

## **THE CAPABILITIES OF SMOKE CONTROL: FUNDAMENTALS AND ZONE SMOKE CONTROL**

**John H. Klote**

**Center for Fire Research**

**National Institute of Standards and Technology**

**Gaithersburg, Maryland, U.S.A. 20899**

**Edward K. Budnick**

**Hughes Associates, Inc.**

**Wheaton, Maryland, U.S.A. 20902**

### **SUMMARY**

This paper discusses the principles of smoke control and the practical application of these principles to zoned smoke control systems. Zoned smoke control can use dedicated fans or the fans of a building's heating, ventilating and air conditioning (HVAC) systems. Application of HVAC systems that serve one or many smoke control zones are discussed. The paper discusses concerns with systems that only purge in an attempt to control smoke movement. Considerations of system activation and acceptance testing are presented.

### **INTRODUCTION**

Many of the concepts presented in this paper were first consolidated and systematically presented in the ASHRAE Smoke Control Manual<sup>1</sup>. These concepts are presented here with an insight gained by years of interaction with users of the manual, including fire protection engineers, mechanical engineers, and code officials. The methods of analysis presented in the ASHRAE manual are still valid, and so no equations are presented in this paper. In addition, the problems of smoke purging are addressed.

Because smoke control is still in the early stages of development, no widely accepted view has emerged as to appropriate applications of this new fire protection tool. Much is known about the physical capabilities of smoke control technology, however there are still widely divergent opinions among the experts concerning many practical points of applying this technology. Areas where differences of opinion exist are identified and discussed in this paper. This paper and the ASHRAE Smoke Control Manual do not address the problems of smoke management of atriums and other large spaces. However, the NFPA Smoke Management Systems Committee is developing a document to address the design of these systems.

This paper discusses the principles of smoke control and the application of these principles to zoned smoke control systems. The term "smoke" is used in this paper in accordance with the definition in NFPA 92A<sup>3</sup> to mean the air-

borne solid and liquid particulates and gases evolved when a material undergoes pyrolysis or combustion, together with the quantity of air that is entrained or otherwise mixed into the mass.

### **PRINCIPLES OF SMOKE CONTROL**

The ASHRAE Smoke Control Manual, NFPA 92A, and this paper consider a smoke control system to be an engineered system that uses mechanical fans to produce airflows and pressure differences across smoke barriers to limit and direct smoke movement. Thus, smoke control uses the barriers (walls, floors, doors, etc.) used in traditional smoke management in conjunction with airflows and pressure differences generated by mechanical fans.

Figure 1 illustrates a pressure difference across a barrier acting to control smoke movement. Within the barrier is a door. The low pressure side of the door is exposed to smoke from a fire. The high pressure side is an area to be protected from smoke. Airflow through the gaps around the door and through other construction cracks prevents smoke infiltration to the high pressure side.

When the door in the barrier is opened, airflow through the open doorway results. When the air velocity is low, smoke can flow against the airflow into the "protected area", as shown in Figure 2. This smoke backflow can be prevented if the air velocity is sufficiently large, as shown

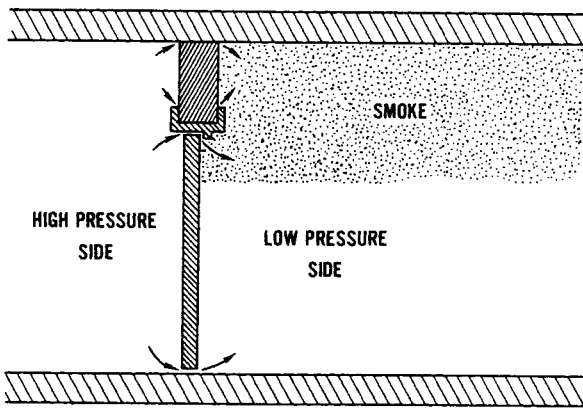


Figure 1. Pressure difference across a barrier of smoke control system preventing smoke infiltration to the high pressure side of the barrier.

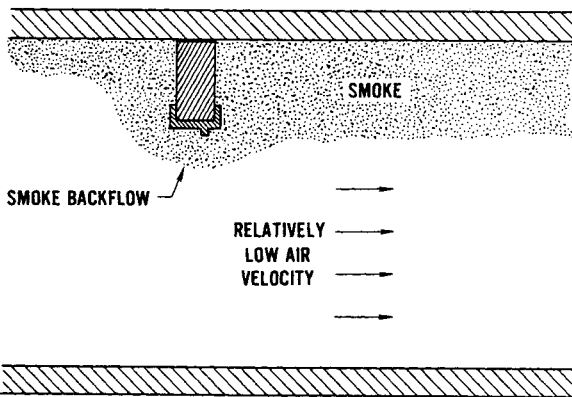


Figure 2. Smoke backflow against low air velocity through an open doorway.

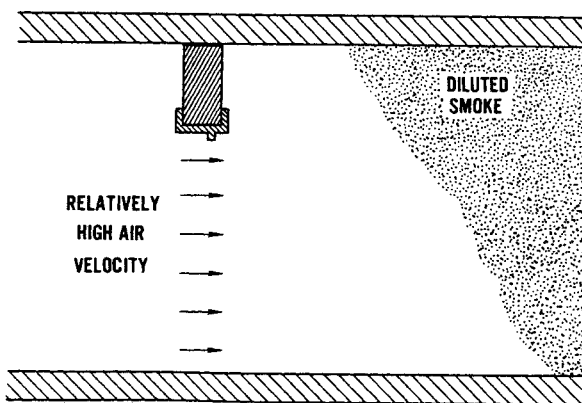


Figure 3. No smoke backflow with high air velocity through an open doorway.

in Figure 3. The magnitude of the velocity necessary to prevent backflow depends on the energy release rate of the fire, and a method of estimating it was developed by Thomas<sup>4</sup>.

Two basic principles of smoke control can be stated as follows:

- Airflow by itself can control smoke movement if the average velocity is of sufficient magnitude.
- An air pressure difference across a barrier can act to control smoke movement.

The use of air pressure differences across barriers to control smoke movement is frequently referred to as pressurization. Pressurization results in airflows through the small cracks and gaps in barriers, thereby preventing smoke backflow through these openings. Therefore, in a strict physical sense, the second principle is a special case of the first principle. However, considering the two principles as separate is advantageous for engineering applications of smoke control. For a barrier with one or more large openings, air velocity is the appropriate physical quantity for both design and testing. When there are only small cracks, as around closed doors, designing to and testing for air velocities is impractical. In this case, the appropriate quantity is pressure difference.

The ASHRAE Smoke Control Manual discusses Thomas' methods of estimating the necessary critical air velocity needed to prevent smoke backflow through a corridor, and this method can be used to obtain an estimate for an open doorway or other large opening. This critical velocity depends on the energy release rate and the width of the opening. A room fully involved in fire could have an energy release rate on the order of  $8 \times 10^6$  Btu/hr. (2.3 MW), and for this fire a critical velocity of about 800 fpm (4.06 m/s) would be needed in order to prevent smoke backflow through a 3 ft (0.9m) wide doorway. A wastebasket fire might be on the order of  $0.43 \times 10^6$  Btu/hr (126 kW). To protect against smoke backflow during this smaller fire, a velocity of about 300 fpm (1.52 m/s) is needed for the same door width. Smoke from a sprinklered fire may be considered to be near ambient temperature due to the cooling effect of water spray. Thomas' method is not appropriate for the small temperature differences due to a sprinklered fire. Based on an analysis by Shaw and Whyte<sup>5</sup>, for a temperature difference of only 3.6°F (2 K), an average velocity of 50 fpm (0.25 m/s) would be needed to prevent smoke backflow.

There are two problems with controlling smoke from unsprinklered fires by airflow. First, the air flow rates are very great requiring expensive fans. Second, the large flows can result in unacceptably large door opening forces at locations away from the large opening. (Acceptable door opening forces are discussed later.) Therefore, airflow is not normally relied on as the primary means to achieve smoke control in buildings. Airflow is appropriate for special applications such as tunnels, but it is not discussed further in this paper.

Pressurization is almost always the means by which smoke control is achieved in buildings. However, the effect of open doors in these barriers must be considered. If doors are opened for only the short time necessary for a person to escape a smoke contaminated space, the resulting small amount of smoke escaping into the protected area probably will not adversely affect the performance of the smoke control system. The potential danger of open doors in smoke barriers needs to be evaluated for each application, keeping in mind the fire evacuation plan and the total fire protection system of the building.

### ZONED SMOKE CONTROL CONCEPT

A building can be divided into a number of smoke zones, each separated from the others by partitions and floors. In the event of a fire, pressure differences produced by mechanical fans are used to limit the smoke spread to the zone in which the fire initiated. The concentration of smoke in this zone goes unchecked. Accordingly, in zoned smoke control systems, it is intended that occupants evacuate the smoke zone as soon as possible after fire detection.

Frequently, each floor of a building is chosen to be a separate smoke control zone. However, a smoke control zone can consist of more than one floor, or a floor can consist of more than one smoke control zone. Some arrangements of smoke control zones are illustrated in Figure 4. When a fire occurs, all of the non-smoke zones in the building, or only zones adjacent to the smoke zone, may be pressurized. When the fire floor is exhausted and only adjacent floors are pressurized as in Figure 4(b), the system is sometimes called a "pressure sandwich." Venting of smoke from the smoke zone is important because it prevents significant over-pressures due to thermal expansion of gases as a result of a fire. Venting can be accomplished in three ways:

- exterior wall vents,
- smoke shafts, and
- mechanical venting (or exhaust).

When the first two methods of venting are used, it is essential that adjacent zones (or all non-smoke zones) be pressurized, in order to maintain pressure differences at the boundaries of the smoke zone. Mechanical exhaust by itself can result in sufficient pressure differences for smoke control. However, in the event of window breakage or a large opening to the outside from the smoke zone, mechanical exhaust might not be able to assure favorable pressure differences. For this reason, it is recommended that mechanical exhaust be used in conjunction with pressurization of adjacent spaces when there is a significant probability of window breakage or some other large opening between the smoke zone and the outside.

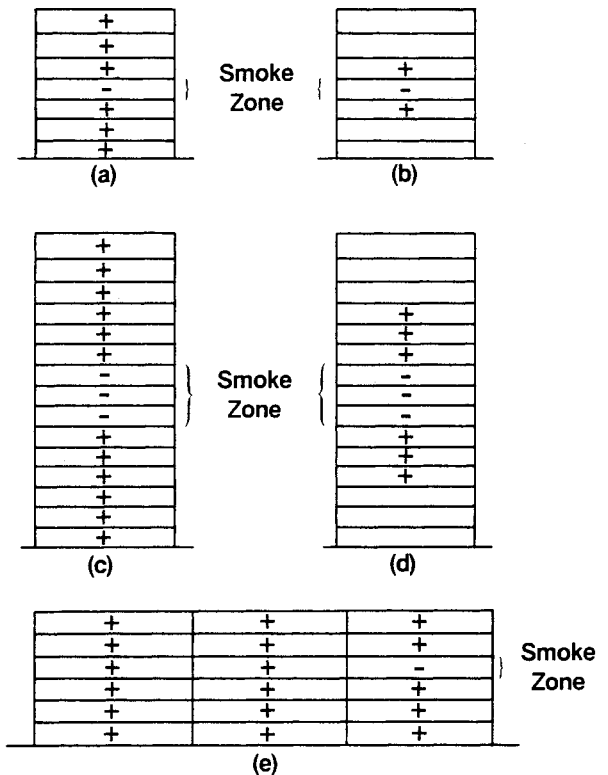
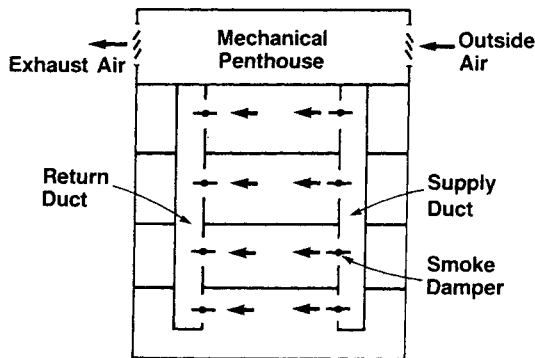


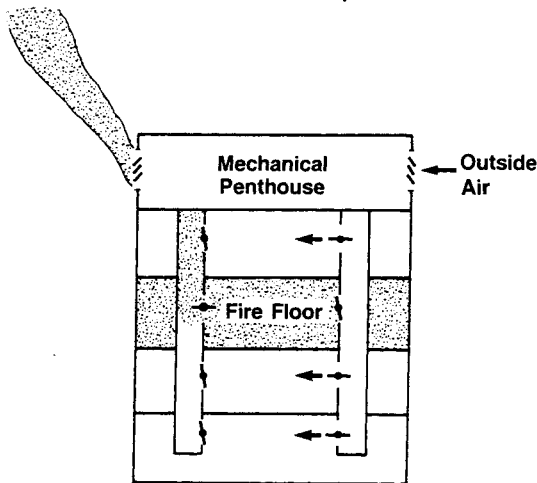
Figure 4. Some arrangements of smoke control zones. NOTE: In the above figures the smoke zone is indicated by a minus sign and pressurized spaces are indicated by a plus sign. Each floor can be a smoke control zone as in (a) and (b) or a smoke zone can consist of more than one floor as in (c) and (d). All of the non-smoke zones in a building may be pressurized as in (a) and (c) or only non-smoke zones adjacent to the smoke zone may be pressurized as in (b) and (d). A smoke zone can also be limited to a part of a floor as in (e).

While zoned smoke control can be accomplished by dedicated fans, systems that use the building's HVAC system fans are most common. For zoned smoke control the HVAC fans function as follows:

- **Smoke Zone.** In the smoke zone, 100 percent of the return air is exhausted to the outside and supply air to the smoke zone is shut off.
- **Non-Smoke Zones.** In the non-smoke zones, supply air is 100 percent outside air and the exhaust air is shut off.



Normal HVAC Operation



Smoke Control Operation with 3rd Floor as the Fire Floor

Figure 5. Schematic of smoke control system using an HVAC system that serves many smoke control zones  
NOTE: 1) Smoke control is achieved by closing the smoke damper in the supply duct to the smoke zone and by closing the smoke dampers in the return duct to the other zones. Return air damper (not shown) must be closed to prevent smoke from being pulled into supply air. 2) For simplicity, distribution ducts on each floor and equipment in the penthouse are not shown.

## HVAC SYSTEM SERVING MANY ZONES

In many buildings, the HVAC system serves many zones as illustrated in Figure 5. For such a system, smoke control is achieved by the following sequence upon fire detection:

- The smoke damper in the supply duct to the smoke zone is closed.
- The smoke dampers in the return duct to non-smoke zones are closed.
- If the system has a return air damper, it is closed.

This pressurizes the non-smoke zones and acts to prevent smoke infiltration of them.

In this paper the term "smoke damper" is used to mean a damper that has been leakage classified in accordance with the standard UL 555S<sup>6</sup>. As a convenience to the reader, a general description of the standard follows. UL 555S is a test method for leakage rated dampers intended for use in heating, ventilating, and air conditioning systems. The test method includes construction requirements and tests for cycling, temperature degradation, duct loading exposure, salt-spray exposure, and air leakage. These smoke dampers are classified as 0, I, II, III, or IV leakage rated dampers which are tested at 250°F (121°C) or at an higher temperatures in increments of 100°F (55°C) above 250°F (121°C). The leakage rates for the differ-

Table 1. Leakage classifications for smoke dampers<sup>6</sup>  
Leakage ft<sup>3</sup>/min/ft<sup>2</sup> (m<sup>3</sup>/s/m<sup>2</sup> x 196)

Classification	At 1 Inches Water	At 4 Inches Water
	(0.249 kPa)	(0.995 kPa)
0	0	0
I	4	8
II	10	20
III	40	80
IV	60	120
Extended Static Range	At 8 Inches Water	At 12 Inches Water
	(1.99 kPa)	(2.99 kPa)
0	0	0
I	11	14
II	28	35
III	112	140
IV	168	210

ent classifications are listed in Table 1. Class 0 dampers with zero leakage under this test method are commonly used at nuclear power plants. Generally, the classes I, II, III and IV are considered appropriate for smoke control in other types of buildings.

The particular class of damper specified should be selected based on the requirements of the application. For example, the dampers in the supply and return ducts shown in Figure 5 can have some leakage without adversely affecting smoke control system performance. Thus a designer might select class II, III or IV smoke dampers for such an application. Further, a designer might choose class I dampers for applications that require a very tight damper (for example the return damper illustrated in Figures 6 and 7).

Some designers have eliminated the smoke

dampers from the return air system in the mistaken belief that the resulting system would still be effective. This idea consists of shutting a smoke damper in the supply to the smoke zone and relying on the return air being pulled from a zone would produce a significant pressure difference. However, shutting the supply to the smoke zone lowers the pressure there and for these supply-damper-only systems the return air flow from the smoke zone is also reduced. Field tests on such systems sponsored by the U.S. Veterans Administration have indicated that these supply-damper-only systems produce insignificant pressure differences<sup>7</sup>. Thus supply-damper-only systems are not recommended. In a fire situation, these small pressure differences can be overcome by buoyancy of hot smoke, stack effect or other normally occurring building air flows. Figure 8 illustrates the failure of a supply-damper-only

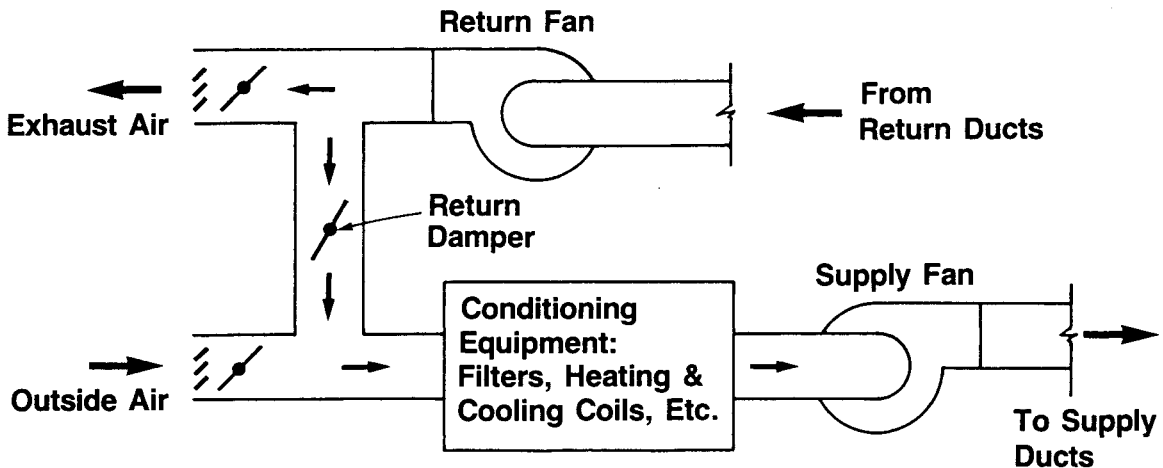


Figure 6. HVAC system with supply and return fans and recirculation capability in the normal HVAC mode.

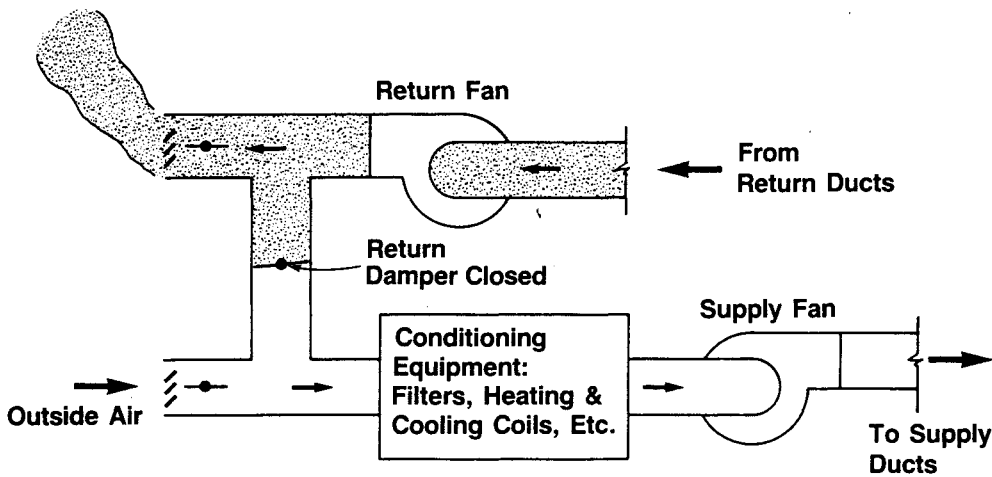
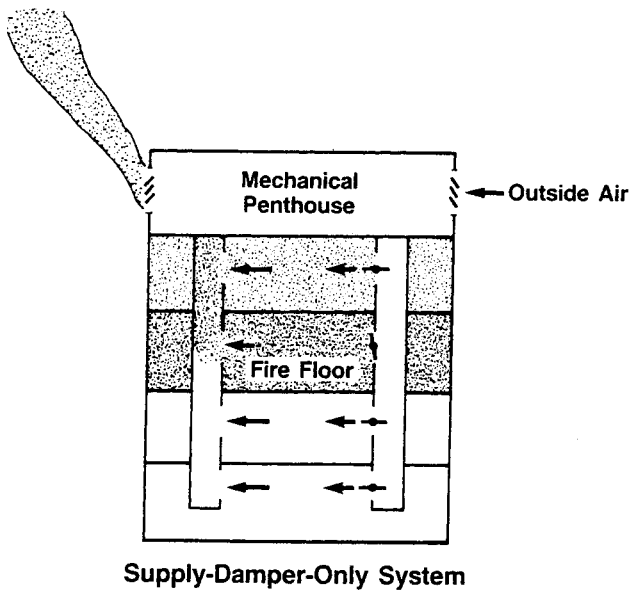


Figure 7. HVAC system with supply and return fans and recirculation capability in the smoke control HVAC mode.



**Supply-Damper-Only System**

Figure 8. Schematic of failure to achieve smoke control by only shutting a smoke damper in the supply duct to the smoke zone

NOTE: 1) This system is not recommended because it generally does not achieve satisfactory pressure differences to control smoke. 2) For simplicity distribution ducts on each floor and equipment in the penthouse are not shown.

system to control smoke movement with resulting smoke flow to the floor above the fire floor due to buoyancy or stack effect. (The computer model for analysis of smoke control systems, ASCOS<sup>®</sup>, can be used to demonstrate the problem with supply-damper-only systems.)

Precautions must be taken to minimize the probability of smoke feedback into the supply air system. Of course exhaust air outlets must be located away from outside air intakes. To conserve energy, most HVAC systems in modern commercial buildings have the capability of recirculating air within building spaces. During normal HVAC operation, the return damper is completely or partially open to allow air from building spaces to be mixed with outside air. This mixture is conditioned and supplied to building spaces to maintain desired temperature and humidity. This process is shown in Figure 6. During smoke control operation the return damper must be tightly closed to prevent smoke feedback into the supply air as is illustrated in Figure 7.

## HVAC SYSTEM SERVING ONE ZONE

For systems where the HVAC system serves only one smoke control zone, smoke control can be achieved by shutting down fans and closing

the return air damper. This kind of system was tested at two new Veterans Administration hospitals<sup>7</sup>, where each floor of each wing was a smoke control zone supplied by a separate HVAC system. This performed well, was especially simple and required no expensive dedicated equipment.

## SMOKE PURGING CAUTION

Dilution of smoke in a zone in which a fire occurs is not a means of smoke control. This process is sometimes referred to as smoke purging, smoke removal or smoke exhaust. Many people have unrealistic expectations about what this approach can accomplish. There is no theoretical or experimental evidence that using a building's HVAC system for smoke dilution will result in any significant improvement in tenable conditions within the fire space. It is well known that most HVAC systems promote a considerable degree of air mixing within the spaces they serve. Because of this and the fact that very large quantities of smoke can be produced by building fires, it is generally believed that dilution of smoke by an HVAC system in the zone in which there is a fire will not result in any practical improvement in the tenable conditions in that zone.

After fire fighters put out a fire, they purge smoke in order to determine that the fire is totally extinguished. This is accomplished by various methods including breaking of windows and use of portable fans. The HVAC system can also be used for this after the fire smoke purging. However, while the fire is burning, it is unrealistic to think that smoke purging will result in any significant improvement in tenable conditions within the fire zone.

## SYSTEM ACTIVATION

System activation is probably the major area of disagreement in the field of smoke control. Primarily, this disagreement is about automatic activation versus manual activation. In the early days of smoke control, there was general agreement that activation of "pressure sandwich" systems should be automatic upon alarm from smoke detectors. Automatic activation by smoke detectors located in building spaces has the clear advantage of fast response.

Some building designers and fire service officials began to realize that smoke detectors could go into alarm on a floor far away from the fire. Thus automatic activation by smoke detectors could result in pressurization of the zone in which the fire occurred. This could force smoke

into other zones. As a result, a vocal minority of officials feel that smoke control should only be activated manually by fire fighters after they are sure of the fire location. However, many involved professionals feel that such manual activation would be so late in the fire development that extensive hazard to life and property damage due smoke would have occurred.

The most recent view on the subject is that zoned smoke control should be automatically activated by an alarm from either heat detectors or sprinkler water flow. Obviously, this approach increases the likelihood of proper identification of the fire zone. For smoldering fires, this approach would result in significantly longer response time. However, for flaming fires, it is believed that the response time with this approach would be short enough so that significant benefit would be realized by the operation of the smoke control system. It is hoped that advances in smoke detector technology and application will improve significantly the ability of these detectors to positively identify the fire zone.

Throughout all this controversy, there was complete agreement that zoned smoke control should not be activated by alarms from pull boxes. The reason can be illustrated by the scenario of a man who observes a fire on an upper floor of a building and decides that the first thing he should do is to get out of the building. On the way down the stairs, he thinks of his responsibility to the other occupants. He stops on a lower floor long enough to actuate a pull box. If that alarm activated a zoned smoke control system, the wrong zone would be identified as the fire zone.

## **ACCEPTANCE TESTING**

Regardless of the care, skill and attention to detail with which a smoke control system is designed, an acceptance test is needed as assurance that the system, as built, operates as intended. Further, many smoke control systems will require adjustments of supply air flow rates or pressure relief vent openings to accommodate the particular leakage characteristics of the building in which they are located. These adjustments can be made in conjunction with the acceptance test. All measurements made during acceptance testing should be recorded and saved for inspection.

NFPA 92A provides a general description of acceptance tests intended to demonstrate that the final integrated system installation com-

plies with the specified design and functions properly. If standby power has been provided for the smoke control system, acceptance tests should be conducted with both normal power and standby power.

For zoned smoke control systems, one zone should be put into the smoke control mode, and the pressure differences at the boundaries of that zone should be measured. After smoke control operation in that zone has been deactivated, another zone should be tested in the same manner. This should be repeated until all smoke zones have been tested. Systems with automatic activation should be activated by putting an appropriate device into alarm.

For stairwell pressurization systems, pressure differences across each stairwell door should be measured with all stairwell doors closed. Then one door should be opened, and pressure difference measurements made at each closed stairwell door. This should be repeated until the number of doors required to be opened by the code authority have been opened.

The major problem with most smoke bomb tests of smoke control systems is that they are intended to test some improvement in smoke conditions in the zone where the fire is located. This is based on the mistaken belief that smoke control is capable of producing a significant improvement in tenable conditions within the zone where the fire is located. These tests are described here in general terms so that the reader can recognize this type of test and understand the problems with them. The smoke control system is put in operation. In the zone which is being exhausted, a number of smoke bombs are ignited. The smoke bombs produce all their smoke in a few minutes, and the zone rapidly fills with this chemical smoke. Because the smoke control system is exhausting air and the chemical smoke from this zone, the concentration of chemical smoke decreases with time. If at some specific time after ignition, a specific object (such as an exit sign) is visible by a human observer at a specific distance (such as 20 ft (6.1m)), the smoke control system is declared a success.

The problems with this type of smoke bomb test are numerous. The criterion for successful operation is subjective. Further, the potential danger of exposing the observer or other people to toxic chemical smoke must be dealt with. The obscuration resulting from smoke in a building fire is much different from that of

chemical smoke. Most flaming fires produce a dense black smoke, while smoke bombs produce a white smoke. At present, no information is available relating smoke obscuration of chemical smoke to that of smoke from building fires. These problems can be overcome by modifications to the test method. However, this would not yield a test relevant for a smoke control system. Because a smoke control system is intended to maintain pressure differences at the boundaries of the smoke zone, the system should be tested by measuring pressure differences. A very serious problem with this type of smoke bomb test is that it can give building occupants and fire service officials a false sense of security. The test can lead people to wrongly think that smoke control is capable of achieving a significant improvement in tenable conditions within the fire space.

Testing the performance of smoke control systems with chemical smoke from smoke bombs is not realistic for flaming fires in unsprinklered buildings. The flow of unheated chemical smoke may be similar to that of smoke from a sprinklered fire or a smoldering fire. However, the gases produced by a large flaming fire in a building are in the range of 1200 to 1800°F (650-980°C). For chemical smoke to produce the same buoyant pressure differences as these gases, the chemical smoke would have to be heated to the same temperatures. Obviously, this is impractical because of the associated danger to life and property.

Chemical smoke or a tracer gas (such as sulfur hexafluoride) can be used to test for smoke feedback into supply air. The general procedure for testing with chemical smoke is described here. A number of smoke bombs are placed in a container, and all bombs are simultaneously ignited. The container is located near the exhaust inlet in the smoke zone being tested so that all of the chemical smoke produced by the bombs is drawn directly into the exhaust air stream. If chemical smoke is detected in the supply air, its path should be determined and blocked, and the smoke feedback test should be conducted again.

Smoke bombs can be useful in locating the leakage paths that sometimes defeat a smoke control system. For example, if the construction of a stairwell is unusually leaky, pressurization of that stairwell may not be possible with fans sized for construction of average tightness. Chemical smoke generated within the stairwell will flow through the leakage paths and indicate their location so that they can be caulked or sealed.

## Summary

Smoke control employs the barriers (walls, floors, doors, etc.) used in traditional smoke management in conjunction with airflows and pressure differences generated by mechanical fans. Smoke can be controlled by pressurization or air flow. However, pressurization is almost always the means by which smoke control is achieved in building situations. Even though a smoke control system can protect building spaces outside of the zone of the fire, it will not reduce significantly the hazard in the fire zone itself. Zoned smoke control can be accomplished by use of dedicated fans or the fans of the building's HVAC system. For zoned smoke control the HVAC fans function as follows:

- **Smoke Zone.** In the smoke zone, 100 percent of the return air is exhausted to the outside and supply air to the smoke zone is shut off.
- **Non-Smoke Zones.** In the non-smoke zones, supply air is 100 percent outside air and the exhaust air is shut off.

For an HVAC system that serves more than one zone, zoned smoke control can be achieved by the use of dampers in the supply and return ducts. Supply-damper-only systems generally produce insignificant pressure differences and are not recommended.

Activation of zoned smoke control systems is a major area of disagreement in the field of smoke control. The idea of automatic activation by smoke detectors became unpopular when it was realized that detectors could go into alarm on a floor far away from the fire. Many feel that zoned smoke control systems should be activated automatically by water flow from sprinklers or heat detectors, while a vocal minority feel that activation should only be manually by the fire service. There is general agreement that zoned smoke control should not be activated by alarms from pull boxes.

The acceptance tests evaluating the performance of smoke control systems should consist of pressure measurement tests. Chemical smoke from smoke bombs is not recommended for testing the performance of these systems relative to possible reduction to the hazard in the zone of the fire. However, chemical smoke can be used to test for smoke feedback into supply air and to locate the leakage paths in construction that sometimes defeat a smoke control system.



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## CONVERSION FACTORS

Multiply	By	To Obtain
Btu	1055	J
Btu/hr	0.293	W
ft	0.3048	m
ft <sup>2</sup>	0.0929	m <sup>2</sup>
ft/min(fpm)	0.00508	m/s
ft <sup>3</sup> /min(cfm)	4.27 x 10 <sup>-4</sup>	m <sup>3</sup> /s
ft <sup>3</sup> /min(cfm)	0.472	L/s
inch water gage (in H <sub>2</sub> O)	248.8	Pa
mile per hour(mph)	0.447	m/s
pound mass (lbm)	0.454	kg
pound(lb)	4.448	N
pound per square inch(psi)	6895	Pa
lbm/ft <sup>3</sup>	16.0	kg/m <sup>3</sup>

Note: The conversion factors have been rounded off to three or four significant figures.