

## THE CAPABILITIES OF SMOKE CONTROL: PART II--SYSTEM PERFORMANCE AND STAIRWELL PRESSURIZATION

Edward K. Budnick, P.E.  
Senior Engineer  
Hughes Associates, Inc.  
Wheaton, MD 20902

John H. Klote, Ph.D.  
Head, Building Fire Physics  
Center for Fire Research  
National Institute of Standards and Technology  
Gaithersburg, MD 20899

### Abstract

This paper discusses pressure difference, performance of smoke control systems, and practical application for pressurized stairwells. Pressurized stairwells are intended to prevent smoke infiltration of the stairwell during a building fire. The topics of limiting height of stairwells, fan location, fan types, single injection, multiple injection, and stairwell compartmentation are discussed. Two design concepts that have been used to deal with pressure fluctuations due to doors opening and closing are over-pressure relief and modulating supply airflow.

### INTRODUCTION

This paper is the second of two papers dealing with the capabilities of smoke control. The first discussed the principles of smoke control and the application of these principles to zoned smoke control systems. This paper discusses performance criteria and stairwell pressurization systems with the intent of preventing smoke infiltration during fires to provide tenable fire egresses. Another goal of these systems is to provide a relatively smoke-free staging area for firefighters.

The number of possible types of smoke control systems is only limited by the ingenuity of designers, contractors and other members of the construction and fire protection communities. It is impossible to provide detailed information for all possible smoke control systems. The intent of the two papers in this series is to discuss, in general, some considerations and alternatives and provide detailed information about a few systems. Omission of a system from the discussion should not be thought of as an indication of a negative attitude of the authors toward that system. Therefore, these papers should not be considered as defining what constitutes an acceptable smoke control system, but they should be thought of as encouragement to members of the construction and fire protection communities to broaden the horizon of smoke control. Of course, smoke control systems should be based on the principles of smoke control using recognized methods of engineering analysis such as those presented in the ASHRAE Smoke Control Manual (Klote and Fothergill 1983).

### APPROACH TO DESIGN ANALYSIS

The methods of design analysis presented in the ASHRAE Smoke Control Manual include applications appropriate for hand held calculators, and more complicated applications which for practical purposes require computer analysis. Chapter 3 of the manual describes the computer program for Analysis of Smoke Control Systems (ASCOS). Since publication of the manual, a version of ASCOS has become available for use on the IBM PC and compatible machines. A disk of this program plus example data files can be obtained for a modest price from the Society of Fire Protection Engineers (60 Battery March Street, Boston, MA 02110).

The methods of analysis in the ASHRAE Smoke Control Manual directly incorporate the effects of friction losses in shafts, temperature differences between the inside and outside of the building, and wind forces. The fire effect of smoke buoyancy is not directly incorporated in the methods of analysis. This fire effect is incorporated indirectly in the analysis by selection of the minimum design pressure differences as input parameters for the analysis. The selection of these pressure differences should be based on engineering understanding of fire protection and of fire growth and development. Later in the paper some suggested values of this parameter are presented. The fire effect of gas expansion is not incorporated in the ASHRAE Smoke Control Manual methods of analysis. Because of the

many leakage paths, it is reasonable to expect that these methods are valid for analysis of smoke control in buildings. However, for unusually tight spaces, such as bank vaults or military ships, the pressure increases due to gas expansion should be considered, and the methods of analysis presented in the ASHRAE manual are not appropriate.

An advantage of the analysis approach in the ASHRAE manual is that it is simple and direct, lending itself to the time and cost constraints of the day-to-day design world. Further, this method lends itself to design of systems for which acceptance testing criteria are straightforward to establish and apply.

The results of two separate series of fire tests on pressurized stairwells (DeCicco 1973, Cresci 1973, Koplun 1973) show that pressurization across barriers acts to prevent smoke infiltration from the low pressure side to the high pressure side of the barrier. Because the building smoke control approach in the ASHRAE manual is based on such pressurization, these fire tests tend to support the belief that the analysis approach of the ASHRAE manual is inappropriate for design of building smoke control systems. To evaluate the analysis approach further and to study the interrelation between building fires and zoned smoke control systems, the Center for Fire Research at the National Bureau of Standards (NBS) is engaged in a project of full scale fires in a building scheduled for demolition. This project has been jointly funded by the U.S. Veterans Administration, ASHRAE, the New Jersey Bell Telephone Company, the Bell Atlantic Telephone Company, and the U.S. West Telephone Company.

**PRESSURE DIFFERENCES**

It is appropriate to consider both a maximum and a minimum allowable pressure difference across a barrier of a smoke control system. The values discussed in this section are based on the recommendations in the proposed NFPA 92A (1987). The maximum allowable pressure difference should be a value that does not result in excessive door opening forces criteria for which is difficult to establish. The force to open a door is the sum of the forces to overcome the door closer and to overcome the pressure differences across the door. A person's physical condition is a major factor in determining a reasonable door opening force for that person. Section 5-2.1.4.3 of the Life Safety Code (NFPA 1985) states that the force required to open any door in a means of egress shall not exceed 30 lb. (133N). For this limitation, maximum allowable pressure differences, calculated by the methods presented in the ASHRAE Smoke Control Manual, are listed in Table 1.

**Table 1. Maximum allowable pressure differences across doors (Inches Water Gage)**

Door Closer Force (lb).	Door Width (inches)				
	32	36	40	44	46
6	0.45	0.40	0.37	0.34	0.31
8	0.41	0.37	0.34	0.31	0.28
10	0.37	0.34	0.30	0.28	0.26
12	0.34	0.30	0.27	0.25	0.23
14	0.30	0.27	0.24	0.22	0.21

Notes:

1. Total door opening force is 30 lb. (133 N)
2. Door height is 7 ft. (2.13 m)

Caution should be exercised in evaluating door closer force, because the force produced by the closer when the door is closing is often different from the force required to overcome the closer when opening the door. Many door closers require less force in the initial portions of the opening cycle than that required to bring the door to the full open position. The door closer force in Table 1 is the force that the door closer exerts on the door at the very beginning of the opening cycle.

As previously discussed, the method of design analysis presented in the ASHRAE manual incorporates the fire effect of buoyancy of smoke by selection of the minimum design pressure difference. The smoke control system should be designed to maintain this minimum value under likely conditions of stack effect and wind and when there is no

building fire (such as during acceptance or routine testing). Some suggested minimum design pressure differences are listed in Table 2. The values for nonsprinklered spaces are those that will not be overcome by the buoyancy forces of hot gases. These values were calculated for a gas temperature of 1700°F, for a neutral plane located at a height of 2/3 of the ceiling height below the ceiling, and with a safety factor of 0.03 inches water gage. If values are desired for other temperatures or ceiling heights, the calculation method presented in Appendix A of NFPA 92A can be used.

Pressure differences produced by smoke control systems tend to fluctuate due to the wind, fan pulsations, doors opening, doors closing, and other factors. Short-term deviations from the suggested minimum design pressure difference may not have a serious effect on the protection provided by a smoke control system. There is no clear-cut value of allowable value of this deviation. It depends on tightness of doors, tightness of construction, toxicity of smoke, air flow rates, and on the volumes of spaces. Intermittent deviations up to 50% of the suggested minimum design pressure difference are considered tolerable in most cases.

**Table 2. Suggested Minimum Pressure Design Difference Across Smoke Barriers (1) (Inches Water Gage)**

<b>Building Type (2)</b>	<b>Ceiling Height</b>	<b>Design Pressure Difference (3)</b>
<b>AS</b>	Any	.05
<b>NS</b>	9 ft.	.10
<b>NS</b>	15 ft.	.14
<b>NS</b>	21 ft.	.18

NOTE 1: For design purposes, a smoke control system should maintain these minimum pressure differences under likely conditions of stack effect or wind.

NOTE 2: AS - Sprinklered, NS - Nonsprinklered.

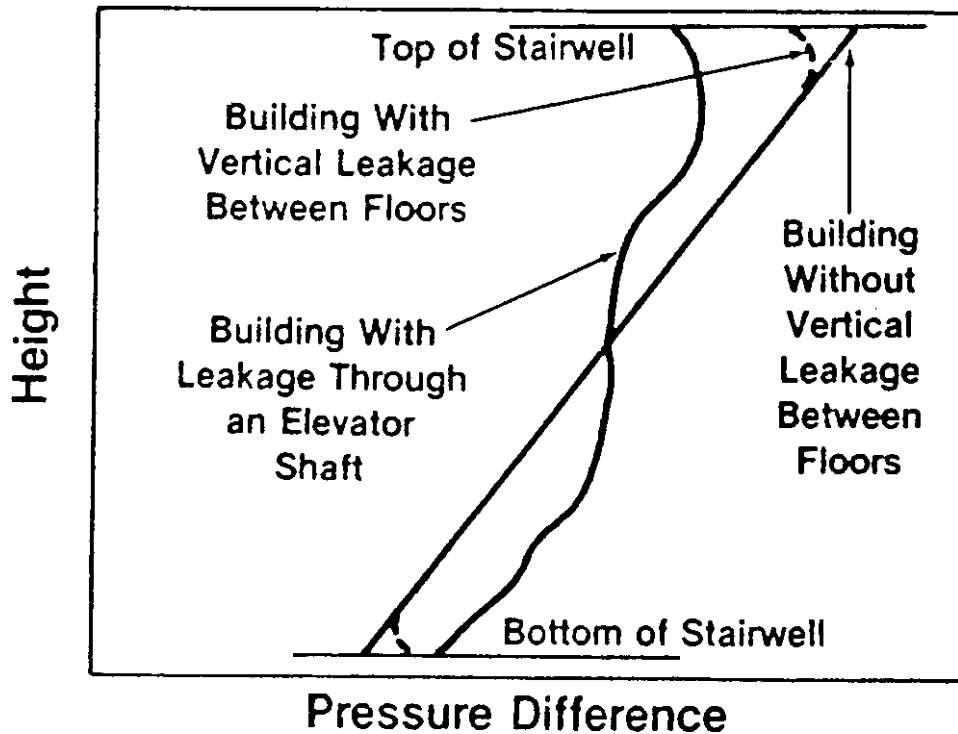
NOTE 3: The pressure difference measured between the smoke zone and adjacent spaces, while the affected areas are in the smoke control mode.

**STAIRWELL PRESSURIZATION CONCEPT**

Many pressurized stairwells are designed and built with the goal of providing a tenable environment within the escape route in the event of a building fire. A pressurized stairwell can meet its objectives, even if a small amount of smoke infiltrates the stairwell.

At first it might appear that the pressure differences from the stairwell to the building would be essentially the same over the height of the stairwell. Unfortunately, this is not the case. Figure 1 shows pressure profiles for stairwells located in buildings with three different leakage characteristics, all with the same stairwell temperatures and building temperatures. These pressure profiles represent winter conditions, that is, an outside temperature less than the inside temperature. The pressure differences in Figure 1 are from the stairwell to the building. Unless otherwise noted, discussions of pressure differences across stairwells in this paper are from the stairwell to the building.

**Figure 1**  
**Pressure Profile for Pressurized Stairwells in Three Buildings**  
**With Different Leakage Characteristics**



For the building without vertical leakage through floors or shafts other than the stairwell, the pressure profile is a straight line as shown in Figure 1. Of course, this leakage characteristic is not representative of many buildings. However, this case is useful because it has been analytically solved and it represents a worst case. (The linear pressure difference allows writing of a differential flow equation that can be integrated from the bottom to the top of the stairwell to obtain the total flow of air out of the stairwell. This analysis is presented in Section 4.3 of the ASHRAE Smoke Control Manual.) It is a worst case in that its minimum pressure difference is less than that for other, more realistic, leakage configurations; and its maximum pressure difference is greater than that for these other leakage configurations. Computer analysis can be performed to include the effects of more complicated building leakage arrangements.

**HEIGHT LIMIT**

As can be seen from this figure, two problems with pressurized stairwells are that the minimum pressure difference may be unacceptably low and that the maximum pressure difference may be unacceptably high. These problems are most likely for tall buildings during periods of extreme outside temperature. In some cases, satisfactory pressurization of a stairwell can be impossible when all doors are closed. By satisfactory pressurization it is meant that nowhere over the stairwell height is the pressure difference greater than the maximum allowable pressure difference or less than the minimum allowable pressure difference.

Evaluation of the height limit can provide an indication if such problems exist. The concept of the height limit, presented in Section 4.4 of the ASHRAE Smoke Control Manual, is based on the worst case of a building without leakage between floors. The height limit,  $H_m$ , is the height below which satisfactory pressurization is possible. For a stairwell in a building without vertical leakage, the analytical solution of a pressurized stairwell in a building without vertical leakage can be extended to yield an equation for the height limit. This equation is presented in the ASHRAE manual as equation 4.19. For a building temperature of 70°F and for winter conditions, the height limit can be obtained from Figure 2. The height limit depends on the following variables:

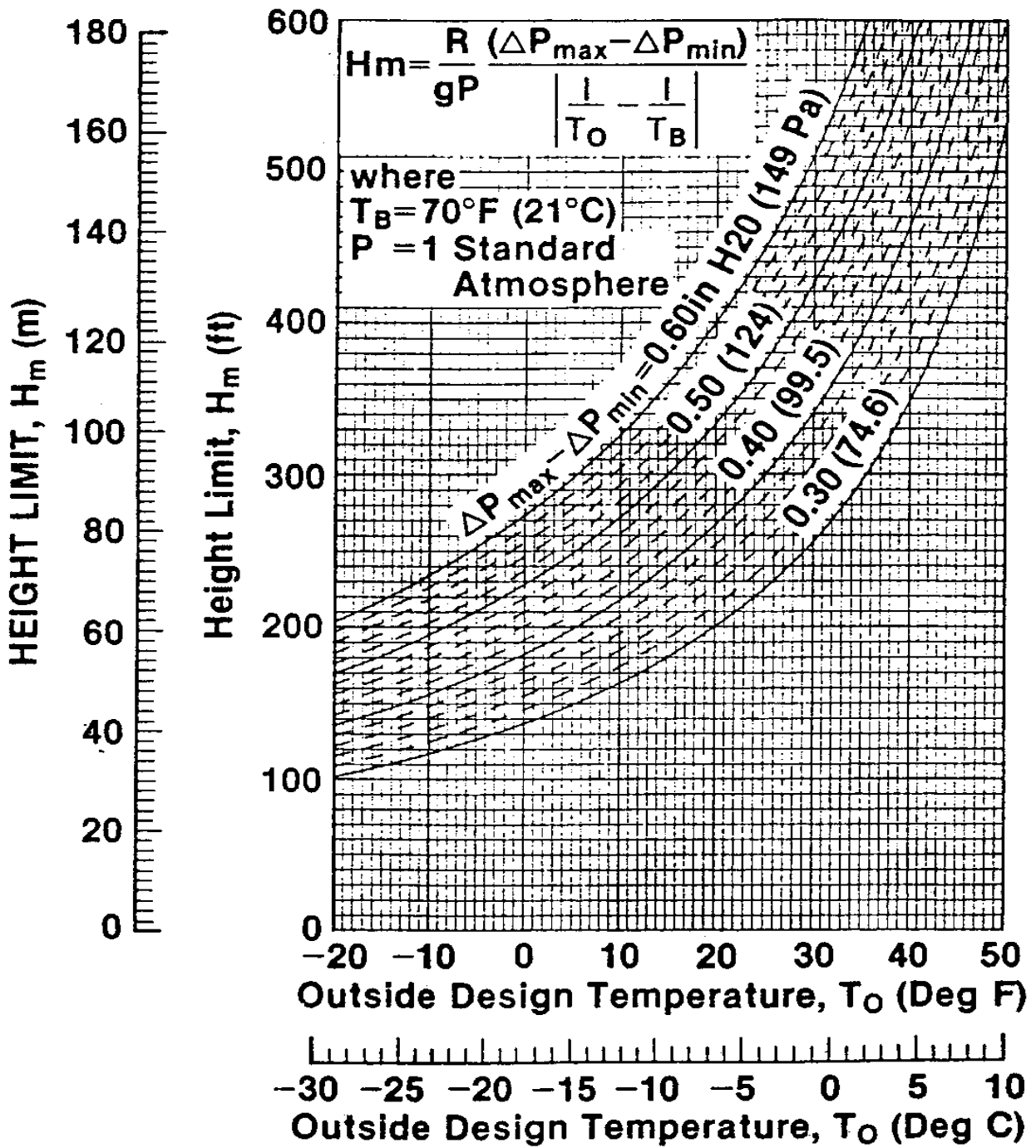
$\Delta P_{max}$	maximum allowable pressure difference between the stairwell and the building
$\Delta P_{min}$	minimum allowable pressure difference between the stairwell and the building
TO	outside design temperature
TB	building temperature

### Example

Is it possible to pressurize a 100-ft.-tall stairwell if the outside design temperature is 0°F? For a 36-inch-wide door and a door closer force of 6 lb, the maximum allowable pressure difference from Table 1 is 0.40 inches water gage. For a nonsprinklered building with 9 ft. ceiling heights, the minimum allowable pressure difference from Table 2 is 0.10 inches water gage.

From Figure 2, the height limit is 136 ft. Because the height limit is greater than the height of the stairwell, satisfactory pressurization is possible. However, if the height limit were less than the stairwell height, it would not necessarily mean that satisfactory pressurization is impossible. This is because the estimate of the height limit was based on a building without vertical leakage and is therefore conservative. The height limit from Figure 2 can be used as a quick way to determine if satisfactory pressurization is possible, but it can not be used to determine that satisfactory pressurization is impossible.

Figure 2  
Height Limit for a Pressurized Stairwell in a Building Without Vertical Leakage



#### INFLUENCE OF AIRFLOW THROUGH ELEVATORS

As previously stated, the pressure differences across a stairwell are not constant over the height of the stairwell. Figure 1 shows pressure profiles for pressurized stairwells located in three buildings with different leakage characteristics, all of which have the same inside and outside temperatures. The three buildings all have the same

leakage areas on each floor. The pressure profiles are for winter conditions; that is, an outside temperature less than the inside temperature.

In a building without vertical leakage between floors or through shafts other than the stairwell, the pressure profile is a straight line as previously mentioned. Figure 1 shows that the profile of a pressurized stairwell in a building with leakage between floors is similar to the straight line, except at the top and bottom of the stairwell. The extent of the deviation depends on the magnitude of the leakage area between floors.

In a building with leakage through an elevator shaft, the pressure profile is considerably different. The curve shown in Figure 1 is only one of many possible different shapes for this type of building. The pressure profiles depend on the leakage areas of the stairwell, the elevator shaft, the elevator vent (if there is one), and the exterior walls, as well as the temperatures of the building and the outside air. Analysis of such a building is complicated and is generally feasible only with the aid of a computer.

As shown in Figure 1, airflow through an elevator shaft tends to reduce the pressure profile extremes. The minimum pressure difference across the stairwell is greater, and the maximum pressure difference is less. This effect allows adequate pressurization of some stairwells that are taller than the height limit, because the height limit was developed for buildings without vertical leakage except through the stairwell. Because pressurization of elevator shafts affects air flow throughout a building, special attention should be paid to the design of pressurized stairwells in buildings with pressurized elevator shafts.

#### **FAN LOCATION**

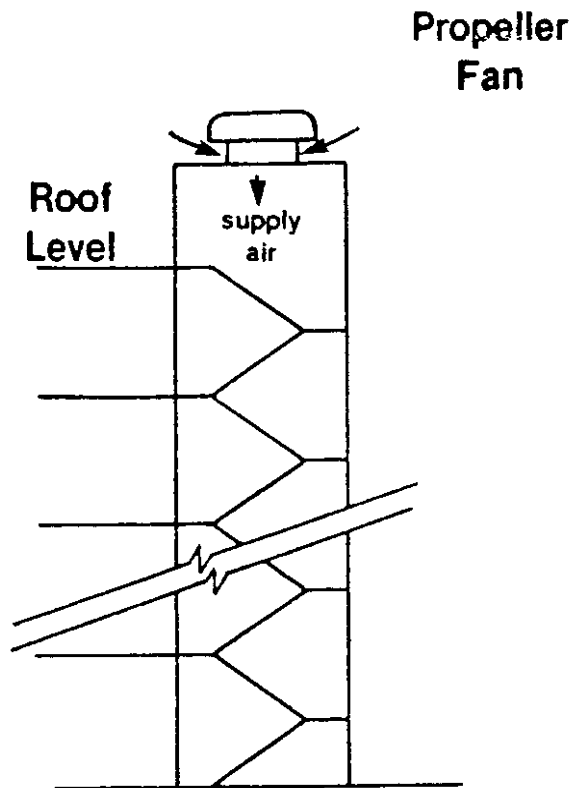
With any stairwell pressurization system, there is the potential for smoke feedback into the pressurized stairwell from smoke entering the pressurization fan intake. Therefore, the capability of automatic shutdown should be considered. The supply air intake should be separated from all building exhausts, outlets from smoke shafts, elevator vents and other openings through which smoke might flow in a building fire. Because hot smoke rises, consideration should be given to locating supply air intakes below such critical outlets. However, outdoor smoke movement that might result in smoke feedback depends on location of the fire, location of the points of smoke leakage from the building, wind speed and direction, and the temperature difference between the smoke and the outside air. At present, too little information is available about such outdoor smoke movement to warrant general recommendations favoring ground-level intakes rather than roof-level intakes. Some designers provide both ground-level and roof-level intakes so that if smoke is detected in one intake that fan can be shut down without loss of stairwell pressurization.

There is concern with locating supply air inlets near the exterior ground floor doors of the stairwell. If a supply inlet is located near this door, the potential exists for much of the supply air to flow directly through the exterior doorway when it is opened thus effectively reducing stairwell pressurization. It is believed that locating inlets only one floor away from exterior doors eliminates this potential.

#### **FAN TYPES**

A stairwell can be pressurized by a single roof-mounted propeller fan as illustrated in Figure 3. The use of propeller fan is not recommended without windshields because of the extreme effect wind can have on the performance of these fans. Propeller fans mounted on walls pose the greatest susceptibility to the adverse effects of wind pressure. The adverse effect will be the greatest for fans located on leeward walls. Because centrifugal fans and in-line axial fans can operate against greater fan head pressures, they are more appropriate to overcome the resistance of systems that include duct work, and they are less susceptible to the adverse effects of wind pressure.

**Figure 3**  
**Stairwell Pressurization by Roof-Mounted Propeller Fan**



### **SINGLE AND MULTIPLE INJECTION**

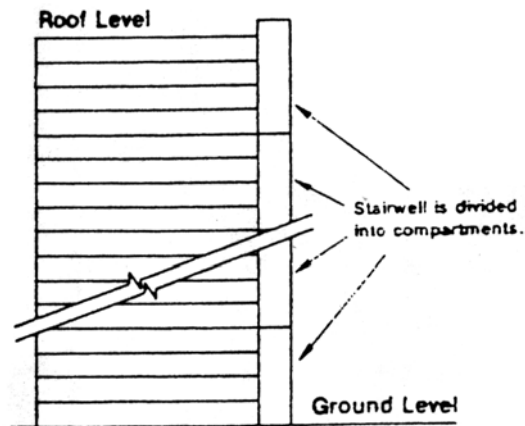
A single injection system is one that has pressurization air supplied to the stairwell at one location. For tall stairwells, single injection systems can fail when a few doors are open near the air supply injection point. This mode of failure is most likely for injection at the ground level when a ground floor door to the outside is open. Thus it is strongly urged that the injection point should not be same level as an exterior door. The ASHRAE Smoke Control Manual indicates that some designers limit the height of top injection stairwells from eight to twelve stories with the intent of preventing loss of pressurization when doors are open near the injection point. Further, the manual recommends careful design for top injection stairwells in excess of eight stories and for all bottom injection stairwells. For taller stairwells, multiple injection is recommended. Further research is needed on the relative merits of single and multiple injection.

### **COMPARTMENTATION**

An alternative to multiple injection is compartmentation of the stairwell into a number of sections, as illustrated in Figure 4. Each compartment has at least one supply air injection point. Compartmentation can also allow pressurization of stairwells that would be too tall to be otherwise satisfactorily pressurized. Unfortunately, when doors between compartments are open, the effect of compartmentation is lost. For this reason, compartmentation is inappropriate for densely populated buildings, where total building evacuation by stairwell is planned in the event of a fire. Compartmentation can be an effective means of providing stairwell pressurization for very tall buildings, when a staged evacuation plan is used and when the system is designed to successfully operate when the maximum number of doors between compartments is open. This maximum number of doors open between compartments would need to be determined by an evacuation analysis. Compartmentation does have a disadvantage from an architectural standpoint in that it probably cannot be achieved without increased stairwell landing area space at some or all floors.



**Figure 4**  
**Compartmentation of a Pressurized Stairwell**



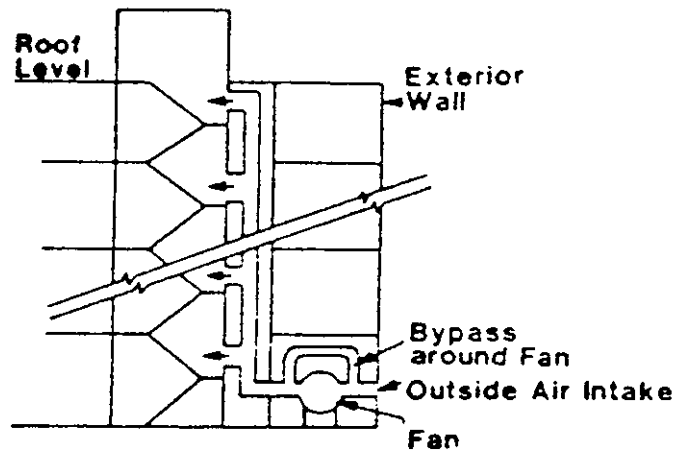
### **SYSTEMS WITH OPEN DOORS**

When a door is opened in a pressurized stairwell, the pressure difference across the remaining closed doors can drop dramatically. The two classes of design concepts that have been used to deal with this problem are over-pressure relief and modulating supply airflow. Systems based on either concept are designed for a number of doors to be open and still maintain adequate pressurization. This design number of open doors should be based on an evacuation analysis.

### **MODULATING SUPPLY AIRFLOW**

In this system the capacity of the fan is sized to provide at least the minimum air velocity when the design number of doors is open. Figure 5 illustrates such a system. The flow rate of air into the stairwell is varied by modulating bypass dampers, which are controlled by one or more static pressure sensors that sense the pressure difference between the stairwell and the building. When all the stairwell doors are closed, the pressure difference increases and the bypass damper opens to increase the bypass air and decrease the flow rate of supply air to the stairwell. In this manner, excessive pressure differences are prevented. The same effect can be achieved by the use of relief dampers on the supply duct when the fan is located outside the building. Supply airflow modulation may also be achieved by varying fan speed, inlet vanes, variable pitch blades, or use of multiple fans. Response times of the controls with any of these systems should be considered.

Figure 5  
Stairtower Pressurization with Bypass Around Supply Fan



### OVER-PRESSURE RELIEF

Over-pressure relief is another method to reduce the pressure difference fluctuations due to stairwell doors opening and closing. Pressure buildup as doors close is relieved by airflow from the stairwell directly to the outside. Exterior relief openings can be subject to adverse effects of wind so windbreaks or windshields are recommended.

Over-pressure relief may be achieved by use of the following hardware:

- automatic opening exterior stairwell door,
- barometric dampers with adjustable counterweights,
- motor-operated dampers controlled by differential pressure sensor, and
- exhaust fan controlled by differential pressure sensor.

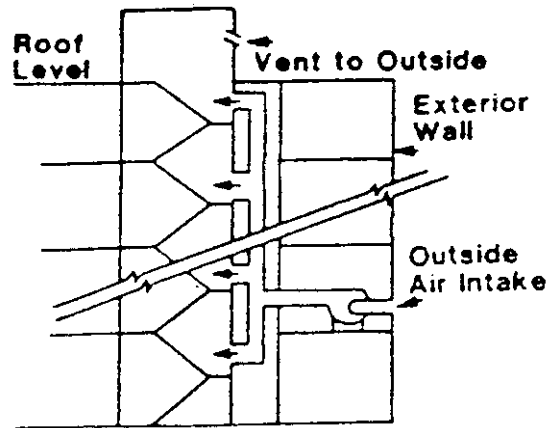
### Automatic Opening Door

Systems using an automatic opening exterior stairwell door are frequently referred to as "Canadian systems" because these simple and cost-effective systems have been extensively used in Canada. The essential features of this system are that air is supplied by one or more fans at relatively constant flow rates and the ground floor exterior stairwell door opens automatically upon system activation. This system eliminates the source of the most severe pressure fluctuations, that is the opening and closing of the exterior door. Under normal conditions, the exterior stairwell door would generally be locked for security reasons. Provisions need to be made so that this lock will not conflict with the automatic operation of the door.

### Barometric Dampers

Barometric dampers with adjustable counterweights can be used to achieve over-pressure relief as illustrated in Figure 6. This is the simplest method of over-pressure relief because of the simplicity of the hardware and the lack of control. The location of the dampers needs to be carefully chosen since dampers located too close to the supply openings can operate too quickly.

Figure 6  
Stairtower Pressurization with Vent to the Outside



NOTE: Supply fan may be located at any level. NFPA 92A states that these dampers can be subject to chattering during operation. This is true and they can chatter during normal building operation which can be a considerable annoyance to building occupants. The possibility that annoyed occupants will prevent this chatter by sealing or wiring a damper closed should be considered when evaluating the appropriateness of this system.

#### **Motor-Operated Dampers**

Motor-operated dampers controlled by a differential pressure sensor can be used to achieve over-pressure relief. These dampers can have pneumatic or electric motor operators, and the sensors should sense the pressure difference between the stairwell and the building.

#### **Exhaust Fan**

An exhaust fan may be used to prevent excessive pressure when all stairwell doors are closed. The fan should be controlled by a differential pressure sensor that senses the pressure difference between the stairwell and the building. The fan should shut off when the pressure difference falls below a specified level. This specified level should be selected so as to prevent the fan from pulling smoke into the stairwell when a design number of open doors has reduced stairwell pressurization.

The methods of design presented in the ASHRAE Smoke Control Manual are sufficient for design analysis of the different systems described above for dealing with the pressure fluctuations due to opening and closing doors. However, a research proposal has been developed by the ASHRAE Fire and Smoke Control Committee (ASHRAE TC 5.6) for a project to evaluate the relative merits of these systems. It is anticipated that this project will provide practical design information that will lead to more effective and less complicated systems.

#### **SUMMARY**

The approach to design analysis of smoke control systems presented in the ASHRAE Smoke Control Manual accounts for the buoyancy effect of hot fire gases by selection of a minimum design pressure difference. The maximum pressure difference caused by a smoke control system should not result in excessive door opening forces. Stairwells are commonly pressurized with the intent of preventing smoke infiltration into the stairwell during a building fire.

For tall stairwells during extreme conditions of outside temperature, satisfactory pressurization of a stairwell can be impossible when all doors are closed. The concept of the height limit can be used to provide an indication if a problem concerning satisfactory pressurization exists. Airflow through unpressurized elevator shafts in buildings results in building air pressures that increase the likelihood of satisfactory pressurization. Compartmentation of a

stairwell into a number of sections is a technique that can be used to allow pressurization of stairwells that would be too tall to be otherwise satisfactorily pressurized.

There is some difference of opinion concerning location of air intakes. At present, too little information is available about such outdoor smoke movement to warrant general recommendations favoring ground-level intakes rather than roof-level intakes. Some designers provide both ground-level and roof-level intakes so that if smoke is detected in one intake that fan can be shut down without loss of stairwell pressurization.

Two design concepts that have been used to deal with pressure fluctuations due to doors opening and closing are over-pressure relief and modulating supply airflow. There are numerous variations on both of these design approaches.

## REFERENCES

Cresci, R.J. 1973. Smoke and Fire Control in High-Rise Office Buildings - Part II: Analysis of Stair Pressurization Systems, Symposium on Experience and Applications on Smoke and Fire Control at the ASHRAE Annual Meeting, June 1973, Louisville, KY, Atlanta, GA, pp. 16-23.

DeCicco, P.R. 1973. Smoke and Fire Control in High-Rise Office Buildings - Part I: Full-Scale Tests for Establishing Standards, Symposium on Experience and Applications on Smoke and Fire Control at the ASHRAE Annual Meeting, June 1973, Louisville, KY, Atlanta, GA, pp. 9-15.

Klote, J.H. and Fothergill, J.W. 1983. "Design of Smoke Control Systems for Buildings," ASHRAE, Atlanta, GA.

Koplon, N.A. 1973. Report of the Henry Grady Fire Tests, City of Atlanta Building Department, Atlanta, GA.

NFPA 1985. Code for Safety to Life from Fire in Buildings and Structures, NFPA 101-1985, Quincy, MA, National Fire Protection Association.

NFPA 1987. Recommended Practice for Smoke Control Systems, draft document. NFPA 92A, Quincy, MA, National Fire Protection Association.

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