

# An Overview to Designing Smoke-Control Systems

By Chas E. Magdanz, P.E., Member ASHRAE

**F**ire professionals use seconds as the unit of time for suggesting evacuation times from buildings.<sup>1,2</sup> Fires grow rapidly, and smoke — the primary killer — spreads much faster than fire. ♦ The logical response to a fire is to flee. However, it is difficult to flee quickly from large-volume buildings, tall buildings, transit tunnels, and underground buildings. Flight can be impossible for physically disabled people, penal inmates, some hospital patients (e.g., critically ill or undergoing surgery), and security personnel at sensitive installations. For these types of buildings and occupants, smoke-control systems provide an added measure of protection.

This article provides an introduction to smoke-control systems and concludes with a list of typical preparations needed for designing smoke-control systems and a list of common design challenges.

## Terminology

The term smoke management is an all-inclusive term that covers physical features, equipment, and methods used separately or in combination to control the movement of smoke. Physical features are passive elements such as smoke resistive construction. Equipment includes items such as fans, operable windows, and smoke detectors. Methods are design schemes such as compartmentation, smoke venting, and smoke control. Compartmentation uses physical features designed to control smoke movement by passively containing it within the smoke-source area. Smoke venting uses non-ducted, stand-alone equipment (i.e.,

smoke vents in building envelopes) designed to control smoke movement by releasing it under its own pressure to the outside. Smoke-control uses equipment (e.g., fans, ductwork, dampers, smoke detectors) designed to control smoke movement by actively and mechanically creating pressure differentials. Smoke-control systems are usually dependent on physical features to work properly.

Closely related to smoke management is fire management, which uses physical features such as fire-rated barriers, equipment such as sprinklers, and methods such as compartmentation. (Locations for rated construction and sprinkler zones are governed by different codes [i.e., building codes and National Fire Protection Association<sup>3</sup>], and those codes do not require inter-coordination. Therefore, smoke and fire compartments are typically not coordinated with sprinkler zones unless the owner deems it important, construction docu-

ments clearly communicate it, and the construction administrator vehemently enforces it. An example where close coordination is needed is an atrium design where the smoke control system is activated by water flow in the sprinkler system.)

## Applicable Authorities

The three types of authorities for smoke-management systems are building codes, guidelines, and code officials.

Building codes are the basic starting point for identifying the need for, and features of, smoke-management systems. Be careful to confirm the exact building code and issue date that applies to your system. Some building codes are performance-based while others are method-based.

When smoke-control systems are required by building codes, guidelines for their design are provided in *NFPA 92A*, *NFPA 92B*, *ASHRAE Guideline 5*, and the *Design of Smoke Management Systems*.<sup>4,5,6,7</sup> Smoke-control system designers need to be aware of their contents.

Because local conditions differ and smoke-control systems can be designed in different ways, designers must discuss the features and acceptance tests for smoke-control systems with all authorities having jurisdiction.

## About the Author

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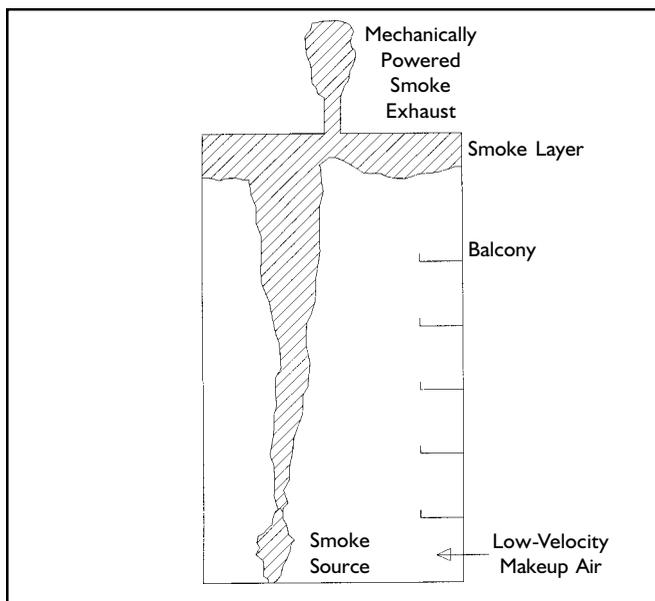


Figure 1: Atrium smoke exhaust.

**Purposes of Smoke-Control Systems**

According to NFPA 92A (2000),<sup>4</sup> the purposes of smoke-control systems include:

- Inhibiting migration of smoke out of the source compartment;
- Inhibiting smoke from entering means of egress (maintaining tenable environment for evacuees);
- Maintaining a tenable environment outside of the source compartment for emergency personnel;
- Protecting life; and
- Reducing damage to property.

Reading between the lines, this list reveals that smoke control is not used to maintain tenable conditions in the fire compartment, and that the means of egress needs to be thoroughly identified and effectively separated from other areas of the building.

**Smoke Control Development**

Smoke management is an ancient concept. When man first built a fire in his dwelling, he quickly realized the need for an opening to vent the smoke.

Modern smoke-control practices began in the 1940s when it had become obvious that ducted air-distribution systems helped distribute smoke well beyond the fire source. This prompted the advent of fire dampers and static smoke-control systems. In 1968, Underwriters Laboratories (UL) published the first UL 555, *Standard for Fire Dampers*.<sup>8</sup> AMCA members adopted the first Standard 500-D, *Test Method for Louvers, Dampers and Shutters* in 1973 for general ventilation and air-conditioning purposes.<sup>9</sup>

Smoke dampers and dynamic smoke-control systems started appearing in the 1970s when it had become obvious the shut-down operation of a static smoke-control system conflicted

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with the need for maintaining clean air distribution in hospital operating rooms. In operating rooms, the distribution of clean air across the patient is a primary defense against infection. When a patient is undergoing surgery, it is inappropriate to shut down the airflow when a smoke event occurs in an adjacent area. For this reason, many surgical-suite air handlers were designed for 100% outside air with the assumption that outside air would be smoke-free.

The first significant smoke-control guidelines (i.e., NFPA) were published in the mid-1980s.<sup>4</sup> During this time, UL published the first UL 555S, *Standard for Leakage Rated Dampers for Use in Smoke Control Systems*.<sup>10</sup>

Industry advances continue with the recent publication of revised Underwriters Laboratories Standards UL555<sup>8</sup> and UL555S<sup>10</sup> for fire and smoke dampers. These revised publications address the differing requirements for dampers used in dynamic systems vs. static systems, as well as dampers exposed to elevated airflow temperatures.

ASHRAE recently published ANSI/ASHRAE Standard 149-2000, *Laboratory Methods of Testing Fans Used to Exhaust Smoke in Smoke Management Systems*.<sup>11</sup> The soon-to-be published companion document, AMCA Standard 212, will establish fan ratings based on existing code requirements.

Together these documents will enable manufacturers to publish performance data for both ambient temperature and elevated temperatures for a given fan. This will allow designers to select a fan while knowing how it will perform during both normal and smoke-exhaust operation.

A tool that is being applied to smoke-control design is computational fluid dynamics (CFD). CFD is an advanced

numerical modeling approach in which physical space is divided into a finite number of tiny cubes. The fire source is located within a relatively small number of these cubes. A computer is then used to solve the governing equations for fluid flow over time for all the cubes to simulate the growth of fire and the spread of smoke. Full-scale fire research has verified the accuracy of CFD modeling.<sup>12,13</sup> This research indicates that properly executed CFD modeling is proving to be quite accurate, and some authorities are beginning to recognize its usefulness and applicability.<sup>14</sup> Because CFD modeling is complicated, it needs to be done by CFD experts.

Complex or nonstandard building layouts or operations are especially suited for CFD modeling.

Research continues in other smoke-control related areas. Examples include the study of appropriate placement of smoke detectors in rooms and ductwork,<sup>19</sup> the phenomenon of

Normal
Normal
Normal
Normal
Pos (+)
Pos (+)
Negative Fire Floor (-)
Pos (+)
Normal
Normal

**Figure 2: Sandwich smoke-control system.**

## Smoke-Resistive Construction

The integrity of smoke-resistive construction can be compromised by the following compounding situations:

1. Building codes typically do not directly identify when floors need to be of a smoke-resistive construction (smoke barrier). They only indirectly identify them by indicating where smoke dampers are required.<sup>17</sup>

2. Where codes require smoke barriers, they most often coincide with fire rated construction (fire barrier). However, the burgeoning industry of Through Penetration Fire Stopping (TPFS) assemblies classified by independent testing laboratories (ITL) typically offers only fire (F) and temperature (T) ratings. Even though at least one manufacturer requests its ITL to test for air leakage under given pressure conditions (L), building codes do not currently recognize or require such a rating at penetrations of smoke barriers.

3. Duct penetrations of fire barriers usually require fire dampers (some exceptions exist). However, when that fire barrier must also be smoke resistive, few manufacturers can provide combination fire/smoke dampers whose classifications allow annular spaces around the outside of dampers to be tightly sealed against smoke leakage.

In fact, many damper classifications are voided if any sealant is used in that annular space because a damper's operation may be compromised if its ability to thermally expand is

impeded by the sealant. Still, many local authorities require contractors to apply sealant around the dampers in specific contradiction to the dampers' classifications.

4. TPFS assemblies are tested under laboratory conditions that often don't match the real world. For example, some piping systems move significantly because of thermal expansion, and all piping systems will move if subjected to sufficient seismic forces. In ITL tests, pipes must be anchored adjacent to the barrier. This implies that every pipe in the field be anchored adjacent to every rated-barrier penetration.

When manufacturers are asked if their sealants are flexible, they reply "yes." When asked how flexible, they respond "more than 25%." When asked how thick their typical layer of sealant is, they reply "half an inch." Therefore, the physical quantity of expected flexibility is only about 1/8 inch, which is less than a steam pipe normally moves not too many feet away from an anchor.

Without an anchor adjacent to every rated barrier on every steam or condensate pipe, either the integrity of the TPFS assembly or the integrity of the pipe insulation at that barrier will be violated the first time the system is used. Some specialized industries (e.g., computer chip manufacturers) are applying novel ideas such as rubber boots (similar to those on front-wheel drive vehicles' constant velocity joints) to prevent passage of smoke through smoke resistive barriers. ●

plugholing as it relates to atrium smoke exhaust (short circuiting of clean air through the smoke layer because of exhaust inlet placement),<sup>16</sup> and tenability in pressurized stairwells.<sup>15</sup>

Issues that need to be addressed in the future include the survivability of system operations. For example, no provisions exist for protecting communication pathways among smoke-control components. The integrity of smoke resistive construction is another unresolved issue (see sidebar, “Smoke Resistive Construction”).

### Smoke-Control Methods

Smoke-control systems are either static or dynamic. During a smoke event in static systems, all fans in the building stop operating, which results in simple compartmentational control of smoke movement (a basic smoke-management method).

During a smoke event in dynamic smoke-control systems, all or selected fans continue to operate in normal or special modes creating pressurized spaces in specific scenarios to control the movement of smoke. Fans in dynamic systems may be used exclusively to exhaust smoke, exclusively to provide clean pressurization air, or under certain circumstances, may perform both functions at different times.

Dynamic smoke-control systems are applied in either stand-alone modes or in collaboration with smoke barriers. An example of a stand-alone dynamic system is an air curtain, which uses only airflow to create a barrier against smoke movement. More prevalent than stand-alone systems are smoke-control systems that depend on smoke barriers to function properly. Examples include atrium exhaust (*Figure 1*), stair pressurization (see sidebar, “Stairwell Pressurization”), elevator-shaft/areas-of-refuge pressurization, and zoned or sandwich-pressurization systems (*Figure 2*). (In typical sandwich systems, the fire floor is exhausted while one or two floors above and one below are pressurized. Zoned smoke-control systems that use one air handler to serve multiple zones are very complex. To simplify installation, commissioning, and long-term system operation, designers should consider providing one air handler per smoke zone.

All smoke-control systems interact with other building systems, most notably electrical and fire-alarm systems. Because smoke dampers close with a fire alarm signal, codes allow the elimination of smoke dampers at smoke barriers in engineered smoke-control systems, which must remain in operation during a smoke event. This exception, however does not apply to fire dampers, which continue to be required at rated fire barriers penetrated by the ductwork of engineered smoke-control systems.

A review of ASHRAE Guideline 5<sup>6</sup> reveals how much of a smoke control system is beyond the direct control of a mechanical engineer. It is critical that the designer of the mechanical smoke-control system coordinate closely with other disciplines to ensure appropriate construction and locations of rated barriers, connection of emergency power, intercon-

## Stairwell Pressurization

Although a thorough explanation of stairwell-pressurization design is beyond the scope of this article, be aware that obtaining and managing functional stairwell pressurization is a challenge in tall stairwells with many doors.

A pressure of 0.05 in. w.c. (12 Pa) on a 3 by 7 ft (0.9 by 2 m) doorway yields more than 5 pounds of pressure against the total surface of the door. During a smoke event, stairwell door positions are quite different than during normal conditions. Good design must consider such things as how much pressure should exist to prevent smoke infiltration when most doors are closed (tight stairwell), how much pressure should exist to prevent smoke infiltration when most doors are open (loose stairwell), and how responsive the stairwell pressurization system is to the opening and closing of doors. Assuming controls are responsive, achieving reasonably uniform pressurization throughout a tall stairwell requires introduction of pressurization air at multiple locations. Remember to coordinate space required for introducing air at multiple locations.

In some jurisdictions, alternatives to mechanical stairwell pressurization may provide a simpler approach. Alternatives include natural or mechanical ventilation for smokeproof enclosures.<sup>18</sup> ●

nection with fire alarm systems, and interfacing with fire suppression systems. (The proper function of total-flooding gaseous agent fire suppression systems can be compromised by smoke-control systems. Air movement required by smoke-control systems can reduce the concentration of gaseous agent below the level required for suppression.)

### Smoke-Control Equipment

Smoke-control equipment can be either dedicated or non-dedicated.<sup>4</sup> Dedicated equipment is used only during a smoke event. Non-dedicated equipment is normally used for other HVAC applications, but also serves a smoke-control purpose during a smoke event.

Dedicated pieces of equipment are less likely to be altered over the life of the building so their operation sequences are likely to be appropriate when needed. Operation and control of a dedicated piece of equipment is relatively simple because each has only one purpose. However, dedicated equipment requires additional space, and it may not receive proper maintenance reducing its reliability. Examples of dedicated equipment are stair-pressurization fans and atrium smoke exhaust fans.

Non-dedicated pieces of equipment are more likely to be maintained, and they require less space because the same equipment serves multiple purposes. Non-dedicated equipment has its disadvantages, including complicated controls for multiple functions and the inadvertent compromise of smoke-control operation caused by upgrades or modifica-

tions to HVAC operations. An example of non-dedicated equipment is an air handler supply fan used to positively pressurize a zone in a sandwich system.

Structures likely to have smoke-control systems include high-rise buildings, prisons, hospitals, covered shopping malls, underground buildings, and transit tunnels. Spaces within structures likely to have smoke-control systems include atria, exit stairs, elevator shafts, areas of refuge, performing-arts stages, and smoke compartments.

## Design Preparations

1. Be aware of code requirements and the owner's desires when identifying the potential need for smoke-control systems. Codes indicate minimum requirements. Occasionally, the owners would like more than the minimum requirement, especially if a need for property protection exists.

2. If you suspect a smoke-control system may be required in your facility, confirm your need with the code authority. (If you believe an alternate approach is applicable, be prepared to discuss it.) Numerous options and design approaches are allowed by the codes. After determining that a smoke-control system is required, carefully select the applicable options and approaches.

3. Review your design approach with the code authority

and discuss acceptance testing. Occasionally, the method of acceptance testing will affect your design approach.

4. Remember to keep your design as simple as possible. The owner must maintain the system for the life of the building.

5. Remember that system testing and false alarms will be the primary load on the system. Think through potential false alarm scenarios, especially regarding weather conditions. A frozen coil during an actual fire event may be acceptable while a frozen coil during a false alarm will not.

6. Remember that the code authority's purpose is to protect the public. The designer's purpose is broader. The designer needs to provide a cost-effective system that serves the owner's needs and is acceptable to the code authority. This can be a challenging balancing act for the designer.

7. Remember to document all conversations and decisions. Consider including with construction documents a simplified diagram of how the smoke-control system interacts with the rest of the HVAC systems.

## Design Challenges

Because locations of rated barriers can have significant impact on duct layouts, the barrier locations should be identified before detailed duct layout begins. Changing barrier locations late in the design process can be catastrophic to the

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designer of the smoke-control system. An example would be in a sandwich smoke-control system where a barrier divides areas on the same floor. Changing barrier locations could require extensive redesign of the air distribution system especially if one air handler is assigned to each smoke zone.

The only sure way to field test a smoke-control design is to provide hot smoke in realistic quantities. Because this is usually impractical, cold smoke is commonly used for acceptance testing. Therefore, true performance of smoke-control systems is postponed until tested during actual fire events, which are reasonably and thankfully rare. Because of the

rarity of true testing, advances in smoke-control technology and solid agreement on design techniques lag behind those of systems that are used daily for their intended application (e.g., HVAC for cooling and heating).

Because of the variety of smoke-control design approaches and the rarity of true testing of smoke-control systems, the mutual education of the code officials, system designers, architects, and owners is a significant challenge and should not be taken lightly. Because the mechanical engineer takes the lead in designing the smoke-control systems, the engineer must also take the lead in this education process.

## ASHRAE's New Smoke Management Book

By John H. Klote, P.E., D.Sc., Fellow ASHRAE

ASHRAE has sponsored the development of a book entitled, *Principles of Smoke Management* that consolidates information about smoke management including many recent technological advances. The authors are myself and James Milke.

The book presents a wealth of information about smoke management. While the book is slanted toward system designers, the information may be useful to code officials and researchers. The book addresses the basic fundamentals, design analysis, pressurized stairwells, pressurized elevators, atrium smoke management and commissioning. Some recent advances are discussed here.

### Heat Release Rate

Probably the most important aspect of a building fire is the heat release rate (HRR), but this has been one of the least understood aspects of smoke management design by many professionals. The temperature and amount of gases produced by a fire are directly related to the HRR, and predictive computer models use the HRR as input. The book describes the stages of fire growth. The technical advances that make accurate HRR measurement possible are discussed, and HRR values for many materials are presented.

### Atrium Systems

New aspects to atrium smoke management included are natural atrium venting, plugholing, minimum design depth of an atrium smoke layer, smoke stratification, and smoke detection. Smoke exhaust is most common in North America, but natural atrium venting is common in many parts of the world such as Europe, Australia and New Zealand.

For atrium smoke exhaust systems, air from below the smoke layer may be pulled into the exhaust if the exhaust flow rate is relatively large. This phenomenon is called *plugholing*, and it can happen with both smoke exhaust and natural smoke venting systems. Methods are discussed to prevent plugholing.

The smoke layer in an atrium system needs to be deep enough to accommodate the ceiling jet. When a smoke plume reaches the ceiling, the smoke turns and flows in a radial direction under the ceiling. This smoke flow is called a *ceiling jet*. The thickness of the ceiling jet is in the range of 10% to 20% of the height from the fire to the ceiling, and the minimum design depth of the smoke layer needs to accommodate the ceiling jet.

Often a stratified layer of hot air forms under the ceiling of an atrium as a result of solar radiation on the atrium roof. When smoke reaches the ceiling, it has been cooled by entrainment of room air. When the smoke temperature is less than that of the stratified air layer, smoke cannot reach ceiling mounted smoke detectors. The book describes methods of using beam detectors to overcome this limitation.

### Tenability Systems

Most smoke management systems provide smoke protection by minimizing occupant's contact with smoke or by keeping smoke completely away from occupants. As the name implies, tenability systems provide smoke protection by maintaining tenable conditions. The systems allow smoke contact, but the systems are designed such that the temperatures and concentrations of combustion products are limited. Hazard analysis is used for tenability system design, and this kind of analysis is a powerful fire protection tool that has application beyond smoke management. To aid designers with hazard analyses, the book provides information about fire scenarios, smoke transport, people movement and tenability calculations.

### Computer Analysis

Smoke management applications of computer modeling have increased dramatically in the last few decades. The book discusses building airflow models, zone fire models, detector actuation models, computational fluid dynamics (CFD) models, elevator evacuation model, and collections of engineering tools. A CD is included with the book that contains many of the programs discussed in the book.

*Principles of Smoke Management* is available at [www.ashrae.org](http://www.ashrae.org) (\$79 Members/\$99 Non-members). ●

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