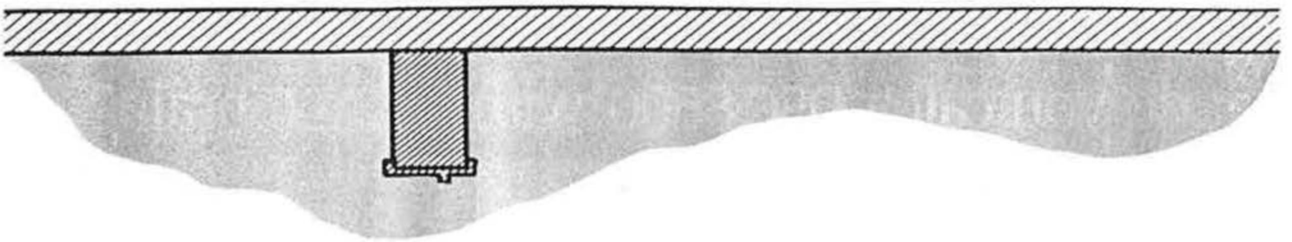

Development of Smoke Management Systems

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Smoke control has been a concern of man since fire was discovered and brought inside for warmth and cooking. Using trial and error, chimneys, flues and fireplaces were invented to control smoke. This paper describes recent significant events which have contributed to the current state of smoke management system design.

Concern for smoke in building fires did not get much attention until a series of high-rise fires in the 1960's. It was the National Research Council of Canada which took the lead in identifying the nature and extent of the fire challenge in high-rise style buildings.[1,2,3] A significant issue was smoke spread caused by what we now refer to as "stack effect" and by HVAC system operation. Following notable high-rise fires in Chicago and New York, Illinois Institute of Technology in 1970 and the US General Services Administration in 1971 held conferences to evaluate and recommend improved fire safety provisions for high-rise buildings.[4] That led to adoption of high-rise building fire safety requirements in the model building codes and those of the major cities of North America. Among the features required were means to prevent smoke from spreading between floors or groups of floors. Among the systems to accomplish this included stair shaft pressurization, HVAC system shutdown, fire floor venting or exhausting, and automatic sprinkler protection. The specific features required or allowed varied among the individual codes. Over time, large volume spaces such as shopping malls and atria became popular, requiring additional smoke management considerations.

Since then, high-rise and atrium buildings have emphasized the need for sophisticated methods of smoke control or smoke management. In a high-rise building, the objective is commonly to prevent or limit smoke spread beyond the area or floor of origin, i.e., "control" smoke. For atrium buildings, the goal is often to direct smoke by exhausting it or venting it safley, i.e., to "manage" the smoke. Throughout this paper, the ASHRAE[5] and NFPA[6,7] definitions of "smoke control system" and "smoke management system" will be used as follows:

- *Smoke Control System*: An engineered system that uses mechanical fans to produce airflows and pressure differences across barriers to limit smoke movement.
- *Smoke Management System*: An engineered system that includes all methods that can be used singly or in combination to modify smoke movement.

This article concerns information about fire size, smoke production and assessing the risk to occupants to be used in designing smoke management systems. Although much of the information presented concerns atria, it actually applies to any large volume space, including covered malls,[6] for example, describes a large volume space as, "An uncompartmented space, generally two or more stories in height, within which smoke from a fire either in the space or in a communicating space can move and accumulate without restriction. Atria and covered malls are examples of large volume spaces." Other examples of such spaces include malls, mega-structures having characteristics of both a mall and an atrium, convention centers and airport terminals.

This paper does not discuss new technology. It is intended to explain work performed since the 1960's to help understand the current state of smoke management system practice and design.

Experience

Although there have been relatively few high-rise fires and little experience with smoke control system performance, there has been an increased awareness of fire safety among the public, and a misguided perception that current materials yield greater smoke and are more toxic than those

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of earlier generations. There has been less fire and smoke control experience with atria. Fires in atria, however, demonstrate the need for testing to see that a system functions as intended.

Current Technology

Current technology for smoke management has dwelt on high-rise protection and atria. The following provides a brief overview of the techniques for these building types.

Smoke Control and High-Rise

Smoke control design is based on empirical and mathematical models. The models need not be sophisticated because the smoke control system for such buildings depends heavily on the building's inherent compartmentation. Pressure differentials across boundaries which form that compartmentation control air movement and thereby control smoke movement. These are the systems used for high-rise buildings. NFPA 92A[7] and Klote and Milke[8] give recommended practices for the design, installation, testing, operation, and maintenance of new and retrofitted mechanical and ventilation systems for smoke control. An approach relying on establishing pressure differentials between floors to control smoke was suggested in the GSA 1971 Conference. It is referred to as "Building Pressurization" or the "Pressure Sandwich" because it exhausts the fire floor while pressurizing the adjacent floors. Although that system is still frequently used, some of the model codes no longer require it.

Building Pressurization

The pressurized building method of controlling smoke in high-rise buildings has been described by Tamura and McGuire.[9] Simply described, the method consists of exhausting the fire floor while pressurizing surrounding floors. Often this is accomplished by operating automatic dampers in the building ventilation system. Return dampers on the fire floor remain open and all other return dampers in the system close. Supply dampers to the fire floor will close and all other supply dampers will remain open. Under this system, some auxiliary means may be needed to keep egress routes free of smoke. Tamura and McGuire[9] suggest an air injection rate of 300 cfm (142 L/s) for each typical stair door into the stair shaft.

In lieu of using the return as an exhaust, the fire floor could be directly vented through automatic dampers, or a smoke shaft could be utilized. Of the three alternatives, the report states that direct venting is considered the most reliable.

Natural Venting

Natural venting to control smoke movement in buildings via vertical shafts is described by Tamura and Wilson.[10] Simply described, the method uses smoke shafts to exhaust smoke from a building. Elevator shafts and stairwell shafts are vented to the outside at the top or bottom. Top venting increases the number of stories from which air flows into the shaft and decreases the number of stories into which air flows from the shaft. Bottom venting has the opposite effect. This method does present a satisfactory arrangement under cold weather conditions. During summertime, a reversal of the normal stack effect could occur and permit smoke to exhaust through the bottom vented shaft. If this were a stairwell, however, occupants would be exposed to smoke as they moved down the stairway to exit at ground level. Another problem can occur in the pressure difference at the bottom of bottom vented shafts during winter conditions. The article reports that the force in a tall building could be excessive for the stairwell door at the base of the shaft. Admittedly, the pressure at the base would also be great for top venting shafts, and could be greater. It is clear why the report states that venting has practical limits as an effective smoke control measure.

Another means of natural venting which has proved to be effective, is to provide a smoke vestibule at each stair with direct access to the outside. The most reliable means to achieve the ventilation is to have an open air balcony. Where weather conditions prohibit such an arrangement, automatically operated dampers on the exterior wall can be utilized.

Stairway Pressurization

The means of smoke control in buildings which has received the most attention both in building codes and in literature, and on which the most testing has been performed, is stairway pressurization. While this method appears to provide a simple and effective means of maintaining egress paths free of smoke, there is controversy on specific arrangements. The controversy is centered around the location for injection of air into the stair shaft. The engineer's primary choices are:

- Top pressurization;
- Bottom pressurization;
- Pressurization of the stair shaft with a pressurized vestibule; and
- Pressurization of multiple levels.

A top pressurization stairwell system is described by Fung.[11] Air was injected in the shaft at the top with additional allowances added for each door opening into the stair: 100 cfm (47 L/s) for each door having a perimeter of not more than 20 ft. (6 m) that was equipped with a tight-fitting weather stripping or 200 cfm (94 L/s) for every other door having a perimeter of not more than 20 ft. (6 m) into the stair shaft.

Each stair shaft had a vent at street level opening either directly outside or into a vestibule or corridor that had a similar opening to the outside having an opening of not less than 0.5 $ft.^2$ ($0.05m^2$) for every door that opened into the stair shaft other than doors at the street level, but in no case should the total equal less than 20 $ft.^2$ ($1.9m^2$). The system was evaluated through smoke movement tests utilizing sulphur hexaflouride (SF6) trace gas. Further evaluations were performed utilizing computer simulation techniques.

While the tests and computer simulation demonstrated that the stairwell would remain free of smoke, the high noise level of the large high-velocity pressurization unit required to achieve pressurization could be objectionable. It was also determined that the force to open stairwell doors under stairway pressurization could be excessive and a design specification would be required to limit the maximum force needed to open the pressurized stairwell doors.

Bottom ventilation of stairs was advocated in a report of fire tests, analyses, and evaluation of stair pressurization and exhaust in high-rise office buildings prepared by the Polytechnic Institute of Brooklyn Center for Urban Environmental Studies.[12] The report concluded that the direction of air flow in the stairs should be upward at all levels. This would prevent any initial smoke and gases which may have entered the stair from traveling downward. The roof terminus for the exhausted smoke and gases was also considered to be preferable to the street (lobby) level (with downward flow) where fire fighters would be entering and occupants leaving. It was learned that when more than three doors open into the stair shaft, the stair pressurization was defeated. In addition, the same problems with the force to open the door as encountered with top pressurization can occur with bottom pressurization.

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Bottom pressurization with the vestibule pressurized were reported by Zinn, Bankston, Cassanova, Powell, and Koplon.[13] The article reports on fire tests conducted at the Henry Grady Hotel in Atlanta. The report concluded that stairwell pressurization at a maximum of 0.15 inches of water column combined with vestibule pressurization prevented smoke movement from the fire area to the stairwell with the stairwell doors closed. In addition, the open-door flow rate used by stairwell and vestibule supply fans prevented the movement of smoke into the stairwell when the vestibule and stairwell doors were held open to the fire area for several minutes. No more than three doors were opened into the stairwell at a time. The effectiveness of the system is in doubt if additional doors were open, which must be assumed during an emergency evacuation.

The report also stated that stairwell door measurements show that the pressure losses are large when a single fan pressurized a vertical shaft in a multi-story building. "Such an arrangement requires unacceptably high pressures near the supply fan in order to maintain necessary minimum pressures at the opposite end of the shaft. The use of several smaller fans is a possible alternative to the single-fan approach. A multi-fan system will require the determination of the number, size and location of fans for optimum pressurization conditions. The multi-fan scheme would also probably reduce the shaft region affected by large pressure tops to open doors."

These techniques have been integrated and applied in building code requirements such as those of BOCA[14] and ICBO.[15]

BOCA[14] requires sprinklers, pressurized stairs, or smokeproof enclosures and HVAC system control for high-rise buildings. No additional smoke control is required on the basis that the aforementioned provisions provide adequate life safety in the absence of floor openings such as atria.

ICBO[15] has similar requirements for high-rise buildings, except pressurized stairs require vestibules. High-rise buildings require smoke control, designed using an approach based on NFPA 92A[7] and NFPA 92B[6]. The system is required to be designed, installed and tested with the intention of providing a tenable environment for the evacuation or relocation of occupants during a fire. The code contains equations from the NFPA documents to be used to accomplish the objective.

Smoke Management and Atria

Smoke management design for atria is more complicated because of the number of factors that affect air and smoke movement. In simple terms, however, the smoke management systems for atria rely on chimney and venting technology. Atrium smoke management considerations and design criteria are found in NFPA 92B (1991a)[6] and *Design of Smoke Management Systems.*[8] Two of the model codes (BOCA;1993[14] ICBO 1994[15]) have adopted atrium smoke management system requirements based on NFPA 92B (1991a).[6] The ICBO provisions have been criticized on the basis that there is a lack of any fire loss history to support the need for elaborate smoke control systems. Some have also taken the position that designers using the Code will rely on automatic sprinklers for fire control when calculating the smoke management system and that it is unlikely that additional smoke management will be necessary for life safety in such cases, making the cost of a smoke management system complying with the ICBO requirements unjustifiable. It is clear that atrium smoke management requirements will continue to receive attention in the model codes.

Design Approach

To properly design smoke management for a large space, one needs to know the heat release rate of the expected fire to determine the fire size. From that, one can estimate the amount of smoke based on the composition of standard building materials. It is then possible to calculate the time for smoke to reach a point that could endanger the occupants and to compare that time to the egress time. If the smoke layer time is less than the egress time, a smoke management system should be provided to exhaust smoke at a minimum of the rate at which the smoke is produced.

Design Fire

As previously noted, the starting point for smoke management system calculations is determining the size of the fire. The purpose is to determine the heat release rate. Until recently, heat release rate data for common objects and the means to use this data were not in a form readily available to design engineers. There is information available now, in NFPA 92B[6], the SFPE Handbook[16] and the NFPA Handbook.[17] One could also estimate heat release rate from fire tests.

A system designer needs to decide whether the fire will be considered a steady fire or an unsteady fire. A steady fire has a constant heat release rate. An unsteady fire is one that varies with respect to time. Fire Protection engineers often use a "t-squared" approximation for unsteady fires. A "t-squared" fire is one in which the burning rate varies proportionally with the square of time. "T-squared" fires are classed by speed of growth, as ultra-fast, fast, medium and slow, based on the time to reach a heat release rate of 1,000 Btu/sec (1,055 kW).

In the absence of specific heat release rate data, one should assume a steady fire. This will yield a more conservative result than using an unsteady fire. An average heat release rate for the design fuel area could be estimated. This is the approach used in BOCA[14] and ICBO.[15] BOCA uses 4,400 Btu/s (4640kW) for mercantile, storage and industrial occupancies and 2,000 Btu/s (2110 kW) for residential and other occupancies; ICBO uses 50 Btu/ft.^{2} · s (567 kW/m^2) for mercantile and residential and 25 Btu/ft.^{2} · s (284 kW/m^2) for offices. In each case, the assumed fire size is 100 square feet (9.3m^2). This is a reasonable assumption for typical spaces protected by automatic sprinklers.

Smoke Production

Having determined the fire size, one can calculate the rate of smoke production using equations such as those found in NFPA 92B.[6] This is the approach used by BOCA. It establishes a design criteria that the smoke management system keep the smoke layer interface above the highest unprotected opening to adjoining spaces or six feet above the highest floor level of exit access open to the atrium. ICBO requires this distance to be ten feet (3 m). The BOCA criteria requires that the smoke be controlled at or above the six feet (1.8 m) level for not less than 20 minutes (1,200 sec.). BOCA contains a calculation method based on NFPA 92B[6] to evaluate compliance with the criteria as follows:

$$Z = 0.67H - 0.28H \ln \left[\frac{tQ^{1/3} H^{2/3}}{A} \right]$$

In SI,

$$Z = 1.11H - 0.28H \ln \left[\frac{tQ^{1/3} H^{2/3}}{A} \right]$$

where:

Z = Height from floor to the smoke interface, feet(m).

t= Time for interface to descend to Z; use 1,200 seconds.

H= Atrium height; floor to flat ceiling, feet(m).

Q= Steady state heat release rate Btu/s (kW).

A= Horizontal cross-sectional area of the above ceiling space being filled, ft^2 (m^2). Maximum A to be used shall be: $A = 21 H^2$.

If the calculations demonstrate that the geometry of the space is such that this performance will be achieved without a mechanical exhaust system, no such system will be required. Based on some calculated examples, however, it appears unlikely to meet the stated criteria without a mechanical exhaust system. If an exhaust system is required, BOCA uses the following equation to determine the minimum exhaust rate:

$$V = 20.8\, Q_c^{1/3}\, Z^{5/3} + 3.98 Q_c$$

In SI,

$$V = 0.070\, Q_c^{1/3}\, Z^{5/3} + 0.00 Z Q_c$$

where:

V= The volumetric rate of smoke production, cfm (L/s).

Qc= Convective portion of the heat release rate, Btu/s (kW) = 0.7Q.

BOCA uses 165°F (74°C) as the temperature of the smoke being exhausted. According to the Appendix A of NFPA 92B, the density of smoke is approximately equal to the density of air. The smoke layer temperature can be calculated to determine the air flow rate. Alternatively, one can use ambient temperature as an approximation, which is how determining the volumetric exhaust rate is treated in an example in an appendix of NFPA 92B. The exhaust rate is then to be adjusted in accordance with a table to allow for increase in time for the smoke layer interface to reach the critical height.

Comparing the exhaust rate determined on this basis with that determined from the air change rate design basis of four or six air changes per hour formerly used in the model codes yields the following:

This analysis demonstrates that the air change rate method causes over-design, i.e., greater exhaust capacity than required, for large volume spaces and under-design for small volume spaces having modest heights.

Occupant Risk

The next step in the process is the response time of detectors which would be used to initiate the smoke management system and occupant evacuation. One would also calculate response time of automatic sprinklers to evaluate if one's assumption about the fire size is appropriate. NFPA 92B[6] and Klote and Milke[8] describe the means to perform these calculations.

Next, one would evaluate the egress time using procedures such as those in NFPA 101,[18] Fruin,[19] the SFPE handbook or the NFPA handbook. The approach is similar to a hydraulic flow calculation.

System Evaluation

Beyond performance standards and criteria, it is necessary to establish a means to determine that the systems achieve the intended objective. Systems must be evaluated during design and after installation. In addition to Klote and Milke, ASHRAE continues to develop documents to advance the state of the art of smoke management.

ASHRAE has developed *Guideline 5-1994, Commissioning Smoke Management Systems.* The purpose of the document is to provide methods for verifying and documenting that the performance of smoke management systems conforms with the design intent. This project was prompted by a recognized need for testing to determine that a smoke management system achieves its design intent using objective methods and measurable results as opposed to unspecified performance objective and criteria such as "exhaust smoke at a rate so as to see an exit sign from 50 feet (15 m) away in 10 minutes" or to "clear smoke in 10 minutes."

ASHRAE has begun a project to prepare a standard "Test Method for Rating Air Moving Equipment for Smoke Control Systems." Among the performance to be considered is capacity, endurance, and reliability under elevated temperatures, intermittent use and accelerated aging. The most significant challenge of the project will be to establish the temperature requirements. There is disagreement within the design community on the need for elevated temperature performance of smoke control fans. The smoke is usually only slightly above ambient having been cooled by dilution and automatic sprinklers. In some cases, however, a fan may be required to function in higher temperatures near the fire. This issue will receive considerable debate.

Table 1

Atrium Area, sq. ft. (m^2)	H, Atrium Height, ft. (mm)	Z, Height to Opening, ft. (mm)	Exhaust Rate, cfm (L/s) Current Code	Exhaust Rate, cfm (L/s) Earlier Code
10,000 (929)	50 (15,240)	42 (12,800)	174,600 (82,400)	50,000 (23,600)
1,000,000 (92,900)	75 (22,860)	66 (20,120)	356,300 (168,200)	500,000 (236,000)

Conclusion

Smoke management system design is becoming more sophisticated and thorough. It is important that the objective of the system be clearly established at the outset of the design and that concurrence of all those involved in designing, approving and operating the building be achieved.

The major fire protection features needed to achieve the smoke management objectives are:

1. A means to control fire growth, usually automatic sprinkler protection.

2. Adequate exit facilities.

3. A detection and alarm system to activate the smoke control system and to notify occupants to initiate evacuation and to summon firefighters.

4. Adequate smoke control hardware: fans, dampers, controls and barriers.

Excerpt From: *Automatic Sprinkler Systems for Fire Protection* by P. Nash and R. A. Young Paramount Publishing Limited 1991. ■

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