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Sprinklered Mercantile Fires

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ABSTRACT

This paper presents results of a project initiated by ASHRAE and the National Research Council of Canada to investigate smoke movement resulting from a sprinklered fire in a communicating space into an adjacent large open area, such as an atrium or retail mall. As part of the joint project, a large-scale test facility was established to investigate smoke flow for sprinklered fires.

In this paper, the results of two full-scale fire test series are discussed. In the first series of tests, a propane burner system was used to simulate design fires, which have an initial unsteady stage followed by a fire with a constant heat release rate. A fast t-squared fire was used for the initial fire growth. This fire was allowed to grow to a predetermined heat release rate and subsequently maintained constant.

The second series of full-scale tests were conducted using three fire scenarios simulating typical fire load arrangements found in retail stores. The three scenarios used were as follows: paper towels in cartons, clothing stored in boxes, and children's toys.

INTRODUCTION

Protecting the occupants of a building from the adverse effects of smoke in the event of a fire is one of the primary objectives of any fire protection system design. Achieving this objective becomes more difficult when dealing with very large spaces, such as an atrium or a mall, where a large number of occupants may be present and the compartment geometries may be complex as well as very large. Because of these difficulties, model building codes place restrictions on the use of such spaces in buildings.

Frequently, in buildings with atria or malls, the communicating spaces (shops, walkways, offices, etc.) open onto the interconnected floor space. In NFPA 92B (1995), it is assumed that it will not be possible to manage smoke within the communicating space without the use of physical barriers to limit smoke movement or methods to limit smoke production, such as controlling the fuel or using automatic sprinklers. Although automatic fire suppression is frequently used to reduce smoke production from fires in a communicating space, there are limited data available on the potential size of sprinklered fires and the transport of smoke cooled by sprinklers. Data such as that produced by Liu (1977) indicate that the smoke from a sprinklered fire may not be buoyant. There are also indications that a sprinklered fire can produce sufficient smoke to result in obscurations that exceed normally accepted tenability limits in the compartment of fire origin (Lougheed 1997).

In 1997, a joint research project (ASHRAE Research Project RP-976) was initiated between the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (ASHRAE), and the National Research Council of Canada (NRC). The objective of this project was to investigate the impact of smoke from a sprinklered fire in a compartment, which is allowed to propagate into a large open area.

Preliminary results of the project were provided in an earlier paper (Lougheed et al. 2000). This paper provided a review of research on the interaction of sprinkler spray with a smoke layer, heat release rate from sprinklered fires, and smoke movement for sprinklered fires. Also, based on tests using steady-state propane fires, approximate heat release rate limits were determined that hot smoke flow was predominant for tests with two and four operating sprinklers.

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In this paper, the results of two full-scale fire test series are provided. In the first series of tests, a propane burner system was used to simulate design fires, which have an initial unsteady stage followed by a stage with a steady heat release rate. A fast t-squared fire was used for the initial fire growth. This fire was allowed to grow to a predetermined heat release rate and subsequently maintained constant.

The second series of full-scale tests were conducted using three fire scenarios simulating typical fire loads found in retail stores. The three scenarios used were as follows: paper towels in cartons, clothing stored in boxes, and children's toys.

The full-scale fire tests were used to investigate sprinkler activation in the test compartment and smoke accumulation in a secondary space representing an atrium or mall. The retail fire scenarios were used to determine the conditions in which nonbuoyant smoke flow would occur. Also, various smoke parameters, including smoke obscuration and CO and CO₂ concentrations, were measured in the secondary space to provide data for hazard analysis.

TEST FACILITY

A large-scale test facility was set up to investigate the impact of sprinklers on smoke movement from a compartment into a large adjacent area. This facility was used in the preliminary tests with propane-fueled fires to determine the parameters that affect the smoke temperature (Lougheed et al. 2000). This test made use of a large-scale atrium physical model used for a previous joint project between ASHRAE and NRC (ASHRAE Research Project RP-899). Detailed information

on the atrium physical model is provided in the paper by Lougheed et al. (1999). For this project, a test compartment was constructed inside the atrium facility. A plan and elevation view of the test compartment and the atrium test facility are shown in Figures 1 and 2, respectively. A detailed description of the test facility is provided in the paper by Lougheed et al. (2000).

Thermocouple trees were located in the test compartment and the atrium facility. The locations of the thermocouple trees in the atrium facility are shown in Figures 1 and 2.

Three thermocouple trees were installed in the opening in the compartment (Figure 3). These thermocouple trees were located at the 1/4 width, center, and 3/4 width of the opening. In addition, two thermocouple trees, with six thermocouples on each tree, were located inside the test compartment (Figure 3). Detailed information on the location and spacing of the thermocouples is provided in an earlier publication (Lougheed et al. 2000).

In addition to the room and opening thermocouple trees, thermocouples were also installed adjacent to each of the four sprinklers in the test compartment.

Two smoke meters were located in the atrium facility near the compartment opening (Figures 1 and 2). These smoke meters were located 3.3 m from the test compartment at the centerline of the opening and were 1.7 m and 3.7 m above the floor of the main test facility. They were used to determine if the smoke exiting the test compartment was nonbuoyant, resulting in downward smoke flow.

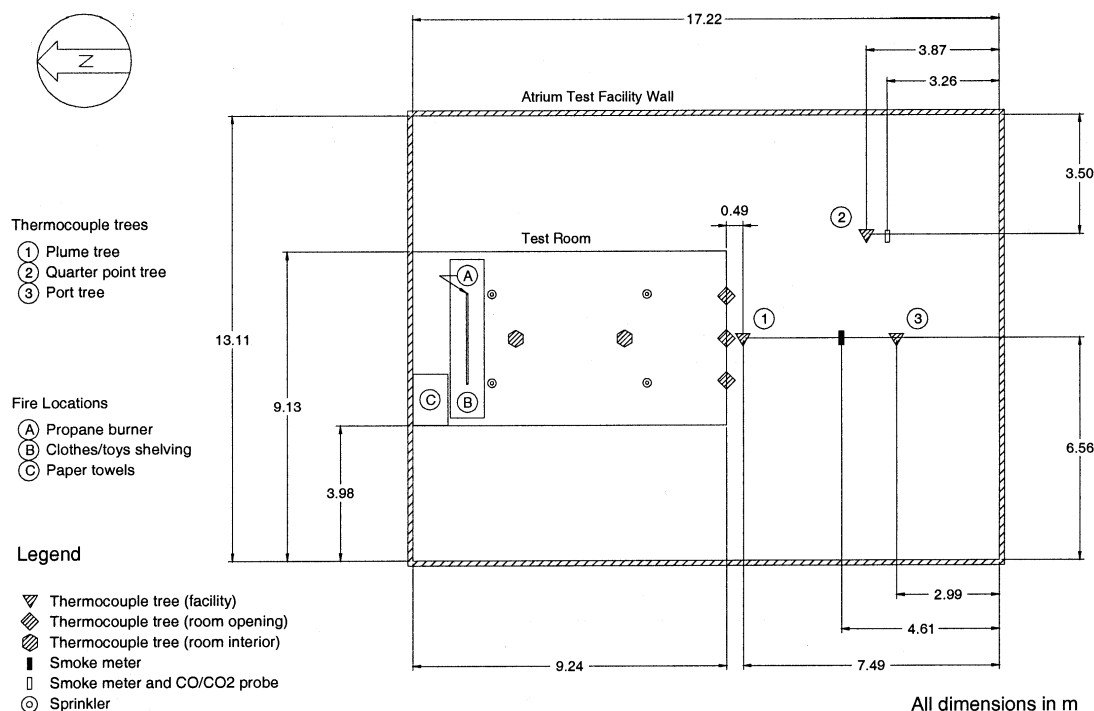


Figure 1 Large-scale atrium facility and instrumentation (plan).

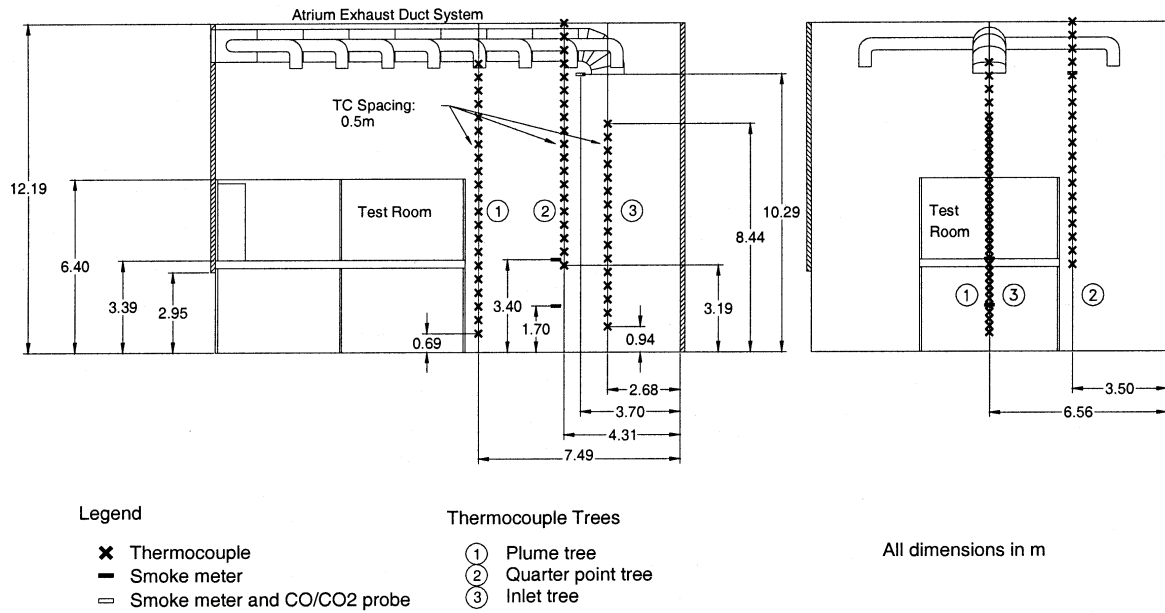


Figure 2 Large-scale atrium facility and instrumentation (elevation).

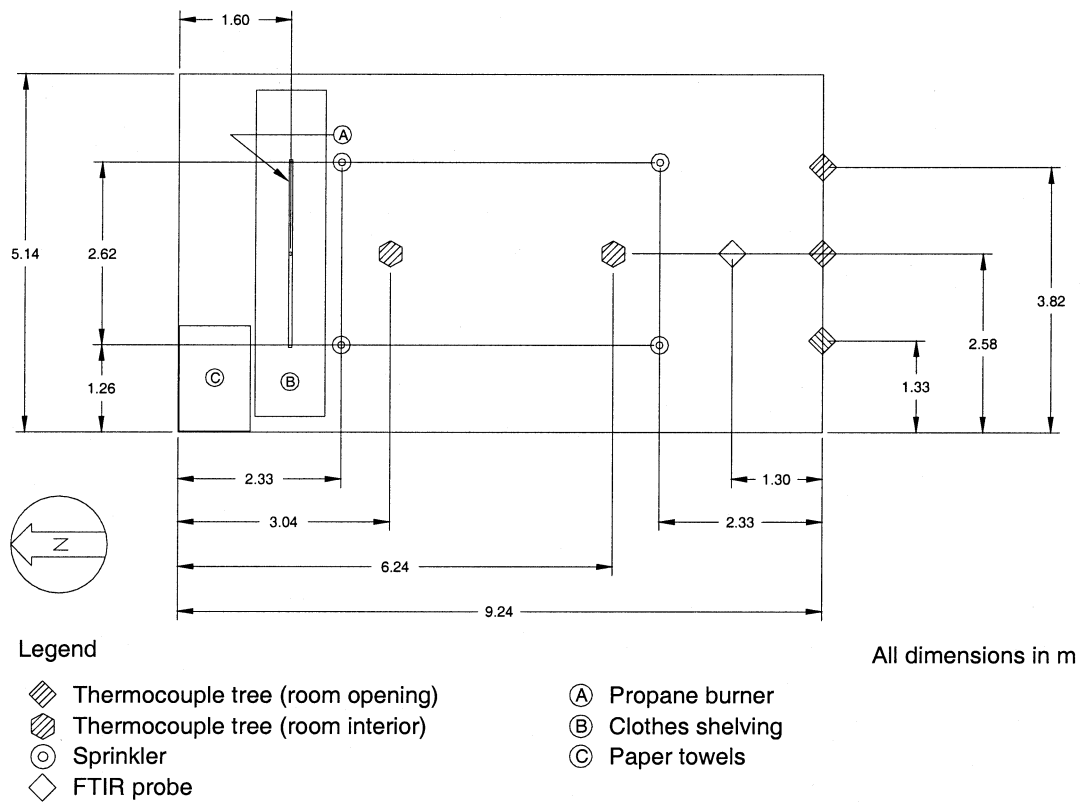


Figure 3 Test room and instrumentation (plan).

For all tests with the mechanical exhaust system operating, O₂, CO, and CO₂ concentrations were measured in the exhaust duct. These measurements, combined with temperature and pressure measurements, were used to determine the heat release rate using the oxygen depletion method.

For the mercantile fire tests, the smoke optical density and CO and CO₂ concentrations were measured near the ceiling of the atrium test facility. The measurement location was at the quarter-point thermocouple tree shown in Figure 1 and was 10.3 m above the floor of the test facility (Figures 1 and 2).

In addition, an FTIR spectrometer was used to provide gas analysis for the mercantile test scenarios. The gas sampling for these measurements varied depending on the test. In the initial tests, the gas was sampled from the exhaust duct at the same location as the gases sampled for the heat release rate measurements. In later tests, the gas sample was extracted from the smoke flow in the upper portion of the test compartment (see Figure 3). The results of these measurements will be provided in a subsequent paper.

Two video cameras were located in the atrium facility (Figures 1 and 2). One camera was on the south wall viewing the fire inside the test compartment. The second camera was mounted on the east wall at the same height as the top of the compartment opening and was used to obtain video records of the smoke plume as it exited the test compartment. Video records were also taken of smoke conditions at floor level.

SPRINKLER SYSTEM

A sprinkler system with four pendent sprinklers was installed in the test compartment. The location of the sprinklers is shown in Figure 3. The protection area for each sprinkler was 12 m² to simulate a sprinkler system in an ordinary hazard occupancy. The distance between the two branch lines was 2.6 m, which is the maximum spacing allowed for an ordinary hazard occupancy. The sprinkler spacing on each branch line was 4.6 m. The sprinklers were 2.3 m from the back wall of the test compartment and 1.3 m from the side wall.

Tests were conducted with two water flow rates selected to provide an application density of 6.1 and 8.1 (L/min)/m², which covers the design range in NFPA 13 (1996) for ordinary hazard occupancies. A pressure gauge was installed in the main sprinkler pipe and was used to monitor the water flow rate during a test. Standard sprinklers with an operating temperature of 74°C were used for all the tests. Standard sprinklers were used to provide a worst case situation in terms of sprinkler activation and, thus, the impact of sprinkler suppression on the initial fire development.

FULL-SCALE FIRE TESTS

As discussed in the previous section, the results of the preliminary tests with the propane-fueled burner determined the heat release rates above which the smoke exiting the compartment would be buoyant. The boundary between buoyant and nonbuoyant flow was dependent on fire location and the sprinkler application density. The results are summarized in Table 1.

TABLE 1
Heat Release Rate Limits for Smoke Flow Regimes

Sprinkler Application Density ((L/min)/m ²)	Burner Location in Test Compartment	Upper Limit Cold Smoke Regime (kW)	Lower Limit Two-Zone Regime (kW)
4.1	Middle	<150	150
4.1	Back	<150	300
6.1	Middle	200	750
6.1	Back	300	750
8.1	Middle	500	750
8.1	Back	800	1000

The preliminary tests also determined the heat release rate above which more than four sprinklers would be expected to activate. The limits within which further sprinklers might operate in the test configuration ranged from approximately 1500 kW for the low sprinkler application density to approximately 2500 kW for the high sprinkler application density.

In this paper, the results of two full-scale fire test series are discussed. The fire loads for these tests were scaled to produce heat release rates in the range determined in the preliminary test series, that is, maximum heat release rates of up to approximately 2500 kW. The setups for these two test series are described in the following sections.

Combination of Unsteady and Steady Fires

For engineering purposes, it is frequently assumed that a fire will grow until it is limited by either fire control activities or the separation distance between neighboring combustibles prevents further fire spread. A t-squared profile is often assumed for the unsteady fire:

$$Q = 1000 \left(\frac{t}{t_g} \right)^2 \quad (1)$$

where

Q = heat release rate from the fire (kW),

t = time after effective ignition (s),

t_g = growth time (s).

For design fire purposes, the effect of sprinklers is frequently accounted for by assuming the fire stops growing after the sprinklers are activated. That is, it is assumed that the fire will continue to burn at the size at which the sprinklers were activated until the fuel is consumed (NFPA 1995).

For this project, the propane burner used in the steady-state fire tests was used to simulate an initially unsteady fire followed by a steady-state fire. A fast t-squared profile with a growth time t_g of 150 s was used for the initial fire growth. The fire was allowed to grow until it reached a predetermined

heat release rate, Q_s . Tests were conducted with Q_s values of 1000 kW, 2000 kW, and 2500 kW. Based on the previous test series with steady fires (Lougheed et al. 2000), these heat release rates cover the range for which buoyant smoke flow would be obtained for sprinklered fires. The location of the propane burner is shown in Figure 3. This location was also used for the mercantile tests with clothing and toys described in the next section.

The propane burner fire tests were used to investigate the following aspects of sprinklered mercantile fires:

1. the activation of the sprinklers,
2. smoke accumulation in the secondary space without mechanical exhaust, and
3. smoke accumulation in the secondary space with mechanical exhaust.

Mercantile Fire Tests

A series of fire tests was conducted simulating fire load scenarios observed in retail stores. The following criteria were used in developing the fire scenarios:

1. The fire loads should be sufficient to produce peak heat release rates, which would activate four sprinklers. However, the peak heat release rates should not exceed 2500 kW for extended periods.
2. The fire location was shielded from direct sprinkler spray. The shielding method was consistent with situations common in occupied areas of stores.
3. The fire loads should be representative of commodities that would be found in retail stores.

Bulk Storage and Display

Frequently, for bulky commodities, such as paper towels and potato chips, among others, a retail outlet will use the original cartons as part of the display in the occupied area. In this way, the impact of such commodities on limited storage area is minimized. However, such displays can result in a substantial localized fuel load in the retail area. For example, stacked paper products with more than 100 cartons were observed in some outlets with the top of the stored items close to the ceiling.

Such fuel loads are frequently stored near the store walls in a back corner. The walls are typically lined with a material, such as medium density fiberboard, pegboard (6 mm thick hardboard), or plywood, which are used to hold shelves. All three materials have similar fire growth rates when evaluated using a standard room test arrangement (Torvi et al. 1999). For this project, the area of the test facility used for the fire tests was lined with plywood.

Three fire tests were conducted with 30-40 cartons containing paper towels. Each carton was 381 mm by 510 mm by 572 mm high. The cartons were stacked in a back corner of the test facility (see Figures 1 and 3). The fuel load and arrangement of the cartons for each test are given in Table 2.

TABLE 2
Fuel Load for Paper Towel Fire Tests

Test	Number of Cartons	Carton Arrangement (Width × Depth × Height)	Fuel Load (kg)
75	30	2 × 3 × 5	208.7
76	32	2 × 4 × 4	223.2
77	40	2 × 4 × 5	279.2

The fuel load includes both cartons filled with paper towels, the plywood lining the walls of the test facility, and wood pallets. For the test arrangement, the width refers to the number of stacked cartons parallel to the back wall of the test compartment.

For the first test, the cartons were not restrained and the boxes fell over during the test, allowing the sprinkler spray access to the fire. In the subsequent tests, the cartons were restrained using wires. This simulated a situation in which the fuel package was part of a larger fuel load.

Shelving Storage

Retail outlets frequently store excess stock in the retail area utilizing the shelving units used for display. One approach is to store the merchandise on top of the shelving. With this approach, a stack of cartons containing merchandise acts as a shield for the displayed items on the shelves. Such storage is most common in retail establishments with high ceiling heights and is thus not typical of the retail areas that were simulated in the test arrangement. As such, this scenario was not evaluated. However, it is a situation that can be found in stores linked to malls and could potentially result in a shielded fire situation. (Note: In retail spaces with ceiling heights of 3-3.6 m, this storage arrangement can result in limited clearance above the stored items. In some cases, the clearance between the sprinkler deflector and the top of the storage does not meet the minimum spacing [457 mm] required by NFPA 13 [1996] resulting in noncode conformance.)

A second approach is to use a multi-level shelving unit or tables for both display and storage. The top of the table or upper shelves is used for display and the lower section is used for storage. This was the situation used for the full-scale fire tests. One series of tests was conducted using clothing stored in cardboard cartons as the fuel load. The second series of tests was conducted using toys in their original packaging. In both cases, the fuel load footprint was limited to a 0.91 m by 4.8 m area. The fuel package was at the same location as used for the propane-fueled tests (see Figures 1 and 3).

The fuel loads used for the clothing test are shown in Table 3. The fuel load listed in Table 3 includes the shelving material with 57 kg of melamine painted particleboard used for each level. However, typically only a small amount of shelving material (<10%) was burnt in these tests. The primary fuel was the clothing and cardboard cartons.

TABLE 3
Fuel Loads for Full-Scale Clothing Fire Tests

Test	Number of Cartons of Clothing	Shelving Levels	Fuel Load (kg)
78	12	1	344.8
79	13	1	350.1
80	24	2	624.3
83	24	2	607.1

Identical fuel packages (95 kg of toys, including packaging materials and 114 kg of melamine painted particleboard) were used for the two tests with toys. The toys were selected to provide a range of polymeric materials (polyethylene, polypropylene, polyurethane, and PVC, among others). The fuel load included the particleboard used for the shelving. However, typically only a small amount of shelving material (<10%) was burnt in the shelving tests. The primary fuel was the toys and the packaging materials, including the cardboard cartons.

For the majority of the tests, a single level rack was used for the fuel package. Particleboard painted with melamine was used to hold the fuel 150 mm above the floor. A second level of particleboard located 997 mm above the floor provided shielding from the sprinkler spray. In addition, two tests were conducted using the clothing with a two-tier shelving system. In these tests, the bottom shelving section was identical to that used in the single-tier test. However, in these tests, cartons containing clothing were placed on the second shelving level and particleboard sheets located 1949 mm above the floor were used to provide shielding.

PROPANE BURNER TEST RESULTS

The propane burner fire tests were used to simulate retail fires with an initial fast t-squared fire growth followed by a steady-state fire. The propane flow rate was controlled using a programmable controller for a valve in the propane line.

A total of 16 tests were conducted using the test parameters shown in Table 4. The first two tests were exploratory in nature conducted to develop the burner control profile. These tests were conducted prior to calibration and the results are not included in the following discussion.

Sprinkler Activation

The sprinkler activation times are shown in Figure 4. The test results were sorted according to heat release rate and the sprinkler application density.

The activation times for the northeast and northwest sprinklers, which were closest to the fire, were consistent from test to test. The activation times for the northwest sprinkler occurred between 170 s and 200 s compared to 190 s and 215 s for the northeast sprinkler. Although the propane burner was symmetrical on the centerline of the test compart-

ment, visual observations indicated a faster fire growth on the west side of the compartment.

The activation time for the southeast and southwest sprinklers show more dependence on the test conditions and, in particular, on the sprinkler application density. For tests with an application density of 6.1 (L/min)/m², the second set of sprinklers typically activated between 231 s and 285 s after the start of the fire. With the 8.1 (L/min)/m² application density, the activation times ranged from 275 s to 473 s. However, the extended activation time in test 65 was atypical. The last sprinkler was usually activated within 350 s.

TABLE 4
Full-Scale Propane Fire Tests

Test	Q_s (kW)	Sprinkler Application Density ((L/min)/m ²)	Exhaust Rate (m ³ /s)
55	1000	8.1	0
56	1000	8.1	0
57	1000	6.1	0
58	2000	8.1	0
59	2000	6.1	0
60	2500	8.1	0
61	2500	6.1	0
62	1000	6.1	0
63	2500	6.1	15.3
64	2500	8.1	15.3
65	1000	8.1	14.5
66	1000	6.1	14.5
67	2500	8.1	8.4
68	1000	8.1	10.0
69	1000	6.1	9.8
70	2500	6.1	10.0

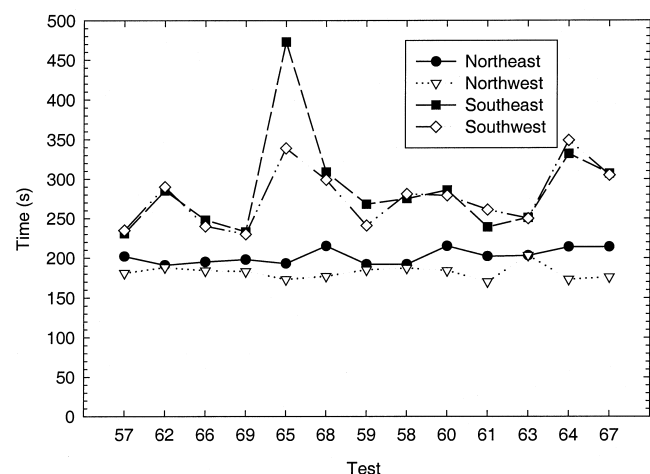


Figure 4 Sprinkler activation times for propane burner tests.

The sprinkler activation data indicate that fires with heat release rates of approximately 1000 kW or higher would activate four sprinklers. With the fast t-squared fires, the activation times for the sprinklers closest to the burner varied by 25-30 s. There was a larger variation in the activation times for the second set of sprinklers. The predominant effect was due to the sprinkler application density.

Heat Release Rates

For tests 63-70, a mechanical exhaust system was used to exhaust the smoke from the test facility. An instrumentation station was located in the exhaust duct to measure the heat release rate using the oxygen depletion method. The heat release rates are shown in Figure 5. Also shown are the programmed heat release profiles with the initial t-squared fire growth phase and subsequent steady-state fire.

Two steady-state fire scenarios (approximately 1000 kW and 2500 kW) were used for the tests. The results show good comparison between the measured and programmed curves during the fire growth phase. The measured heat release rates in the steady-state phase were approximately 25% higher for the nominal 1000 kW tests and 10% lower for the 2500 kW tests. This variation in the heat release rates was systematic, indicating it was most likely due to variability in the controller and the propane fuel system. This conclusion is consistent with the opening temperature results discussed in the next section.

Temperatures in the Compartment Opening

In the preliminary tests with a steady-state propane-fueled burner, the variations in the temperatures measured in the compartment opening versus heat release rate were determined (Lougheed et al. 2000). The temperatures were dependent on the sprinkler application density, the height above the floor of the compartment, and the heat release rate for the fire.

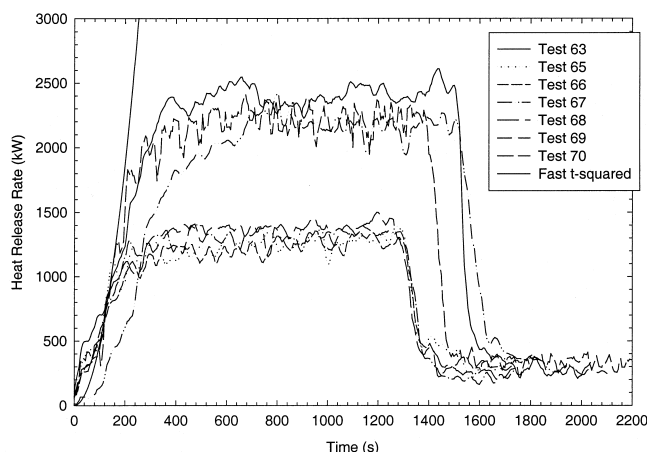


Figure 5 Measured heat release rates for propane burner tests.

In Figure 6, the temperatures measured at six levels in the compartment opening during the steady-state phase of the t-squared fire tests are compared with the temperature profiles determined with the steady-state fire tests. The sprinkler application density was 8.1 (L/min)/m². The temperature profiles are comparable for the two series of tests.

Smoke Accumulation

For tests 63-70, an exhaust fan was used to vent smoke from the large space adjacent to the test compartment. The fan was operated at two nominal exhaust rates. The mass flow rate measured in the exhaust duct is shown in Table 5. All tests had an extended period with a steady heat release rate (see Figure 5).

The temperatures, measured at the thermocouple tree located at the quarter-point of the large space, were used to determine the height of the smoke layer above the floor. The smoke layer interface height was determined using the 80% temperature rise criteria developed in the investigations on atrium exhaust (Lougheed et al. 1999). This criterion assumes that the smoke layer interface is located at the height at which the measured temperature is 80% of the temperature measured in the smoke layer. The results are shown in Table 5.

The thermocouples used to estimate the smoke layer height were spaced at 0.5 m. Also, with the sprinklered fires, the temperature difference produced in the large space was small. As a result, there is a degree of uncertainty in the estimated location for the smoke layer interface.

In addition to the estimates using the 80% criterion, the smoke layer interface was also estimated by determining the height at which the maximum slope in temperature was located. This criterion has been used in some references as the basis for estimating the height of the smoke layer interface (Luo et al. 1997). The smoke layer interface heights estimated using this criterion were consistent with those estimated using the 80% temperature criterion, with the location of the interface typically 0.5 m lower using the maximum slope method.

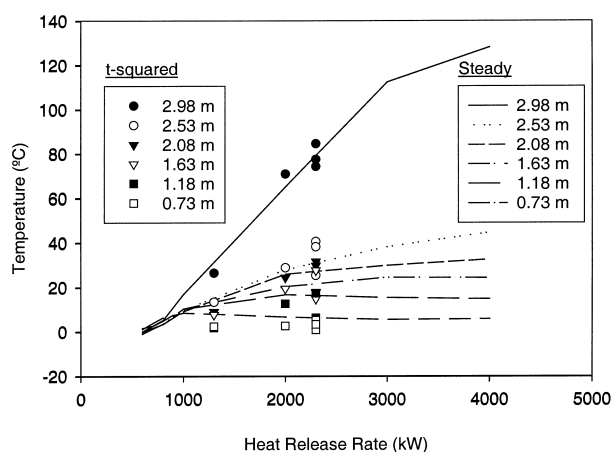


Figure 6 Temperatures in compartment opening.

TABLE 5
Smoke Levels in Steady-State Fire Phase

Test	Heat Release Rate (kW)	Smoke Layer Height (m)	Mass Flow Rate Duct (kg/s)	Mass Flow Rate, Equation 3 (kg/s)
63	2300	8.7	12.8	14.2
64	2300	8.5	12.8	13.4
65	1300	8.5	12.1	10.3
66	1300	8.7	12.1	11.0
67	2300	7.2	7.0	8.9
68	1300	7.5	8.3	7.4
69	1300	8.2	8.2	9.4
70	2300	7.7	8.3	10.5

There are two methods provided in NFPA 92B for estimating the mass flow rate in plumes produced by fires in communicating spaces. The first method assumes the plume is through wall openings, such as windows or doors. In this case, the mass flow rate is determined using an equivalent axisymmetric plume using a correction factor given by the following relation:

$$a = 2.4A_w^{2/5}H_w^{1/5} - 2.1H_w^{1/2} \quad (2)$$

where

- a = correction factor (m),
- A_w = area of ventilation opening (m^2),
- H_w = height of the ventilation opening (m).

The mass flow rate in the plume from the opening is given by

$$\dot{m} = 0.071Q_c^{1/3}(z_w + a)^{5/3} + 0.0018Q_c \quad (3)$$

where

- \dot{m} = mass flow rate in plume at height z_w (kg/s),
- a = correction factor (m),
- Q_c = convective portion of the heat release rate (kW),
- z_w = height above the top of the opening (m).

The mass flow rate at the smoke layer interface height estimated using Equation 3 is shown in Table 5. The top of the opening in the test compartment was 6.4 m above the floor of the atrium test facility (Figure 3). The mass flow rate estimated using Equation 3 is comparable to the mass flow rate measured in the duct. The variation is $\pm 20\%$, which is reasonable considering the uncertainties in the estimates for the various parameters.

The data are limited. However, the variation in the mass flow rate does not show any dependence on the major parameters varied in the test. This includes the sprinkler application density, heat release rate, and exhaust mass flow rate.

The mass flow rate from a communicating space can also be estimated using an equation developed for balcony spill

plumes, if the fire is assumed to be immediately adjacent to the opening. In this case, the mass flow rate is given by

$$\dot{m} = 0.36(QW^2)^{1/3}(Z_b + 0.25H) \quad (4)$$

where

- \dot{m} = mass flow rate in plume (kg/s),
- Q = heat release rate (kW),
- W = width of the plume as it spills under the balcony (m),
- Z_b = height above the balcony (m),
- H = height of the balcony above the fuel (m).

Mass flow rate estimates using Equation 4 were more than twice the mass flow rate measured in the exhaust duct. As such, this approach did not provide a good estimate of the mass flow rate produced by the sprinklered fires. This is reasonable as the fire location was inside the compartment well away from the opening.

MERCANTILE FIRE TEST RESULTS

A series of full-scale fire tests were conducted with typical fuel loads found in retail stores. This included stacked cartons containing paper towels, clothing in boxes on shelves, and toys in their original packaging. The fuel loads for the tests were scaled such that the maximum heat release rate would be less than 2500 kW. The fire area was shielded using typical situations found in stores. All tests except test 76 with paper towels were conducted using a sprinkler application density of 8.1 (L/min)/ m^2 . For test 76, the sprinkler application density was 6.1 (L/min)/ m^2 .

The mercantile fire tests simulated fire scenarios that would be controlled using four or fewer sprinklers. A detailed description of the test setup was provided in a previous section. In this section, the results of these tests are used to investigate the hazard in a large space as a result of a sprinklered fire in an adjacent mercantile area.

Heat Release Rates

The heat release rates measured for the mercantile fire tests are shown in Figures 7 and 8. The results for tests 76 and 82 are not included. In test 76, the sprinklers extinguished the fire and the heat release rate was minimal. For test 82, there was a problem with the instrumentation in the exhaust duct, resulting in erroneous data.

In the test procedure, the exhaust system used to simulate smoke management in the large space was also used for the heat release rate measurements. To simulate the automated activation of the system using smoke alarms or other control measures, the exhaust system was not turned on until the first sprinkler was activated. As a result, there was no heat release rate measurement prior to 150-200 s.

The fast t-squared fire curve is also shown. The time scale for the theoretical curve was shifted by 100 s. The fire growth rates for the clothing and toy tests were comparable to the fast t-squared rate after the initial incubation period.

For the tests with the clothing and toys, the heat release rate reached a maximum in the initial 300-400 s followed by a steady-state plateau with heat release rates in the 1000-1500 kW range. In both cases, there was a subsequent decrease in the heat release rate as the fuel was depleted.

With the toys, the decay phase was relatively short compared with the clothing scenario. In the latter case, the clothing provided a thick fuel bed with the burning predominantly on the exterior surfaces of the fuel. As a result, an extended time was required to fully deplete the fuel load. For example, the heat release rate for test 83 exceeded 500 kW for up to 1000 s after the ignition.

The heat release rate varied from test to test with the paper towel fire load. In test 75, the fire growth was slowed by the initial sprinkler operation. It subsequently increased to a peak of 1200 kW before the boxes fell, exposing the fire to the sprinkler spray.

In test 77, the boxes were held in place using wires. This resulted in an extended test as the fire burrowed into the fuel package. There was a slow increase in the fire for the initial 1200 s followed by a steady phase at a heat release rate of 1300 kW. After 2200 s, there was an extended decay phase until the fire was extinguished at 4600 s. This fire profile is indicative of a buried fire in an extended bulk fuel package.

Sprinkler Activation

The sprinkler activation times for the mercantile fire tests are shown in Table 6.

For tests with toys and clothing, the fire location was the same as used in the propane burner tests (Figure 3). Overall, the activation times for the sprinklers are comparable for the three fuel packages. The initial sprinkler activation was at

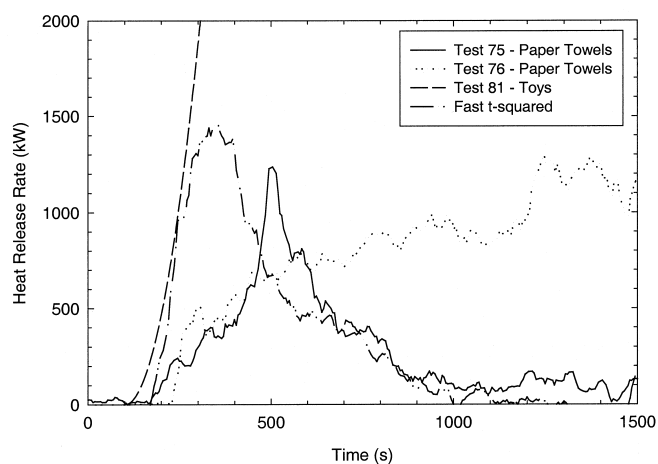


Figure 7 Heat release rates for paper towel and toy fire tests.

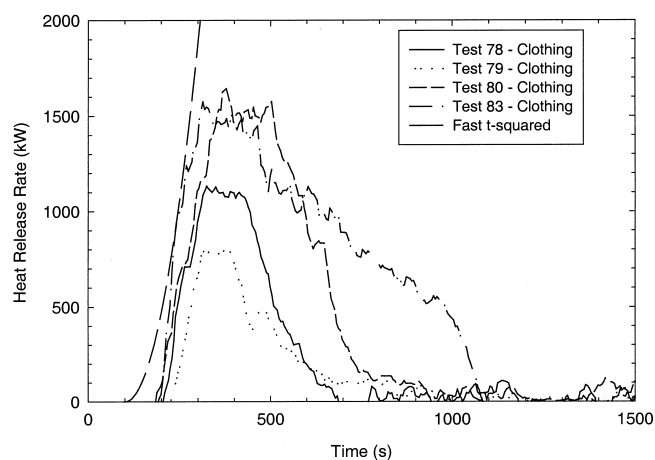


Figure 8 Heat release rates for clothing fire tests.

165-175 s for the toy tests and at 200-210 s for the clothing tests, and all four sprinklers were activated by 300 s.

For tests with paper towels, the fuel package was located in a back corner of the test compartment. With this location (Figure 3), the distance over which the smoke produced by the fire had to travel through the sprinkler spray was increased, resulting in further cooling of the smoke. As a result, the activation time for the second and subsequent sprinklers was delayed relative to the other three fire scenarios.

For test 77, in which the fire continued to grow after initial sprinkler operation (Figure 7), the sprinklers near the front of the compartment were eventually activated, resulting in a cooling of the hot layer exiting the compartment opening. However, even with the cooling by the water spray over the 9 m length of the test compartment, the temperatures near the ceiling remained above ambient and the smoke was buoyant.

TABLE 6
Sprinkler Activation Times for Mercantile Fire Tests

Test	Fuel	NE Sprinkler (s)	NW Sprinkler (s)	SE Sprinkler (s)	SW Sprinkler (s)
75	Paper Towels	338	184	n/a*	n/a
76	Paper Towels	297	n/a	n/a	n/a
77	Paper Towels	401	246	n/a	1171
78	Clothing	205	199	n/a	243
79	Clothing	219	211	246	238
80	Clothing	265	198	299	284
81	Toys	197	165	234	256
82	Toys	178	175	272	277
83	Clothing	199	199	247	246

* n/a—not activated

TABLE 7
Smoke Levels in Mercantile Fire Tests

Test	Peak Heat Release Rate (kW)	Smoke Layer Height (m)	Mass Flow Rate Duct (kg/s)	Mass Flow Rate, Equation 3 (kg/s)
75	1500	8.7	11.8	11.7
76	n/a*	8.7	13.6	n/a
77	1300	8.2	10.8	9.5
78	1250	8.7	11.5	10.8
79	1000	8.7	11.2	9.8
80	1650	7.7	8.8	8.9
81	1400	7.7	9.0	8.2
82	n/a	7.2	7.7	n/a
83	1550	7.7	8.8	8.6

* n/a—not available

Smoke Accumulation

An exhaust fan was used to vent smoke from the large space adjacent to the test compartment. The fan capacity for the mercantile fire tests was the same as the lower condition used for the propane burner simulations. The mass flow rate measured in the exhaust duct is shown in Table 7.

The volume of the test facility above the top of the opening was limited. As a result, there was a rapid filling (<90 s) with smoke even though the exhaust fan was operating. With the limited temperature increase produced by the sprinklered and the large (0.5 m) spacing between the thermocouples, it was impossible to determine the smoke filling versus time profile. However, a minimum smoke layer height during the steady heat release phase could be determined. The results are shown in Table 7. As with the propane burner tests, this height was estimated using the temperatures measured by the ther-

mocouple tree located at the quarter-point of the large volume space.

The smoke mass flow rates estimated using Equation 3 are also shown in Table 7. The calculated mass flow rates are based on the measured heat release rates and the minimum smoke layer heights. As with the propane burner tests, there is a good comparison between the measured flow rate in the exhaust duct and the estimated smoke mass flow rate for those cases.

The major differences occur in those cases in which an extended plateau in the heat release rate was not observed. In these cases, using the peak heat release rate in Equation 3 will result in a high estimated smoke mass flow rate.

Overall, the estimated and measured mass flow rates differed by 10-25%. Considering the uncertainties in the measurements, this is a reasonably good comparison, indicating that the smoke flow rate from the test compartment

produced by the sprinklered fire can be approximated, assuming the relationship developed for smoke flow through an opening (Equation 3).

Smoke Measurements in the Upper Layer

For the mercantile fire tests, CO and CO₂ concentrations and smoke obscuration were measured in the upper layer in the secondary test space at the location shown in Figures 1 and 2. The smoke density measurements are shown in Figure 9. The CO and CO₂ concentrations are shown in Figures 10 and 11, respectively.

The peak smoke obscurations ranged from approximately 0.1 OD/m for tests 78 and 79 to a maximum of 0.8 OD/m in test 81. (The smoke data are not available for tests 82 and 83. However, the CO₂ results for these tests are comparable to those measured in tests 80 and 81. It is expected that the smoke densities should also be comparable.)

For tests 78 and 79, the visibility range was 5-10 m. This is approaching the minimum visibility range, which is generally suggested for occupants familiar with a building or able to dash to safety (3-5 m). However, it exceeds the minimum 15-20 m visibility range (0.04-0.08 OD/m) that is suggested for the safe evacuation of occupants who are not familiar with the building (Tamura 1994).

The maximum smoke density levels of 0.4-0.8 OD/m (1-2 m visibility) measured in the other tests exceed the normal tenability criteria. However, these levels are lower than the 4-10 OD/m, which can be reached under adverse fire conditions.

The maximum CO concentrations were in the range of 0.02-0.08% (Figure 10). These levels are lower than the levels that would cause incapacitation with extended exposure (0.14-0.17% for 30 minute exposures [Purser 1995]). However, with maximum concentrations of 0.08%, the CO levels did approach the tenability limits.

The CO₂ concentrations are shown in Figure 11. There was a rapid increase in the CO₂ levels between 200 s and 400 s after the fire was ignited. This is consistent with the fire growth observed during the tests in which there was an initial slow fire development followed by rapid increase in heat release rate (Figures 7 and 8).

Following the initial fire development, the CO₂ concentration remained constant for up to 300 s. This period coincided with the stage of the fire during which the heat release rate was constant and the smoke level was maintained at a fixed height.

There was a subsequent decrease in the CO₂ concentrations during the decay phase of the fire. The time required for the fire to decay was dependent on the type of fuel. In the toy tests, the fuel load was quickly depleted, resulting in a rapid decrease in fire size. For the test with clothing stored in boxes, a deep fuel bed was formed, resulting in a slower decrease in the fire size. The CO₂ measurements indicate there was smoke accumulation in the upper level of the secondary space for up to 900 s (15 min).

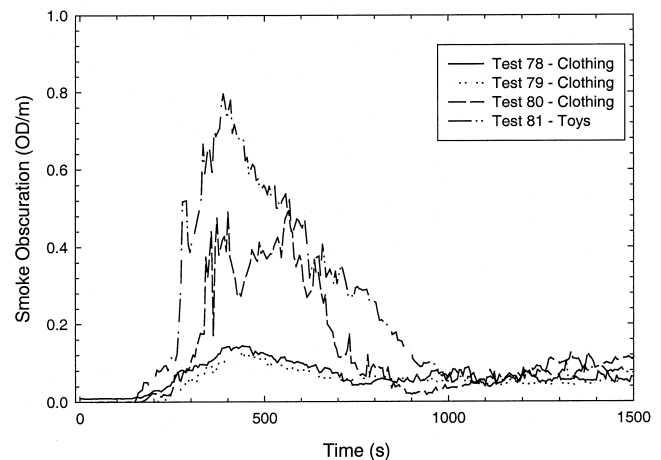


Figure 9 Smoke obscuration in the upper layer for mercantile fire tests.

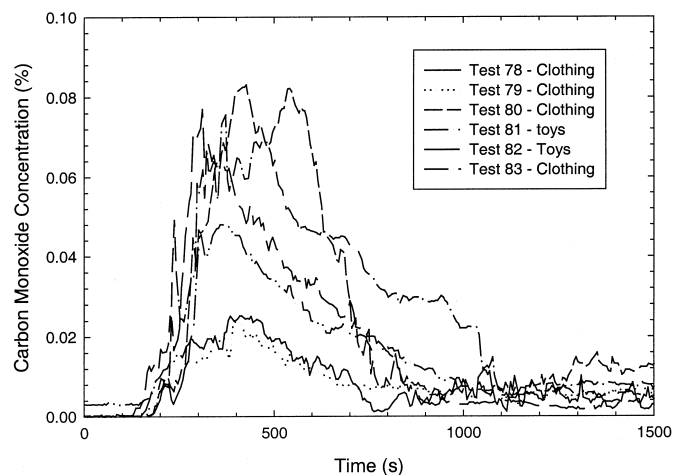


Figure 10 Carbon monoxide concentrations in the upper layer for mercantile fire tests.

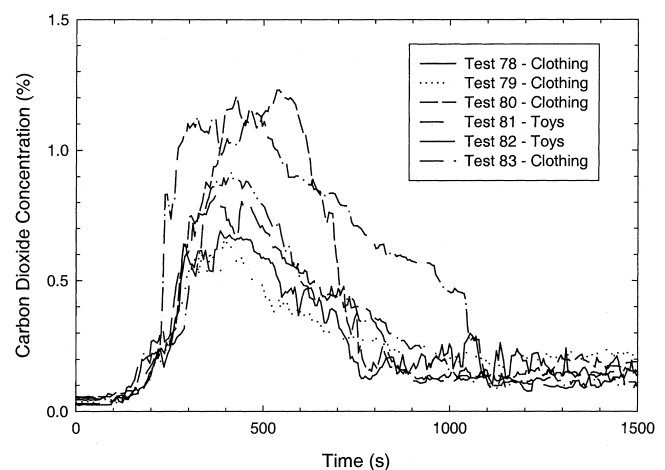


Figure 11 Carbon dioxide concentrations in the upper layer for mercantile fire tests.

Smoke Obscuration for Nonbuoyant Smoke

In addition to the smoke density measurements in the upper layer of the secondary space, the smoke density was also measured at two heights near the compartment opening (Figures 1 and 2). These devices were used to measure the smoke obscuration in any nonbuoyant smoke produced by the fire.

The smoke densities measured with the device 3.4 m above the floor of the secondary test space are shown in Figure 12. The obscuration levels at the two measurement heights were comparable and the results shown are typical of those measured at the two heights.

During fire development and the steady heat release phase, there was no indication of smoke at the two measurement locations. Initial smoke accumulation was 600-900 s after the fire was ignited. This was during the decay of the fire as the heat release decreased below the minimum required to maintain a buoyant smoke flow with the sprinklers operating. The heaviest accumulation of smoke was for the clothing tests in which the fire decay was relatively slow, resulting in extended time during which nonbuoyant smoke was produced.

With the exhaust fan operating, the smoke densities were less than 0.2 OD/m. In test 80, the fan was shut off in the latter stage of the test. The smoke density subsequently increased to 0.6 OD/m.

At 0.2 OD/m (approximately, 5 m visibility range), the smoke densities measured for the nonbuoyant smoke did exceed the levels suggested for occupants unfamiliar with a building. However, the physical extent of smoke outside the test compartment was limited and building occupants could readily move outside the area with nonbuoyant smoke.

The above comment applies only to the smoke in the secondary space. Within the sprinklered compartment, there was a rapid smoke accumulation throughout the test compartment with fire decay and the subsequent cooling of the smoke by the sprinkler spray. This is consistent with observations during other full-scale fire tests with sprinklers (Heskestad 1991; Loughheed et al. 2000). This indicates that the nonbuoyant smoke produced during the decay phase of the fire is of more concern for occupants in the fire compartment or in confined spaces, such as corridors connected to the fire compartment. In these locations, it is more likely that the occupants can become enveloped in the rapidly descending nonbuoyant smoke layer.

For all tests except test 80, the smoke exhaust system was used in the large secondary space. In test 80, the smoke exhaust system was shut off at approximately 1000 s after the fire was started. There was a subsequent increase in smoke obscuration to 0.6 OD/m, indicating an increased smoke accumulation near the compartment opening without the exhaust fan. This is consistent with observations on smoke flow made during the tests. The nonbuoyant smoke exiting the compartment initially flowed down and away from the opening. However, with the exhaust fan operating, the smoke flow did

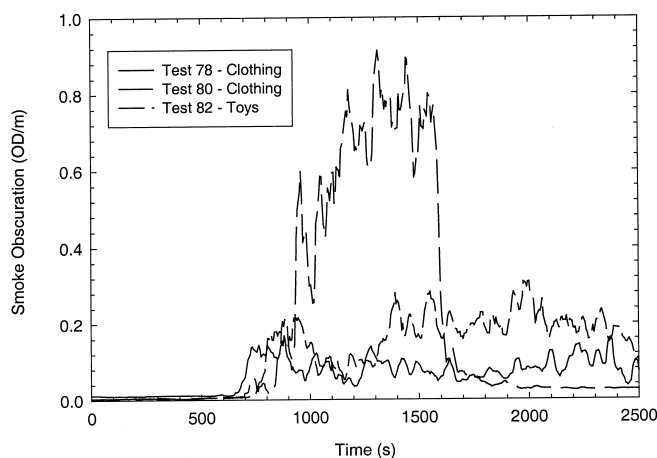


Figure 12 Smoke obscuration below test compartment for mercantile fire tests.

not reach the floor of the main facility. Once the smoke flow was 3-4 m from the compartment opening, the general flow pattern was up.

DISCUSSION AND CONCLUSIONS

Fire Size

Because of the size limitations of the test facility, the fuel load and thus the maximum fire size for the tests discussed in this paper were limited. Specifically, only four sprinklers were included in the fire compartment. Based on the preliminary work with steady-state propane burner fires, it was determined that the maximum heat release rate should be less than 2500 kW (Loughheed et al. 2000). Otherwise, the temperature in the smoke layer would exceed 100°C and more than four sprinklers would be activated. (The temperature in the buoyant smoke layer with the sprinklers operating is dependent on a number of factors, including fire location, fire size, ceiling height, and sprinkler application density, among others. The 2500 kW limit is for four operating sprinklers with an application density of 8.1 [L/m]/m² with the fire located midway between the back wall of the test compartment and the first set of sprinklers as shown in Figure 3.)

There is very limited information in the literature regarding the number of sprinklers activated by fires in various occupancies. However, indications are that in only 10% of fires or less are more than four sprinklers activated (Johnson 1998). Similar results were found using four years of accumulated data in the U.K. fire statistics for fires in public access areas of retail premises (Morgan 1998). Specifically, it was determined that for 133 fires in such premises, more than four sprinklers were activated in eight incidents and more than two sprinklers in 52 incidents.

Thomas (1997) provides an overview of the fire statistics for retail premises from the U.S. for the years 1983 to 1993. The results indicate that with sprinklers present and operated,

the extent of flame damage was reduced compared to the fires with sprinklers not present. With sprinklers present and operated, the fire extent was limited to the object of origin or to the area of the room of origin for 76% of the fires. Of the remaining fires, 14% had flame damage limited to the room of fire origin and the remaining 6% of fires had flame damage extending beyond the room of fire origin. This is compared with about 25% of the fires having flame damage beyond the compartment of fire origin for the case without sprinklers.

Similarly, there was a reduction in the number of fires resulting in smoke damage beyond the room of fire origin for fires with sprinklers present and operated (approximately 34%) compared with 45% for fires with sprinklers not present.

By comparison, the fire scenarios used in the full-scale fire tests were able to consistently activate four standard response sprinklers. For the shielded shelving scenarios (toys and clothing), the fire was limited to an approximately 5 m² area of the test compartment. In terms of fire size (heat release rate), the test scenarios should cover 75-90% of the fires that occur in retail premises.

To summarize, the fire scenarios did not simulate the 5 MW convective heat release rate fires with a fire area of 10 m² that are frequently used as design fires for retail applications (NFPA 1995; Hansell and Morgan 1994). Fires larger than 2500 kW should activate more than four sprinklers and were beyond the limits of the test facility. However, the fire scenarios used in the tests did produce heat release rates of 1000- 2500 kW and results should be comparable to or exceed those produced by most fires in retail mall situations.

Sprinkler Activation

For both the propane burner fires and the mercantile fire simulations, four standard response sprinklers were activated. The response time was dependent on a number of factors, including the maximum heat release rate for the fire and the sprinkler application density.

There was minimal variation in the activation time of the first two sprinklers. The activation of the third and fourth sprinkler showed more dependence on the test scenario. However, even for these sprinklers, there was not a substantial variation in activation times.

Smoke Accumulation

The smoke temperature, and thus its buoyancy, were dependent on the fire size. If the heat release rate for the fire exceeded 1000 kW, a hot upper layer was formed and the smoke flow exiting the compartment was buoyant. The smoke temperature profiles measured in these tests were consistent with those measured using the steady-state propane burner fires discussed in the previous paper (Lougheed et al. 2000).

For both the propane burner fires and the mercantile fires, there was an extended period of time during which the fire heat release rate exceeded 1000 kW. During this phase of the fire, the smoke level in the large secondary space was determined and the smoke mass flow rate into the smoke layer estimated,

using the measured flow rates in the smoke exhaust system. These measured results were comparable to the mass flow rates calculated using the equation provided in NFPA 92B (NFPA 1995) for smoke flow rate into an atrium through an opening. However, the measured mass flow rates were more than 50% lower than the estimates calculated using the equations for balcony spill plume (NFPA 1995).

During the fire decay stage with the mercantile fires, the heat release rate decreased to less than 1000 kW. The smoke in the compartment became nonbuoyant, resulting in smoke accumulation outside the compartment opening. The accumulation of nonbuoyant smoke was more extensive for the clothing tests than with the toys. With the clothing, a relatively deep fuel bed was formed, resulting in a slower fire decay compared to the tests with toys in which there was a more rapid depletion of fuel.

Smoke Properties

The smoke optical density and CO and CO₂ concentrations were measured in the upper portion of the large secondary space. In several of the mercantile fire tests, the CO concentrations and the smoke optical densities approached or exceeded tenability limits. This indicates that for the more severe fires in retail premises, the conditions in the smoke layer during the initial stages of the fire could impede occupant egress. However, during this stage of the fire, the buoyant smoke could be removed from the large space using the smoke exhaust system. This system was able to limit the smoke filling in the secondary portion of the test facility.

The smoke optical densities were also measured in the nonbuoyant smoke produced during the fire decay. The smoke levels did approach tenability limits. However, the area encompassed by the nonbuoyant smoke in the larger space was limited. Also, the accumulation of nonbuoyant smoke occurred late in the fire event (after 10-15 min). By this time, the building occupants should have moved away from the fire area.

The accumulation of nonbuoyant smoke was more rapid within the compartment. Although there was no direct measurements of the smoke density, visual observations would indicate that it exceeded the tenability limits. This would suggest that the nonbuoyant smoke could be a greater threat to occupants in confined areas, including the fire compartment and adjacent corridors. However, even in these situations, previous work indicates there should be sufficient time for occupants to safely evacuate the immediate fire (Lougheed 1997).

It was also observed that with the exhaust fan operating, there was a general upward flow of the nonbuoyant smoke once it had moved away from the compartment opening. This resulted in a decrease in the smoke obscuration throughout the large secondary area. As such, a smoke exhaust system could provide an additional level of protection during the later stages of a fire.

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