Comparative performances of mechanical smoke exhaust system, zoned smoke control and pressurized building method of smoke control

Tamura, G. T.; MacDonald, R. A.

Publisher's version / Version de l'éditeur:

ASHRAE Transactions, 99, 1, pp. 488-495, 1993

National Research Council Canada
Institute for Research in Construction

Conseil national de recherches Canada
Institut de recherche en construction

NRC·CNRC

Comparative Performances of Mechanical Smoke Exhaust System, Zoned Smoke Control, and Pressurized Building Method of Smoke Control

by G.T. Tamura and R.A. MacDonald

Reprinted from:
ASHRAE Transactions (99)1, 1993
pp. 488-495
(Paper presented at the ASHRAE Winter Meeting
Held in Chicago, IL. USA, January 23-27, 1993)
(IRC Paper No. 3397)

NRCC 36851
IRC-P- 3397

Canada

COMPARATIVE PERFORMANCES OF MECHANICAL SMOKE EXHAUST SYSTEM, ZONED SMOKE CONTROL, AND PRESSURIZED BUILDING METHOD OF SMOKE CONTROL

G.T. Tamura, P.E.
Fellow ASHRAE

R.A. MacDonald

ABSTRACT

Nonfire and fire tests were conducted in the 10-story experimental fire tower to evaluate the performance of the mechanical smoke exhaust system, zoned smoke control system, and pressurized building method of smoke control. All three systems have something in common—mechanical exhaust of the fire floor.

Tests with fire temperatures of 450°C and 650°C indicated that the tower was kept smoke free outside the fire compartment with each system when all stair doors were closed. However, when one or two stair doors were open, including the one on the fire floor, smoke contamination of the stairshaft occurred for all three systems. For the mechanical smoke exhaust system, the entire tower was contaminated when two stair doors were opened. For the zoned smoke control system, only the stairshaft was contaminated, and, for the pressurized building method, the stairshaft and the floor space of the floor above the fire was contaminated. When another stair door was opened, the floor spaces of several floors were contaminated for the zoned smoke control system, whereas the contamination pattern remained unchanged for the pressurized building method of smoke control.

INTRODUCTION

Smoke is recognized as the major killer in building fires. Smoke is toxic and can reduce visibility to hamper occupants from evacuating a building during a fire. Although a fire can be confined to a room or floor, smoke can leave the fire compartment to spread rapidly into stairs and elevator shafts and then to other floor spaces. Escape routes can become untenable before occupants are able to reach the outdoors, particularly in high-rise buildings where time to evacuate may be long.

Various smoke control measures to protect occupants from such smoke hazards are described in the ASHRAE smoke control design manual (Klote and Fothergill 1983). One of the measures described is the zoned smoke control system, which involves venting the fire floor and pressurizing adjacent floor spaces. When only a few floors above and below the fire floor are pressurized, this measure is sometimes referred to as the "pressure sandwich" system. In this paper, this system is referred to as zoned smoke control (ZSC).

In the ASHRAE smoke control design manual, zoned smoke control also includes the system that calls for pressurizing all floor spaces, except the vented fire floor. In the Supplement to the National Building Code of Canada (NRCC 1990) and in this paper, this system is referred to as the pressurized building method of smoke control (PBSC). In the latter document, the level of building pressurization required is that necessary to raise the building pressures above those outside for the full height of the building to overcome adverse pressures caused by stack action in winter.

Some measure of smoke control can also be achieved by mechanically venting the fire floor and leaving other floors unpressurized. This system is referred to here as the mechanical smoke exhaust system (MSES).

The three systems (ZSC, PBSC, MSES) have mechanical venting of the fire floor in common. These systems are amenable to using the supply air systems of the HVAC systems for pressurizing floor spaces with outside air and to using the return or exhaust air systems for venting the fire floor to outside, provided that the building is sprinklered.

These three smoke control systems were tested in the 10-story experimental fire tower under nonfire and fire conditions of 460°C and 650°C. Stair doors were operated during these tests. The results of the tests for the three systems were evaluated and compared for their effectiveness in controlling smoke movement.

George T. Tamura is a senior research officer and **Robert A. MacDonald** is a senior technical officer at the Institute for Research in Construction, National Research Council Canada, Ottawa, Ontario.

EXPERIMENTAL FIRE TOWER

All tests were conducted in the National Fire Laboratory's 10-story, reinforced concrete fire tower comprising an experimental tower and an attached service tower. The typical floor height is 2.6 m except for the first and second floors, which are 3.6 m. The plan view of a typical floor is shown in Figure 1.

The experimental tower contains all the shafts and other features necessary to simulate air and smoke movement patterns of a typical multi-story building with a center core, including the elevator, stair, smoke exhaust, service, supply, and return-air shafts. All joints in the walls of the reinforced concrete structure are sealed to minimize uncontrolled air leakages. The exterior walls and walls of the vertical shafts are provided with variable openings that can be set to provide desired leakage areas of typical buildings. The leakage areas of the tower were set to simulate those of a building with average airtightness and a floor area of 904 m^2, or seven times that of the floor area of the experimental fire tower. The values of leakage areas for the tower given in Table 1 were chosen from measurements of multi-story buildings conducted by Shaw et al. (1973) and Tamura and Shaw (1976).

Two propane gas burner sets, each capable of producing heat at an output of 2.5 mW, are located on the second floor. Outside wall vents in the east and west walls of the second floor, each with an area of 0.464 m^2, can be opened remotely during a fire test to simulate broken windows.

A separate structure, adjacent to the tower, houses the air moving and heating plant. The air ducts run underground through a short tunnel to the bottom of the experimental fire tower. One system handles the main air supply and heating load and the other supplies outside air, either to the experimental stair and elevator shafts or to vestibules located between the entrances to these shafts and the burn area on each floor. An exhaust fan located on the roof can exhaust any floor to the outdoors through the return air shaft.

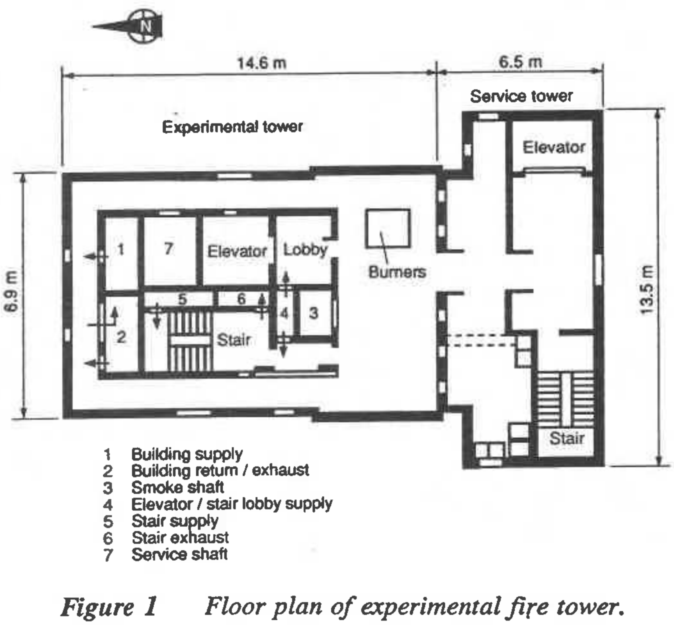

Figure 1 *Floor plan of experimental fire tower.*

TABLE 1
Leakage Flow Areas Per Floor of the Experimental Fire Tower*

Location	Area (m^2)
Outside walls	
East wall for each floor	0.037
West wall for each floor	0.037
Second floor east wall vent open	0.464
Second floor west wall vent open	0.464
Elevator	
Floor space to elevator shaft	0.006
Floor space to elevator lobby (lobby door closed)	0.028
Elevator lobby to elevator shaft (elevator doors closed)	0.070
Stairs	
Stairshaft wall	0.004
Stair door (closed)	0.023
Stair door (open)	1.950
Vertical Shafts	
Floor space to service shaft	
All floors except on second floor	0.102
Second floor	0.47
Floor space to supply air shaft	
All floors except on pressurized floors	0.186
Pressurized floors	0.37
Floor space to return air shaft	
Exhaust air shutters closed on all floors except on second floor	
Second floor	0.49
Ceiling	0.052

*Based on measurements in real buildings and simulating the air leakage characteristics of a building with a floor area of 904 m^2

Temperatures are measured at 10 different locations on each floor using chromel-alumel thermocouples. Pressure differences across the various walls are measured using 18 static pressure taps mounted flush with the walls on each floor. All pressure lines are connected to a 24-port pressure switch equipped with a diaphragm-type magnetic reluctance pressure transducer and located on the same floor in the service area. Carbon dioxide concentrations are measured at six locations on each floor in the shafts, lobbies, corridors, and burn area by copper sampling tubes connected to a 12-port sampling switch unit with a nondispersive infrared gas analyzer. All measuring devices are controlled and monitored by a computer-based data acquisition and control system.

DESCRIPTION OF TEST SMOKE CONTROL SYSTEMS

The three smoke control systems (MSES, ZSC, and PBSC) are schematically illustrated in Figure 2. All systems involved mechanical venting of the second floor, which has the propane gas burners used to generate test fire tempera-

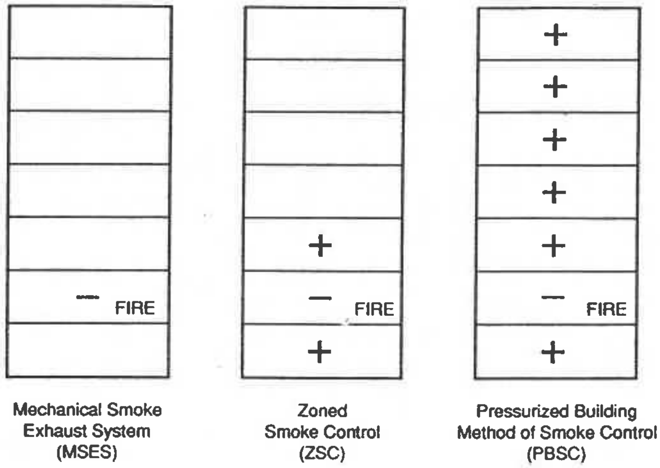

Figure 2 *Description of test smoke control systems.*

tures. With the exhaust air inlet shutters of the return air shaft closed on all floors except the one on the second floor, "smoke" on this floor was exhausted through the return air shaft and out at the rooftop through an exhaust fan having a capacity of 9 m^3/s at 125 Pa. The exhaust rate was adjusted to depressurize the fire floor to produce a pressure difference of 25 Pa across the stair door. This also resulted in similar pressure differences across the walls of the elevator shaft. The pressure difference of 25 Pa was intended to prevent smoke spread caused by the buoyancy force of fire. Where the floors were pressurized, the outdoor air supply rate (fan capacity of 14 m^3/s at 600 Pa) was adjusted before operating the exhaust fan to produce floor pressurization of 25 Pa with reference to outside. For all smoke control systems, the supply air shutter on the second floor, which was not pressurized, was kept closed.

Table 2 gives the supply air and exhaust air rates for the three systems. The exhaust air rate for MSES of 4.42 m^3/s represents an air change rate of about five, based on the floor volume simulating a floor area of 904 m^2 referred to previously. The air change rate of five is within the range of those measured in several multi-story buildings (Tamura and Shaw 1978). The exhaust rate required to produce a negative pressure of 25 Pa decreased as the supply air rate for floor pressurization was increased.

TEST PROCEDURE

Initially, each smoke control system was tested under nonfire conditions with all stair doors closed. This was followed by opening stair doors on the fire floor, the first floor (exit to outdoors), and the one above the fire floor. These tests were conducted first with the exterior wall vents on the second floor closed and, secondly, with them open. Pressure differences throughout the fire tower were measured and, for each test condition with the stair door open on the second floor, the average air velocity at this opening was obtained by conducting a 21-point hot wire anemometer traverse. The duration of each test was at least 15 minutes.

TABLE 2
Description of Smoke Control Systems

Description of Smoke Control Systems

Mechanical Smoke Exhaust System (MSES)

No Supply Air for Pressurization

Second Floor Exhaust
25 Pa across stair door
Exhaust Rate - 4.42 m^3/s

Zone Control System (ZSC)

Pressurization of Floors 1 and 3 – 25 Pa

Supply Air Rate on	Floor 1 –	1.27 m^3/s
	Floor 3 –	1.21 m^3/s
	Total	2.48 m^3/s

Second Floor Exhaust
25 Pa across stair door with Floors 1 and 3 pressurized
Exhaust Rate – 3.73 m^3/s

Pressurized Building Method of Smoke Control (PBSC)

Building Pressurization - 25 Pa (ref pressure inside)

Supply Air to Floors 1, 3 – 10
Total Outside Supply Air Rate – 4.90 m^3/s

Second Floor Exhaust
25 Pa across stair door with building pressurization (ref pressure fire floor)
Exhaust Rate – 3.23 m^3/s

The nonfire tests were followed by fire tests conducted under the following conditions:

- At a fire temperature of 450°C and with the exterior wall vents on the second floor closed, the door-opening sequence mentioned previously was followed. When a smoke backflow at the stair door opening on the second floor was observed, the stair door was gradually closed until backflow was prevented and the door angle noted.
- At a fire temperature of 650°C and with exterior wall vents open (simulating broken windows), a test procedure similar to the one for the 450°C test was followed.

Tests were also conducted to determine the performance of the smoke exhaust system with the damper on the fire floor open but with dampers on a few other floors open as well. All tests were conducted with a wind speed of less than 20 Km/h to minimize the effect of wind on building pressures.

RESULTS AND DISCUSSIONS

Nonfire Condition

The airflow and pressure difference patterns for the three systems are shown in Figures 3, 4, and 5. For all

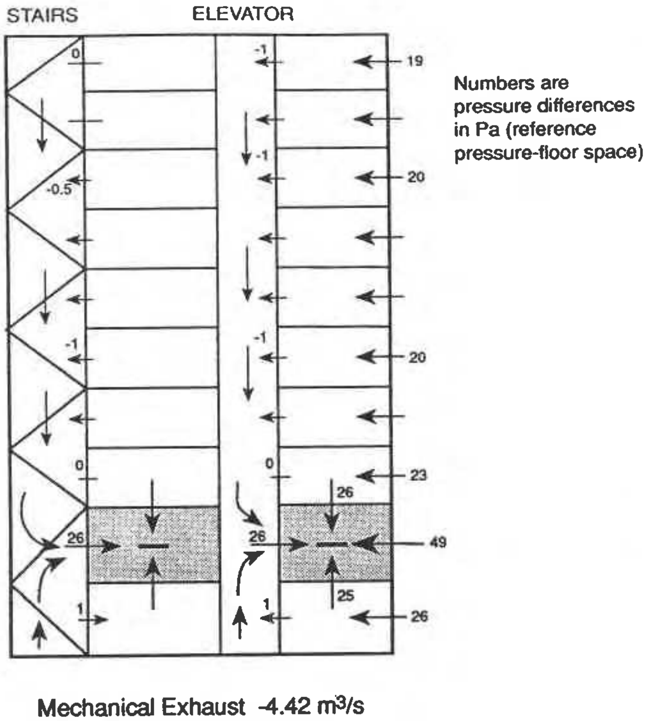

Figure 3 *Airflow and pressure difference patterns caused by mechanical smoke exhaust system (MSES)—nonfire.*

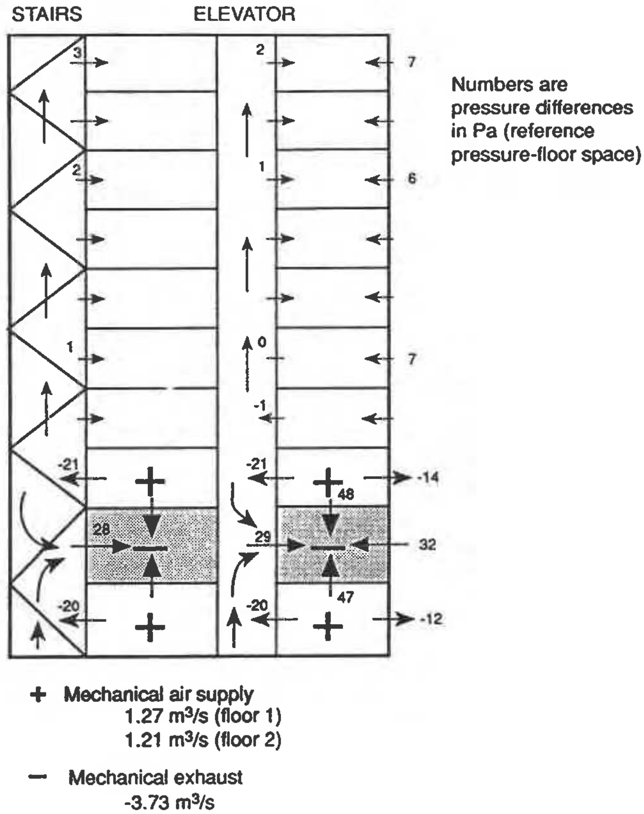

Figure 4 *Airflow and pressure difference patterns caused by zoned smoke control (ZSC)—nonfire.*

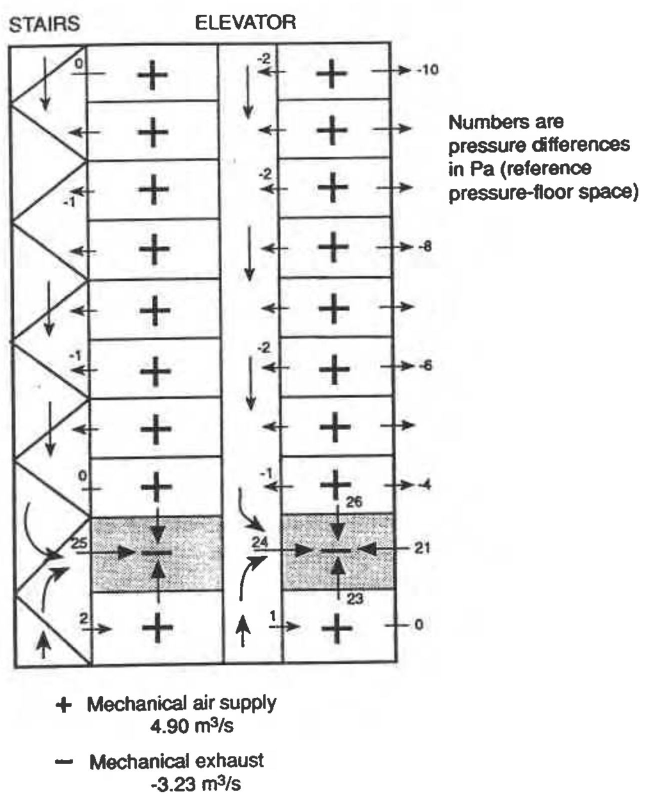

Figure 5 *Airflow pressure difference patterns caused by pressurized building method of smoke control (PBSC)—nonfire.*

three systems, the direction of airflow is into the fire floor from stairs, elevator, and service (not shown) shafts, from floors above and below, and from the outdoors. For MSES and PBSC, air flowed from the floor spaces into stair and elevator shafts and out from them into the floor space of the second floor. For ZSC, the direction of flow was from the stair and elevator shaft into floor spaces, except on the first and third pressurized floors, where the direction of flow was from the floor spaces into the stairshaft to pressurize the stairshaft. Also for the ZSC, the pressure differences across the floor and ceiling constructions of the second floor were about double those of MSES and PBSC.

For MSES, the entire building, along with the second floor, was depressurized with pressure differences across the outside walls of 19 to 26 Pa, except for the second floor, which were about double these values. For ZSC, except for floors 1 and 3, which were pressurized, the remainder of the floors were depressurized but much less than for MSES. The pressure differences across the outside walls on floors 1 and 3 were about 6 to 7 Pa. For PBSC with an initial pressurization of 25 Pa with respect to outdoor pressures, the pressure difference across the outside walls was reduced to 0 on the first floor and to 10 Pa on the tenth floor when the second floor was exhausted to produce a pressure difference across the stair door of 25 Pa.

Table 3 gives the average air velocities at the open stair door on the second floor during nonfire tests with the second floor outside wall vents closed. When the stair door on the second floor was opened, the air velocities at the stair door opening for the three systems were less than 1 m/s, the value specified in some building codes to prevent smoke backflow at this opening. The air velocities through open doorways required to prevent smoke backflow for various fire temperatures are given in Figure 6 (Tamura 1991).

The flow of air into the second floor through the open stair door resulted in an increase in pressures on the second floor, which reduced the pressure difference across the elevator shaft from 25 Pa to about 15 Pa for the three systems. Air velocities at the stair door on the second floor increased when additional stair doors were opened, accompanied by a further reduction in the pressure difference across the elevator shaft walls. These were more than 1 m/s when the stair doors of floors 2 and 3 were opened and more than 2 m/s when the stair doors of floors 2 and 1 were opened and when stair doors on floors 1, 2, and 3 were opened.

Table 3 also lists cases with the outside wall vents on the second floor open during which the air velocities were much lower compared to those with the outside wall vents closed.

TABLE 3
Comparison of Air Velocity at Open Stair Door and Pressure Difference Across Elevator Door on the Second Floor—Nonfire Tests, Summer Condition

	Mechanical Exhaust (MSES)		Zone Smoke Control (ZSC)		Pressurized Building (PBSC)	
Outside Wall Vents Closed						
Open Doors on Floor:	Stair Air Vel m/s	Elev Press Diff Pa	Stair Air Vel m/s	Elev Press Diff Pa	Stair Air Vel m/s	Elev Press Diff Pa
2	0.60	17	0.93	14	0.56	15
2, 3	0.98	–	1.35	–	1.14	8
2, 1	2.21	0	–	–	2.32	8
2, 1, 3	2.23	3	2.44	2	–	–
Outside Wall Vents Open						
Open Doors on Floor:						
2	0.31	3	0.39	5	0.45	9
2, 3	0.43	3	1.13	2	–	–
2, 1	1.63	0	–	–	1.07	8
2, 1, 3	1.60	1	2.22	1	1.20	6

*Reference pressure – floor space

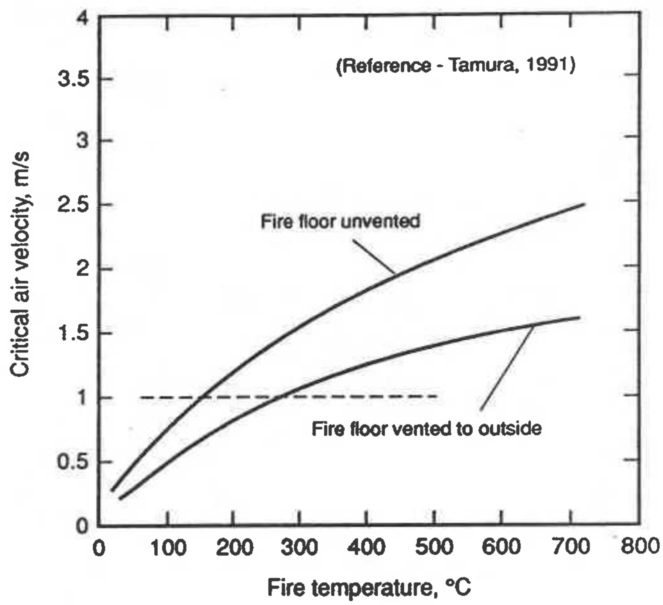

Figure 6 *Critical air velocity vs. fire temperature.*

Fire Conditions

The results of fire tests (450°C with outside wall vents closed and 650°C with outside wall vents open) with all stair doors closed indicated that the three smoke control systems maintained positive pressurization around the fire floor to confine smoke to this floor while maintaining the remainder of the building smoke free. This was essentially the case for the zoned smoke control system tested by Klote (1990) with a wood crib fire in a seven-story building.

The results of the fire tests for open stair doors, given in Table 4, indicate that, with a fire temperature of 450°C and the outside wall vents on the second floor closed, smoke backflow occurred when the stair door was opened on the second floor. Smoke backflow also occurred when the stair doors were opened on the second and third floors. Smoke backflow was prevented when the open stair door angle was reduced from 90° to 10° for MSES, to 13° for ZSC, and to 16° for PBSC with only the stair door on the second floor open. When the stair door on the third floor was also opened, the door angles required to prevent smoke backflow were 14° for MSES, 48° for ZSC, and 56° for PBSC.

When stair doors were opened on floors 2, 1, and 3, smoke backflow was prevented for MSES and ZSC. The data are missing for PBSC, but presumably no smoke backflow occurred for this system either, as the door angle to prevent smoke backflow with stair doors open on floors 2 and 1 was 76°. However, with an increase in the flow of air through the stair door opening, the pressures in the fire floor increased to reverse the pressure difference across the elevator shaft wall, causing smoke to flow from the fire floor into the elevator shaft for MSES and ZSC. With MSES for cases with the stair doors open on floors 1 and

TABLE 4

Comparison of Smoke Backflow at Open Stair Door and Door Open Angle Required to Prevent Smoke Backflow—Fire Tests, Summer Condition*

	Mechanical Exhaust (MSES)	Zone Smoke Control (ZSC)	Pressurized Building (PBSC)
Fire 450°C, Outside Wall Vents Closed			
Open Stair Doors on Floor:			
2	SB (10°)	SB (13°)	SB (16°)
2, 3	SB (14°)	SB (48°)	SB (56°)
2, 1	NSB	–	SB (76°)
2, 1, 3	NSB	NSB	–
Fire 650°C, Outside Wall Vents Open			
Open Stair Doors on Floor:			
2	–	SB (13°)	SB (13°)
2, 3	–	SB (50°)	SB (46°)
2, 1	–	–	NSB
2, 1, 3	–	SB (46°)	NSB

* No Smoke Backflow – NSB
Smoke Backflow – SB
Door Angle to Prevent Smoke Backflow – (°)

3, and also floors 2, 1, and 3, the flow direction at the holes in the floor of floor 3 (representing floor leakage openings) was from floor 2 (the fire floor) into floor 3 and, from there, into the vertical shafts. The maximum stair temperatures recorded with only the stair door on the second floor open were 139°C for MSES, 107°C for ZSC, and 112°C for PBSC. They decreased to normal temperatures at floor 5. Stair temperatures were much lower when additional stair doors were opened.

With a fire temperature of 650°C and with a total exterior wall vent area of 0.93 m^2 (Table 4), smoke backflow occurred with the stair door open on floor 2 and also with doors open on floors 2 and 3 for ZSC and PBSC. No fire tests at 650°C were run for MSES. No smoke backflow occurred for PBSC when stair doors were opened on floors 1 and 2 and also on floors 1, 2, and 3, whereas with ZSC, smoke backflow occurred when stair doors on floors 1, 2, and 3 were opened. The case with open stair doors on floors 1 and 2 was not run. It is likely that smoke backflow would have occurred for this case as well. For both low- and high-temperature fire tests, pressure differences across the walls of the elevator shaft were more favorable in preventing smoke flow into this shaft for PBSC than for ZSC.

Table 5 shows the smoke concentration patterns with open stair doors on floors 1 and 2 for MSES and floors 2 and 3 for ZSC and PBSC and for a fire temperature of 450°C and with the exterior wall vents closed. From the smoke obscuration viewpoint, an area is assumed to be

TABLE 5

Smoke Concentration Patterns with Open Stair Doors—Fire Tests, Summer Condition

Floor	Smoke Exhaust (MSES) Smoke conc., %			Zone Control (ZSC) Smoke conc., %			Pressurized Building (PBSC) Smoke conc., %		
	Stair	Elev	Floor	Stair	Elev	Floor	Stair	Elev	Floor
10	8	0	1	2	0	0	0	0	0
8	16	0	7	6	0	0	0	0	0
6	9	0	6	5	0	0	0	0	0
3	17	0	16	4	0	0	2	0	2
2	5	0	100	3	0	100	3	0	100
1	0	0	1	0	0	0	0	0	0.

Notes:
Smoke Density – % of that in the burn area of the second floor
Fire temperature – 450°C; outside wall vents on second floor closed
Stair doors open on Floors 1 and 2 for MSES
Stair doors open on Floors 2 and 3 for ZSC and PBSC

reasonably safe if it is not contaminated to an extent greater than 1% of that in the vicinity of the burn area (McGuire et al. 1970). The concentration of CO_2, as one combustion product, can be considered as a surrogate indicator of smoke and is expressed as a percentage of the concentration of CO_2 in the burn area of the second floor. For MSES, stairshafts and several floor spaces were contaminated with smoke (with concentrations above 1%), whereas only the stairshaft was contaminated for ZSC and the stairshaft and the floor space of the third floor were contaminated for PBSC.

When stair doors were opened on floors 1, 2, and 3, smoke concentrations were between 1% and 2% on the floor spaces of floors 3, 4, 8, and 9 for ZSC and between 3% and 18% for MSES. The smoke concentration pattern remained the same for PBSC when the stair doors were opened on floors 2, 3, and 5.

Tests conducted at the same fire temperatures for combined mechanical venting and stair pressurization systems (Tamura 1990) kept the stairshaft free of smoke with up to four open stair doors, although the remainder of the tower was contaminated with smoke. In general, to cope with the adverse effect of opening doors, which can disrupt the effective operation of most smoke control systems, the fire temperatures and hence fire pressures need to be reduced by installing fire suppression systems. As well, the area of stair door opening should be reduced by installing vestibules to stair door access.

The Effect of Open Smoke Dampers to the Exhaust Shaft on Floors Other than the Fire Floor

Mechanical exhaust of the fire floor was common to all three systems tested. The exhaust system consisted of a vertical shaft with a closed damper in the wall of the shaft on each floor and a fan on top of the shaft to exhaust above the roof to the outdoors. In the event of a fire, only the

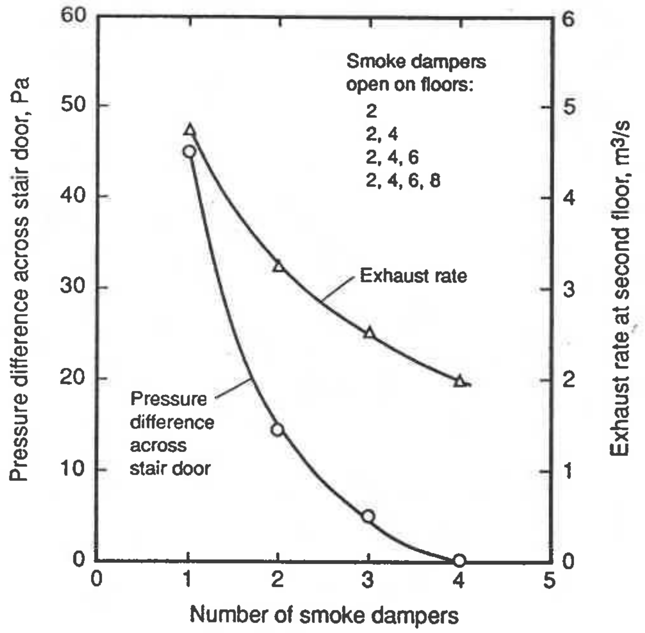

Figure 7 *Effect of open smoke dampers on exhaust rate and pressure difference across stair door on second floor.*

damper on the fire floor is supposed to be opened to exhaust to the outside. The rate of exhaust can be seriously affected if dampers on floors other than the fire floor are also opened.

To investigate this, a nonfire test was conducted with an exhaust shaft (damper area of 0.49 m^2) in the experimental fire tower with the second floor as the fire floor. Initially, a damper on the second floor was opened and this floor was exhausted at 4.72 m^3/s to produce a pressure difference across the stair door of 44 Pa. Dampers on floors 4, 6, and 8 were then opened in succession while the exhaust rates and the pressure differences across the stair door were recorded.

The results of the test are shown in Figure 7. When a damper on the fourth floor was opened, the exhaust rate was reduced by 31% and the pressure difference across the stair door by 68%. When, in addition, the damper on the sixth floor was opened, the reductions were 49% for the exhaust rate and 91% for the pressure difference; with the damper on the eighth floor also opened, they were 60% and about 100%, respectively.

When a building is pressurized and the mechanical exhaust system is malfunctioning, as when dampers are inadvertently opened or left open, the pressures on the fire floor would be higher than outside. In such a case, when a stair door on the fire floor and an exit door on the ground floor are open, smoke is likely to flow into the stairshaft and down and out through the exit door to the outdoors to hamper evacuation.

As seen in Figure 7, failure of even one damper to close can greatly reduce the exhaust rate on the fire floor and the required pressure difference across the stair door. Hence, some means of monitoring the opening and closing of dampers at the central control station are needed during a fire, as well as for periodic maintenance checks. In this respect, a dedicated system would normally have all the smoke dampers closed and, in the event of fire, only the smoke damper on the fire floor would be opened. This would be more reliable than using a central return air system as exhaust, which would require closing all branch dampers except the one on the fire floor.

SUMMARY

The performances of the mechanical smoke exhaust system (MSES), zoned smoke control (ZSC), and pressurized building method of smoke control (PBSC) were evaluated under nonfire and fire conditions. The results of the tests are as follows:

- All three systems prevented smoke spread when all stair doors were closed.
- For fire tests at 450°C with exterior wall vents closed and two stair doors, including the one on the fire floor, opened, the stairs and all floor spaces were contaminated with smoke for MSES, only part of the stairshaft was moderately contaminated with smoke for ZSC, and only the stairshaft and floor above the fire floor were contaminated with smoke for PBSC. When one additional door was opened, a number of floor spaces were moderately contaminated with smoke for ZSC, whereas the extent of contamination remained the same for PBSC.
- It was shown that, even when one extraneous smoke damper was opened, the exhaust rate of the fire floor and the favorable pressure difference across the stair door were decreased drastically.

When stair doors are opened, smoke contamination of the stairshaft and other areas of a building can be expected. This was also the case for stair pressurization systems (Tamura 1992). Sprinkler systems would reduce fire pressures and, hence, reduce the amount of smoke backflow. Lobbies to stairshafts would minimize the number of stair door openings by permitting either the stair door or the vestibule door to be closed while entering or leaving the stairshaft. Further tests of these smoke control systems under sprinklered fire conditions are required.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the contributions of D.W. Carpenter and V.A. Fortington in carrying out tests in the experimental fire tower.

REFERENCES

Klote, J.H. 1990. Fire experiments of zoned smoke control at the Plaza Hotel in Washington, D.C. *ASHRAE Transactions* 96(2): 399-416.

Klote, J.H., and J.W. Fothergill, Jr. 1983. *Design of smoke control systems for buildings*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

McGuire, J.H., G.T. Tamura, and A.G. Wilson. 1970. Factors in controlling smoke in high buildings. *ASHRAE SymposiumBulletin, Fire Hazards in Buildings*, San Francisco, CA.

NRCC. 1990. Supplement to the National Building Code of Canada. Chapter 3, Measures for fire safety in high buildings, pp. 69-130. Ottawa: National Research Council of Canada.

Shaw, C.Y., D.M. Sander, and G.T. Tamura. 1973. Air leakage measurements of the exterior walls of tall buildings. *ASHRAE Transactions* 79(2): 40-48.

Tamura, G.T. 1990. Fire tests of stair pressurization systems with mechanical venting of the fire floor. *ASHRAE Transactions* 96(2): 384-392.

Tamura, G.T. 1991. Determination of critical air velocities to prevent smoke backflow at a stair door opening in the fire floor. *ASHRAE Transactions* 97(2): 627-633.

Tamura, G.T. 1992. Assessment of stair pressurization systems for smoke control. *ASHRAE Transactions* 98(1): 66-72.

Tamura, G.T., and C.Y. Shaw. 1976. Air leakage data for the design of elevator and stair shaft pressurization systems. *ASHRAE Transactions* 82(2): 179-190.

Tamura, G.T., and C.Y. Shaw. 1978. Experimental studies of mechanical venting for smoke control in tall office buildings. *ASHRAE Transactions* 84(1): 54-71.