquad (18)$$

where T_r is the absolute temperature of the fan for normal conditioning and ϕ is the allowable fraction reduction in $\dot{m}_e$. For example, if a reduction of 20% in the mass flow rate is acceptable and T_r is 70°F (21°C), the maximum allowable fan temperature is 203°F (95°C).

9. PRESSURES WITH CONSTANT AT FLOW RATE

This section presents the equations describing the pressure differences produced by a smoke control system when the mass flow rate through leakage paths in the barriers of the fire floor is constant. This constant mass flow rate occurs when the changes in $\dot{m}_e$ and dm/dt do not have any significant effect on the pressure on the fire floor. Approaches for minimizing these effects are discussed in the preceding sections. Further, this analysis can be appropriate when there is a large opening to the outside from the smoke zone. The mass flow from other spaces into the fire floor through path k can be expressed as

$$\dot{m}_{ki} = C A_k \sqrt{2 \rho_n \overline{\Delta p}_k} \tag{19}$$

where

$$\overline{\Delta p}_k = \frac{4}{9} \left[\frac{\Delta p_{kh}^{3/2} - [\Delta p_{kh} + (\rho_n - \bar{\rho}_{knf})gh]^{3/2}}{2\Delta p_{kh} + (\rho_n - \rho_{knf})gh} \right]^2 \tag{20}$$

where $\bar{\rho}_{knf}$ is the average density on the fire floor in room n in the vicinity of path k. The pressure differences on the fire floor in the vicinity of the path k are

$$\Delta p_{ko} = \Delta p_{kh} + (\rho_n - \bar{\rho}_{knf})gh \tag{21}$$

where h is the floor-to-ceiling height. Provided that the average pressure difference, $\overline{\Delta p}_k$, and densities, ρ_n and $\bar{\rho}_{knf}$, are known, Equation (19) determines mass flow rate, Equation (20) determines Δp_{kh}, and Equation (21) determines Δp_{ko}. The average densities are determined from the average temperatures and the ideal gas law. The pressure differences are strong functions of density $\bar{\rho}_{knf}$, which is determined from the ideal gas law. Thus, the pressure differences are strong functions of temperature in the vicinity of the flow paths.

10. ANALYSIS OF SMOKE FLOW TO UPPER FLOORS

This section presents a simple method of analysis of smoke flow to the upper floors of buildings with the intent of providing insight into some circumstances when smoke control would be appropriate. As with other evaluations of building airflow and smoke transport (McGuire and Tamura 1975; Klote 1989), this analysis is based on the law of conservation of mass, the ideal gas equation, the stack effect equation, the concept of effective flow areas, and the assumption of no flow through floors of the building. This analysis is unique in that it leads to an analytic expression for the concentration of a pollutant on an upper floor of the building.

Figure 32 is a diagram of the upper portion of a building. Mass flow rate is considered steady, even though the concentration of pollutants changes. The neutral plane is a horizontal plane where the pressure inside the shaft equals that outside the buildings. For leakage paths that are relatively uniform from floor to floor, the neutral plane is located near the mid-height of the building. If there is a large opening in the shaft to the outside, the neutral plane will be between that opening and the mid-height. Further discussion of locations of the neutral plane is provided by Klote (1989). This analysis is for floors above the neutral plane and for outside temperatures less than shaft temperatures ($T_a < T_{sh}$ where subscripts a and sh are for outside and shaft).

Because there is no leakage through the floors, the mass flow rate from the stairwell to any floor equals that from the floor to the outside. This mass flow rate can be expressed as

$$\dot{m} = C\, A_e \sqrt{2\, \rho_{sh}\, \Delta p} \qquad (22)$$

where Δp is the pressure difference from the stairwell to the outside and A_e is the effective flow area between the stairwell to the outside. The ASHRAE smoke control manual provides an equation for effective flow paths in series where the fluid in all the paths has the same temperature. The analysis can be extended for different temperatures:

$$A_e = \left(\frac{1}{A_{sh}^{\;2}} + \frac{T_{fl}}{T_{sh}} \frac{1}{A_a^{\;2}} \right)^{-1/2} \qquad (23)$$

The pressure difference is expressed by the stack effect equation

$$\Delta p = \frac{g\, P_{atm}}{R} \left(\frac{1}{T_a} - \frac{1}{T_{sh}} \right) z \qquad (24)$$

The conservation of mass equation for a pollutant on a floor above the neutral plane is

$$\frac{dc_{fl}}{dt} = \frac{\dot{m}}{V_{fl}\, \rho_{fl}} (c_{sh} - c_{fl}) \qquad (25)$$

where c_{fl} and c_{sh} are the concentrations of the pollutant in the stairwell and on the floor. The solution to this differential equation is

$$\frac{c_{fl}}{c_{sh}} = 1 - e^{-\lambda t} \qquad (26)$$

where

$$\lambda = \frac{\dot{m}}{V_{fl}\ \rho_{fl}} \qquad (27)$$

The above equations can be used to estimate the concentrations of toxic gases on any floor above the neutral plane. Bukowski et al. (1989) present a comprehensive discussion of the tenability limits for temperature, radiant flux, smoke obscuration, oxygen depletion, and numerous toxic gases. On floors far removed from the fire, the hazards due to temperature and radiant flux are believed to be insignificant. A complex analysis could be made including smoke obscuration and many gases. However, the first-order model above does not seem to warrant such an exhaustive tenability analysis. In order to obtain a rough idea of the extent to which smoke spread should be a concern in high-rise building, only the hazard due to CO is considered. However, this should not be taken to mean that other toxic gases, O_2 depletion or smoke obscuration might not have a significant effect.

Carbon monoxide forms carboxyhemoglobin (COHb) in the blood, which reduces the oxygen-carrying capacity of the blood. Based on the research of Steward (1973), the cumulative COHb level in the blood of adult humans can be estimated by

$$\Delta(\text{COHb}) = 5.98 \times 10^{4}\ (\Delta t)(\text{CO})^{1.036} \qquad (28)$$

where Δ(COHb) is the percent increase in COHb in the blood during the time interval, Δt, in minutes due to CO concentration in ppm. Normally there is a small background level of COHb in the blood. Based on research of Alarie and Zullo (1974), an initial value of 0.75% COHb is used for this paper. For this analysis, a 25% calculated COHb was chosen as the level at which incipient incapacitation may occur based on the work of Kimmerle (1974).

The above equations were used to make a theoretical toxic gas hazard analysis of the Plaza Hotel for fires of longer duration and higher CO production than those of the test series. The values of parameters used for these calculations are listed in Table 4. The leakage areas are those used for the design of the smoke control system (Klote 1988a). An outside temperature of 20°F (-7°C) was selected to provide strong upward airflow due to stack effect. The shaft temperature was selected at 70°F (21°C) because temperatures in the stairwell increased only a few degrees during the fires without smoke control. However, the effects of increased shaft temperature are discussed later. The temperature on the upper floor was 70°F (21°C) because this temperature did not increase more than a small fraction of a degree for any of the fires. The height above the neutral plane was chosen as 30 ft (9.14 m), which would be at the top floor for a neutral plane located at the mid-height of the building. From other fire experiments, the CO levels on the fire floor can be from 2% to 5%. Because the CO in shafts would be a fraction of this, CO in the shaft was evaluated over the range of 0.10 to 1.00%.

Figure 33 shows the CO concentrations on the floor for this range of shaft concentrations. As expected, CO levels and time to incapacitation are a strong function of CO concentration in the shaft. Times to incapacitation on a floor above 30 ft (9.14 m) above the neutral plane are 34 minutes to 2 hours for CO concentrations in the shaft of 1.00% and 0.10% respectively. For occupants who can exit the building early, this is not a problem. Occupants who are trapped on upper floors by smoke or by physical disabilities can be in real danger. Because of smoke obscuration and toxicity, it sometimes takes hours for the fire service to get to those so trapped.

For buildings taller than the Plaza Hotel, the smoke problem can be more severe. This is not just because of increased travel distances for evacuation and rescue. At greater heights above the neutral plane, the pressure difference from the shaft to the building increases. This results in more smoke laden air flowing into the floor. Figure 34 shows CO concentrations on floors of different heights above the neutral plane calculated at 0.5% CO in the shaft. Times to incapacitation on these floors are 32 to 50 minutes for heights above the neutral plane of 180 ft (54.9 m) to 30 ft (9.14 m), respectively. This does not take into account the fact that many taller buildings have greater floor volumes and different leakage areas. However, it is apparent that building height is not as important as CO concentration in the shaft.

Higher shaft temperatures increase the pressure difference from the shaft to the building, thus increasing the mass flow to the floor. This results in greater concentrations on floors above the neutral plane. The effect of shaft temperature is shown in Figure 35. Times to incapacitation on a floor 30 ft (9.14 m) above the neutral plane are 37 to 40 minutes for shaft temperatures of 600°F (316°C) to 70°F (21°C), respectively. CO concentration and time to incapacitation are not very strong functions of shaft temperature. The most important factor is shaft concentration and the next is height above neutral plan.

The analysis presented in this section can be used in conjunction with an engineering evaluation of the evacuation capacity of a building to help determine if a smoke control system would be of value for a particular building.

11. FUTURE EFFORTS FOR RESEARCH AND TECHNOLOGY TRANSFER

The ASHRAE smoke control manual is an example of technology transfer from research to application. This publication is currently being revised and expanded by the author, and many of the findings from this project will be incorporated. These include the following:

1. The approach to design pressure differences will be revised to include the effect of open windows.

2. Improved recommendations concerning the size of smoke control zones and fan operating temperatures will be included.

3. Improved treatment of smoke movement in buildings will be provided.

Additional research is needed in the following areas:

1. More needs to be learned about the interaction between fire and the smoke control system. For the tests without smoke control, the CO production was much higher than for those with smoke control. However, if the fuel were not limited, the tests with smoke control might have been considerably different. Information is needed concerning the effect of smoke control on CO production. This paper presents methods of minimizing the adverse effects of fan temperature and expansion of gases on smoke control pressurization. Further experiments are needed to study these effects. Such experiments could be full-scale. However, scale modeling seems appropriate because it is economical and lends itself to parametric studies.

2. The relation between sprinklers and smoke production needs study. The test with the quick-response sprinkler resulted in limited smoke production and no smoke problem beyond the fire floor. The on-off sprinkler resulted in considerable smoke production and smoke levels away from the fire floor. However, there are so many factors involved, that further study is needed. Important considerations are smoke obscuration and generation of toxic gases. This information is needed to develop an approach to evaluate the relative benefits of smoke control for specific applications.

12. SUMMARY AND CONCLUSIONS

1. For the conditions of the example calculations in this paper (typical of a large fire in a multi-story building), incipient incapacitation of people trapped above the neutral plane due to CO from a fire below the neutral plane was calculated to occur after an exposure of about a 30 minutes to 2 hours. Time to incipient incapacitation depends on the concentration of CO in building shafts, temperatures of gases in building shafts, outside temperature, and leakage areas throughout the building. The theoretical hazard analysis presented in this paper can be used in conjunction with an engineering evaluation of the evacuation capacity of a building to help determine if a smoke control system would be of value for a particular building.

2. For the fires of this experimental series, the zoned smoke control system effectively maintained positive pressurization around the fire floor.

3. The approach to minimum pressure differences in the ASHRAE smoke control manual and NFPA 92A is based on the tacit assumption of a constant mass flow rate into the zone where the fire is located. To evaluate this

assumption, a model was developed of mass flow in the smoke zone. Agreement between experimental results and calculations based on the model were good. The following two items are based on this model.

4. Expansion of gases in the smoke zone can reduce the pressure differences at the boundaries of the smoke zone. As a fire develops, gases on the fire floor are heated and expand. The increased volume of gases due to expansion flowed out of the fire floor with the rest of the gases exhausted by the fan. Accordingly, the mass flow rate into the fire floor is decreased by the same amount. The decrease in flow into the fire floor is accompanied by a decrease in pressure difference across the boundaries of the fire floor. Equation (17) can be used to design systems so that the pressurization decrease due to expansion is small. An alternative approach is to allow some smoke leakage from the smoke zone for a short period of time.

5. High-temperature gases going through a smoke control exhaust fan can result in a significant loss of system pressurization. Equation (18) can be used to evaluate this effect.

6. Delays before smoke control activation should be of short duration for unsprinklered fires. In test 7, smoke leakage during the four-minute delay resulted in relatively high levels of CO and CO_2 many floors away from the fire.

7. With few exceptions, smoke bombs should not be used for acceptance tests. These exceptions include testing for smoke feedback into supply air and locating leakage paths in construction. Chemical smoke is so different from smoke due to a flaming fire that persons observing a smoke bomb test can develop a false sense of security.

8. The hydrostatic equation [equation (1)] is appropriate for defining pressures for zoned smoke control applications and probably most fire modeling applications.

9. Control wiring needs to be protected from fire damage. During test 12, the smoke control fans stopped due to fire damage to the control wiring. Obviously, this caution can be extended to the total control system, the electrical power supply system, and any other items that are needed for the smoke control system to operate.

13. ACKNOWLEDGMENTS

This project was sponsored by the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE); Bell Atlantic Telephone Company; New Jersey Bell Telephone Company; U.S. Fire Administration; Department of Veterans Affairs, and US West Incorporated. Member companies of the Air Movement and Control Association (AMCA) donated fans for this project.

Before this series of experiments, the Plaza Hotel in Washington, DC was used by the Capitol Police as an office building and was under the authority of the U.S. Senate. The author expresses his appreciation to the U.S. Senate Committee on Rules and Administration for approving use of the Plaza Hotel Building by the Center for Fire Research (CFR) for this project. Appreciation is extended to the Capitol Police Department for providing building security and especially for searching the building with dogs before each fire to protect against accidentally exposing persons to the hazards of fire. Thanks are due to the DC Fire Department for having a manned fire engine stand by during our fires.

Appreciation is also expressed to the Architect of the Capitol, George White, for the support his staff generously extended to CFR throughout this effort. Thanks are extended to Ray Carrol, Chief Engineer of the Office of the Architect of the Capitol, who took a very personal interest in this project. Appreciation is expressed to Newell Anderson, Head Structural Engineer of the Office of the Architect of the Capitol, for advice concerning protection of the structural system of the Plaza Hotel. The author is most indebted to Ken Lauziere, Head Fire Protection Engineer of the Office of the Architect of the Capitol, for the daily support he and his staff provided. This support was most important considering that we were operating miles away from our laboratories and supply shops in Gaithersburg, MD. Further, Lauziere should be credited with the idea of using the Plaza Hotel Building for fire research.

Some of the people who provided advice concerning planning and funding during the early stages of the effort were Jim Brownell of US WEST, Jack Buckley of I. A. Naman & Associates, Doyle Carrington and Ken Faulstich of the Department of Veterans Affairs, Mike Dillon of Dillon Consulting Engineers, Peter Hanly and Jerry Jolette of AMCA, Vince Hession of Bell Communications Research, John Kempmeyer of Maida Engineering, Lew Parks of the New Jersey Bell Telephone Co., Bill Schmidt formerly of the U.S. Veterans Administration, Tom Smith and Ed Wall of the U.S. Fire Administration, John Stratton of the Sheet Metal and Air Conditioning Contractors National Association (SMACNA), George Tamura of the National Research Council of Canada, and Chuck Yaunches of the Bell Atlantic Corporation.

The fans for this project were loaned to CFR by member companies of AMCA. Special thanks are extended to Jim Schwier of the Lau Division of Philips Industries for coordinating this effort among the AMCA members and for his valuable counsel concerning fan technology.

The actual work of preparation, instrumentation, and experimentation was done by a CFR project team consisting of Dan Alvord, Kevin Greenaugh, Darren Lowe, Roy McLane, Bill Rinkinen, Gary Roadarmel, and Dick Zile. This work was

physically and mentally demanding and often very dirty. Each member of the team made unique contributions. The dedication, skill, and ingenuity of this project team were in large part responsible for the success of the project. Words are inadequate to describe the author's warm feelings of appreciation for each member of the team. It was an honor to have been associated with such an outstanding group.

Special appreciation is extended to my secretary, Marva Brown, who acted as the unofficial member of the project team back at the laboratory. Doug Walton of CFR was most helpful in planning and conducting the sprinklered fires. Emil Braun and Ken Steckler of CFR provided advice concerning instrumentation. Of course, without the considerable support of CFR management, this project would not have been possible.

With a project this large, it is impossible to thank everyone individually for their support. Contributions have been made by many electricians, engineers, firefighters, locksmiths, plumbers, police officers, scientists, secretaries, technicians, and other professionals working for numerous organizations. The author expresses appreciation to everyone who contributed.

14. NOTATION

A	area
C	flow coefficient
c	concentration of pollutant
g	acceleration of gravity
I_o	intensity of light at the beginning of the pathlength of smoke meter
I_x	intensity of light remaining after it has passed through the pathlength of smoke meter
m	mass
$\dot{m}$	mass flow rate
p	pressure
p_{atm}	absolute pressure of atmosphere
R	gas constant
T	absolute temperature
$\overline{T}$	average absolute temperature
V	volume
$\dot{V}$	volumetric flow rate
w	width of opening
x	pathlength of smoke meter
ϕ	allowable fraction reduction in $\dot{m}_a$.
$\underline{\rho}$	density
ρ	average density
Δp	pressure difference
δ	smoke obscuration is expressed in terms of optical density per unit distance of pathlength

Subscripts:

a	outside
e	exiting volume or effective flow area
f	fire floor
fan	fan
fl	floor
h	elevation h above datum elevation or height of opening
i	into volume
k	path in boundary of V_f
n	a room or other space within V_f
o	datum elevation
r	normal operating conditions
s	stairwell
sh	shaft

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Table 1. Ceiling Heights and Window Size for Plaza Hotel

Ceiling Height Above Floor:	in	(m)
Typical Hotel Room and Bathroom	106	(2.69)
Typical Corridor	103	(2.62)
Typical Floor of Stairwell	106	(2.69)
Fire-hardened Room (Burn Room for Test 12)	90	(2.29)
Fire-hardened Portion of Corridor	94.5	(2.40)
Window Opening in Fire-hardened Room for Test 12:		
Height	48	(1.22)
Width	46	(1.17)
Sill Height Above Floor	27.5	(0.70)

Table 2. Instrumentation List

Number	Thermocouple[1] Trees
00-04	basement stairwell[2]
05-09	basement[3]
10-14	1st floor stairwell[2]
15-19	1st floor corridor[3]
20-24	2nd floor stairwell[2]
26-31	2nd floor burn room[4]
32-37	2nd floor corridor by smoke meter[5]
38-43	2nd floor corridor by stairwell[5]
44-49	2nd floor corridor by elevator[6]
50-54	3rd floor stairwell[2]
55-59	3rd floor corridor[3]
60-64	4th floor stairwell[2]
65-69	4th floor corridor[3]
70-74	5th floor stairwell[2]
75-79	5th floor corridor[3]
80-84	6th floor stairwell[2]
85-89	6th floor corridor[3]
90-94	7th floor stairwell[2]
95-99	7th floor corridor[3]

Number	Thermocouple[1]
25	outside air
100	load platform
101	outlet of second floor exhaust fan
102	inlet of second floor exhaust duct
103	second floor fan room

Number	Smoke Meters[7]
146	2nd floor corridor (not operating for tests 3, 7, and 12)
147	3rd floor corridor (not operating for tests 3, 7, and 12)
148	7th floor corridor (not operating for tests 3, 7, and 12)
125	3rd floor stairwell (operating for test 11 only)
126	7th floor stairwell (operating for test 11 only)

Table 2. Continued

Number	Pressure Differences (not operating for test 12)
127	stairwell to basement[8]
128	stairwell to outside at basement level[8]
129	1st floor to 2nd floor[9]
130	stairwell to 2nd floor near floor[10]
131	stairwell to 2nd floor near ceiling[11]
132	2nd floor to 3rd floor[12]
133	stairwell to 4th floor[8]
134	stairwell to outside at 4th floor[8]
135	stairwell to 7th floor[8]
136	stairwell to outside at 7th floor[8]

Number	Gas Analysis[13]
143	CO on floor 2 (operating for tests 1, 3, 5, 7, 9, 10, 11, and 12)
144	CO_2 on floor 2 (operating for tests 1, 3, 5, 7, 9, 10, and 11)
145	O_2 on floor 2 (operating for tests 1, 3, 5, 7, 9, 10, and 11)
137	CO on floor 3 for test 3 and on floor 7 for tests 5, 7, 9, 10, and 11)
138	CO_2 on floor 3 for test 3 and on floor 7 for tests 5, 7, 9, 10, and 11)
139	O_2 on floor 3 for test 3 and on floor 7 for tests 5, 9, 10, and 11)

Number	Wind Velocity (operating for all tests except 12)
120	10 ft (3 m) above roof (tests 1 to 3)
121	10 ft (3 m) above roof (tests 4 to 15)

Number	Wind Direction (operating for all tests except 12)
121	10 ft (3 m) above roof (tests 1 to 3)
122	10 ft (3 m) above roof (tests 4 to 15)

Table 2. Continued

Number	Load Platform (operating for all tests)
123	Located in second floor corridor for all tests except test 12 where it was in second floor burn room

Notes:

[1]All thermocouples operating for tests 1 to 11 except for the second thermocouple trees during test 1. During test 12 only the top two thermocouples of each second floor tree operated.

[2]Thermocouples located 0.25, 26.5, 53.0, 79.5, 105.75 in. (0.0064, 0.673, 1.35, 2.02, 2.69 m) above floor.

[3]Thermocouples located 0.25, 25.75, 51.5, 77.25, 102.75 in. (0.0064, 0.654, 1.31, 1.96, 2.61 m) above floor.

[4]Thermocouples located 0.25, 18.0, 36.0, 54.0, 72.0, 89.75 in. (0.0064, 0.457, 0.914, 1.37, 1.83, 2.28 m) above floor.

[5]Thermocouples located 0.25, 18.9, 37.8, 56.7, 75.6, 94.25 in. (0.0064, 0.480, 0.960, 1.44, 1.92, 2.39 m) above floor.

[6]Thermocouples located 0.25, 20.6, 41.2, 61.8, 82.4, 102.75 in. (0.0064, 0.523, 1.05, 1.57, 2.09, 2.61 m) above floor.

[7]Smoke meters located 60 in. (1.52 m) above floor.

[8]Pressure difference probes located 60 in. (1.52 m) above floor.

[9]First floor pressure difference probes located at ceiling level, and second floor pressure difference probe located at floor elevation.

[10]Pressure difference probes located 6.0 in. (0.152 m) above floor.

[11]Pressure difference probes located 90.5 in. (2.23 m) above floor.

[12]Second floor pressure difference probes located at ceiling level, and third floor pressure difference probe located at floor elevation.

[13]Gas probes located 60 in. (1.52 m) above floor.

Table 3. Test Schedule[1]

Test	Test Type	Fire Load[2] lb (kg)	Zoned Smoke Control[3]	Stairwell Pressurization[4]	Activation Time[5] (min)	Condition of Stairwell Doors at: Basement to Outside	2nd Floor[6]	7th Floor
1	Wood Fire	300 (136)	off	off	-	closed	closed	closed
2	Smoke Bomb	-	on	off	0	closed	closed	closed
3	Wood Fire	200 (91)	on	off	0	closed	closed	closed
4	Smoke Bomb	-	off	off	-	closed	½ inch	open
5	Wood Fire	300 (136)	off	off	-	closed	½ inch	open
6	Smoke Bomb	-	on	on	0	open	½ inch	open
7	Wood Fire	300 (136)	on	on	0	open	½ inch	open
8	Smoke Bomb	-	on	on	4	open	½ inch	open
9	Wood Fire	300 (136)	on	on	4	open	½ inch	open
10	Sprinklered	300 (136)	off	off	-	closed	½ inch	open
11	Sprinklered	300 (136)	off	off	-	closed	½ inch	open
12	Wood Fire	600 (272)	on	on	0	open	½ inch	closed

Notes:

[1] All fires in the second floor corridor, and all windows closed except for test 12 where:

a. the fire was in the fire-hardened room on the second floor, and

b. the window in that room was open.

[2] Fire load is approximate.

[3] Zoned smoke control consisted of pressurization of first and third floors at 2000 cfm (0.94 m^3/s) each, and exhaust of the second floor at the same rate.

[4] Stairwell pressurization consisted of supplying 7000 cfm (3.3 m^3/s) into the stairwell at the first floor with the exterior basement door open.

[5] Activation time is the time after ignition that the smoke control system and stairwell pressurization system are turned on.

[6] Second floor door designation ½ inch indicates that the door was cracked open ½ inch.

Table 4. Values used for example calculation of smoke flow above neutral plane

Values used for all calculations:

Temperature of outside air, T_a	20°F (-7°C)
Temperature of air on floor, T_{fl}	70°F (21°C)
Leakage area between shaft and building, A_{sh}	0.24 ft^2 (0.022 m^2)
Leakage area between building and outside, A_a	0.41 ft^2 (0.038 m^2)
Volume on floor, V_{fl}	20000 ft^3 (566 m^3)

Values used unless otherwise indicated:

Temperature of air in shaft, T_{sh}	70°F (21°C)
Height above neutral plane, Z	30 ft (9.14 m)
Concentration of CO in shaft, c_{sh}	0.50%

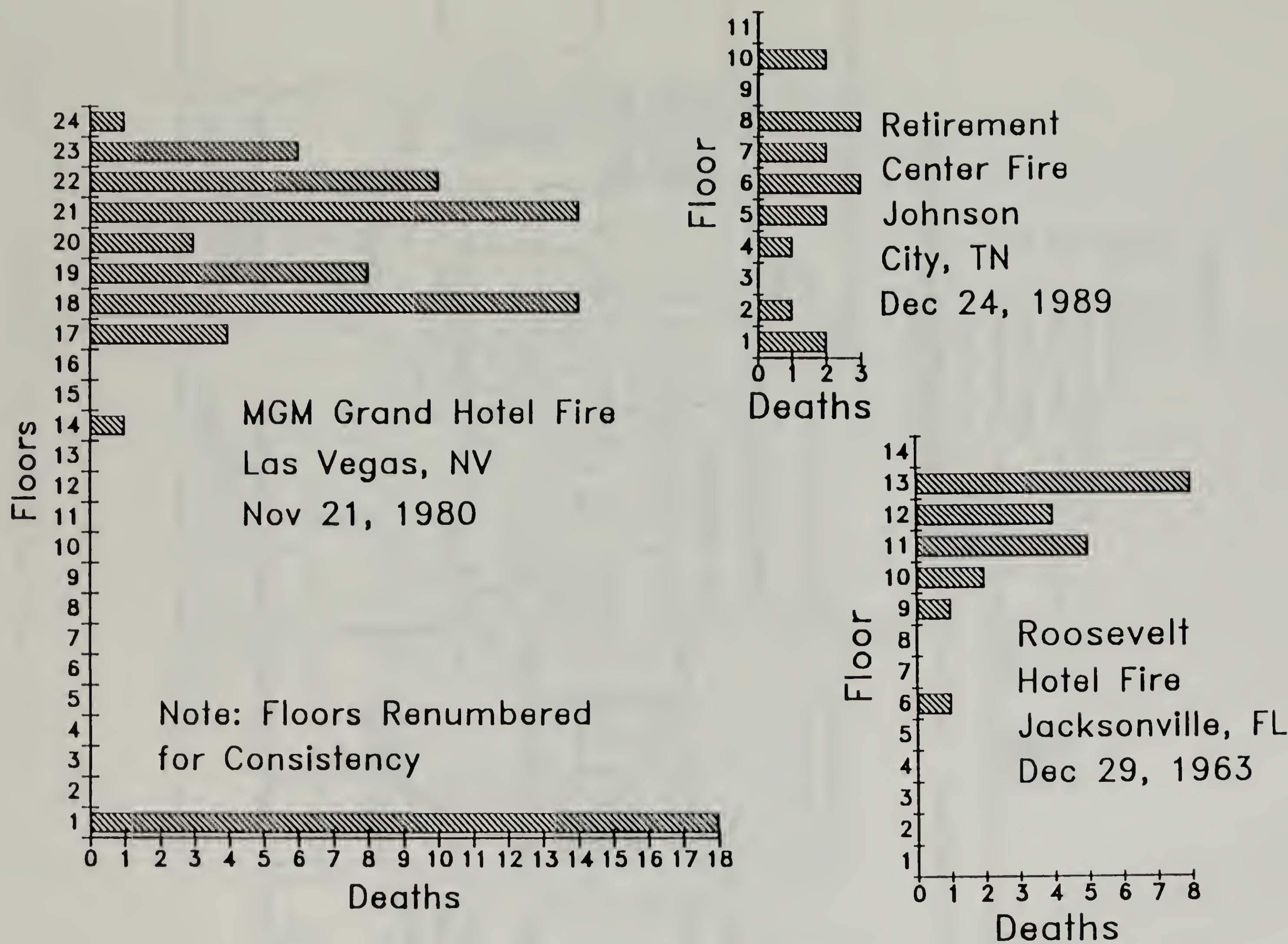

Figure 1. Deaths by floor for three fires where the fire was located on the first floor

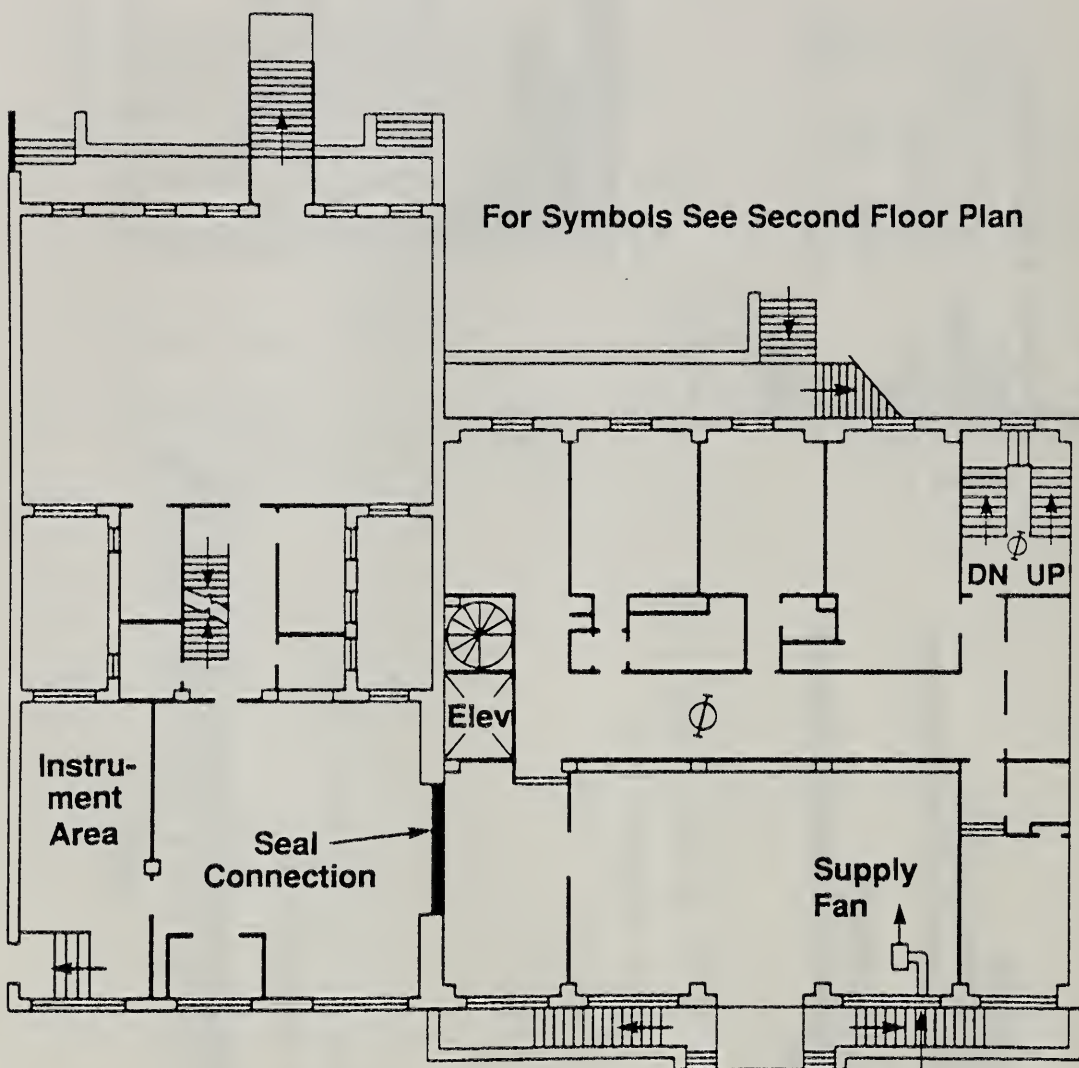

Figure 2. First floor plan of the Plaza Hotel

SYMBOLS:

UP Up
DN Down
Elev Elevator
∅ Thermocouple Tree
G Gas Probe (for CO, CO_2 and O_2)
S Smoke Meter
P Differential Pressure Probe at Floor to Ceiling Below
P/P Differential Pressure Probe Across Wall

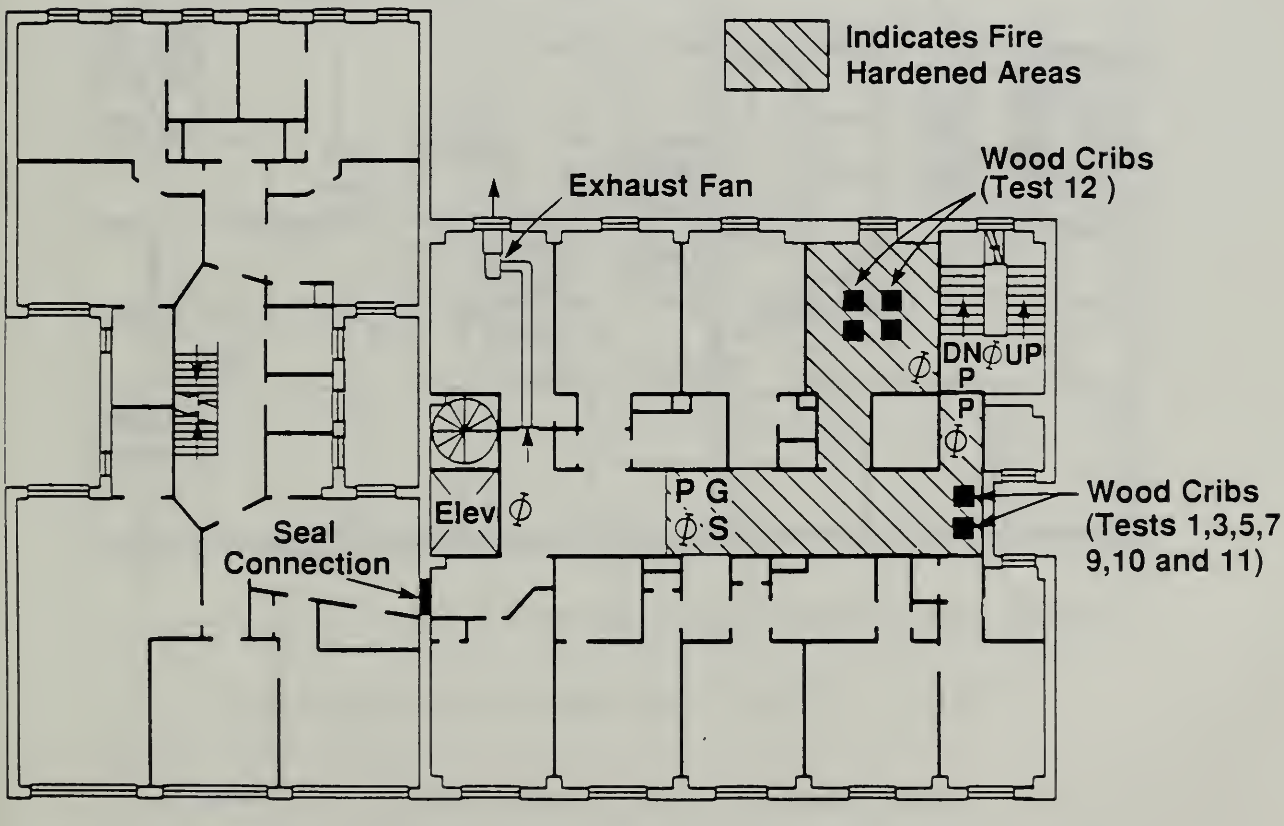

Figure 3. Second floor plan of the Plaza Hotel

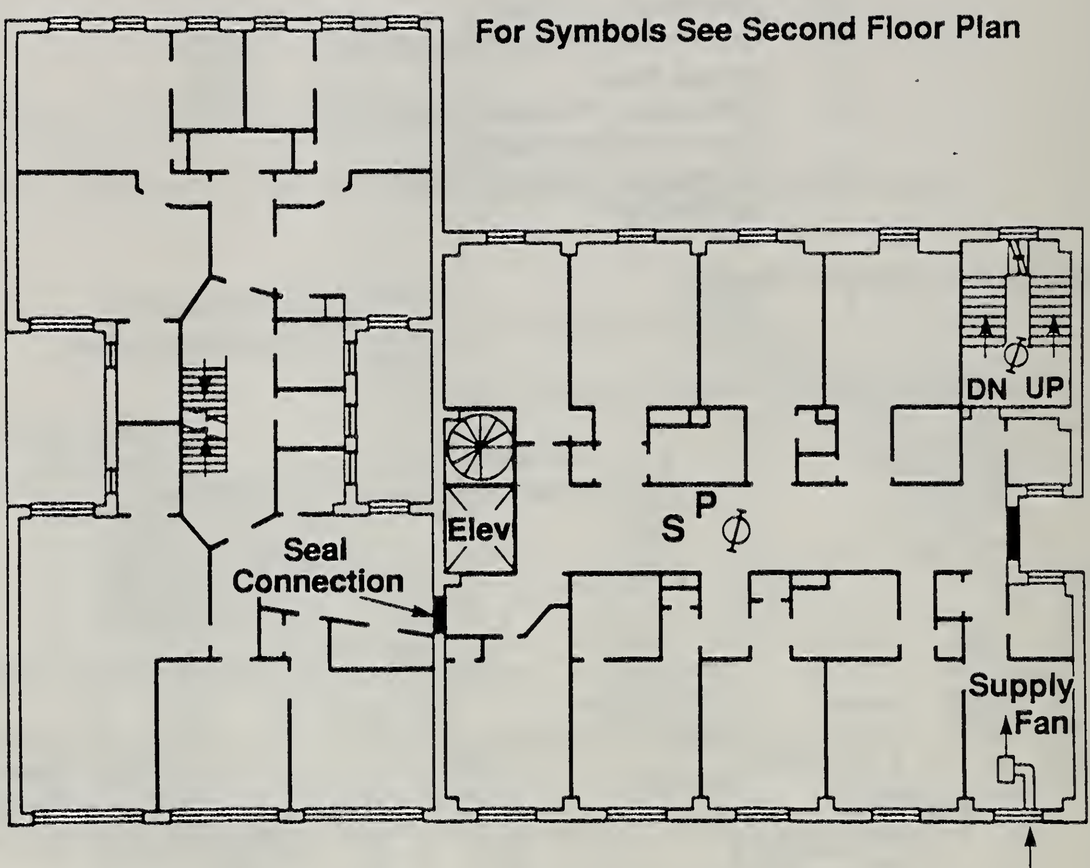

Figure 4. Third floor plan of the Plaza Hotel

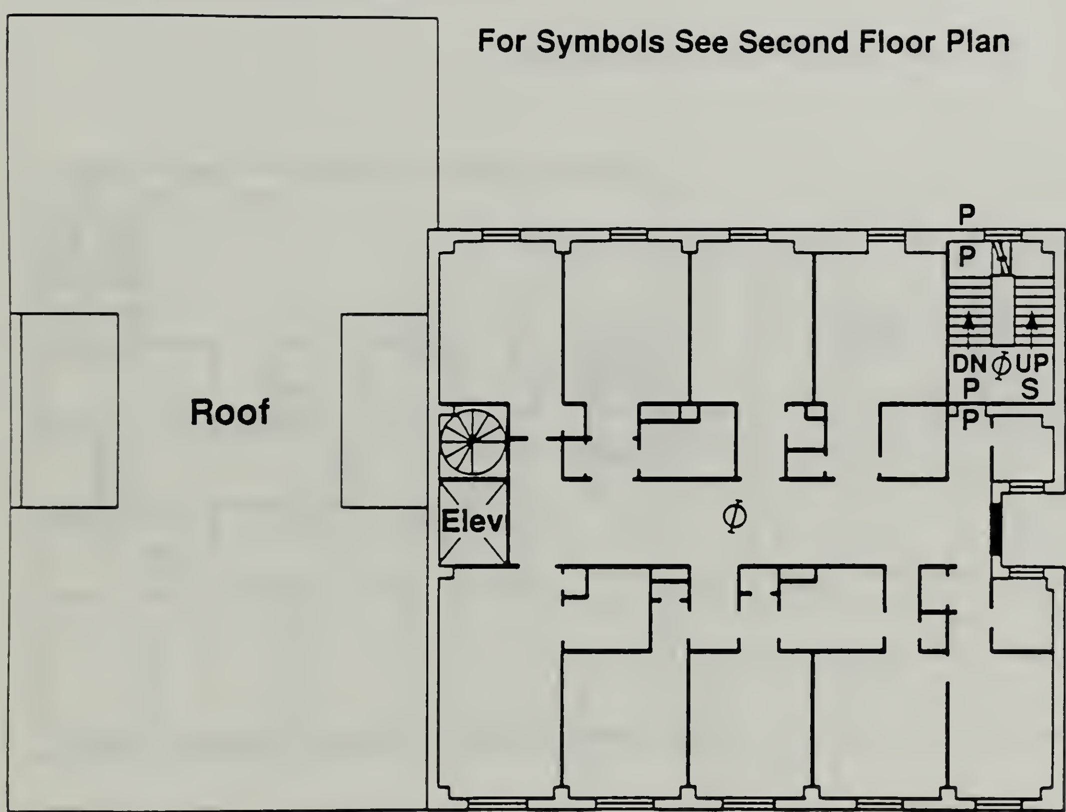

Figure 5. Fourth floor plan of the Plaza Hotel

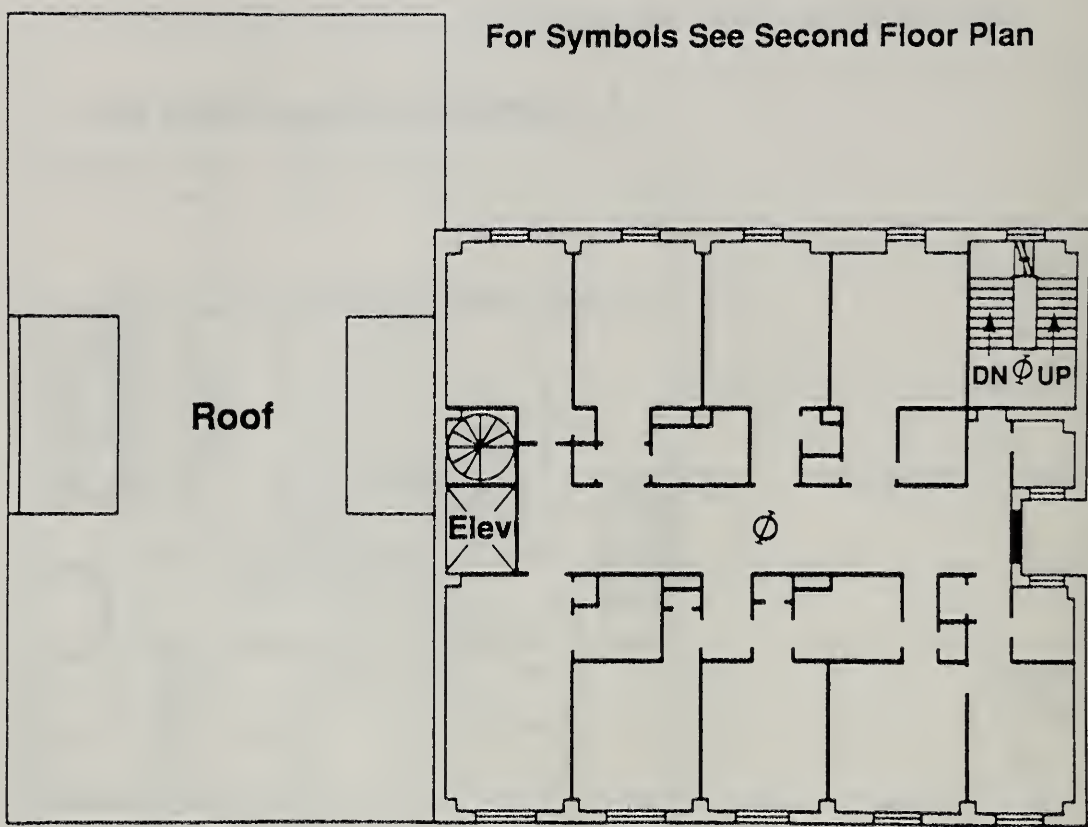

Figure 6. Typical Plan for the fifth and sixth floors Plaza Hotel

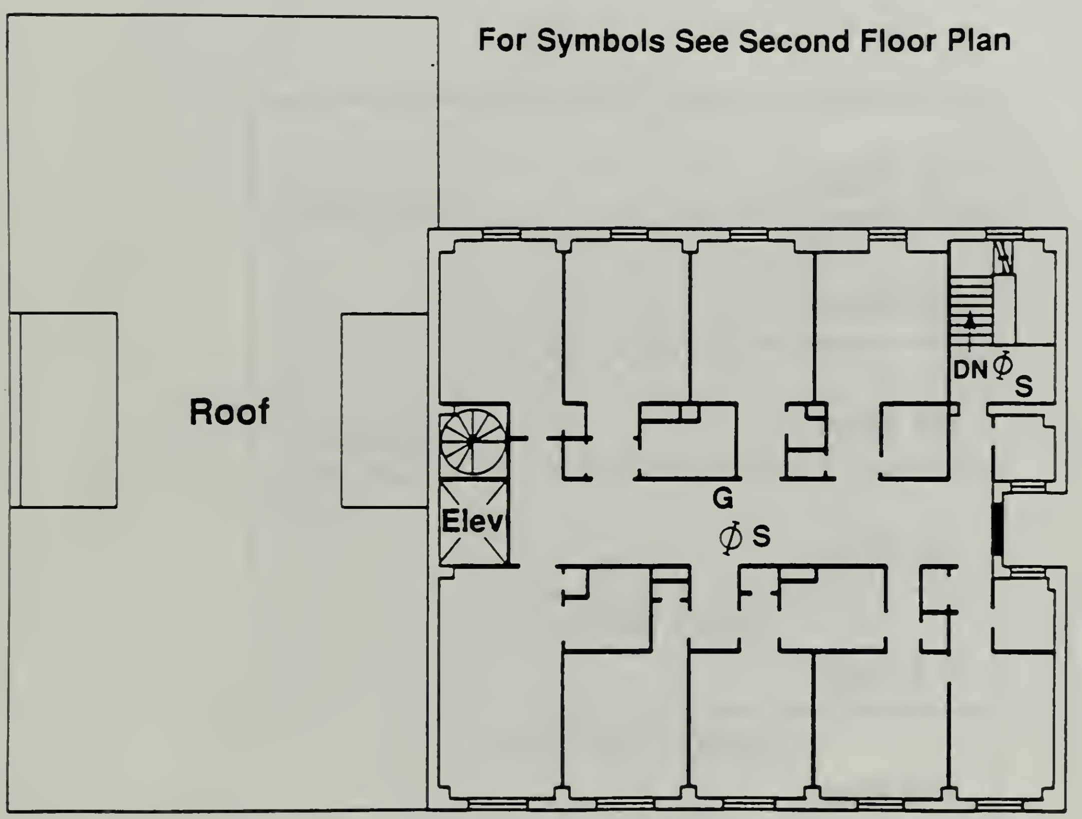

Figure 7. Seventh floor plan of the Plaza Hotel

Notes:

1. The second floor is the smoke zone, and it is exhausted at about six air changes per hour.
2. The first and second floors are pressurized at about six air changes per hour.
3. The stairwell is pressurized by 9000 cfm, and the exterior stairwell door remains open throughout pressurization.

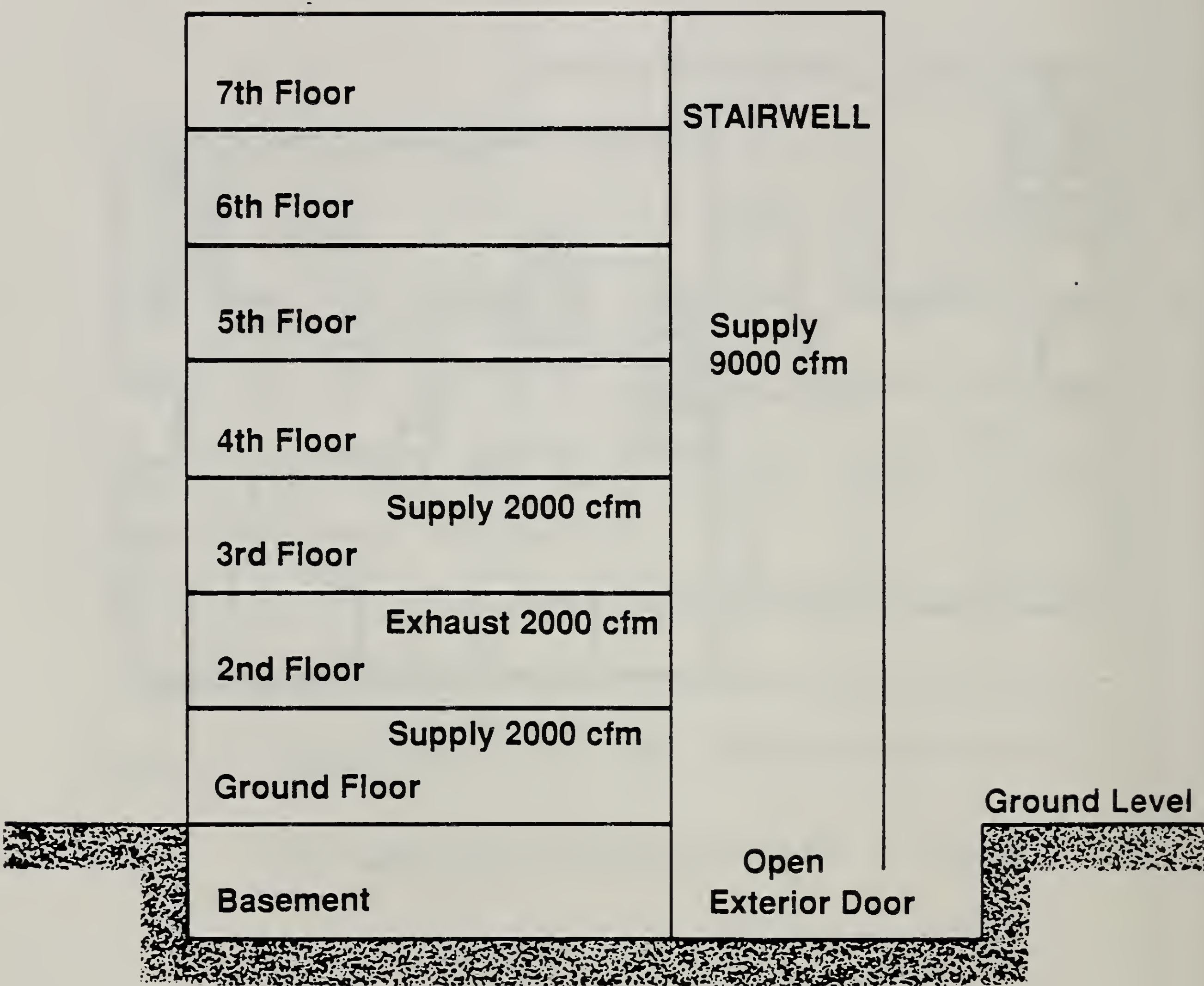

Figure 8. Schematic of the smoke control system

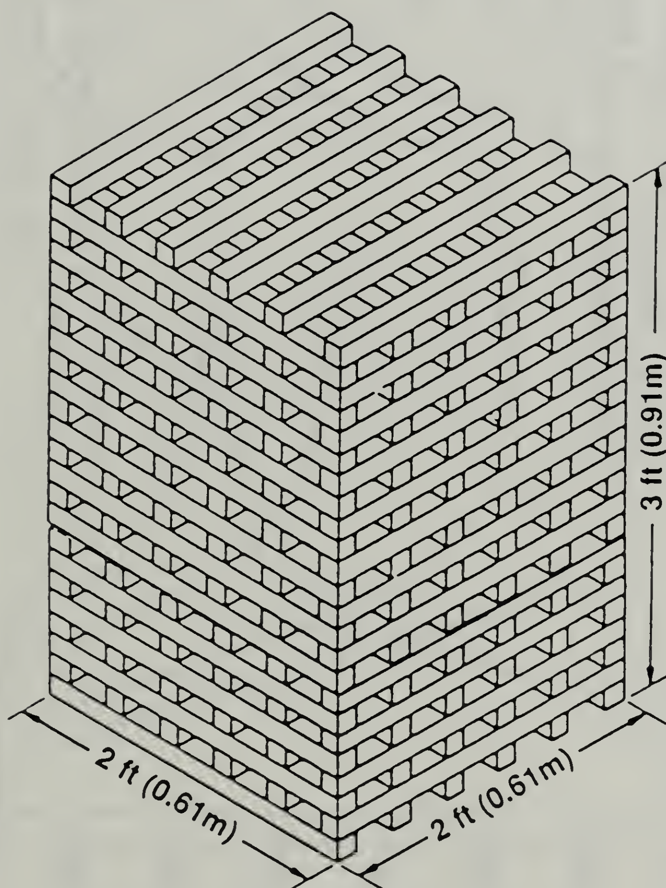

Figure 9. Configuration of nominal 150 lb (68 kg) wood crib

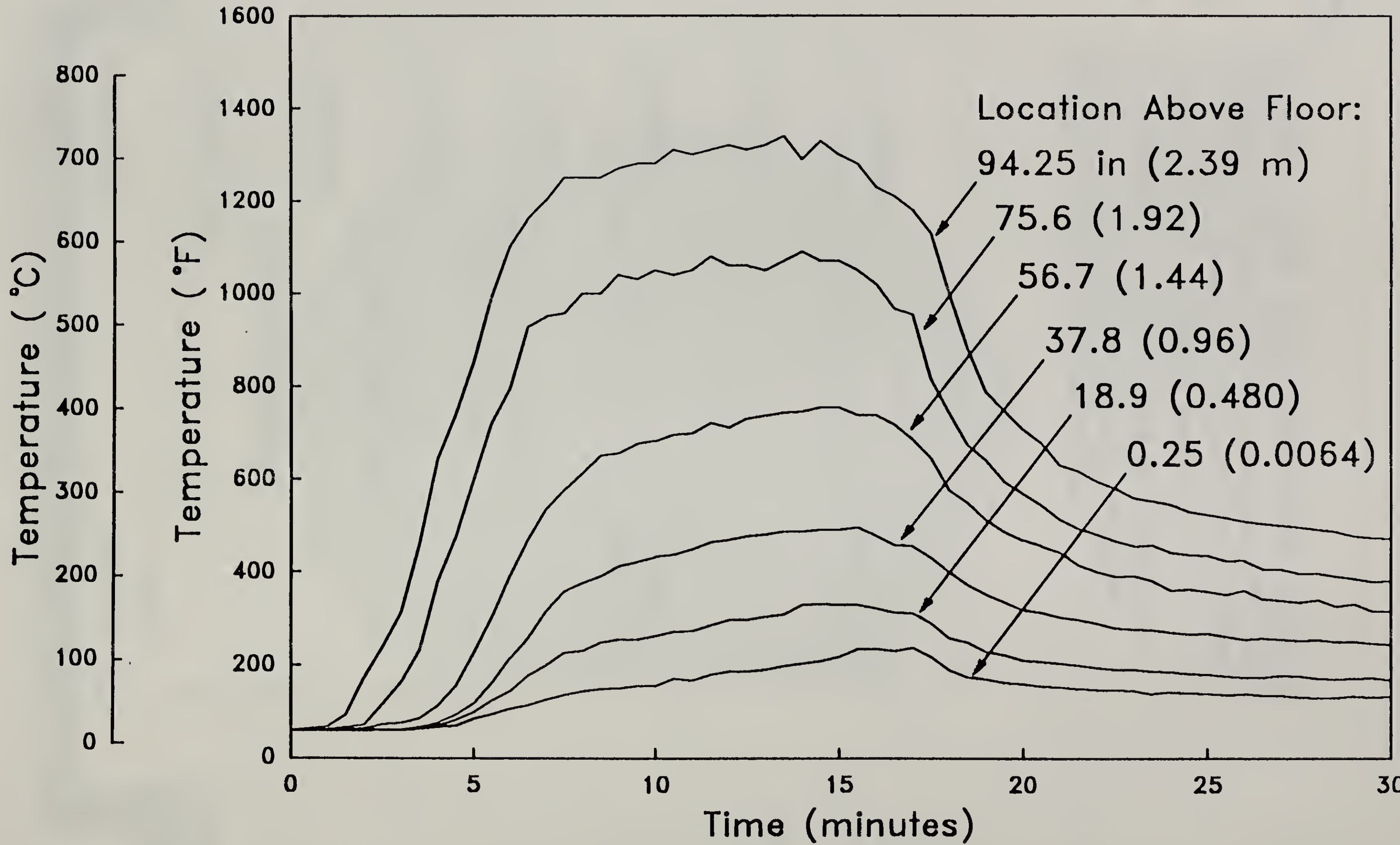

Figure 10. Temperatures at the center of the corridor on the fire floor for test 7

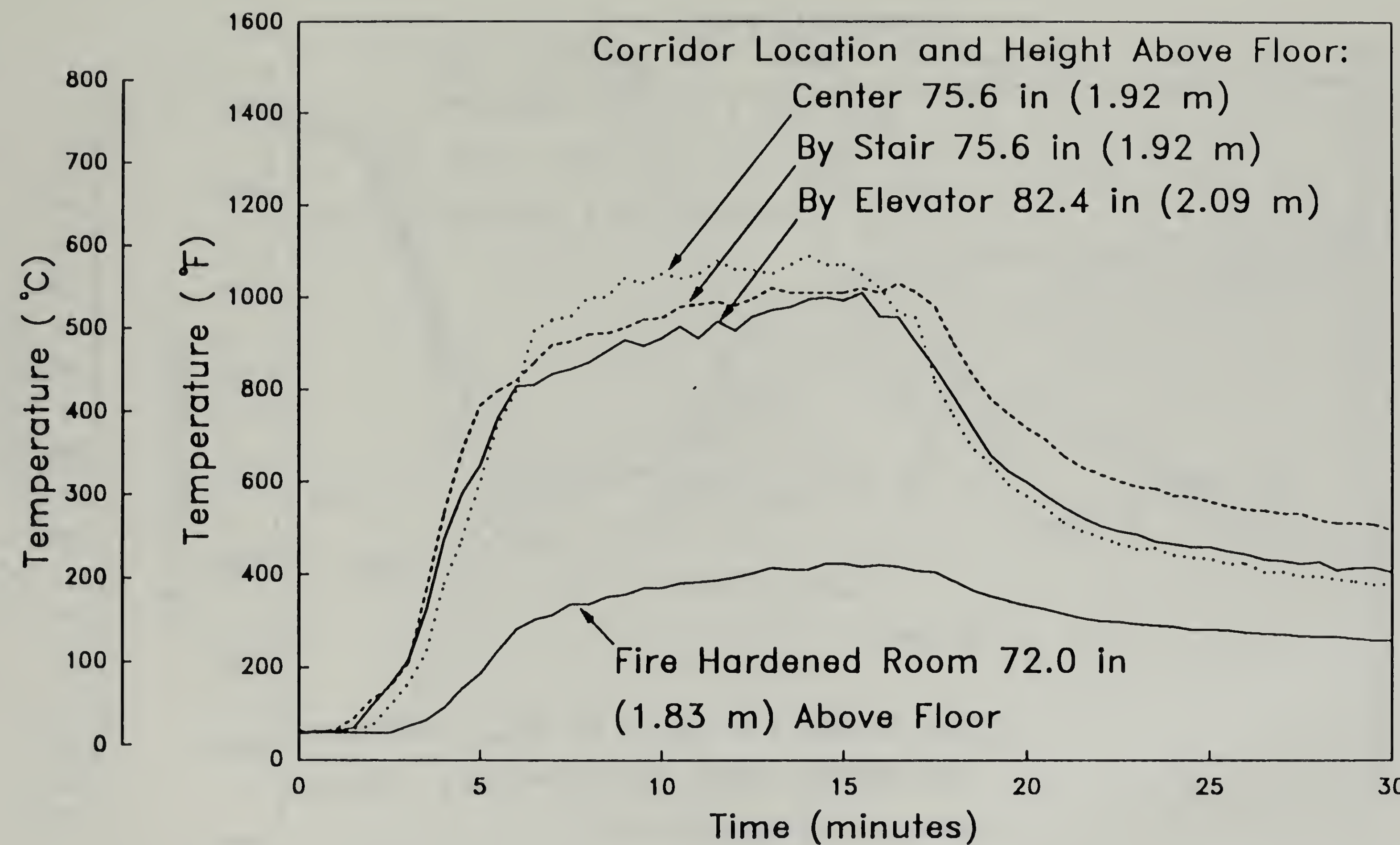

Figure 11. Comparison of temperatures at different locations on the fire floor for test 7

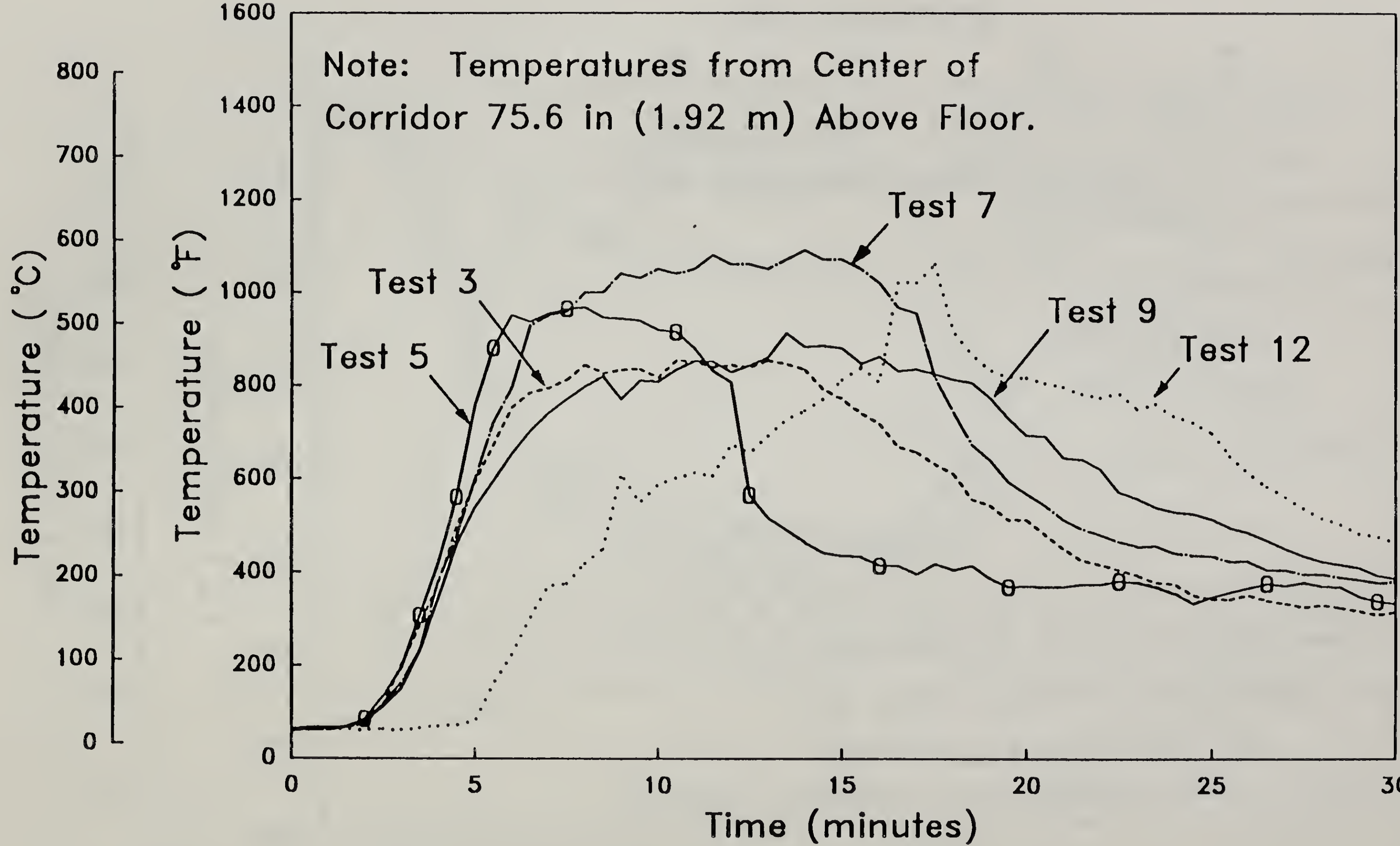

Figure 12. Comparison of temperatures in the corridor on the fire floor

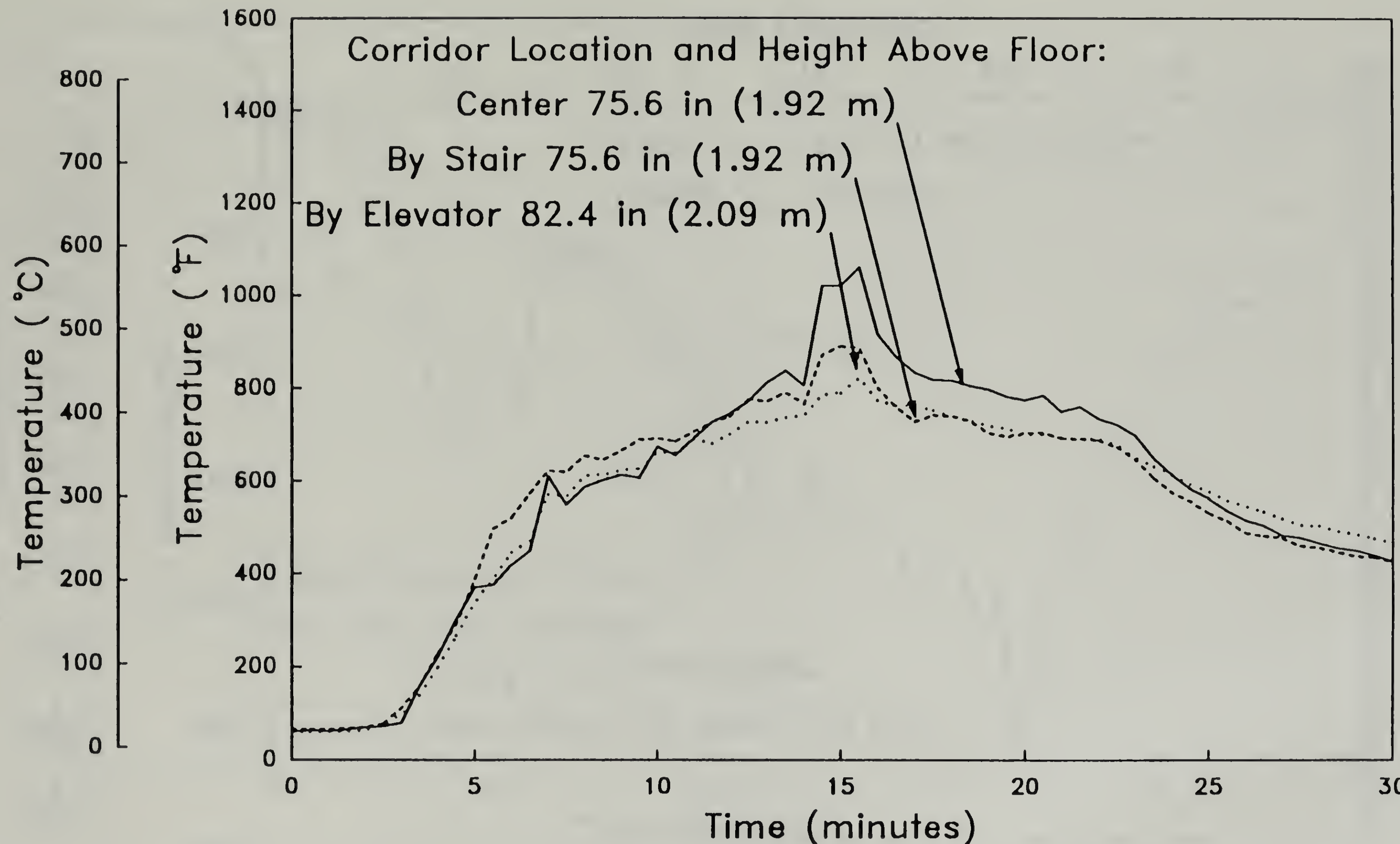

Figure 13. Corridor temperatures for test 12

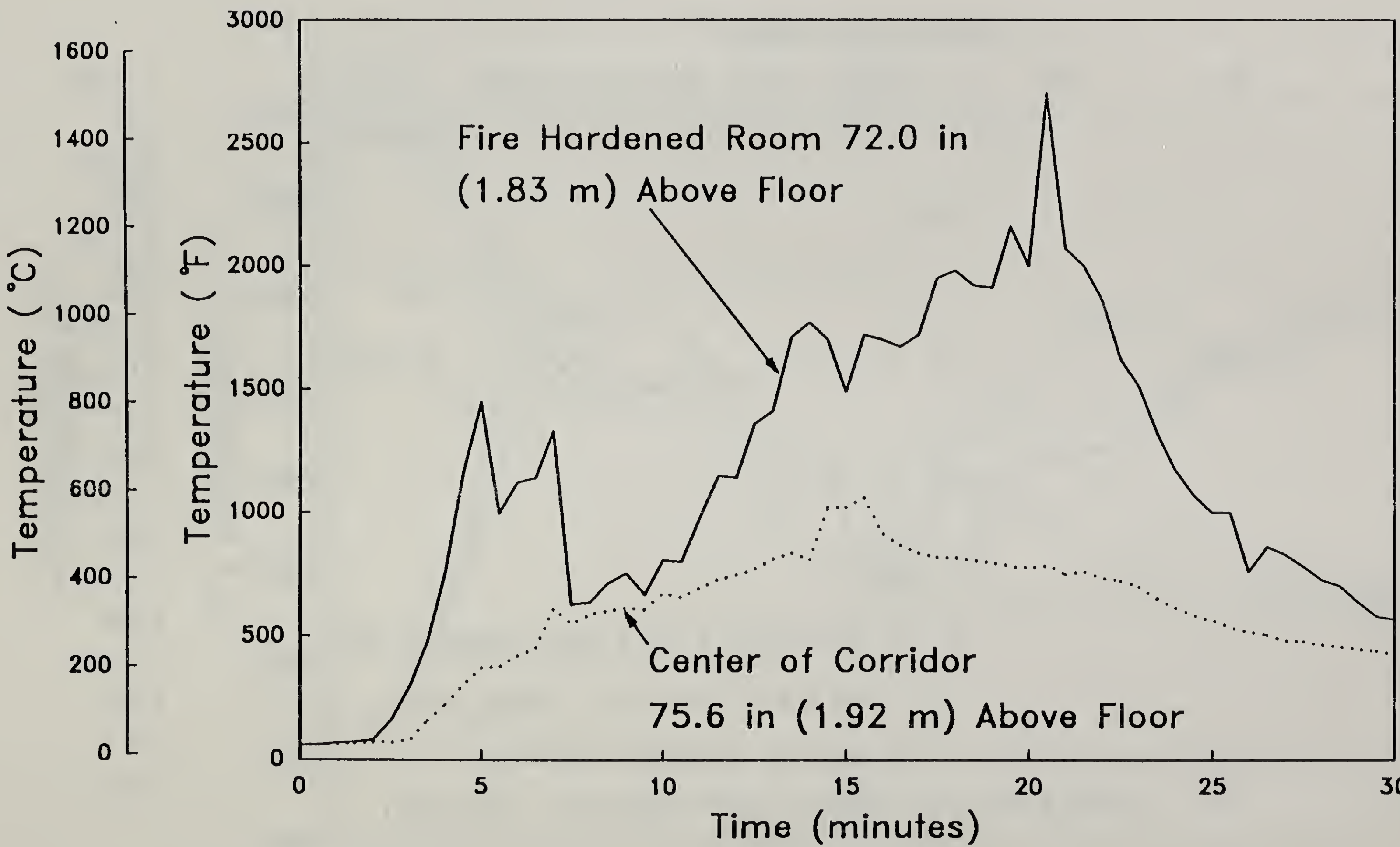

Figure 14. Burn room temperature for test 12

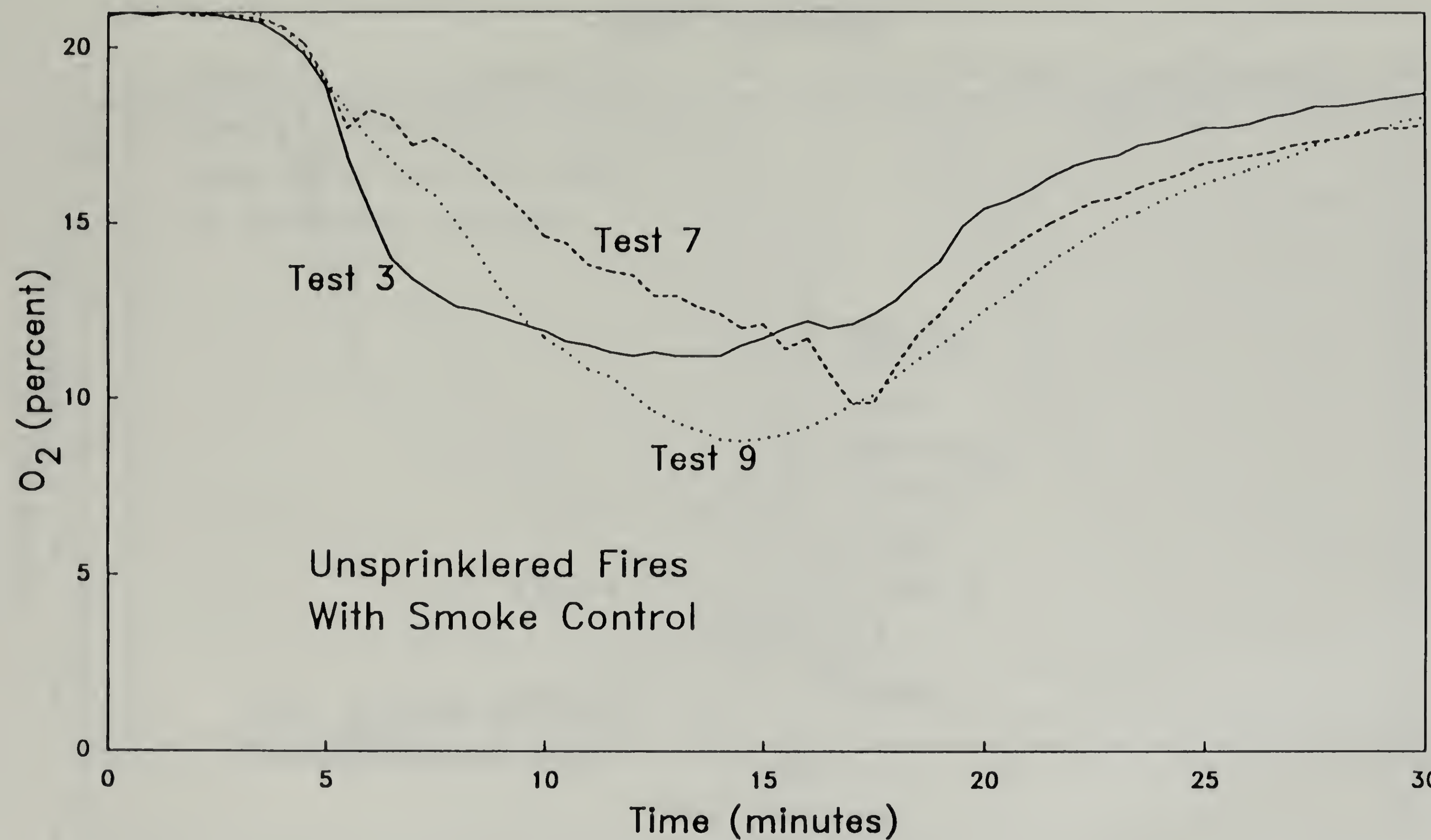

Figure 15. O_2 concentrations on the fire floor for unsprinklered fires with smoke control

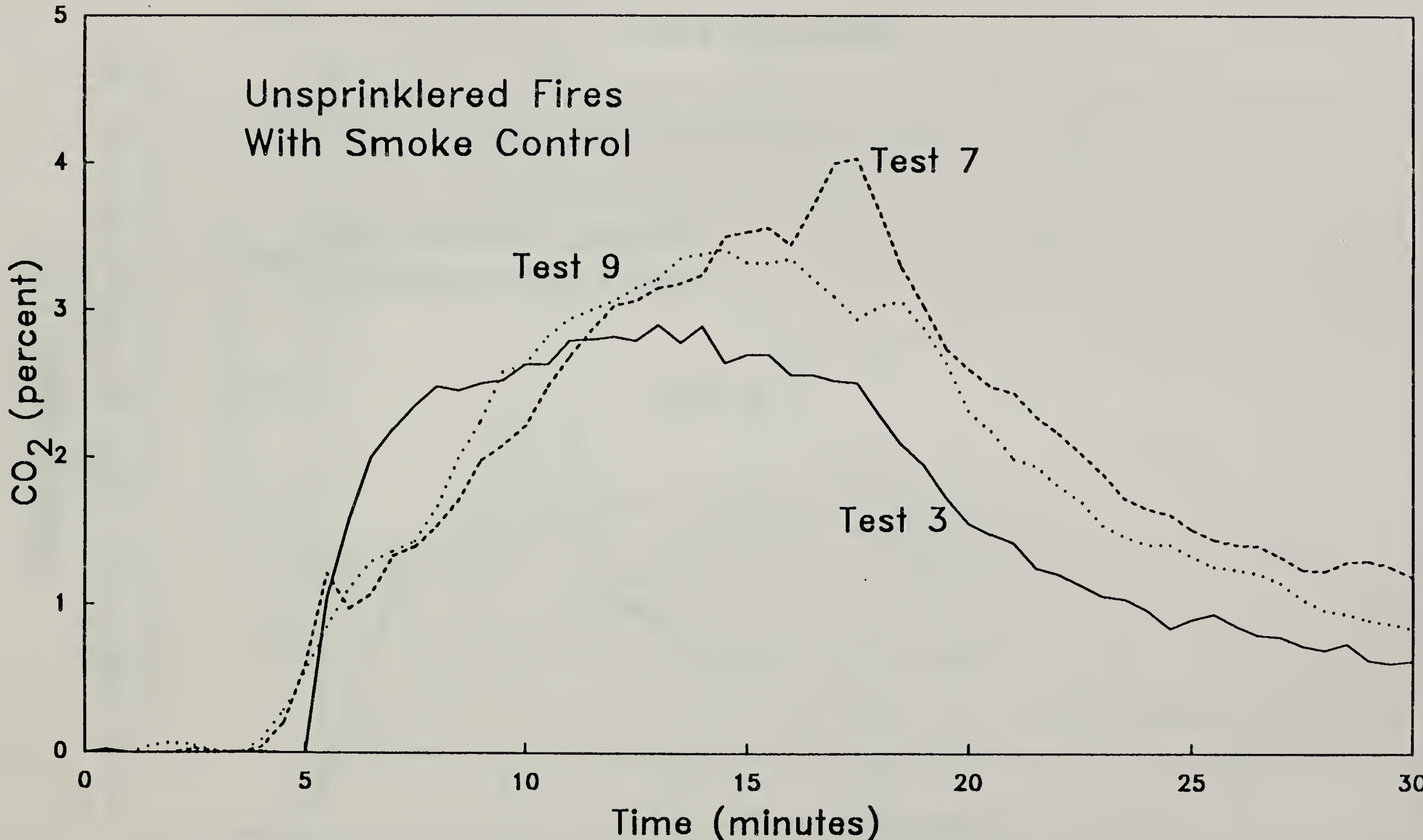

Figure 16. CO_2 concentrations on the fire floor for unsprinklered fires with smoke control

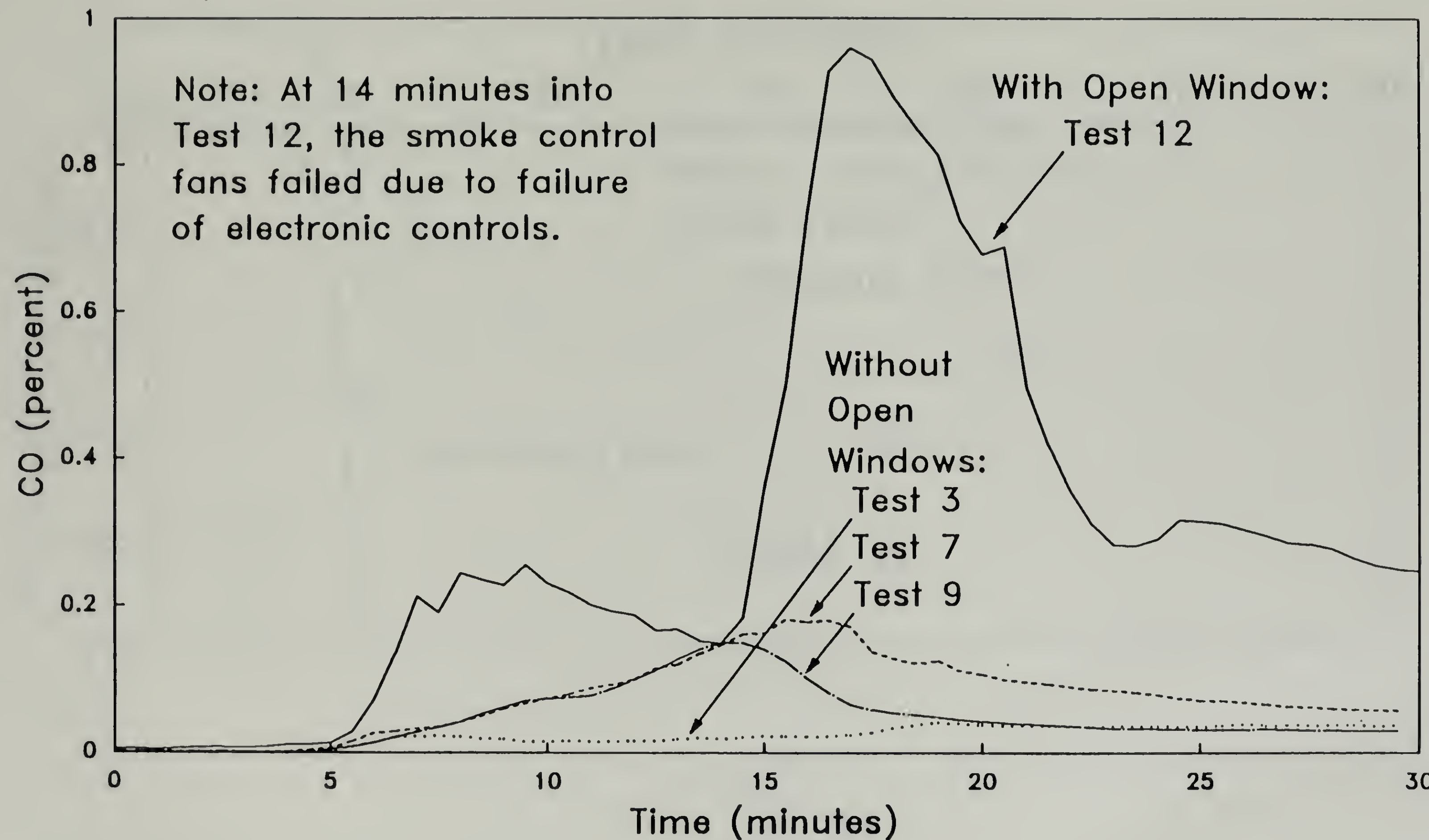

Figure 17. CO concentrations on the fire floor for unsprinklered fires with smoke control

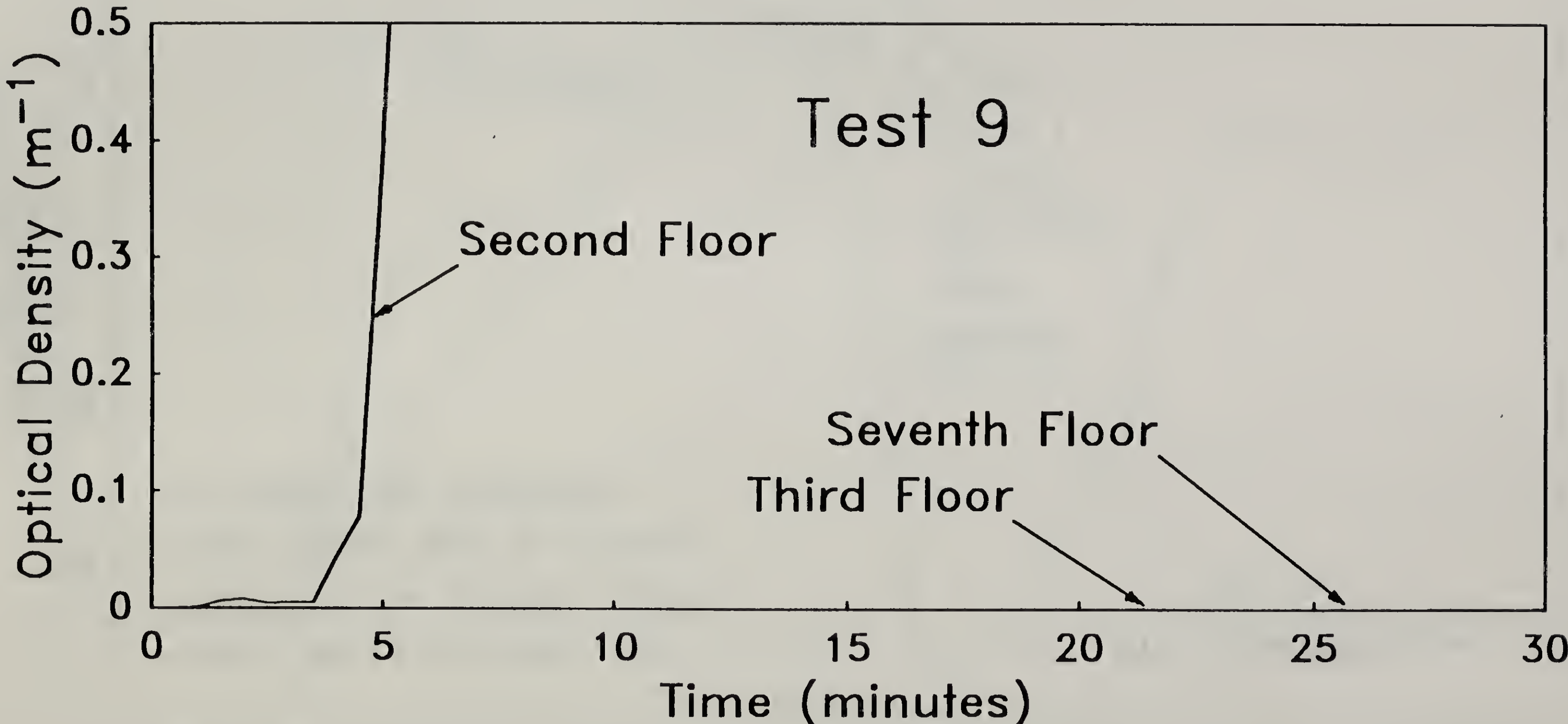

Figure 18. Smoke obscuration for unsprinklered fire test with smoke control

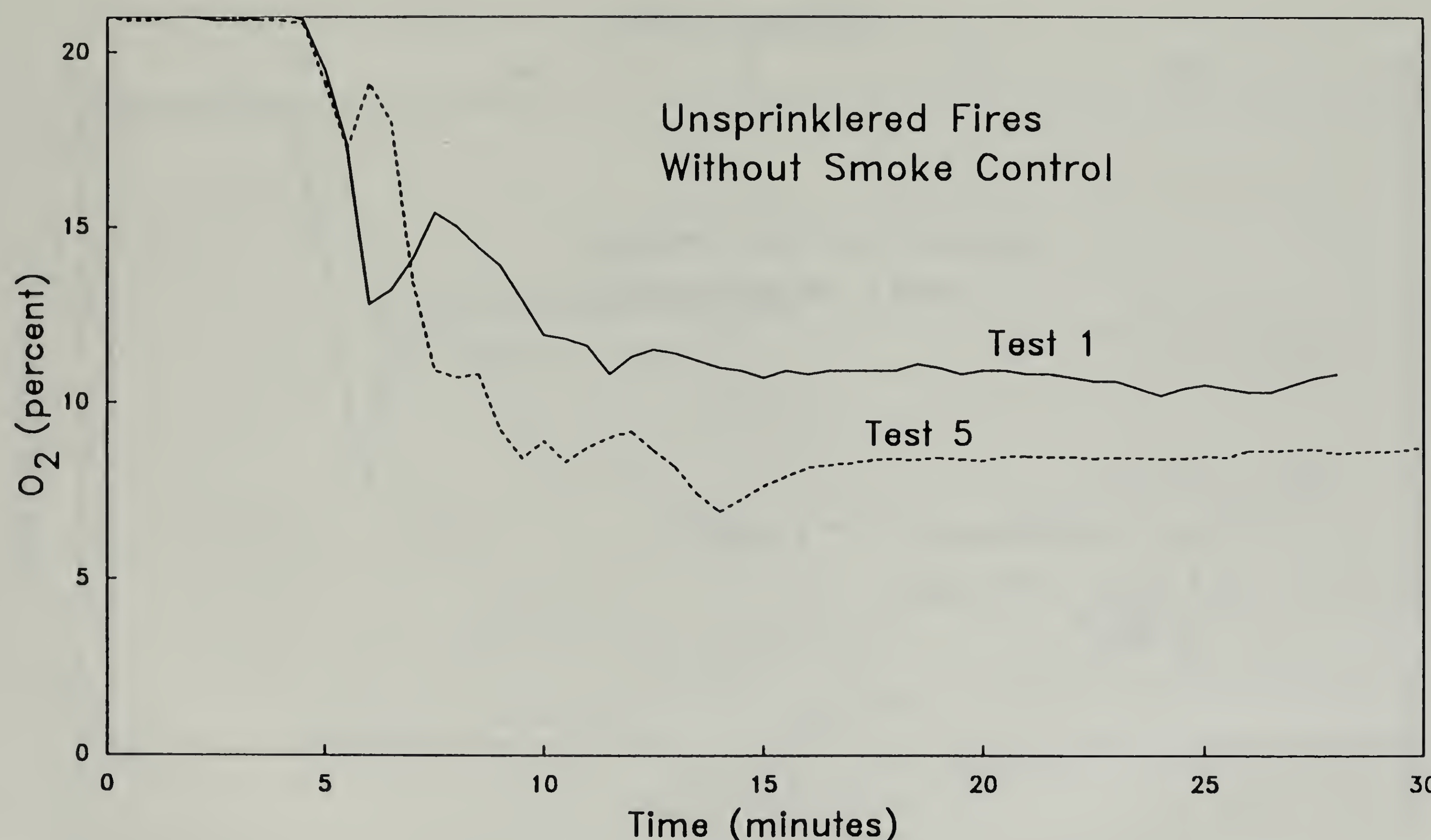

Figure 19. O_2 concentrations on the fire floor for unsprinklered fires without smoke control

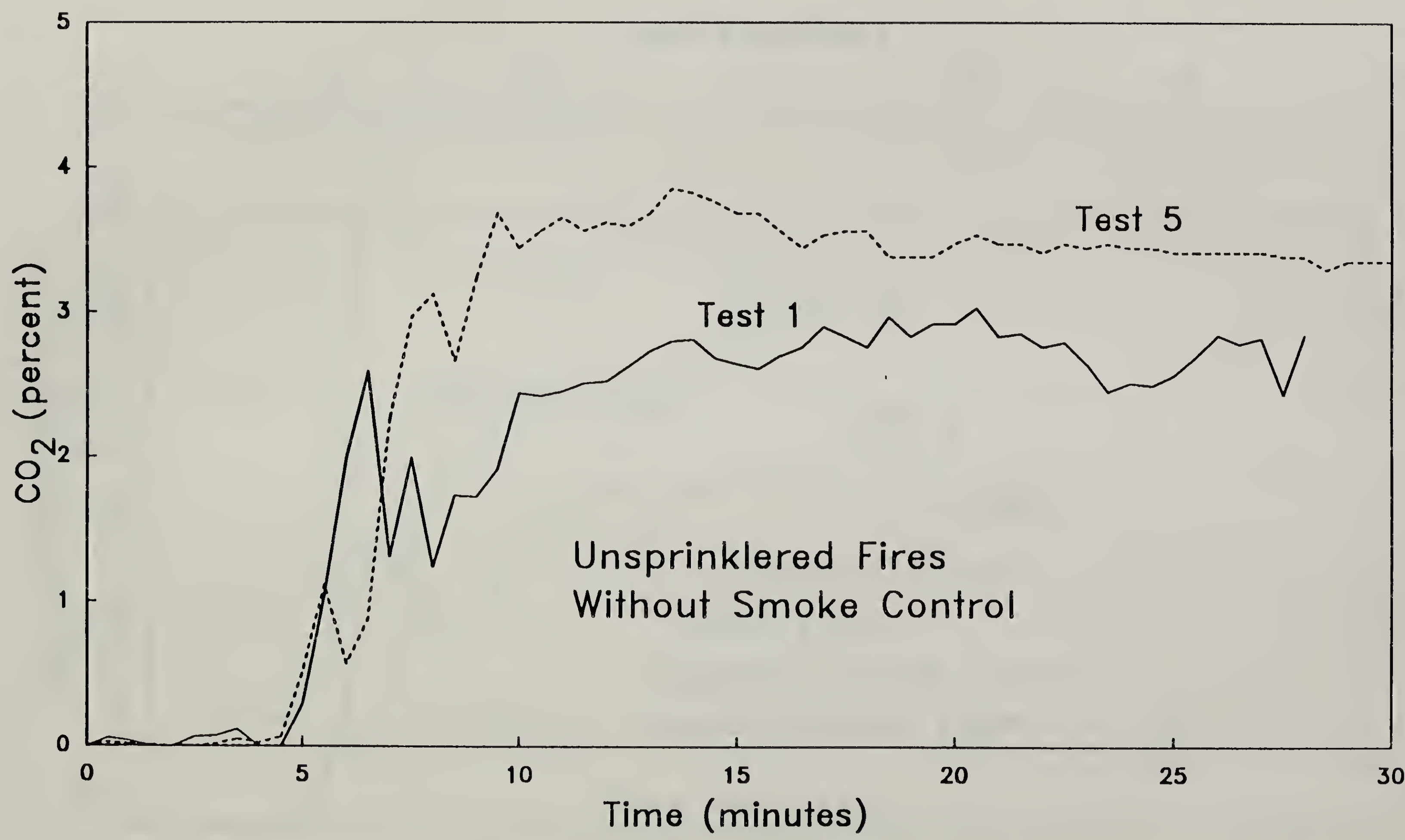

Figure 20. CO_2 concentrations on the fire floor for unsprinklered fires without smoke control

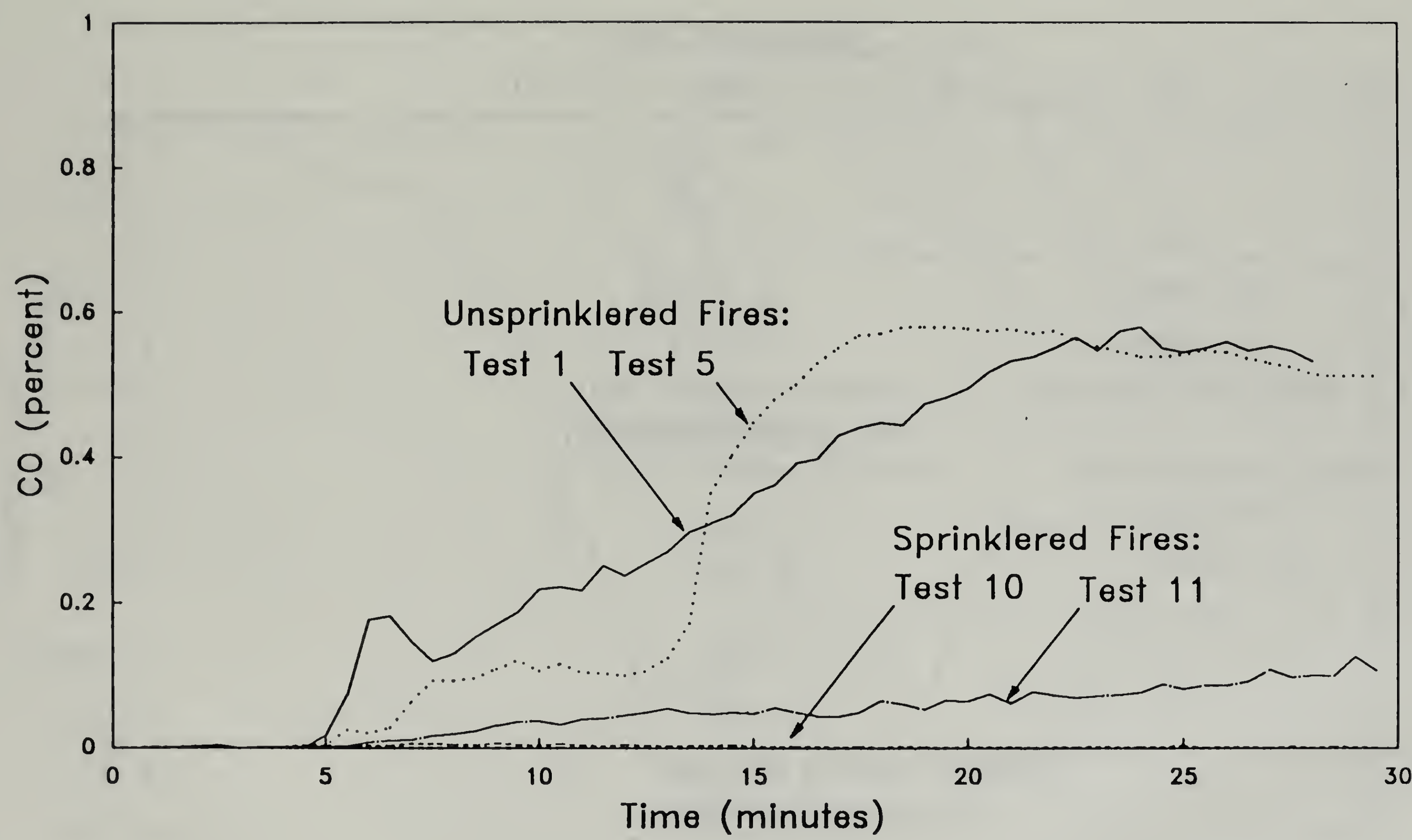

Figure 21. CO concentrations on the fire floor for unsprinklered fires without smoke control

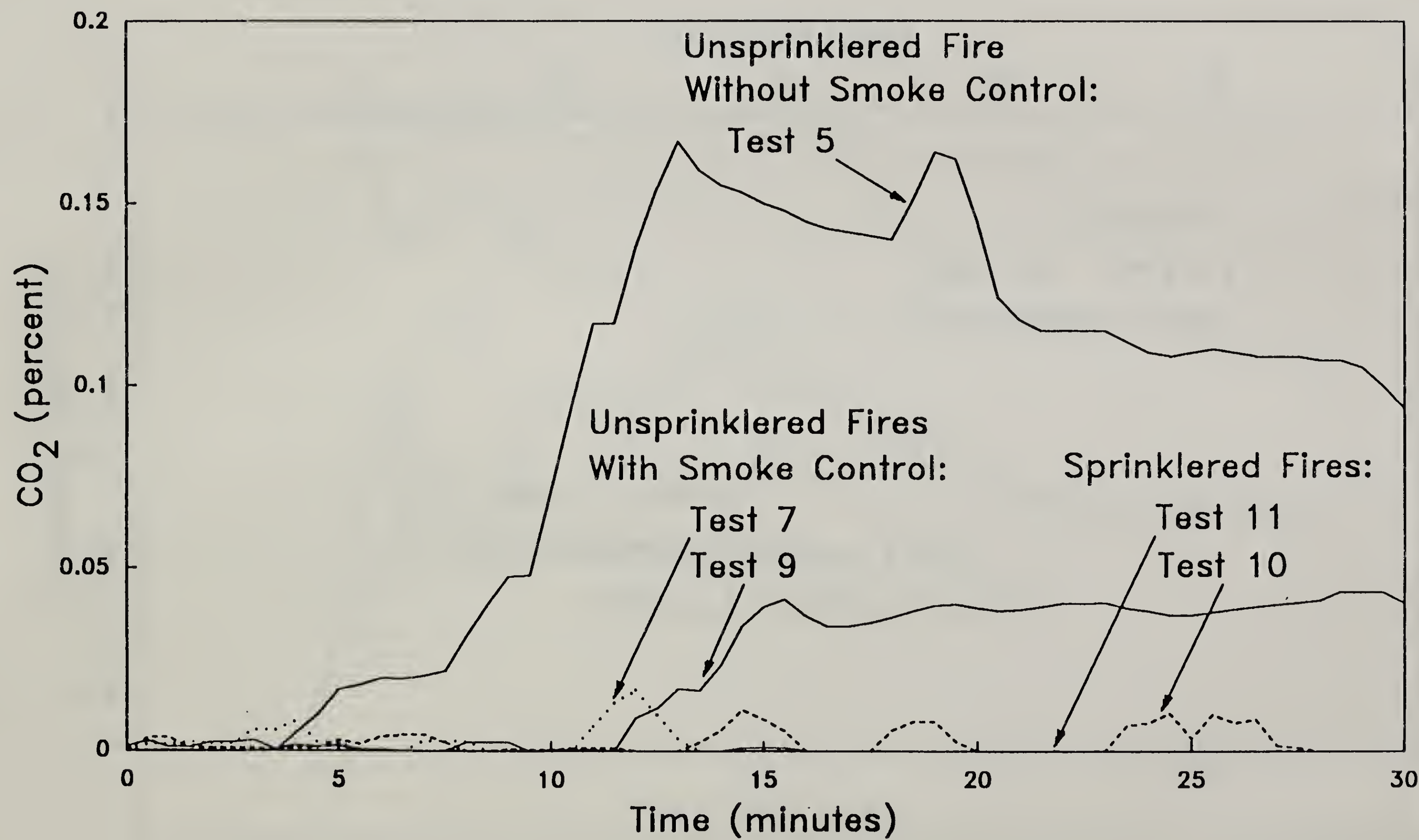

Figure 22. CO_2 concentrations on the seventh floor

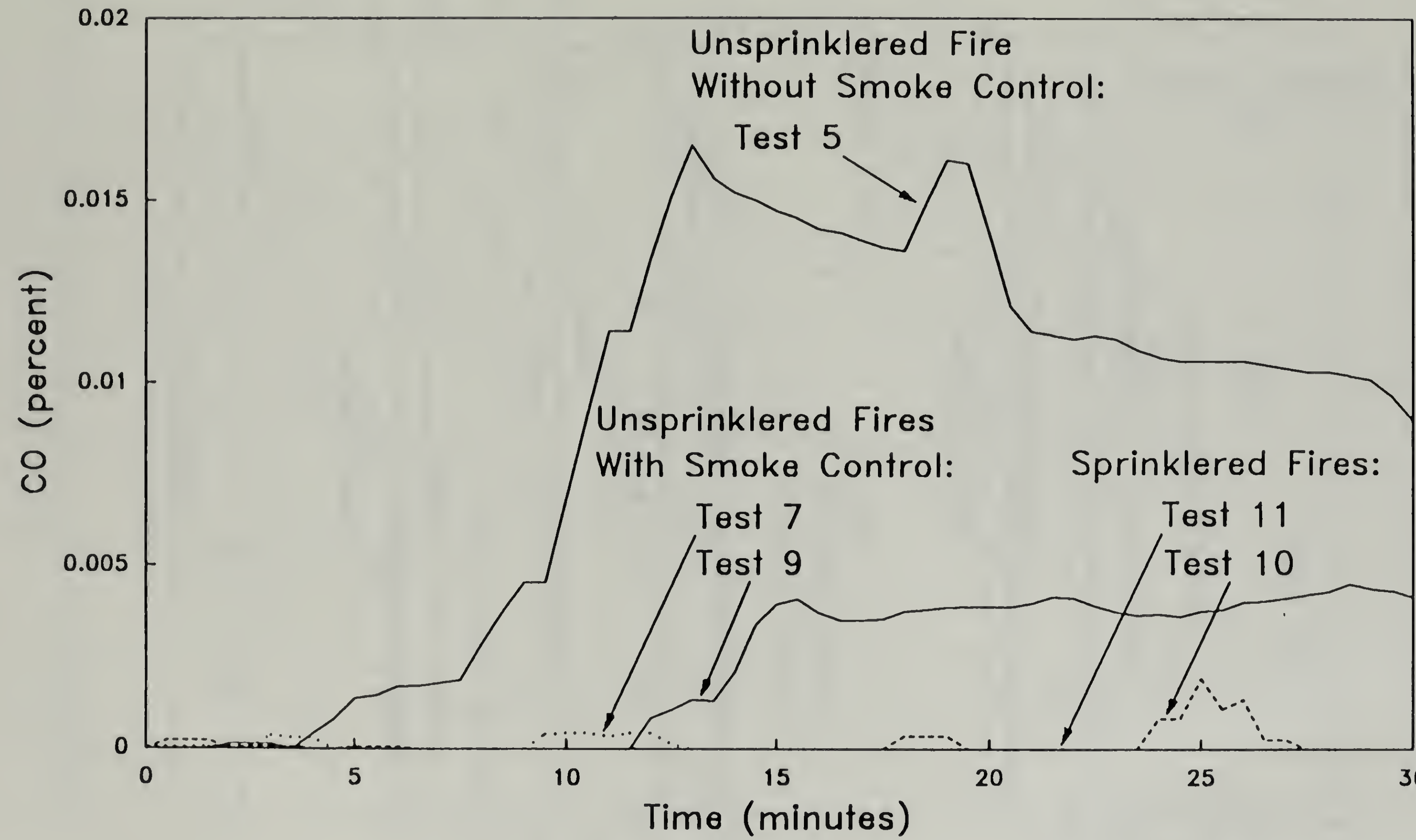

Figure 23. CO concentrations on the seventh floor

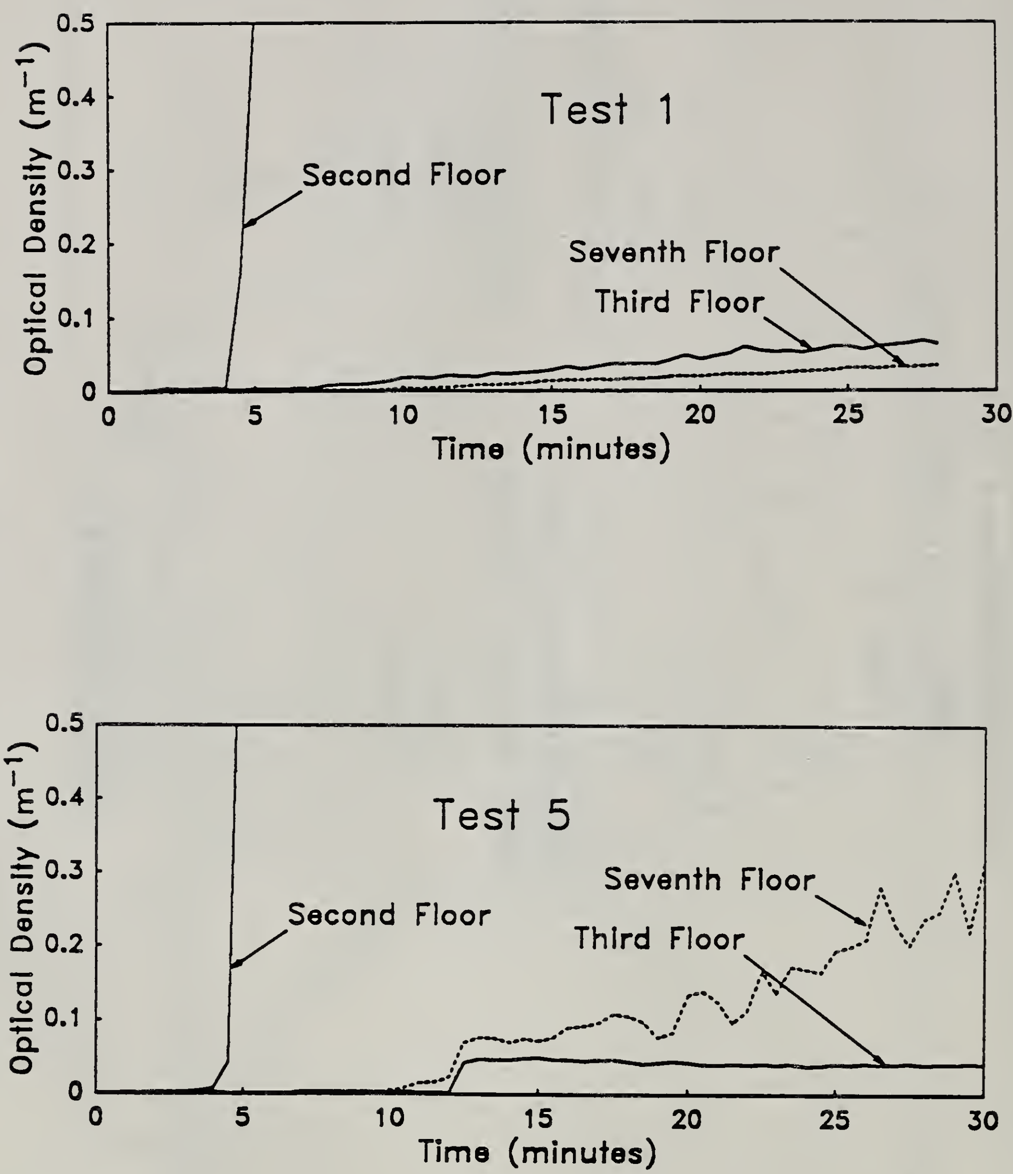

Figure 24. Smoke obscuration for unsprinklered fires without smoke control

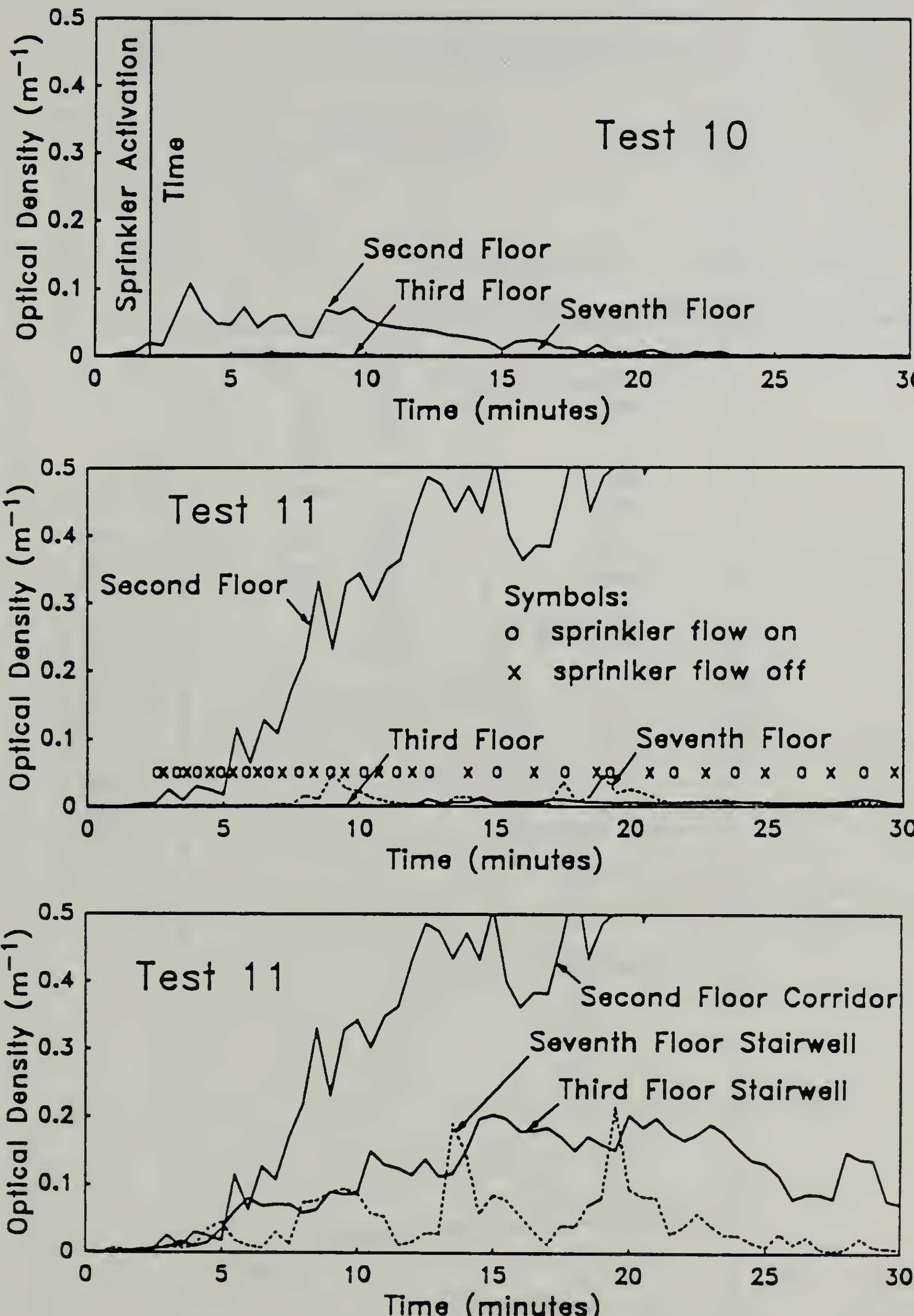

Figure 25. Smoke obscuration for sprinklered fire tests without smoke control

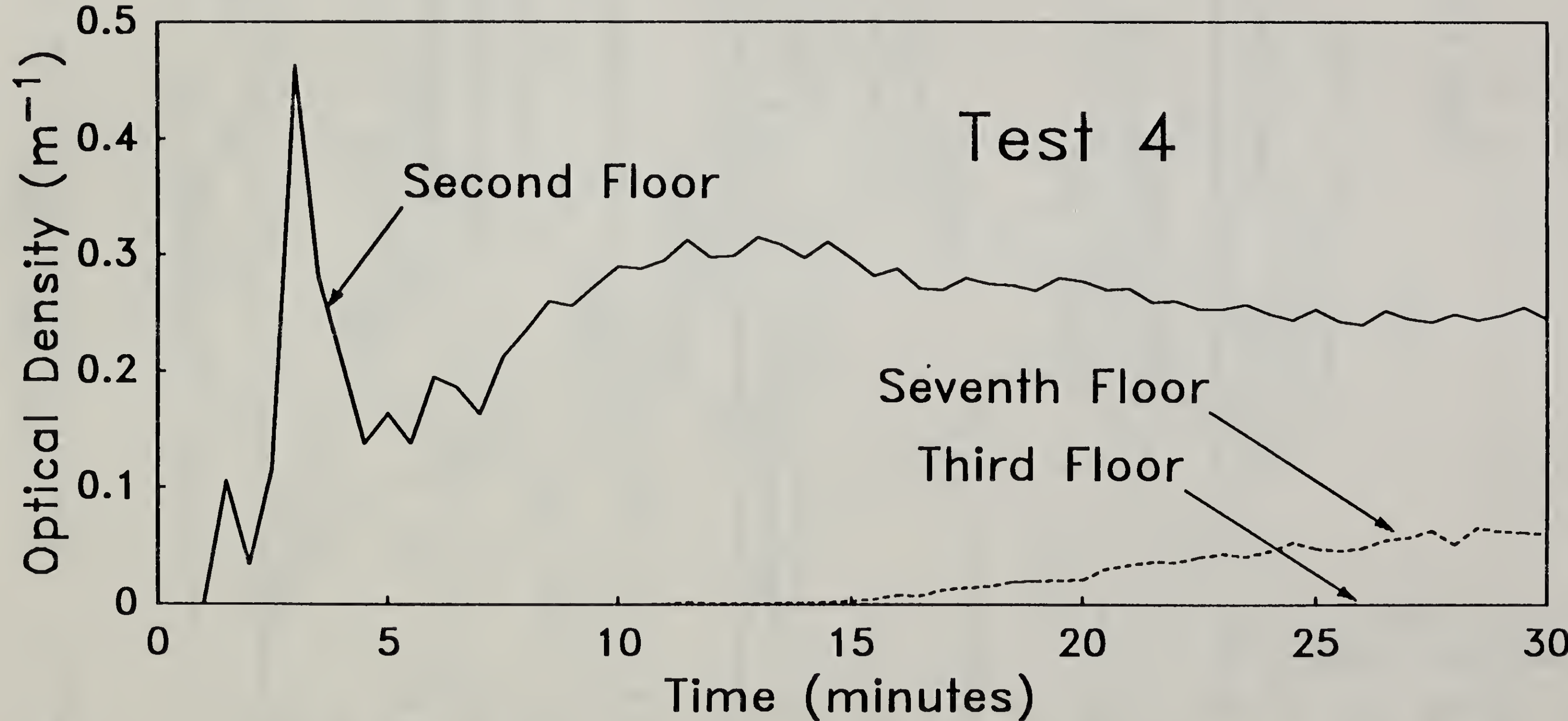

Figure 26. Smoke obscuration for smoke bomb test without smoke control

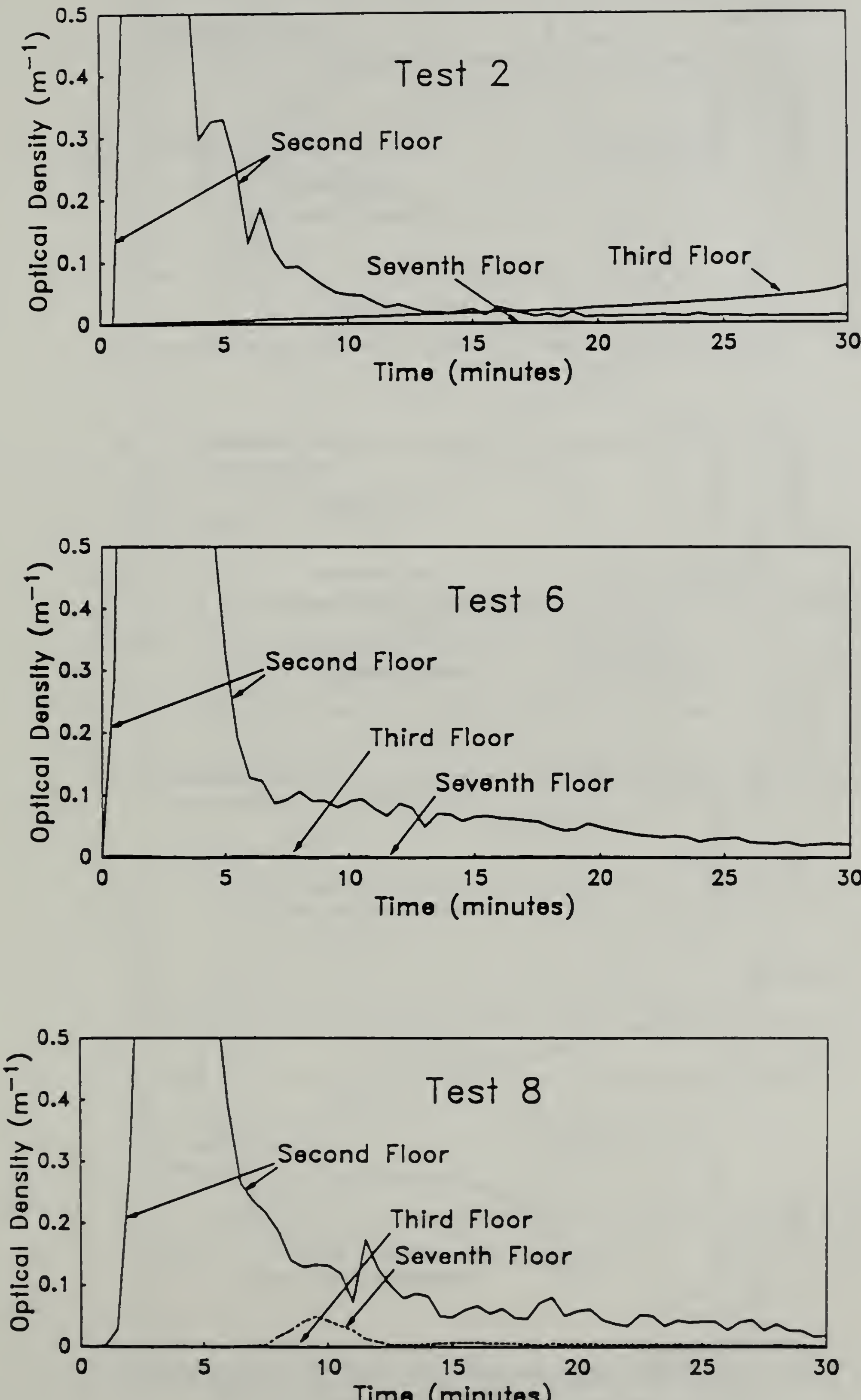

Figure 27. Smoke obscuration for smoke bomb tests with smoke control

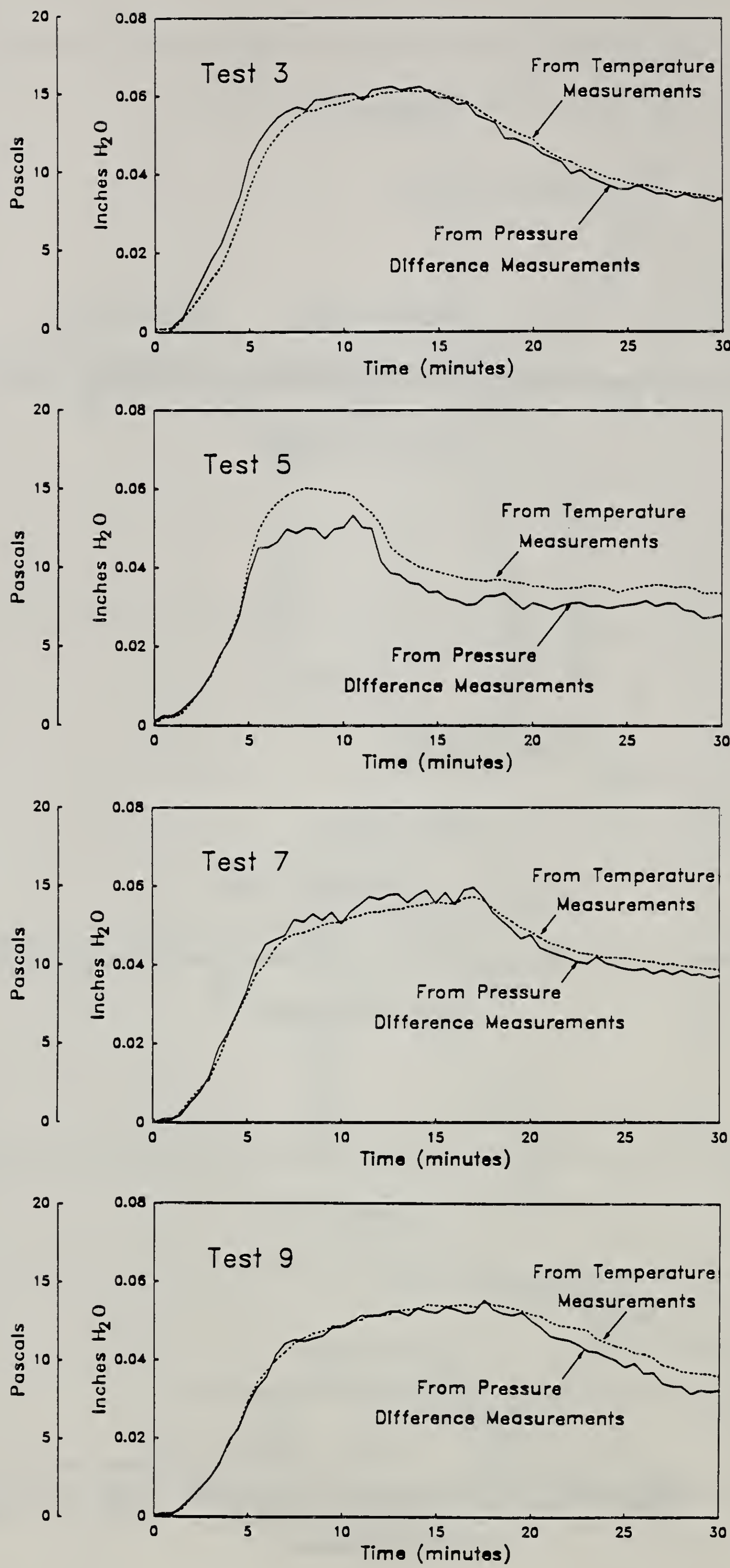

Figure 28. Comparison of Δp_o - Δp_h calculated from pressure difference measurements and from temperature measurements

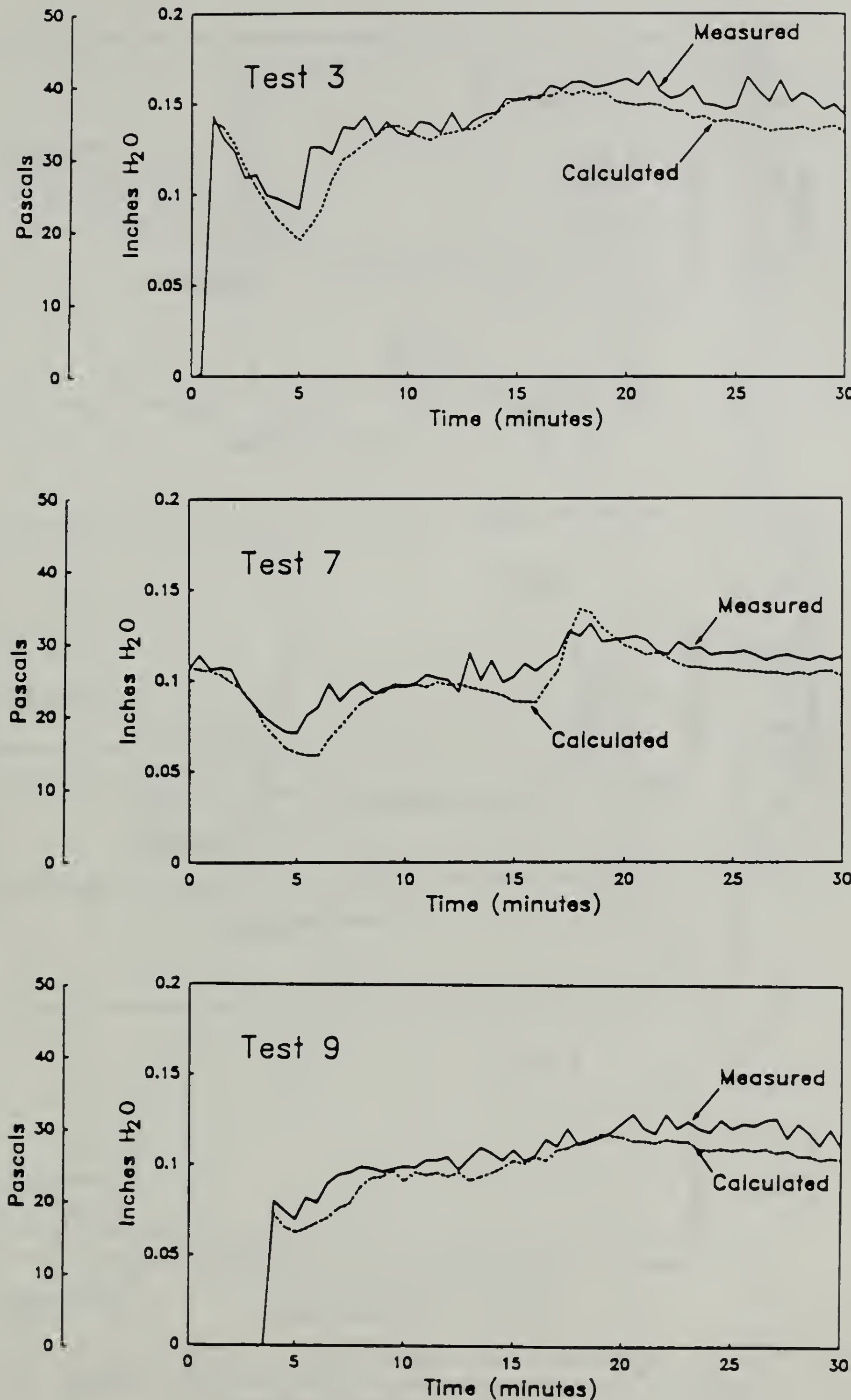

Figure 29. Comparison of measured and calculated pressure difference, Δp_o, from the stairwell to the fire floor near the floor for tests with smoke control

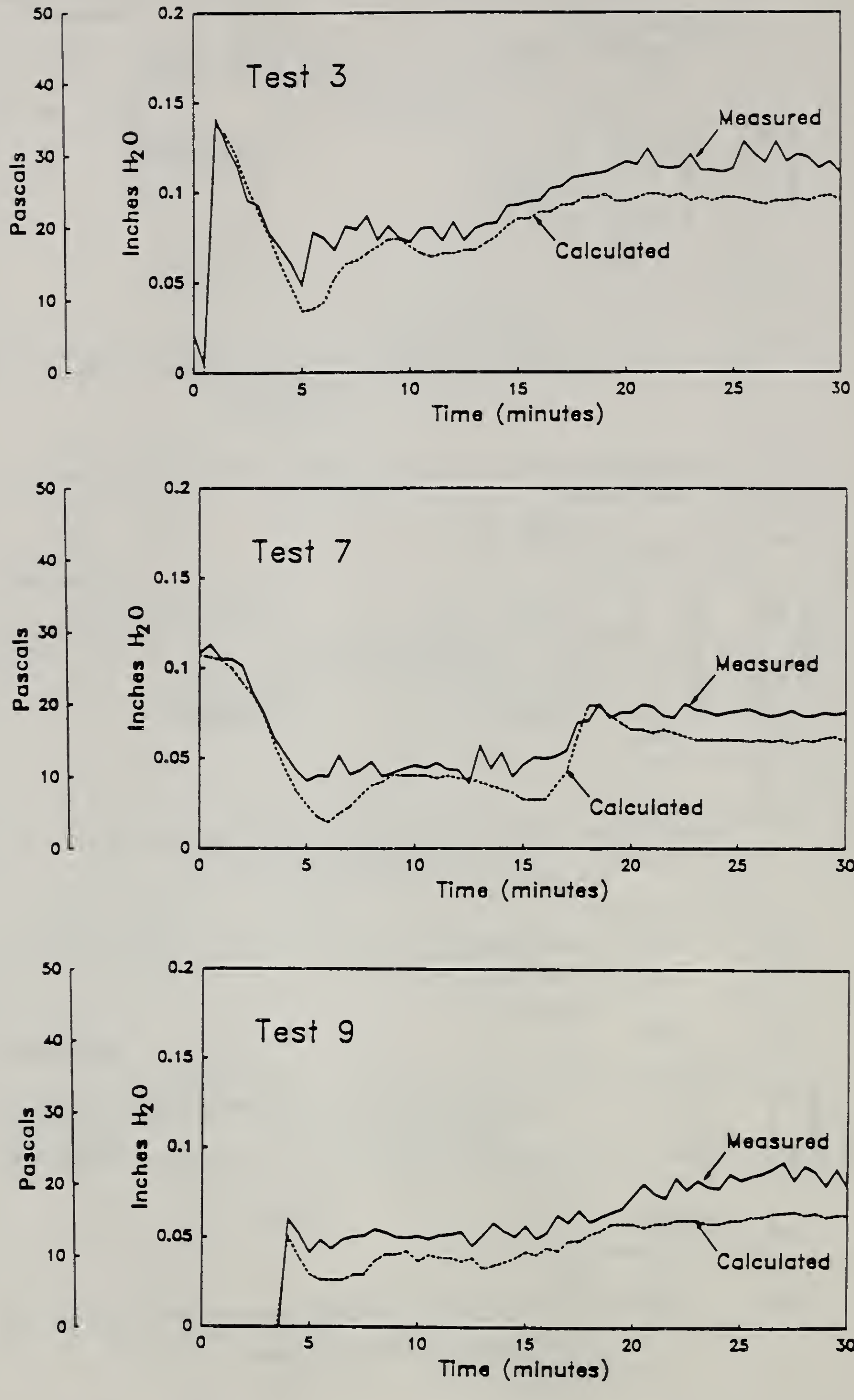

Figure 30. Comparison of measured and calculated pressure difference, Δp_h, from the stairwell to the fire floor near the ceiling for tests with smoke control

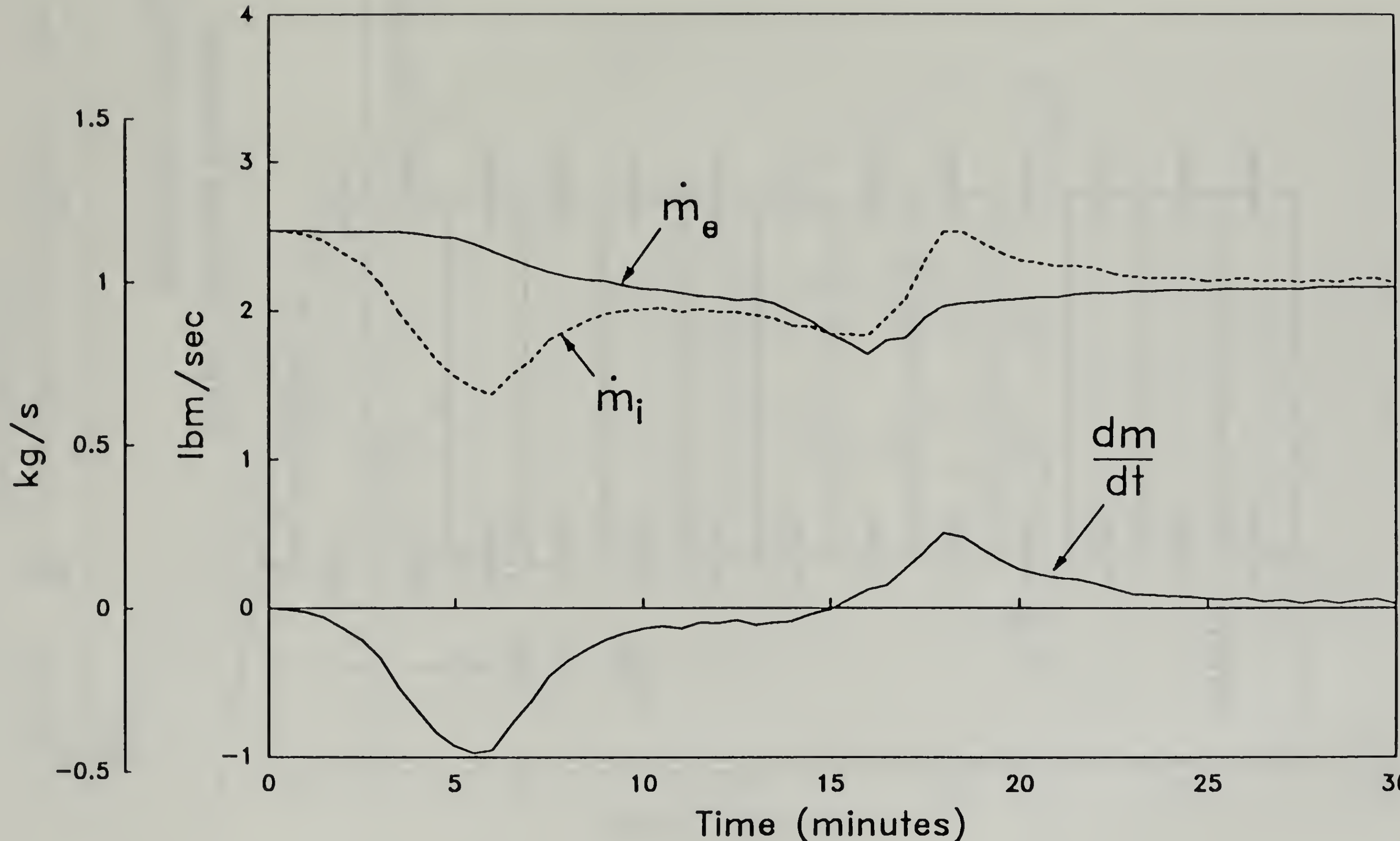

Figure 31. Graphical representation of the continuity equation for test 7

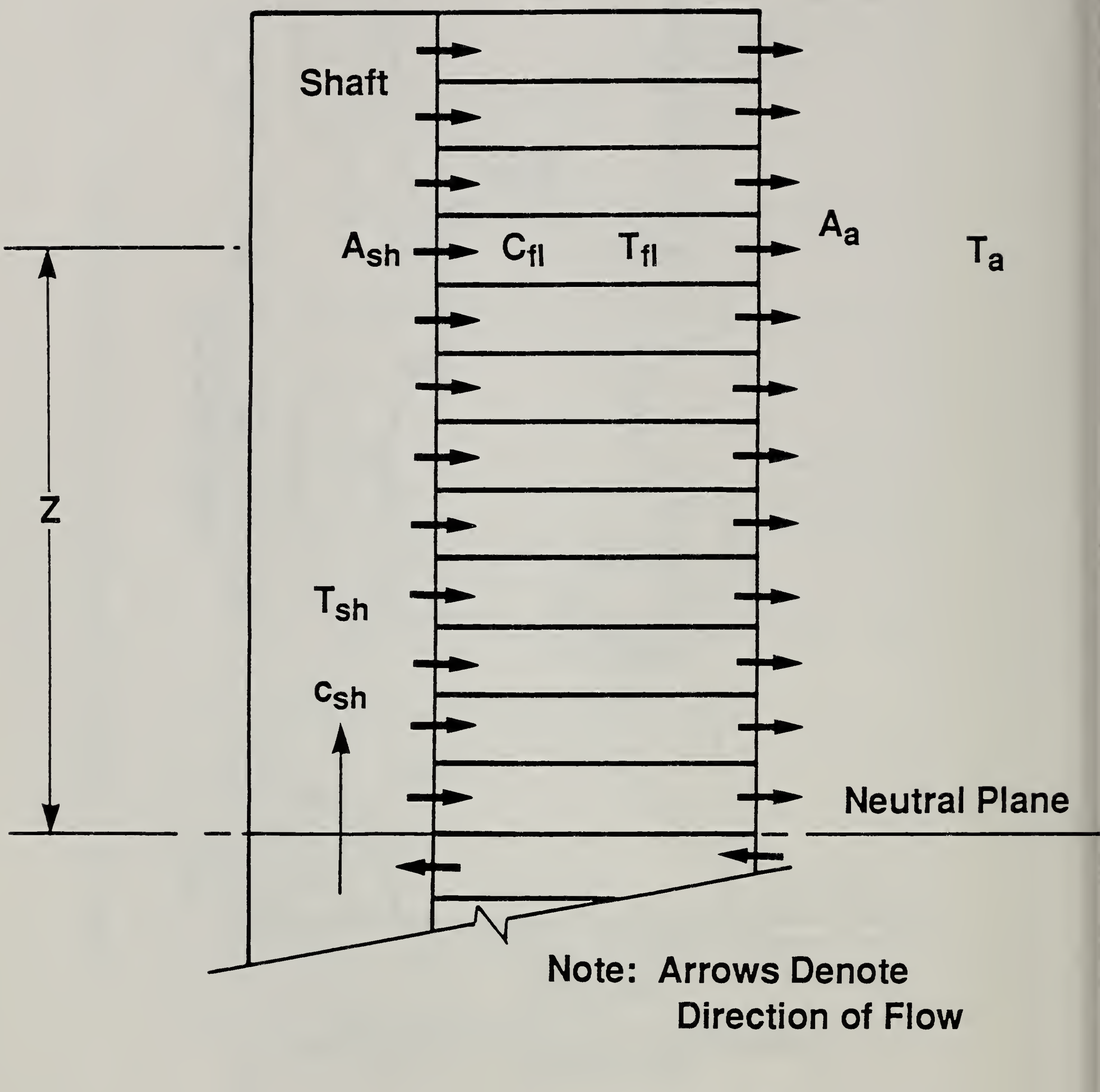

Figure 32. Flow in building above the neutral plane

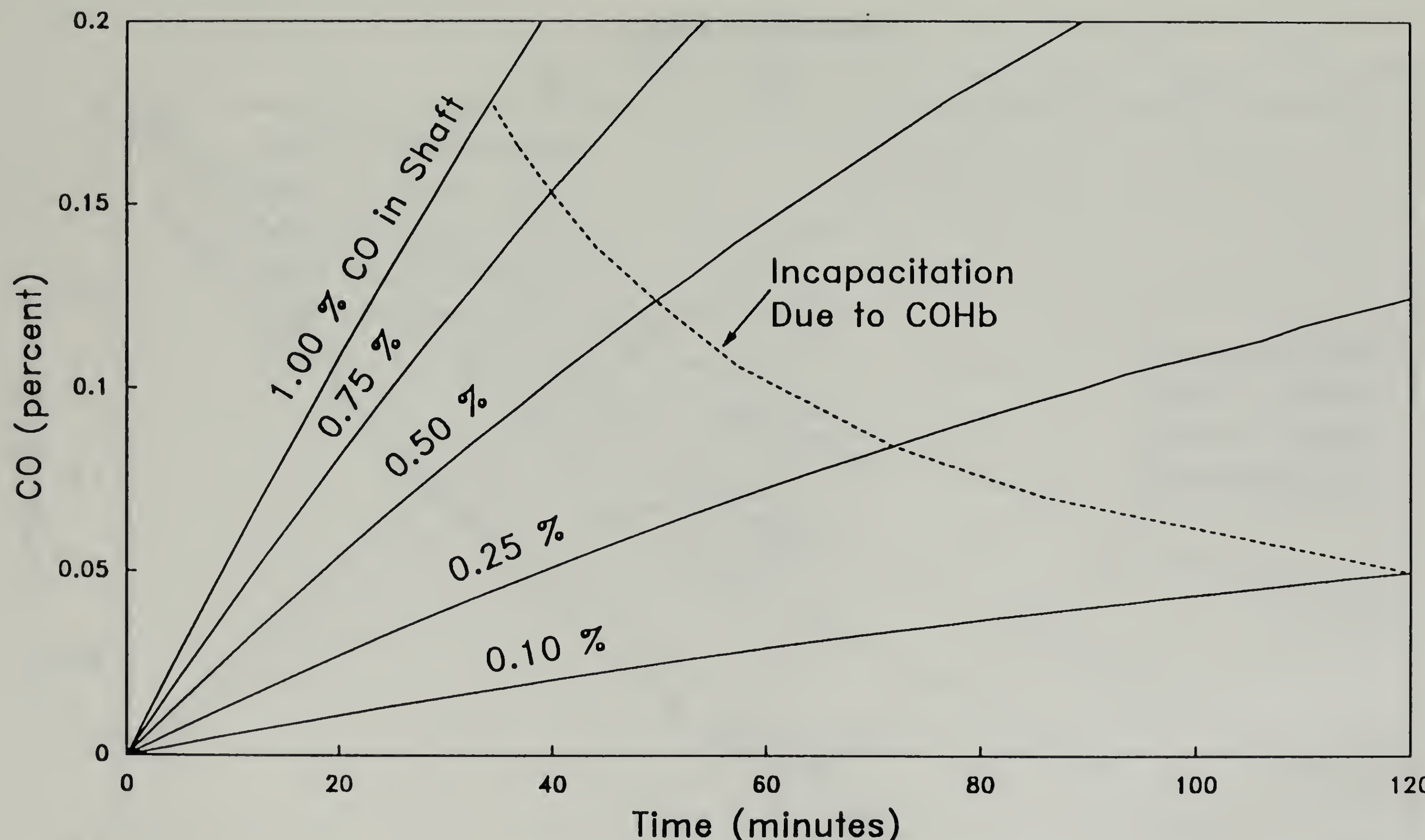

Figure 33. Calculated CO levels in building for different CO concentrations in shaft (Values of other parameters are listed in table 4.)

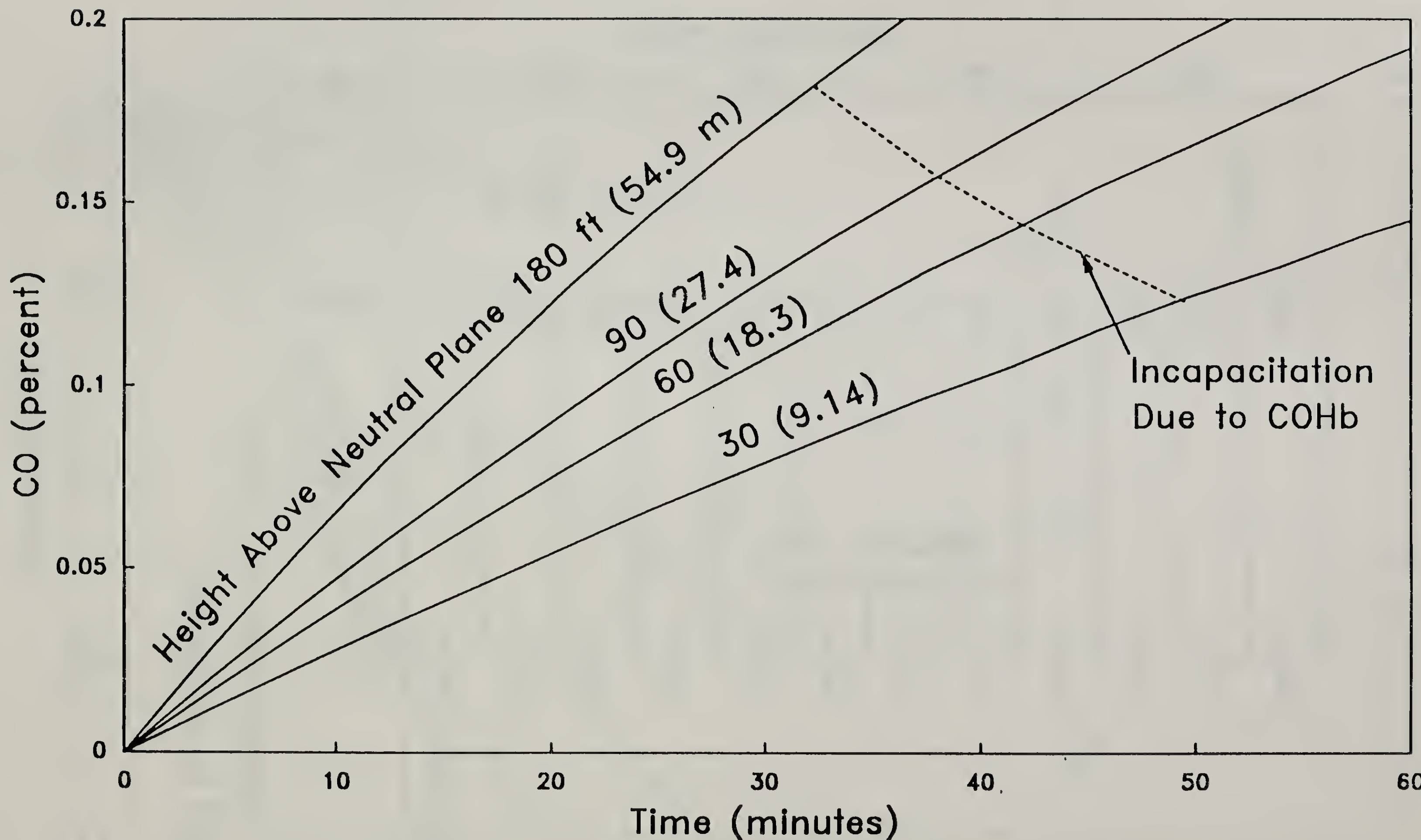

Figure 34. Calculated CO levels in building for different heights above the neutral plane (Values of other parameters are listed in table 4.)

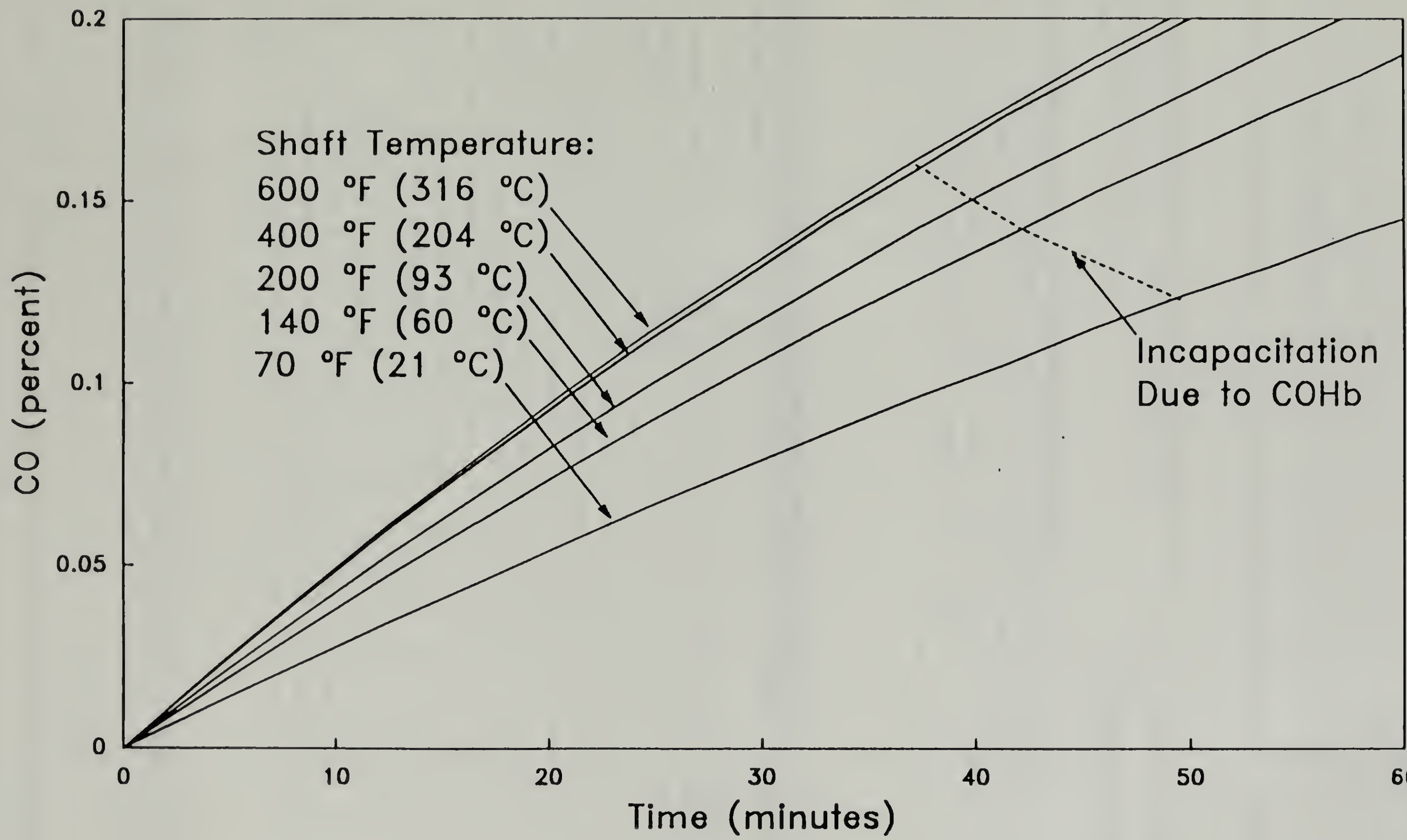

Figure 35. Calculated CO levels in building for different shaft temperatures (Values of other parameters are listed in table 4.)

NIST-114A
(REV. 3-89)

U.S. DEPARTMENT OF COMMERCE
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY

BIBLIOGRAPHIC DATA SHEET

1. PUBLICATION OR REPORT NUMBER
NISTIR 90-4253

2. PERFORMING ORGANIZATION REPORT NUMBER

3. PUBLICATION DATE
April 1990

4. TITLE AND SUBTITLE
Fire Experiments of Zoned Smoke Control at the Plaza Hotel in Washington DC

5. AUTHOR(S)
John H. Klote

6. PERFORMING ORGANIZATION (IF JOINT OR OTHER THAN NIST, SEE INSTRUCTIONS)
U.S. DEPARTMENT OF COMMERCE
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
GAITHERSBURG, MD 20899

7. CONTRACT/GRANT NUMBER

8. TYPE OF REPORT AND PERIOD COVERED

9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS (STREET, CITY, STATE, ZIP)
American Society of Heating, Regrigerating, and Air-Conditioning Engineers, Inc., Atlanta, GA 30329; Bell Atlantic Telephone Co., Arlington, VA 22201; New Jersey Bell Telephone Co., Newark, NJ 07101; U.S. Fire Administration, Emmitsburg, MD; U.S. Veterans Administration, Washington, DC 20420; US West Incorporated, Denver, CO 80202

10. SUPPLEMENTARY NOTES

☐ DOCUMENT DESCRIBES A COMPUTER PROGRAM; SF-185, FIPS SOFTWARE SUMMARY, IS ATTACHED.

11. ABSTRACT (A 200-WORD OR LESS FACTUAL SUMMARY OF MOST SIGNIFICANT INFORMATION. IF DOCUMENT INCLUDES A SIGNIFICANT BIBLIOGRAPHY OR LITERATURE SURVEY, MENTION IT HERE.)

A series of full-scale tests were conducted to evaluate the current approach to zoned smoke control systems with and without stairwell pressurization. Smoke movement and the performance of smoke control systems were studied with smoke generated from unsprinklered wood fires, sprinklered wood fires, and smoke bombs. As expected, the zoned smoke control system prevented smoke migration beyond the fire floor. The minimum pressure difference approach to achieve smoke control for zoned smoke control systems was evaluated. This minimum pressure difference approach is based on a tacit assumption of a constant mass flow rate into the zone where the fire is located. To evaluate this assumption, a model was developed for mass flow in the smoke zone. Agreement between experimental results and calculations based on the model was good. Concerns about expansion of combustion gases and fan temperatures were identified. Approaches to deal with these problems were developed. The experiments showed that chemical smoke from smoke bombs is very different from hot smoke from flaming fires. With few exceptions, smoke bombs should not be used for acceptance tests. Additional research is needed concerning smoke generation of sprinklered fires and concerning the interaction of fires and smoke control.

12. KEY WORDS (6 TO 12 ENTRIES; ALPHABETICAL ORDER; CAPITALIZE ONLY PROPER NAMES; AND SEPARATE KEY WORDS BY SEMICOLONS)
fire tests; smoke control; smoke transport; sprinklers; stack effect; stairwells

13. AVAILABILITY
- [X] UNLIMITED
- [ ] FOR OFFICIAL DISTRIBUTION. DO NOT RELEASE TO NATIONAL TECHNICAL INFORMATION SERVICE (NTIS).
- [ ] ORDER FROM SUPERINTENDENT OF DOCUMENTS, U.S. GOVERNMENT PRINTING OFFICE, WASHINGTON, DC 20402.
- [X] ORDER FROM NATIONAL TECHNICAL INFORMATION SERVICE (NTIS), SPRINGFIELD, VA 22161.

14. NUMBER OF PRINTED PAGES
75

15. PRICE
A04

ELECTRONIC FORM