NISTIR 4551

DESIGN MANUAL FOR SMOKE CONTROL SYSTEMS

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United States Department of Commerce
National Institute of Standards and Technology

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PREFACE

This manual consolidates and systematically presents data and calculational procedures for use by smoke control system designers, and design criteria is discussed. Fundamental issues of smoke control include reliability, activation, smoke obscuration, toxicity, and the driving forces of smoke movement. The mechanisms of compartmentation, dilution, air flow, pressurization, and buoyancy are used by themselves or in combination to manage smoke conditions in fire situations. A computer program for analysis of smoke control systems is presented. Systems for stairwell pressurization, elevator smoke control, and zoned smoke control are presented. Numerous example calculations are included.

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Students of fire protection engineering at the University of Maryland have provided input about many aspects of smoke management. In particular, the ideas of Ross Mowery and Charles Fleischmann had a significant impact on the data input description for the computer program ASCOS. So many professionals from various fields have provided ideas that are the basis of much of this manual that it is impossible to thank them all individually. In addition, the author wishes to thank the following reviewers for their ideas and constructive criticism:

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NOMENCLATURE

A	area
a	dilution rate
b	temperature factor
C	flow coefficient, general coefficient, or contaminant concentration
c	specific heat
C_o	initial contaminant concentration
C_w	pressure coefficient
d	distance from doorknob to knob side of door
E	energy release rate
F	force
F_r	force to overcome door closer and other friction
g	acceleration of gravity
h	height
H	height of stairwell
Hm	height limit
K_d	coefficient from the door opening force equation
K_f	coefficient from the flow equation
K_g	coefficient from equation for flow factor
K_s	coefficient for stack effect and buoyancy equations
K_{pt}	coefficient for velocity from pitot-static tube
K_v	coefficient from the Thomas equation for critical air velocity
K_w	coefficient from wind pressure equation
$\dot{m}$	mass flow rate
$\dot{m}_f$	net mass flow rate due to HVAC system or to pressurization system
$\dot{m}_o$	mass flow rate from outside
$\dot{m}_u$	upward mass flow in shaft
n	wind exponent
N	number of floors
P	pressure
P_{atm}	atmospheric pressure
Q	volumetric flow rate
R	gas constant of air
T	absolute temperature
t	time
V	velocity
W	width
ΔP	pressure difference
$\overline{\Delta P}$	average pressure difference
ρ	density

Subscripts

B	building
b	bottom of stairwell or stairwell section
e	effective
F	fire compartment
g	geometric
h	distributed per unit height
I	inside

k	critical
max	maximum
min	minimum
O	outside
S	stairwell
t	top of stairwell or stairwell section
T	total
w	wind

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Chapter 1. INTRODUCTION

Smoke is recognized as the major killer in fire situations. Smoke often migrates to building locations remote from the fire space, threatening life and damaging property. Stairwells and elevator shafts frequently become smoke-logged, thereby blocking evacuation and inhibiting rescue and fire fighting. The MGM Grand Hotel fire (Best and Demers 1982) is an example of the smoke problem. The fire was limited to the first floor, but smoke spread throughout the building. Some occupants on upper floors were exposed to smoke for hours before rescue. The death toll was 85, and the majority of the deaths were on floors far above the fire. The MGM Grand is not unique in this respect as is illustrated by the fires at the Roosevelt Hotel (Juillerant 1964) and Johnson City Retirement Center (Steckler, Quintiere and Klote 1990). All these fires were located on the first floor, but the majority of deaths were on upper floors (figure 1.1)[1]. The concept of smoke control was developed as a solution to the smoke problem[2].

The general public is unaware of how fast a fire can grow and of how much smoke that can be produced by a fire, and this unawareness extends to many designers and other related professionals. Because such an awareness is necessary to the evaluation of design parameters for smoke control systems, the following example is provided.

This example is fire test N-54 performed at the Health Care Test Facility at the National Institute of Standards and Technology Annex in Gaithersburg, MD. For technical details of this unsprinklered fire test, the reader is referred to a report by O'Neill, Hayes, and Zile (1980). The floor plan of the test facility is shown in figure 1.2.

In this test, various fabrics representing common clothing materials were hung on wire coat hangers and arranged loosely in a wooden wardrobe. A cardboard box containing crumpled newspaper was placed on the floor of the wardrobe. The test started when the crumpled newspaper was ignited by a match. Following ignition, the left hand door of the wardrobe was closed tightly while the right hand door was left partially open resulting in a 3 in (76 mm) opening along the vertical edge of the door.

At one second after ignition, no flame or smoke was visible. At 80 seconds, flames were visible flowing from the top of the wardrobe, a layer of smoke was covering the ceiling of the burn room, and smoke had flowed into the corridor forming a one foot thick layer just below the corridor ceiling. At 110 seconds, flames were flowing from the top two-thirds of the wardrobe opening,

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[1] During the intensive activity of fire fighting and rescue, the locations of some of the bodies are not recorded. Thus figure 1.1 is limited to the deaths for which the locations were known.

[2] As discussed later in Preliminary Design Considerations, smoke control is only one of many techniques available to fire protection engineers.

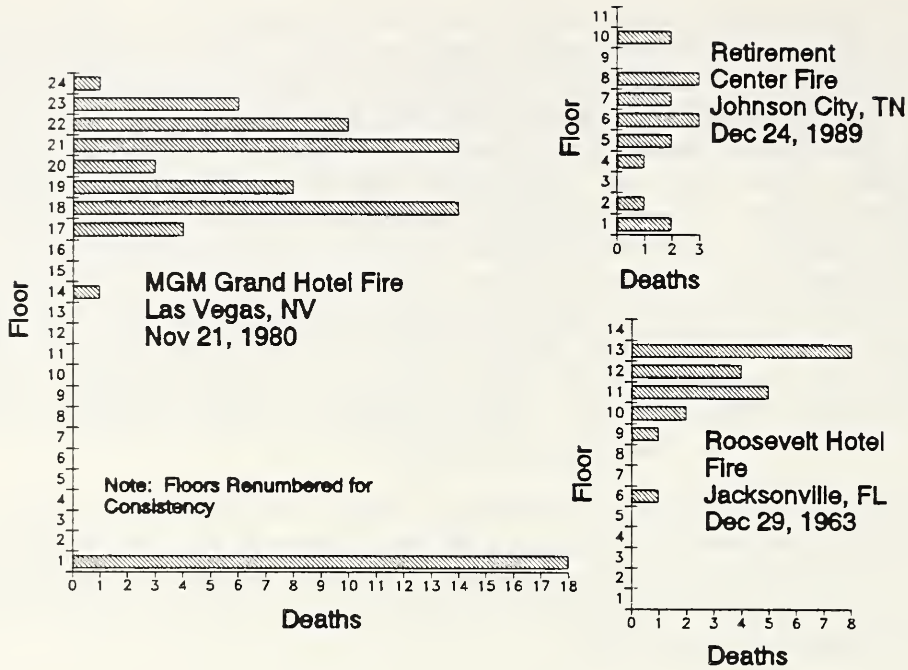

Figure 1.1 Deaths by floor for three fires where the fire was located on the first floor

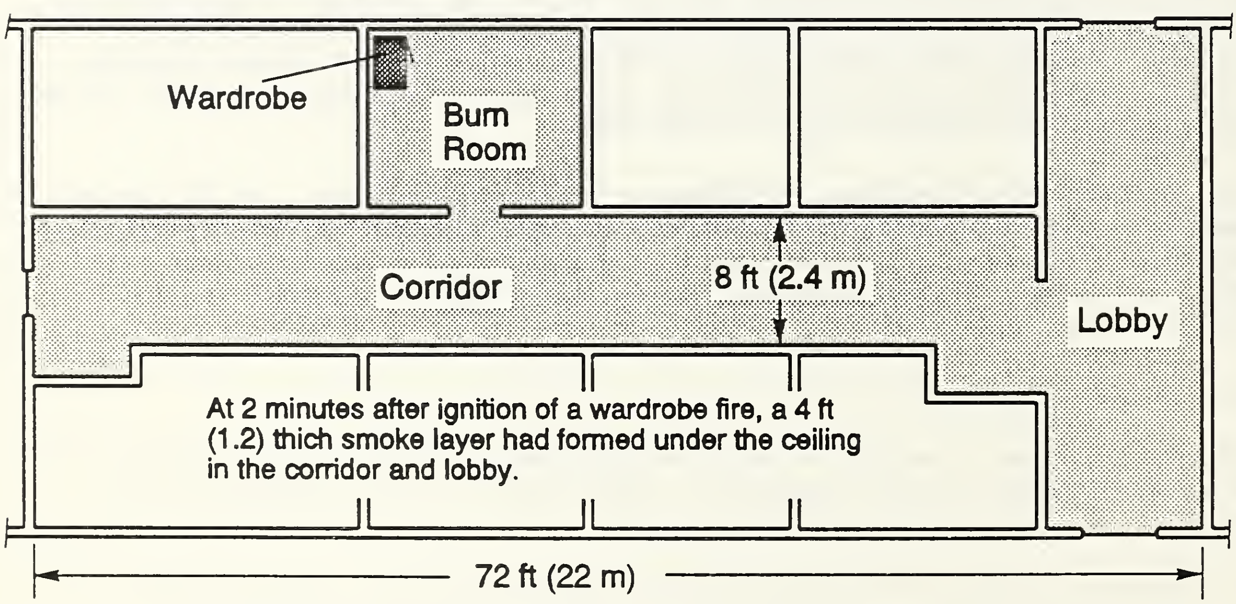

Figure 1.2 Floor plan of the Health Care Test Facility at the NIST Annex

and the smoke flowing out of the burn room doorway had increased significantly. At 120 seconds after ignition, flames were flowing from the entire opening of the wardrobe door, and the layer of smoke in the corridor and lobby had descended to approximately 4 ft (1.2 m) below the ceiling.

Such very rapid fire growth and accompanying smoke production represent a real possibility in actual wardrobe fires and perhaps even closet fires. Many other fire scenarios are possible. For example, a latex or a polyurethane filled mattress ignited by an adjacent wastebasket fire would reach about the same stage of development in six minutes that wardrobe test N-54 reached in two minutes.

As a solution to the smoke migration problem, the concept of <u>smoke management</u> has developed. Smoke movement can be managed by use of one or more of the following mechanisms: compartmentation, dilution, air flow, pressurization, or buoyancy. These mechanisms are discussed in detail in Chapter 4. The use of pressurization produced by mechanical fans is referred to as smoke control by NFPA 92A (1988). By this definition, stairwell pressurization (Chapter 7), elevator pressurization (Chapter 8), and zoned smoke control (Chapter 9) are all types of smoke control systems.

The primary emphasis of this manual is on systems that use pressurization produced by mechanical fans. The use of pressurization to control the flow of undesired airborne matter has been practiced for at least 50 years. For example, it has been used in buildings, such as experimental laboratories, where there is a danger of poison gas or bacteriological material migrating from one area to another; they have been used to control the entrance of contaminants where a dust-free environment is necessary; they have been used where radiation migration and contamination could occur; and they have been used in hospitals to prevent the migration of bacteria to sterile areas. However, the use of airflow and pressurization to control smoke flow from a building fire is a fairly recent adaptation.

1.1 SCOPE

The intent of this manual is to provide practical state-of-the-art design information to engineers who have been charged with the design of smoke control systems. This chapter contains general background information. Chapter 2 discusses the nature of smoke including obscuration and toxicity. Chapter 3 is devoted to smoke movement in buildings, and the individual driving forces of smoke movement are discussed in detail. Chapter 4 contains a fundamental discussion of topics which are essential for design of systems to manage smoke movement. Design parameters for such systems are:

- The leakage areas of flow paths throughout the building.
- The design weather data.
- Pressure differences across boundaries of smoke control systems.

- Airflow through openings in boundaries of smoke control systems.

- The number of doors likely to be open in the boundary of a smoke control system.

Chapter 5 is a description of the computer program for analysis of smoke control systems (ASCOS). Background information is provided about ducts, fans, fire dampers, smoke dampers, and fan powered ventilation systems in Chapter 6. Chapter 7 pertains to stairwell pressurization, and Chapter 8 to elevator smoke control. Chapter 9 is devoted to zoned smoke control. The important topic of commissioning and routine testing is treated in Chapter 10.

It may be noted that pressurized corridors, smoke shafts, "smokeproof" towers, and atrium smoke management have been omitted. Pressurized corridors have been omitted because there is insufficient data to ensure the validity of system concepts and calculational procedures. It is hoped that the scope of a future version of this manual will be broadened to include these topics. Even though there is insufficient data to discuss corridor pressurization, the fundamental principles discussed in the manual apply, and the methods of computer analysis by network modeling presented in Chapter 6 are appropriate.

1.2 EQUATIONS AND UNITS OF MEASUREMENT

Considering that this manual is primarily intended for design, it seems most appropriate that units should be specified for every equation. However, the topic of smoke control is relatively new, and there is no text to refer to for the derivation of many of the equations used. Further, it was desired that the text be in both English units and the International System Units (SI). It would be unacceptably cumbersome to present derivations using both commonly used English units and SI units. The equations used for derivations are dimensionally homogeneous, and they can be used with the SI system, the slug pound system, and the pound mass poundal system (Appendix A). These dimensionally homogeneous equations are easily identified because no units are specified for them in the text. However, all of the equations that the reader is likely to use for design analysis are given in both English and SI units. These equations are easily identified, because the appropriate units for the equation are specifically indicated in the text.

1.3 SMOKE CONTROL SYSTEM PERFORMANCE

The objectives of a smoke control system are to reduce deaths and injuries from smoke, reduce property loss from smoke damage, or to aid firefighters. Many designers feel that life safety is the primary objective of smoke control, however, many systems have been built with the primary objective of property protection. Regardless of the objective, the methods of design analysis presented in this manual are applicable.

Theoretically, a smoke control system can be designed to provide a safe escape route, a safe refuge area or both. However, a smoke control system can meet its objectives, even if a small amount of smoke infiltrates protected areas. However, for this manual, smoke control systems are designed on the basis that no smoke infiltration will occur.

1.4 PRELIMINARY DESIGN CONSIDERATIONS

Smoke control should be viewed as only one part of the overall building fire protection. Two basic approaches to fire protection are to prevent fire ignition and to manage fire impact. Figure 1.3 shows a simplified decision tree for fire protection. The building occupants and managers have the primary role in preventing fire ignition. The building design team may incorporate features into the building to assist the occupants and managers in this effort. Because it is impossible to prevent fire ignition completely, managing fire impact has assumed a significant role in fire protection design. Compartmentation, suppression, control of construction materials, exit systems, and smoke management are examples. The NFPA Fire Protection Handbook (NFPA 1986) and the SFPE Handbook of Fire Protection Engineering (SFPE 1988) contain detailed information about fire safety.

Many factors will affect the design of a smoke control system. Before the actual mechanical design of the system can proceed, the potential constraints on the system should be determined and the design criteria established. This section introduces some considerations peculiar to smoke control system design, some of which are merely listed below, since detailed discussion is beyond the scope of this manual. However, published works on some of these subjects are cited in the bibliography in Appendix B.

- Occupancy type and characteristics.
- Evacuation plan.
- Refuge areas.
- Distribution of occupant density.
- Human life support requirements.
- Form of detection and alarm.
- Fire service response-to-alarm characteristics.
- Fire suppression system characteristics.
- Type of heating, ventilating and air-conditioning (HVAC) system.
- Energy management system.
- Building security provisions.
- Controls.
- Status of doors during potential fire condition.
- Potential fire threats.
- Internal compartmentation and architectural characteristics.
- Building leakage paths.
- Exterior temperatures.
- Wind velocity.

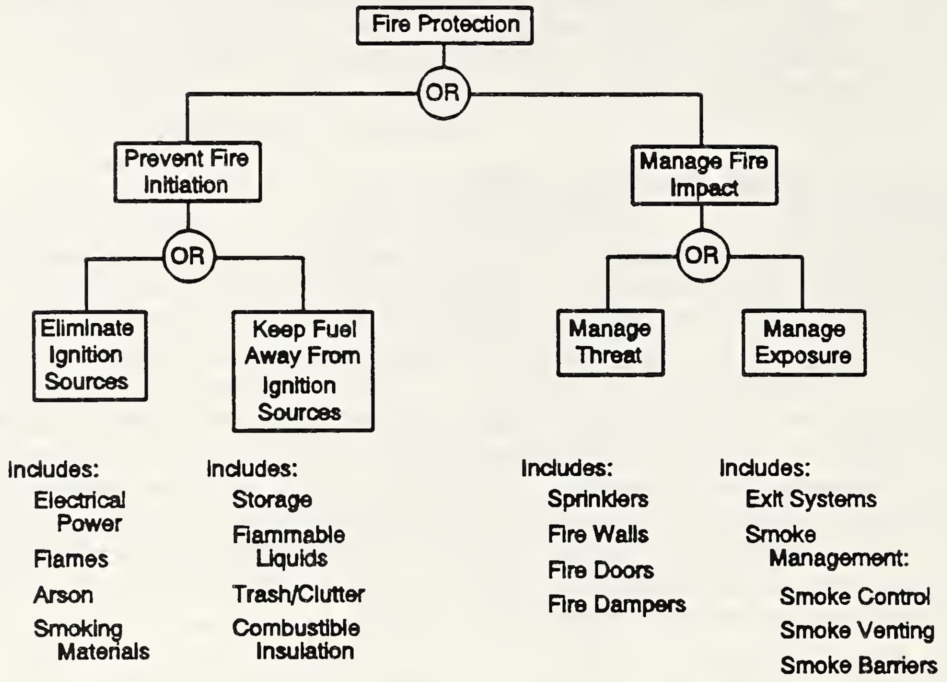

Figure 1.3 Simplified fire protection decision tree

1.5 FLEXIBILITY AND RESILIENCY

To help assure smoke control system performance, the approaches of flexibility and resiliency can be employed. The concept of flexibility consists of using design features that allow for easy adjustment of a smoke control system in order to achieve acceptable performance. A resilient system is one that resists serious adverse effects due to pressure fluctuations.

During the design of a new building, the leakage paths throughout the building can only be estimated. Therefore, the smoke control design calculations constitute only an approximate representation of the pressures and airflows that will occur as a result of the smoke control system in the actual building. The introduction of flexibility into a smoke control system allows for variations in leakage from the originally estimated values. Because it is difficult to measure leakage paths in existing buildings, the concept of flexibility is also useful for retrofit of smoke control in existing buildings. In many systems, flexibility can be achieved by the use of fans with sheaves[3] to allow several flow rates, a variable flow fan for the same purpose, or by dampers that can be manually adjusted to obtain desired pressure differences.

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[3] A sheave is the wheel with a grooved rim sometimes called a belt wheel. By exchanging a sheave for one of another diameter, the rotational speed of the fan and its flow rate are changed.

The pressure fluctuations often occur during a fire when doors are opened and closed and when windows are opened, closed or broken. To resist such fluctuations, resiliency can be incorporated in a system by use of automatic control to reduce the pressure fluctuations. For example, in pressurized stairwells, automatic control can be used in the supply fan bypass system to reduce the effect of opening and closing stairwell doors. An alternative is to keep the exterior stairwell door open during pressurization. This eliminates what is probably the major source of fluctuations, that is the opening and closing of the exterior stairwell door. The concepts of flexibility and resiliency are discussed further where they apply to specific smoke control applications.

1.6 FIRE SUPPRESSION SYSTEMS

Automatic suppression systems are an integral part of many fire protection designs, and the efficacy of such systems in controlling building fires is well documented. However, it is important to recognize that while the functions of fire suppression and smoke control are both desirable fire safety features, they should not be readily substituted for each other. One of the best ways to deal with the smoke problem is to stop smoke production. To the extent that a suppression system slows down the burning rate, it reduces the smoke problem. For fires that are suppressed rather than extinguished, some smoke is produced. This smoke can move through the building due to various driving forces discussed in Chapter 3. On the other hand, well designed smoke control systems can maintain tolerable conditions along critical egress routes but will have little effect on the fire.

In addition to the fact that the systems perform different functions, it is important that the designer consider the interaction between smoke control and fire suppression. For example, in the case of a fully sprinklered building, the pressure difference needed to control smoke movement is probably less than in an unsprinklered building due to the likelihood that the maximum fire size will be significantly smaller than in an unsprinklered building.

A smoke control system can adversely affect performance of a gaseous agent (such as Halon, CO_2 or N_2) suppression system when the systems are located in a common space. In the event that both systems are activated concurrently, the smoke exhaust system may exhaust the suppressant gas from the room, replacing it with outside air. Since gas suppression systems commonly provide a single application of the agent, the potential arises for renewed growth of the fire.

A general guideline would be that the gaseous agent suppression system should take precedence over the smoke control system. An extremely desirable feature in such spaces would be the ability to purge the residual smoke and the suppressant gas after the fire was completely extinguished and to replace them with fresh air. This ability to replace the atmosphere in these spaces in the post-fire period is very important from a life-safety viewpoint, since some gas suppressants are asphyxiants at normal design concentrations.

1.7 ENERGY CONSERVATION

The smoke control system must be designed to override the local controls in a variable air volume HVAC system so that the air supply necessary to pressurize nonfire spaces is supplied. Also, if there is an energy management system or a 24-hour clock system, the designer must ensure that the smoke control system will take precedence over the local control system, so that the necessary air is supplied or exhausted according to the design approach. It is a good general rule that smoke control should take precedence over energy conservation features in both new designs and retrofits.

1.8 SYSTEM ACTIVATION

Probably, system activation is 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 would result in the opposite of the desired operation, that is smoke would be forced 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 are concerned that such manual activation could be so late in the fire development that significant hazard to life and damage to property would result. Such delayed activation can suddenly transport a body of smoke that is highly charged with unburned hydrocarbons, carbon monoxide and other toxic gases and depleted of oxygen to remote locations. This can result in a wave like movement of toxic gases or flame to remote areas.

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. This can only be accomplished if the detector or sprinkler zones are compatible with the smoke control zones. Using heat detector or sprinkler flow signals for activation 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 has been complete agreement that zoned smoke control should not be activated by alarms from manual stations (pull boxes). The reason can be illustrated by the scenario of a man who observing a fire on an upper floor of a building 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 manual station. If that alarm activated the smoke control system, the wrong zone would identified as the fire zone.

Because of the long response time and the maintenance problem of clogging with airborne particles, it is generally agreed that smoke detectors located in HVAC ducts should not be the primary means of smoke control system activation. A means of activation of higher reliability and quicker response time is needed. However, an alarm from a duct-located detector can be used in addition to such a primary means of activation. A signal from only this secondary means might be unusual, but it should be able to activate the smoke control system.

Most stairwell pressurization systems operate in the same manner regardless where the fire is located. Therefore, it generally is agreed that most stairwell pressurization systems can be activated by the alarm of any device located within the building. It is recommended that zoned smoke control systems be equipped with a remote control center from which the smoke control system can be manually overridden. Such a control center should be easily identifiable and accessible to the fire department.

1.9 RELIABILITY OF SMOKE CONTROL

The intent of this section is to provide insight into the need for acceptance testing, routine testing, and relative importance of system simplicity. The following should not be thought of as an exhaustive treatment of smoke control reliability. Due to the difficulty of obtaining data about the reliability of components of smoke control systems, the simple calculations that follow are only very rough estimates. However, it is believed that the insight gained justifies this treatment despite these limitations. Further, the same reliability concerns that apply to smoke control systems apply to all life safety systems, and the following discussion may be of general interest beyond smoke control.

The discussion is limited to series systems which are systems that operate only if all the components operate, as is true of many smoke control system designs. Redundancies (such as back-up power) are not included in this analysis. The reliability, R, of a series system is the product of the reliabilities, R_i, of the components.

$$R = \prod_{i=1}^{n} R_i \tag{1.1}$$

Usually, discussions of reliability progress from this point with the assumption that all components operate initially and that failures occur with time after system installation. For this assumption to be appropriate, a program of acceptance testing and defect correction is necessary. Such commissioning must include an installation check of all components, tests of system performance during all modes of operation, repair of defects, and retesting until all defects are corrected. Current construction practices are such that system commissioning is not always this exhaustive. For this reason, attention is first given to reliability of systems without commissioning followed by a discussion of reliability of systems for which all components operate after commissioning.

1.9.1 Reliability Before Commissioning

For newly installed components, the reliability can be thought of as the likelihood that the component will both be installed properly and be in good working condition when it is delivered to the construction site. There are an enormous number of errors that can occur during manufacture, transportation, storage, and installation that can cause a component to fail to operate. Problems such as motors wired for the wrong voltage, motors not connected to power, dampers failing to close, fans running backward, holes in walls, and automatic doors failing to close have been observed in newly built smoke control systems. Based on experience with field testing of smoke control systems, it is estimated that the reliability of components in non-commissioned systems is 0.90 or higher. An important consideration regarding the reliability of a component in a non-commissioned system is if that component is part of a HVAC system. In hot or cold weather, building occupants demand that the HVAC system provide comfort conditions. Thus, for a new building in extreme weather, it can be considered that the reliability of the HVAC system fan will approach unity. Based on field observations, it is believed that other components will have a lower reliability. The following reliabilities were chosen for example calculations for new systems that have not been commissioned:

Fans of a forced air HVAC system	0.99
Other components	0.94

These values were arbitrarily selected, but the relative values between them are based on the discussion above. Table 1.1 lists calculated reliabilities of such systems made up of many components. It can be observed from this table that the more components a system has, the less likely the system is to operate before it has been commissioned. The most reliable new system would be one that only uses the HVAC system fans. A large complicated system consisting of many components (table 1.1, system 5) has very little chance of operating before commissioning. The trend of lower reliability for complicated systems agrees with observations of the author at numerous field tests of systems of various degrees of complexity. Probably the most important point to be made from this discussion is the need for commissioning of new systems.

Table 1.1 Estimated system reliability for new smoke control system that has not been commissioned

System	No. of HVAC System Fans	No. of Other Components	Reliability[1] of New System Before Commissioning	Mean Life[2] of Commissioned System (months)
1	3	0	0.97	116
2	0	3	0.83	46
3	3	9	0.56	14
4	5	18	0.31	8
5	5	54	0.03	3

1. System reliabilities calculated from equation (1.1). For purposes of these calculations, the reliabilities of fans of a forced air HVAC system were taken as 0.99, and other components were taken as 0.94.

2. Mean lives calculated from equation (1.3). For purposes of these calculations, the failure rates of fans of a forced air HVAC system were taken as 10^{-6} per hour, and other components were taken as 10^{-5} per hour.

1.9.2 Mean Life of Commissioned Systems

For this discussion, all system components are considered to operate at the end of the commissioning process. A commonly used relation for the reliability of components is the exponential distribution:

$$R_i = \exp(-\lambda_i t) \tag{1.2}$$

where λ_i is the failure rate of the component. The mean life, L, of a system is

$$L = \frac{1}{\sum_{i=1}^{n} \lambda_i} \tag{1.3}$$

Some typical ranges of failure rates of some components and systems are shown in figure 1.4. It can be seen that failure rates vary over large ranges and that failure rates vary considerably with equipment type. It seems that the failure rate of HVAC system fans would be lower than those of other components. If these fans fail, building occupants desiring heating or cooling tend to put pressure on maintenance personnel to get fans repaired quickly. Smoke control systems are only needed for a short time over the life of a building. Thus when an HVAC system fan is called upon for smoke control duty, it seems that it will be more likely to operate than other components. To account for this, the effective failure rate of HVAC system fans can be thought of as being much smaller than other components. The following failure rates were arbitrarily selected for example calculations, but their relative values are based on the above discussion:

Fans of a forced air HVAC system	10^{-6} per hr
Other components	10^{-5} per hr

Table 1.1 shows mean lives of systems composed of various numbers of components. It can be observed that systems composed of a few components have long mean lives, while those made up of very many components have short lives. This tends to support the view that simple systems are more reliable, and this view is supported by observations in the field. However, it should be cautioned that systems should not be overly simple, that is they should have the features needed to achieve desired performance at likely conditions during a fire. Further, the above simple analysis did not include the beneficial effects of redundancies. However, it is safe to conclude that unnecessary system complexities should be avoided. The mean lives listed in table 1.1 also indicate that routine testing and repair of smoke control systems is needed so that the systems will probably be in good working order when they are needed. A similar statement can be made concerning all life safety systems.

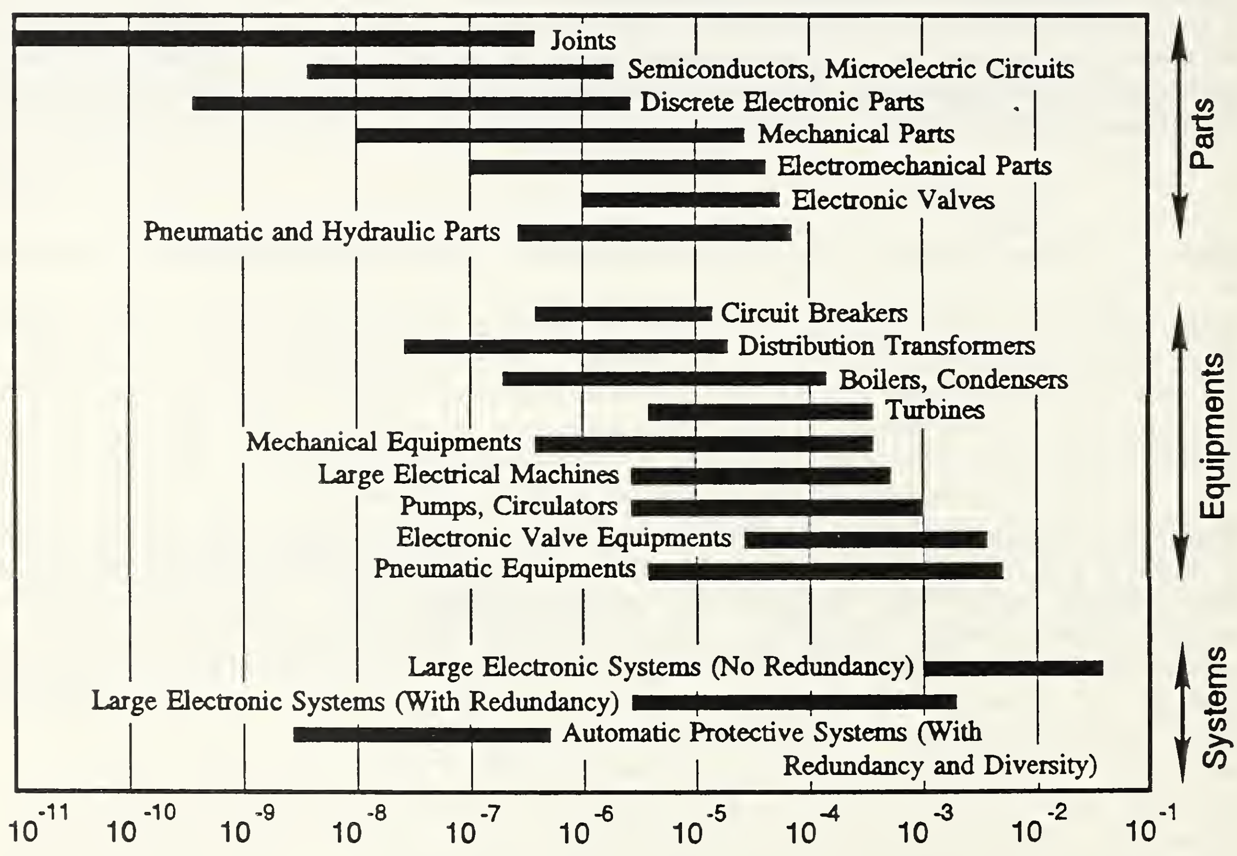

Figure 1.4 Typical ranges of failure rates [adapted from Lees (1980)]

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Chapter 2. NATURE OF SMOKE

In this manual, the term "smoke" is used in accordance with the NFPA 92A (1988) definition which states that smoke consists of the airborne 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. The products of combustion usually include particulates, unburned fuel, water vapor, carbon dioxide, carbon monoxide, and some other toxic and corrosive gases. As smoke moves through a building, air mixes into the smoke mass, and the concentration of combustion products in the smoke decreases. Including air that is entrained or otherwise mixed facilitates discussions about fire smoke management in atriums and other large spaces. Generally smoke is thought of as being visible, but the above definition includes "invisible smoke" due to the burning of materials that produce little of no particulate matter such as hydrogen, natural gas, and alcohol.

Information about smoke hazards is useful in evaluating the effects of small quantities of smoke migrating into "protected spaces," and it is useful in evaluating the consequences of smoke migration without smoke protection. This chapter concentrates on smoke hazards due to toxicity, temperature, and light obscuration. Exposure to toxic gases and elevated temperatures are direct hazards to life, but reduced visibility due to smoke obscuration can be a significant indirect hazard. Frequently, people become disoriented in fire situations because they cannot see through heavy smoke. If they remain in the building too long, they fall victim to exposure to toxic gases or elevated temperatures. Most of the information in this chapter about toxicity and the effects of temperature has been adapted from the Technical Reference for Hazard I by Bukowski et al. (1989). Because smoke control is concerned with protection of people and property at locations remote from the fire, the effects of thermal radiation are not addressed in this manual.

2.1 SMOKE OBSCURATION TERMINOLOGY

Many different methods of expressing smoke obscuration are used in fire science and fire protection engineering, and this section discusses some of the common methods. The fraction of light transmitted through the pathlength of smoke is called the transmittance, and is written as

$$T = \frac{I_x}{I_o} \tag{2.1}$$

where:
T = transmittance, dimensionless
I_o = intensity of light at the beginning of the pathlength
I_x = intensity of light remaining after it has passed through the pathlength

The units for light intensity are arbitrary, and such units are unnecessary for discussions of smoke obscuration and even for measurements of smoke obscuration. Transmittance is measured by monitoring the attenuation of a beam of light passing through a pathlength, x, of smoke as illustrated in figure 2.1. The light can be from a columnated source or a laser. When the atmosphere is "smoke free," the intensity of light remaining after it has passed through the pathlength is almost exactly the same as the intensity at the beginning of the pathlength, and the transmittance is almost exactly one. It follows that the transmittance of a beam passing through "visible smoke" is less than one. Neutral density filters which allow only a specific fraction of the light to pass through are used to calibrate light meters. Thus, the voltage (or current) output of the photo cell can be calibrated to give transmittance directly.

The properties of smoke are expressed routinely in terms of the transmittance as either optical density or attenuation coefficient. Optical density per unit distance is defined as

$$\delta = - \frac{\log_{10} T}{x} \qquad (2.2)$$

where:
δ = optical density per unit distance, ft^{-1} (m^{-1})
T = transmittance, dimensionless
x = distance of light travel or the pathlength, ft (m)

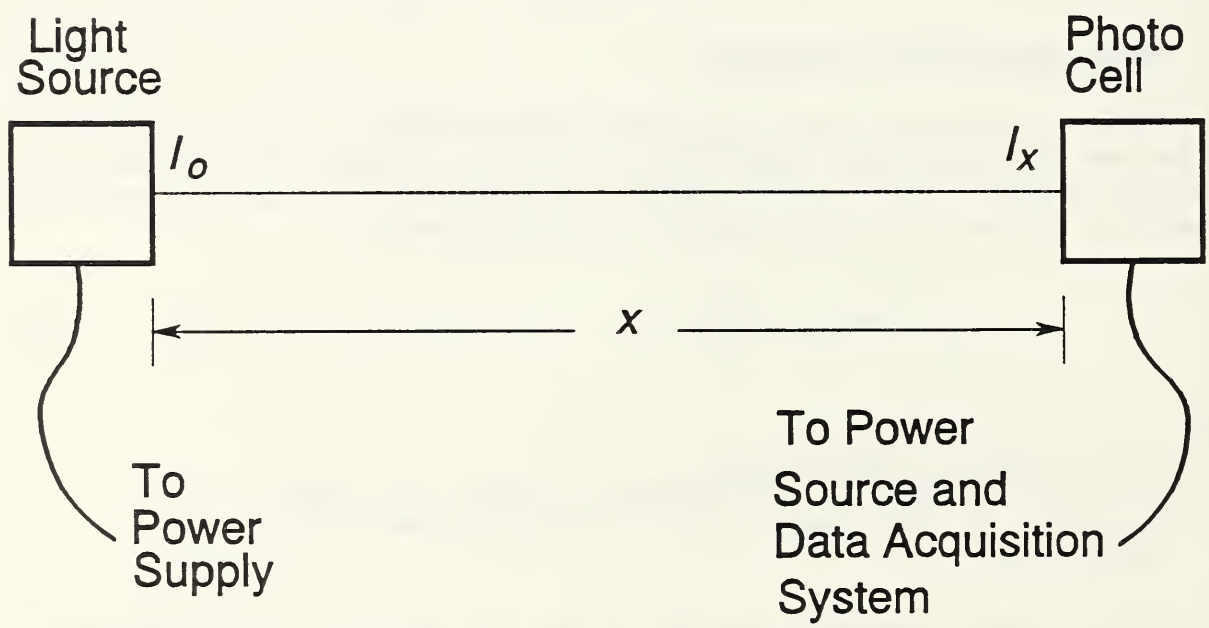

Figure 2.1 Smoke meter used to measure smoke obscuration

The attenuation coefficient per unit distance is defined as

$$\alpha = - \frac{\log_e T}{x} \qquad (2.3)$$

where α is the attenuation coefficient per unit distance in units of ft^{-1} (m^{-1}). Percentage obscuration is occasionally used, and it is defined as

$$\lambda = 100 (1 - T) \qquad (2.4)$$

where λ is the dimensionless percentage obscuration. Table 2.1 lists some values of optical density, attenuation coefficient and percentage obscuration for different path lengths. Equations for conversion among optical density, attenuation coefficient, and percentage obscuration can be useful when comparing smoke obscuration data from one research paper or engineering report to another. By substituting expressions for $\log_{10}$ T and $\log_e$ T from equations (2.2) and (2.3) into the identity $\log_e T = \log_e 10 \log_{10} T$ (note that $\log_e 10$ is approximately 2.303) the following relation is developed

Table 2.1 Comparison of different methods of expressing smoke obscuration

Transmittance T	Percentage Obscuration λ	Pathlength x, ft(m)	Optical Density δ, $ft^{-1}(m^{-1})$	Attenuation Coefficient α, $ft^{-1}(m^{-1})$
1.00	0	any	0	0
.90	10	1 (.305)	.0458 (.150)	.105 (.344)
		10 (3.05)	.00458 (.0150)	.0105 (3.44)
.60	40	1 (.305)	.222 (.728)	.511 (1.68)
		10 (3.05)	.0222 (.0728)	.0511 (.168)
.30	70	1 (.305)	.523 (1.72)	1.20 (3.94)
		10 (3.05)	.0523 (.172)	.120 (.394)
.10	90	1 (.305)	1.00 (3.28)	2.30 (7.55)
		10 (3.05)	.100 (.328)	.230 (.755)
		30 (9.14)	.0333 (.109)	.0767 (.252)
.01	99	1 (.305)	2.00 (6.56)	4.61 (15.1)
		10 (3.05)	.200 (.656)	.461 (1.51)
		30 (9.14)	.0667 (.219)	.154 (.504)

$$\alpha = 2.303\ \delta \qquad (2.5)$$

Equation (2.5) can be solved for optical density as

$$\delta = 0.4343\ \alpha \qquad (2.6)$$

Substituting equation (2.4) into equation (2.2) yields an expression for optical density in terms of percentage obscuration.

$$\delta = -\frac{\log_{10}(1 - \lambda/100)}{x} \qquad (2.7)$$

An expression for the attenuation coefficient in terms of percentage obscuration can be developed in a similar manner.

$$\alpha = -\frac{\log_{e}(1 - \lambda/100)}{x} \qquad (2.8)$$

An expression for percentage obscuration in terms of optical density and pathlength can be developed by substituting equation (2.2) into equation (2.4).

$$\lambda = 100\ (1 - 10^{-\delta x}) \qquad (2.9)$$

An expression for percentage obscuration in terms of attenuation coefficient and pathlength can be developed by substituting equation (2.3) into equation (2.4).

$$\lambda = 100\ (1 - e^{-\alpha x}) \qquad (2.10)$$

2.2 VISIBILITY THROUGH SMOKE

The general relation between visibility and smoke obscuration is

$$V = K/\alpha \qquad (2.11)$$

where:

α = attenuation coefficient, m^{-1}

V = visibility, m

K = proportionality constant (table 2.2)

Table 2.2 Recommended Values of Proportionality Constant for Visibility Relation Based on Research of Jin (1974, 1975 and 1985)

Situation	K
Light-Emitting Signs	6
Reflecting Signs	2
Building Components in Reflected Light	2

The visibility is the obscuration threshold which is the distance at which an object can just be seen. The proportionality constant is dependant on the color of smoke, the illumination of the object, the intensity of background illumination, and visual acuity of the observer. Jin (1974, 1975, 1985) conducted tests determining visibility of light-emitting and reflecting signs. Signs in a smoke filled chamber were observed from outside through a glass window, and the results for light-emitting signs are shown in figure 2.2. White smoke was produced by smoldering fires, and black smoke was produced by flaming fires. Visibility through the white smoke was less, probably due to higher light scattering. It is well known that scattering of background lighting can significantly reduce visibility of lighted signs, but quantitative data about the effect of background illumination is needed. Jin found that the proportionality constant ranged from 5 to 10 for light emitting

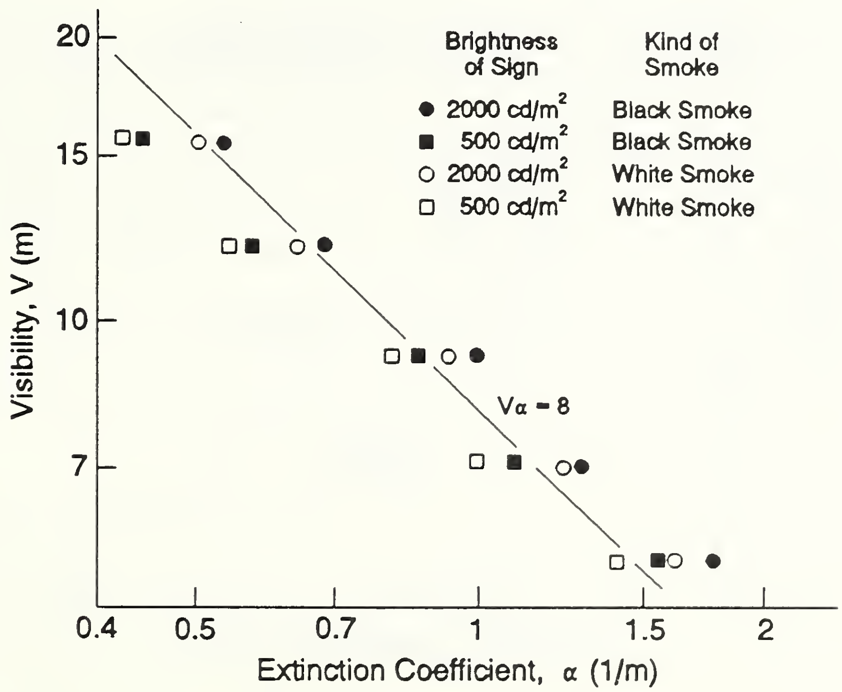

Figure 2.2 Relation between the visibility of light-emitting signs and smoke obscuration [Adapted from Jin (1985)]

signs. For reflecting signs, the constant ranged from 2 to 4. Jin indicates that the minimum value of visibility for reflecting signs may be applicable for the visibility of other objects such as walls, floors, doors, and stairs. Based on Jin's research the values of K are recommended in table 2.2.

The above information about visibility does not take into account the irritating effects of smoke on the eyes. Jin (1985) conducted tests correlating the visibility and walking speed of subjects exposed to irritating smoke with the attenuation coefficient. There are shortcomings with correlating physiological effects with an optical property of smoke, since the effects would seem to be primarily caused by chemical components of smoke. However, the effects of eye irritation are so significant that Jin's work on the topic is discussed below.

Figure 2.3 shows the relation between visibility and obscuration for irritating and non-irritating smoke for a light-emitting sign. The irritating smoke was white smoke produced by burning wood cribs, the less irritating smoke was produced by burning kerosene. The visibility relation of equation (2.11) is not valid for irritating smoke. In thick irritating smoke, subjects could not keep their eyes open long enough to read the sign. Figure 2.4 shows the relation between smoke obscuration and walking speed of people walking down a corridor in irritating and non-irritating smoke. Both eye irritation and

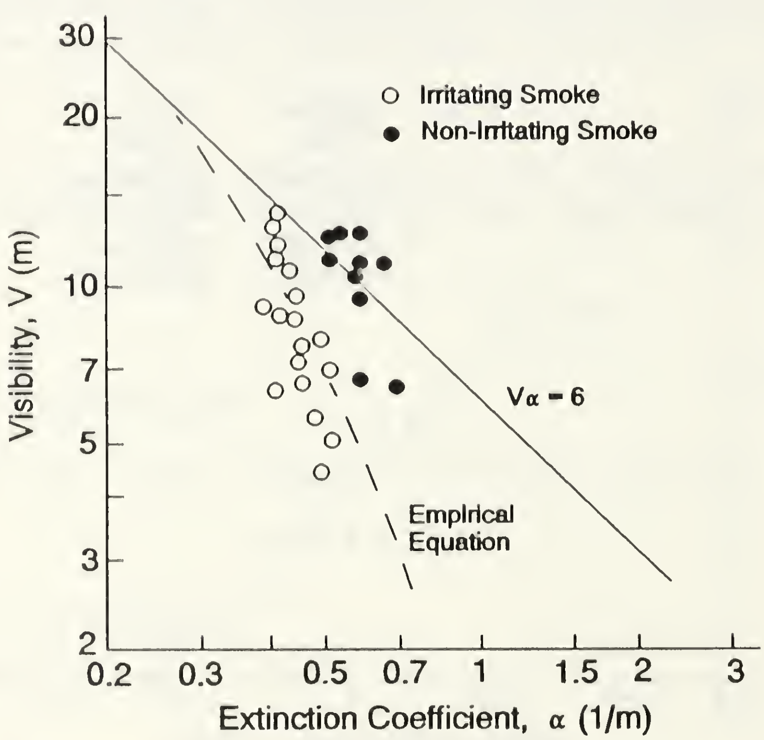

Figure 2.3 Relation between the visibility of light-emitting signs and smoke obscuration for irritating and non-irritating smoke [Adapted from Jin (1985)]

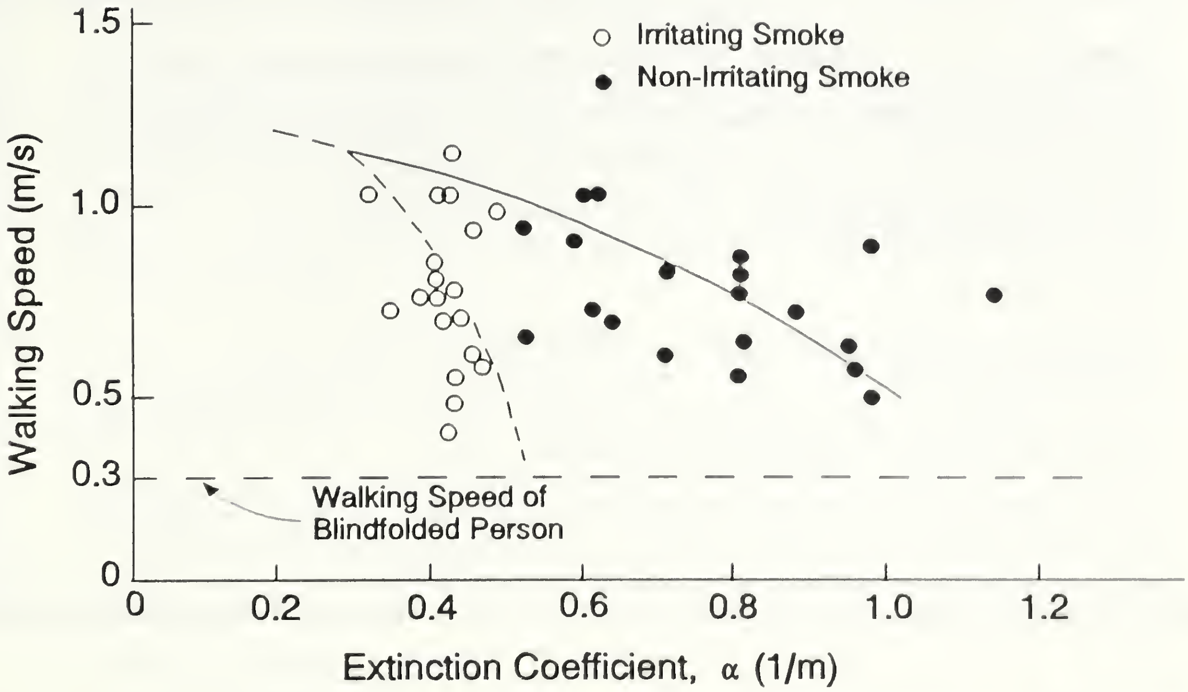

Figure 2.4 Walking speed in irritating and non-irritating smoke [Adapted from Jin (1985)]

smoke density affect walking speed. Walking speed decreases with attenuation coefficient for both smokes, but it is much worse for irritating smoke. For an extension coefficient of 0.4 m^{-1}, the walking speed through irritating smoke was about 70% of that through non-irritating smoke. For extinction coefficients greater than 0.5 m^{-1}, the walking speed decreased to about 1 ft/sec (0.3 m/s), the speed of a blindfolded person. The drop in walking speed was because subjects could not keep their eyes open, and they walked in a zigzag or went step by step as they held the side wall.

Jin (1985) developed an empirical relation for visibility in irritating smoke

$$V = \frac{K}{\alpha} \left(0.133 - 1.47 \log_{10}\alpha\right) \qquad \left\{ \begin{array}{l} \text{Only for} \\ \alpha \geq 0.25 \text{ m}^{-1} \end{array} \right. \tag{2.12}$$

where:

α = attenuation coefficient, m^{-1}

V = visibility, m

K = proportionality constant (table 2.2)

Example 2.1 Visibility of light-emitting sign through smoke

The optical density of smoke is 0.13 m^{-1}. How far away can a person be expected to see a light-emitting sign if the smoke does not irritate their eyes? Also, how much does the answer change for irritating smoke?

From table 2.2, K = 6

Extinction coefficient is $\alpha = 2.303\ \delta$, so $\alpha = 0.30\ m^{-1}$.

From equation (2.11), V = 6/.3 = 20 m or 66 ft, the distance the sign can be seen through non-irritating smoke.

From equation (2.12), $V = 20\ [.133 - 1.47\ \log_{10}(.3)] = 18$ m or 59 ft, the distance the sign can be seen through irritating smoke.

Example 2.2 Visibility of doors and walls

In example 2.1, what is the visibility of walls and doors?

From table 2.2, K = 2

Extinction coefficient is = 0.30 m^{-1}.

From equation (2.11), V = 2/.3 = 6.7 m or 22 ft, the distance that wall and doors can be seen through non-irritating smoke.

From equation (2.12), $V = 6.7\ [.133 - 1.47\ \log_{10}(.3)] = 6.0$ m or 20 ft, the distance the sign can be seen through irritating smoke.

Example 2.3 Walking speed through smoke

What walking speed can be expected for smoke with an attenuation coefficient of 0.3 m^{-1}? Also, what would it be for an extinction coefficient of 0.4 m^{-1}?

For α = .3 m^{-1} and from figure 2.4, the walking speed is about 1.1 m/s or 3.6 ft/s. This is the same for irritating and non irritating smoke.

For α = .4 m^{-1} and from figure 2.4, the walking speed is about 0.7 m/s or 2.3 ft/s for irritating smoke. For non-irritating smoke, the walking speed is about 1 m/s or 3 ft/s.

Note: If the smoke gets much heavier than about α = 0.5 m^{-1}, the walking speed will slow down to that of a blindfolded person.

2.3 EFFECTS OF TEMPERATURE

The effects of temperature as an exposure limit under fire conditions have not been well studied. Industrial hygiene literature primarily gives data for heat stress under conditions of prolonged, typically 8 hour, exposures. The older literature, as it relates to fire, has been reviewed by Simms and Hinkley (1960). Based on that review, they could not make any recommendations of tenability values.

Experimental data from studies with pigs have shown no injuries at 248°F (120°C) for 2 min, 212°F (100°C) for 5 min, and 194°F (90°C) for 10 min (Moritz et al. 1947 and NFPA 1946). The skin of pigs is somewhat similar to human skin, and to this extent the above data is relevant for humans. Some experimental data for humans have been reported which show that temperatures of 212°F (100°C) could be withstood by a clothed, inactive adult male for about 30 min before intolerable discomfort is reached; a 167°F (75°C) exposure could be withstood for about 60 min (Blockley and Taylor 1949). These experimental values seem high. To place them in context, Zapp (1974) has stated that "...air temperatures as high as 212°F (100°C) can be tolerated only under very special conditions (i.e., still air) for more than a few min, and that some people are incapacitated by breathing air at 65°C [149°F]...". Crane (1978) has recommended that for healthy, clothed, adult males, collapse due to elevated temperatures will occur when the exposure time, t, exceeds the following value:

$$t = 4.1\times10^{8}/[(T - B_2)/B_1]^{3.61} \qquad (2.13)$$

where:
t = time to collapse, minutes
T = air temperature, °F (°C)

B_1 = constant, 1.8 (1.0)
B_2 = constant, 32. (0)

This expression, however, does not take into account the relative humidity of the air. The time to collapse decreases as the humidity increases. Because moisture is a product of combustion, elevated humidity is expected in fire gases.

Criteria for temperature are, in fact, especially difficult to set, since the temperature at which adverse effects are noted depends not only on the exposure time, but also on the relative humidity. Thus, for instance, in a study of acclimated adult males to a sauna exposure at 212°F (100°C) and 22% R.H. for 15 min, it was seen, despite physiological indications of stress, that no ill effects occurred (Leppäluoto et al. 1975). Similar concurring studies are available for 185-194°F (85-90°C) exposures for 20 min (Kosunen et al. 1976). In the room of fire origin, it can be expected that the air will be nearly, if not totally, saturated with water vapor. In this case, medical recommendations are that "Air at temperatures above about 50°C [122°F] produces severe discomfort in the oral, nasal, and esophageal passages if it is close to saturation with water vapor" (Bell 1972).

The permeability and insulating value of the clothing worn can also have a significant effect on the ability to withstand elevated temperatures. For long exposures (greater than 30 min), extensive experimental data are available (e.g., Veghte and Webb 1957). Similar data have not been obtained for short exposures, such as may occur in building fires, however. In previous fire hazard evaluation recommendations, the tenability values for brief exposures at face level ranged from 149°F (65°C) (NFPA 1959) to 212°F (100°C) (Budnick 1978).

Purser (1988) proposed the following approximate relation for time to incapacitation due to convected heat for naked humans exposed to elevated temperatures with low air movement

$$t = \exp[5.1849 - 0.0273(T - B_2)/B_1]$$

or in another form (2.14)

$$T = \frac{B_1}{0.0273}\left(5.1849 - \log_e t\right) + B_2$$

where:
t = time to incapacitation, minutes
T = air temperature, °F (°C)
B_1 = constant, 1.8 (1.0)
B_2 = constant, 32. (0)

This relation produces a more realistic response prediction than simply a limiting temperature, since it allows for the time-dependant nature of the heat transfer to the subject. Equation (2.14) is based on an average between dry and humid air. Equations (2.13) and (2.14) are applicable for temperatures in the range of 140 to 292°F (60 to 200°C). Equation (2.14) provides more conservative estimates than does equation (2.13).

Example 2.4 Incapacitation temperature

In a space where people are expected to wait for up to 30 minutes for rescue, calculate a conservative temperature that could be used as an upper limit for design.

During a fire, the temperature in this space would be expected to increase with time. Equation (2.14) is for a constant temperature over the time, and its use is conservative. From this equation, the temperature is 150°F (66°C).

2.4 TOXICITY OF SMOKE

Studies on the causes of fire deaths have typically indicated that CO poisoning accounts for roughly one-half of total fatalities (Berl and Halpin 1976, Harland and Woolley 1979). The remaining half is accounted for by direct burns, explosive pressures, and various other toxic gases. Although the analysis of blood cyanide (which would come from exposure to hydrogen cyanide) in fire victims is sometimes reported in autopsy data, blood carboxyhemoglobin saturation, resulting from exposure to CO is often the only data provided. This provides no information on the potential effect of other toxic gases on the lethality. Nonetheless, a significant emphasis on studying other toxic gases is placed by most research organizations in this field, due to the fact that high hazards may exist from additional combustion products whose presence is suggested by the decomposition chemistry, although not necessarily confirmed by medical evidence. Table 2.3 lists, in order of increasing estimated toxicity, those primary gases which have been suggested by various investigators as being potentially significant in fire situations. Human data are in most cases unavailable, and even primate data are rare. The tabulated values represent the estimated LC_{50}'s (in ppm), i.e., those concentrations which would be lethal to 50% of the exposed subjects for the specified time. Data on the combined effects are, as yet, rare, inconsistent, and insufficient for a general tabulation (Clayton and Clayton 1982, Gaume et al. 1982, Higgins et al. 1972, Kaplan et el. 1984, Kimmerle 1974, Levin et al. 1987a & b, Pryor et al. 1975, Saito 1977, Sakurai 1987, Tsuchiya 1986, Wohlslagel et al. 1976).

Oxygen deprivation is a special case of gas toxicity. Data on oxygen deprivation alone, without any other combined gas effects, suggest that incapacitation occurs when oxygen levels drop to approximately 10% (Kimmerle 1972). Exposure to decreased oxygen levels alone is very unlikely in fire, however. More commonly expected is some diminution in oxygen levels together with the presence of CO, CO_2, and other toxic species. Such combinations have been explored, providing a few experimental points (Levin et al. 1987a). Currently, the potential effects of reduced oxygen are addressed in the Fractional Effective Dose parameter discussed below.

Table 2.3 Preliminary list of primary toxic gases

Gas		Assumed LC_{50} (for humans) 5 min (ppm)	30 min (ppm)	Reference	Reference data (species, minutes) h=man r=rat m=mouse p=primate gpg=guinea pig ham=hamster rbt=rabbet
CO_2	carbon dioxide	>150,000	>150,000	Levin et al. (1987)	r
C_2H_4O	acetaldehyde		20,000	Sax (1984)	LC(m,240)=1500 LC_o(r,240)=4000 LC(ham,240)=17,000
				ACGIH (1980)	LC(r,30)=20,000 LC(r,240)=16,000
$C_2H_4O_2$	acetic acid		11,000	Levin et al. (1987)	LC(m,60)=5620
NH_3	ammonia	20,000	9,000	Sakurai (1988)	EC(m,5)=20,000 EC(m,30)=4400
				Nishimaru (1985)	EC(r,5)=10,000 EC(r,30)=4000
HCℓ	hydrogen chloride	16,000	3,700	Hartzell et al. (1985)	r,p
				Higgins et al. (1972)	LC(r,5)=40,989
CO	carbon monoxide		3,000	Levin et al. (1987)	LC(r,30)=4600
				Kimmerle (1974)	LC(h,30)=3000
HBr	hydrogen bromide		3,000	Sax (1984)	LC(m,60)=814 LC(r,60)=2858
NO	nitric oxide	10,000	2,500	ACGIH (1980)	1/5 as toxic as NO_2
					LC(h,1)=15,000
COS	carbonyl sulfide		2,000	Sax (1984)	LC_o(var.,35-90)=1000-1400
H_2S	hydrogen sulfide		2,000	Sax (1984)	LC(m,60)=673 LC_o(h,30)=600 LC_o(ham),5=800
				Kimmerle (1974)	LC(h,30)=2000
HF	hydrogen fluoride	10,000	2,000	Sax (1984)	LC(gpg,15)=4327 LC(p,60)=1774 LC_o(h,30)=50
					LC(m,60)=456 LC(r,60)=1276
				Higgins et al. (1972)	LC(r,5)=18,200
				Kimmerle (1974)	LC(gpg,2)=300 LC(m,5)=6247 LC(r,5)=18,200
C_3H_4N	acrylonitrile		2,000	Sax (1984)	LC(gpg,240)=576 LC(r,240)=500
COF_2	carbonyl fluoride		750	ACGIH (1980)	LC(r,60)=360
NO_2	nitrogen dioxide	5,000	500	Sakurai (1988)	EC(m,5)=2500 EC(m,30)=700
				Nishimaru (1985)	EC(r,5)=5000 EC(r,30)=300
				Higgins (1972)	LC(m,5)=83331 LC(r,5)=1880
C_3H_5O	acrolein	750	300	Sax (1984)	LC(m,360)=66 LC_o(p,10)=153
				Kaplan et al. (1984)	LC(p,5)=505 to 1025
CH_2O	formaldehyde		250	Sax (1984)	LC_o(r,240)=250
				Kimmerle (1974)	LC(r,30)=250 LC(r,240)=830(??)
				ACGIH (1980)	LC(cat,480)=700 LC(m,120)=700
SO_2	sulfur dioxide	500		Sax (1984)	rodents poor, LC_o(m,300)=6000
				Kimmerle (1974)	LC(var.,5)=600 to 800
HCN	hydrogen cyanide	280	135	Levin et al. (1987)	LC(r,5)=570 LC(r,30)=110
				Higgins et al. (1972)	LC(r,5)=503 LC(m,5)=323
				Kimmerle (1974)	LC(h,30)=135 LC(h,5)=280
$C_9H_6O_2N_2$	toluene disocyanate		≃100	Sax (1984)	LC(gpg,240)=13 LC(rbt,180)=1500
					LC(r,360)=600 LC(m,240)=10
				Kimmerle (1974)	LC(m,r,rbt,gpg,240)=9.7 to 13.9
$COCℓ_2$	phosgene	50	90	Sax (1984)	rec. 50 ppm short exp.
				Clayton and Clayton (1982)	LC(h,30)=90
C_4F_8	perfluoroisobutylene	28	6	Sax (1984)	LC(r,10)=17 LC(r,5)=28

Notes: EC is concentration for effect, and LC_o is concentration at which first lethal effects are observed

Toxicity from fire atmospheres can result not only from gases, but also from solid aerosols, or from material adsorbed onto soot particles. Data in this field are almost non-existent (Stone et al. 1986).

2.3.1 Fractional Effective Dose (FED)

Researchers at BFRL (Babrauskas et al. 1986), Huntingdon Research Centre (UK) (Purser 1988), and at the Southwest Research Institute (SwRI) (Hartzell et al. 1986) have been exploring the hypothesis that the observed effect of the exposure of animals (and humans) to the products generated by burning materials can be explained by the impact of a small number of the gases actually released during combustion. That is that, while there are hundreds of compounds that can be identified, the effect is caused by only a few (N) key gases. By investigating the effect of exposure to these key gases, singly and in combination, a predictive model can be constructed. Thus, this model is referred to as the N-Gas model.

Once such a predictive model is produced, a material is tested in a toxicity screening protocol, measuring the time-dependent concentrations of the gases included in the model. The model is used to predict the observed result, with a successful prediction indicative of the material's toxicity being only from those gases. If the prediction is unsuccessful, there are other gases of importance which would then be identified, studied in pure form, and included in the N-gas model. In this way, the model would be extended until the combustion toxicity of most important materials can be properly predicted for a range of combustion conditions.

The first version of such a model has been derived from the pure gas studies of Levin et al. (1986), and Hartzell et al. (1986). It includes the gases CO, CO_2, and HCN, along with reduced oxygen, combining their effect in a parameter called Fractional Effective Dose (FED) which is dimensionless and is defined as lethal at a value of one. The hypothesis of FED states that the total observed effect equals the sum of the effects of each of the component parts. That is, if one receives 50% of the lethal dose of CO and 50% of the lethal dose of HCN, death will occur. This has, in fact, been demonstrated by Levin et al. (1987a), for these two gases. Simply stated then, FED is the sum of the effects of each of the gases toward the total effect on the exposed person.

Since it is the major combustion product implicated in fire deaths, CO was the first gas studied in a long series of pure gas experiments. Rats were exposed to varying concentrations of pure CO for various times, and the concentrations necessary to produce deaths of 50% of the exposed animals (the LC_{50}) for each exposure time was determined. The plot of these data (fig. 2.5), shows that the curve has two asymptotes; an exposure time (about 1 min) below which no effect is seen for any concentration, and a concentration (about 1700 ppm) below which no effect is seen for any time. In the former case, this would represent such physiological effects as breath holding and the time required for the gas to be transferred to the blood and then to the tissues. In the latter case, this represents an exposure concentration for which the equilibrium concentration of COHb in the blood is below the level which causes a lethality (Levin et al. 1987a).

To account for these effects in the N-Gas model, a linear regression was performed on the curve of CO concentration versus 1/time. After adjusting the constants for a best fit to the data available and maintaining appropriate significant figures, this results in the following equation:

$$(C_{CO} - 1700)t = 80000 \tag{2.15}$$

where C_{co} is the CO concentration in ppm and t is the exposure time in minutes for lethality at that concentration. Note that the threshold concentration is included but that the minimum exposure time for effect is zero as a conservative assumption.

The FED is the dose received (dose is the time integral of the concentration) divided by the critical dose to produce the effect. As shown in figure 2.5, the critical dose is not constant, but rather varies with concentration. Thus, equation (2.15) is used within the FED calculation to determine the critical dose at the particular incremental concentration [see fig. 2.6 (Levin et al. 1986)].

Following the work with CO, the effect of CO_2 on the observed CO toxicity was studied. The result of this work (shown in fig. 2.7 (Levin et al. 1987b) was the observation that the "effective toxicity" of CO increases linearly with increasing CO_2 concentration, doubling at a level of 5% (50000 ppm). The physiological effects of the CO_2 are to increase the respiration rate and reduce the blood pH, producing a metabolic acidosis.

These data were used to produce a CO_2 "correction" to the CO term in the calculation of FED whereby the denominator is multiplied by the following factor:

$$[(100{,}000 - C_{CO2})/100{,}000] \tag{2.16}$$

where C_{CO2} is the concentration of CO_2 in ppm. While the data show this effect diminishing above 5% CO_2, the model holds the correction constant at 5% and above as a conservative assumption. Also note that the data were only taken at 30-min exposure times. Preliminary data on shorter times indicates that CO_2 may have no effect, probably due to the fact that the acidosis takes long times to develop. Thus, in the absence of complete data, the conservative assumption is made that the effect holds for all times.

HCN and the combination of CO and HCN were similarly studied. The data on HCN (Levin et al. 1986) showed that the lethal dose (time-integral of concentration) was relatively constant at a value of 3100 ppm-min for exposure times from 2 to 30 min. Thus, this value is used in the HCN term of the FED calculation. The data on CO and HCN combinations showed that the effects are directly additive (Levin et al. 1987a) (again for 30-min exposures). This is not surprising since they both act to reduce the transfer of oxygen to the

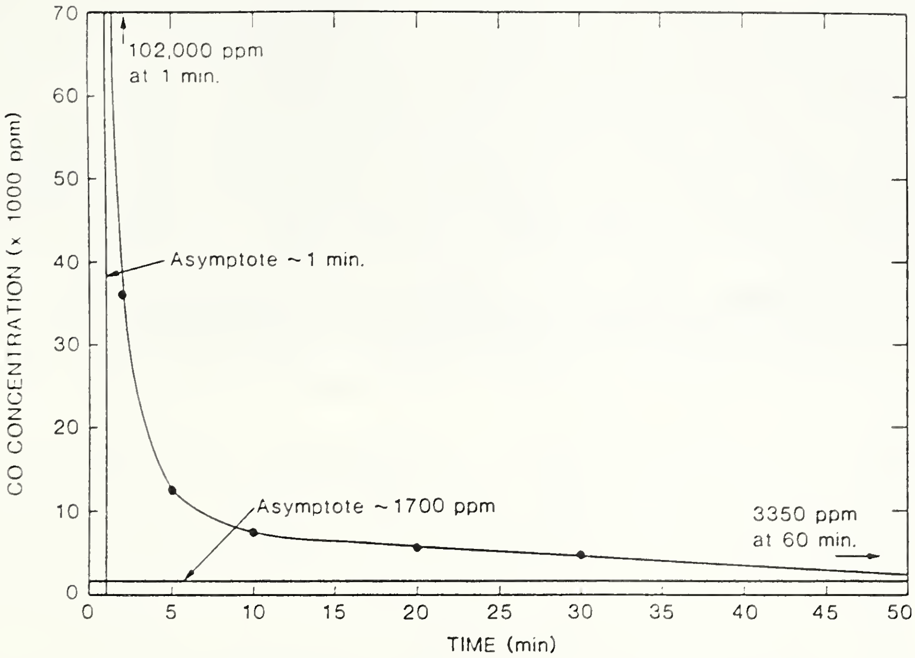

Figure 2.5 Carbon monoxide concentration versus time to lethality of 50% of exposed rats (Bukowski et al. 1989)

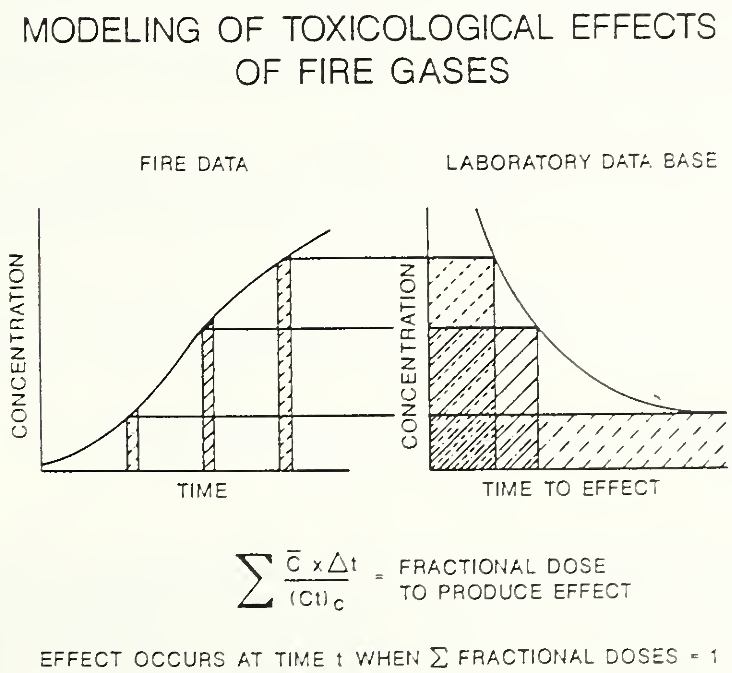

Figure 2.6 Fractional effective dose (Bukowski et al. 1989)

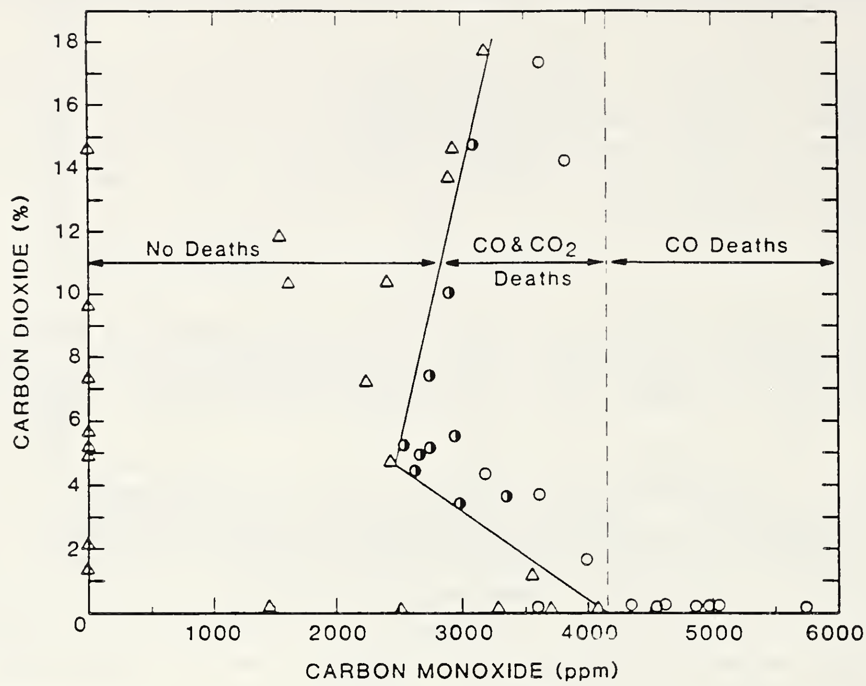

Figure 2.7 Combination of carbon monoxide and carbon dioxide which is lethal to 50% of exposed rats (Bukowski et al. 1989)

tissues; CO by tying up the hemoglobin so that it cannot carry the oxygen, and HCN by preventing the utilization of the oxygen by the tissues.

Finally, the other combinations of gases were studied in the presence of diminished levels of oxygen. These were also found to be additive to the effects of CO and HCN in producing anoxia.

The resulting equation for FED, which represents the current N-Gas model (N=4) is as follows:

$$FED = \sum \left\{ \frac{\bar{C}_{CO}\ \Delta t}{\bar{C}_{CO}[80{,}000/(\bar{C}_{CO} - 1700)]\ [(100{,}000 - \bar{C}_{CO2})/100{,}000]} + \frac{\bar{C}_{HCN}\ \Delta t}{3100} \right\} + \frac{(9.2 - \bar{C}_{O2})\ (\Delta t)}{15.2} \quad (2.17)$$

where:

$\bar{C}_{co}$ = average concentration of CO over the time interval Δt, ppm
$\bar{C}_{co2}$ = average concentration of CO_2 over the time interval Δt, ppm
$\bar{C}_{o2}$ = average concentration of O_2 over the time interval Δt, ppm
$\bar{C}_{HCN}$ = average concentration of HCN over the time interval Δt, ppm
Δt = time interval, min

The reader is referred to example 3.17 for an example of calculation of the FED. The predictive capability of equation (2.17) was tested against the material toxicity data included in the NBS Toxicity Screening Protocol report (Levin et al. 1982). It should be noted that the oxygen term was not tested since the test protocol is designed to maintain the oxygen at its ambient value. First, the average gas concentration data provided in the report was used, assuming a constant value throughout the 30-min exposure period (i.e. a square-wave exposure). The equation successfully predicted the observed results of 14 materials, with two more within 10%. Levin proposed an equation for predicting the interactions of these same gases for 30-min, square-wave exposures only (Levin et al. 1987a), which successfully predicts the results of the same 16 materials plus flaming red oak. Equation (2.15) falls 30% short on red oak, and the reason for this is currently unclear.

Next, the exposure time-independent nature of equation (2.17) was tested against the data reported by Hartzell et al., for two ramped exposures to CO only (Hartzell et al. 1985). The equation predicted the results of the slower ramp within the standard deviation stated and predicted a somewhat shorter time to death for the faster ramp.

Since the gas data reported in the NBS report were averages over 30 min while, in fact, they increased exponentially over some finite time in the experiment, the actual gas analyzer data from the tests of four materials were obtained and input into the equation. The results showed that, for materials which produced only within-exposure fatalities (except MOD,NF), the predicted FED reached unity (lethal) at 30 min. For materials which produced some or all post-exposure fatalities, the predicted FED reached unity earlier, in some cases, as early as 10 min. This would indicate that this is the time at which a lethal dose was received, even though the death occurred later. Additional information about toxicity is provided by Levin et al. (1988a and 1988b).

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Chapter 3. SMOKE MOVEMENT

In building fires, smoke often migrates to locations remote from the fire space. Stairwells and elevator shafts can become smoke-logged, thereby blocking evacuation and inhibiting fire fighting. In this chapter several of the driving forces of smoke movement are discussed, methods of determining the neutral plane are provided, and some general comments are made concerning smoke movement. The information in this chapter also is applicable to the migration of other airborne matter such as hazardous gases, bacteriological matter or radioactive matter in laboratories, hospitals, or industrial facilities. However, the discussion in this chapter is primarily aimed at smoke movement. The concept of effective flow areas is quite useful for analysis of smoke movement and of smoke control systems, and this topic is addressed next.

3.1 EFFECTIVE FLOW AREAS

The paths in the system can be in parallel with one another, in series, or a combination of parallel and series paths. The effective area of a system of flow areas is the area that results in the same flow as the system when it is subjected to the same pressure difference over the total system of flow paths. This is analogous to the flow of electric current through a system of electrical resistances. The following analysis is for the same flow coefficients for each flow path and for constant air temperature. Variations in flow coefficients and temperature are addressed later.

3.1.1 Parallel Paths

Three parallel leakage areas from a pressurized space are illustrated in figure 3.1. The pressure difference, ΔP, is the same across each of the leakage areas. The total flow, Q_T, from the space is the sum of the flows through the leakage paths:

$$Q_T = Q_1 + Q_2 + Q_3 \tag{3.1}$$

The effective area, A_e, for this situation is that which results in the total flow, Q_T. Therefore, the total flow can be expressed as:

$$Q_T = K_o C A_e \sqrt{\frac{2\ \Delta P}{\rho}} \tag{3.2}$$

The flow through area A_1 can be expressed as

$$Q_1 = K_o C A_1 \sqrt{\frac{2\ \Delta P}{\rho}} \tag{3.3}$$

The flows Q_2 and Q_3 can be expressed in a similar manner. Substituting the expressions for Q_1, Q_2 and Q_3 into equation (3.1) and collecting like terms yields:

$$Q_T = K_o C(A_1 + A_2 + A_3) \sqrt{\frac{2\ \Delta P}{\rho}} \tag{3.4}$$

Comparing this with equation (3.2) yields:

$$A_e = A_1 + A_2 + A_3 \tag{3.5}$$

The above logic can be extended to any number of flow paths, and it can be stated that the effective area of n individual leakage paths in parallel is the sum of the individual flow areas.

$$A_e = \sum_{i=1}^{n} A_i \tag{3.6}$$

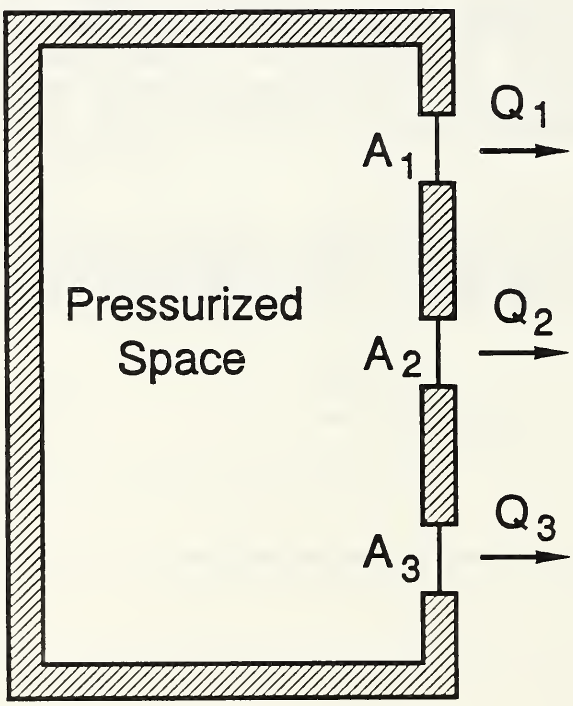


Figure 3.1 Leakage paths in parallel

Example 3.1 Effective flow area for parallel paths

In figure 3.1, if A_1 is 1.08 ft^2 (0.10 m^2) and A_2 and A_3 are both 0.54 ft^2 (0.05 m^2), what is the effective flow area of the system?

From equation (3.5), A_e = 2.16 ft^2 (0.02 m^2).

3.1.2 Series Paths

Three leakage paths in series from a pressurized space are illustrated in figure 3.2. The flow rate, Q, is the same through each of the leakage areas. The total pressure difference, ΔP_T, from the pressurized space to the outside is the sum of the pressure differences ΔP_1, ΔP_2, and ΔP_3 across each of the respective flow areas, A_1, A_2, and A_3:

$$\Delta P_T = \Delta P_1 + \Delta P_2 + \Delta P_3 \tag{3.7}$$

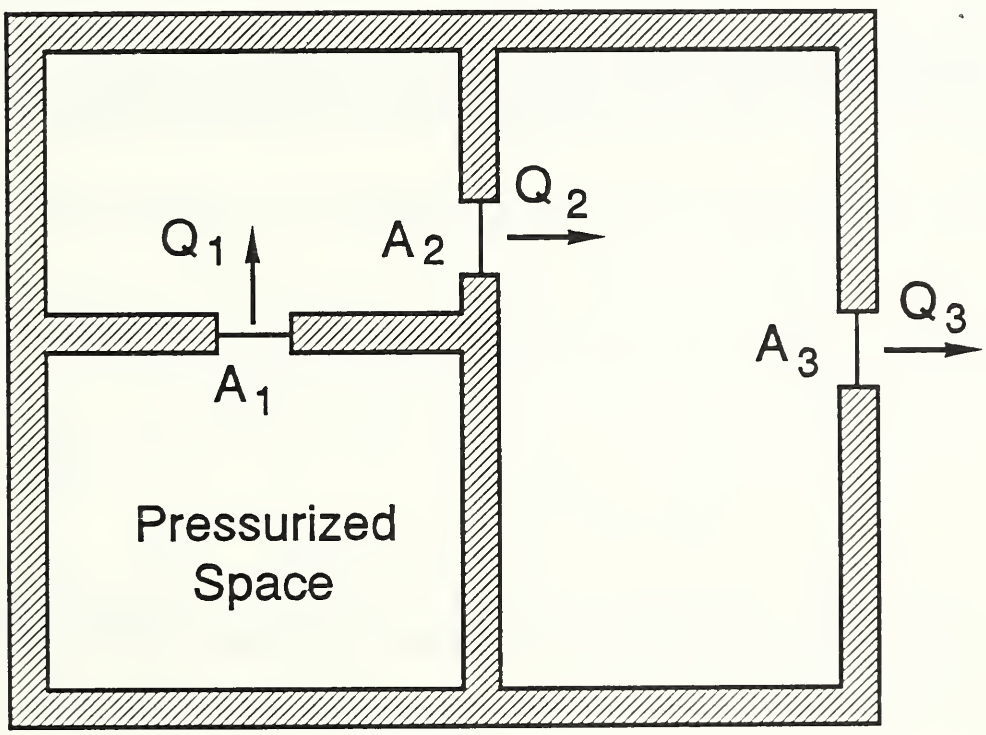


Figure 3.2 Leakage paths in series

The effective area for flow paths in series is the flow area that results in the flow, Q, for a total pressure difference of ΔP_T. Therefore, the flow, Q, can be expressed as:

$$Q = K_o C A_e \sqrt{\frac{2\ \Delta P_T}{\rho}} \tag{3.8}$$

Solving for ΔP_T yields:

$$\Delta P_T = \frac{\rho}{2}\left(\frac{Q}{K_o C A_e}\right)^2 \tag{3.9}$$

The pressure difference across A_1 can be expressed as:

$$\Delta P_1 = \frac{\rho}{2}\left(\frac{Q}{K_o C A_1}\right)^2 \tag{3.10}$$

The pressure differences ΔP_2 and ΔP_3 can also be expressed in a similar manner. Substituting equation (3.9) and the expressions for ΔP_1, ΔP_2, and ΔP_3 into equation (3.7) yields an expression for the effective flow area.

$$A_e = \left(\frac{1}{A_1^{\,2}} + \frac{1}{A_2^{\,2}} + \frac{1}{A_3^{\,2}}\right)^{-1/2} \tag{3.11}$$

This same reasoning can be extended to any number of leakage areas in series to yield:

$$A_e = \left(\sum_{i=1}^{n} \frac{1}{A_i^{\,2}}\right)^{-1/2} \tag{3.12}$$

where n is the number of leakage areas, A_i, in series. In smoke control analysis, there are frequently only two paths in series, and the effective flow area for this case is:

$$A_e = \frac{A_1 A_2}{\sqrt{A_1^{\,2} + A_2^{\,2}}} \tag{3.13}$$

Example 3.2 Two equal series paths

Calculate the effective leakage area of two paths of 0.22 ft^2 (0.02 m^2) in series.

For two equal flow areas ($A = A_1 = A_2$), equation (3.13) becomes

$$A_e = 0.707\ A$$

and the effective area of this system is 0.156 ft^2 (0.0145 m^2).

Example 3.3 Two unequal series paths

Calculate the effective flow area of two paths in series, where the flow areas are:

$A_1 = 0.100$ ft^2 (0.00929 m^2) $A_2 = 1.00$ ft^2 (0.0929 m^2)

From equation (3.13), $A_e = 0.0995$ ft^2 (0.00924 m^2)

This example illustrates that, when two areas are in series and one is much larger than the other, the effective area is approximately equal to the smaller area.

Example 3.4 Effective flow area of four series paths

Calculate the effective flow area of the following areas that are in series.

$A_1 = A_2 = 0.100$ ft^2 (.00929 m^2)
$A_3 = A_4 = 1.00$ ft^2 (0.0929 m^2)

From equation (3.13), $A_e = 0.0704$ ft^2 (0.00654 m^2)

3.1.3 Combination of Paths in Parallel and Series

The method of developing an effective area for a system of both parallel and series paths is to combine systematically groups of parallel paths and series paths. The system illustrated in figure 3.3 is analyzed as an example.

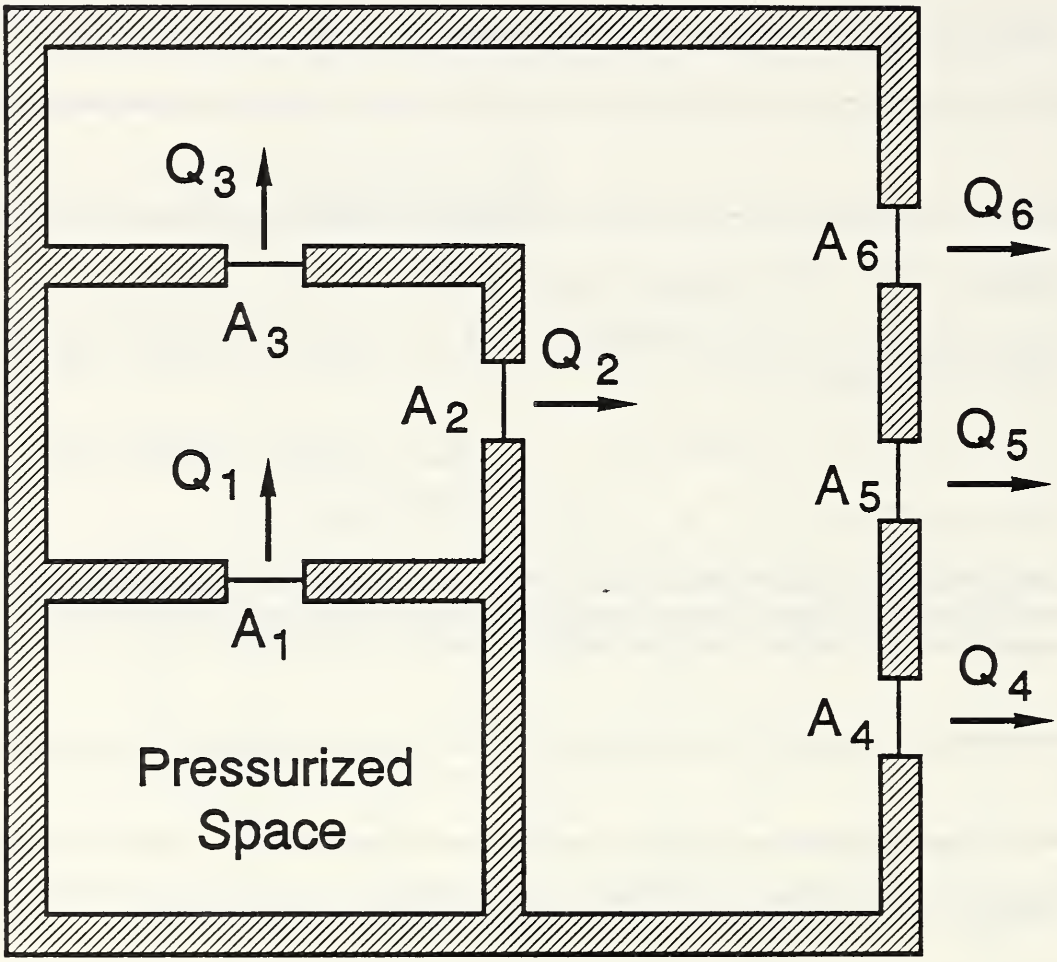


Figure 3.3 Combination of leakage paths in parallel and series

The figure shows that A_2 and A_3 are in parallel; therefore, their effective area is:

$$A_{23e} = A_2 + A_3$$

Areas A_4, A_5, and A_6 are also in parallel, so their effective area is:

$$A_{456e} = A_4 + A_5 + A_6$$

These two effective flow areas are in series with A_1. Therefore, the effective area of the system is given by:

$$A_e = \left(\frac{1}{A_1^2} + \frac{1}{A_{23e}^2} + \frac{1}{A_{456e}^2} \right)^{-1/2}$$

Example 3.5 Combination of paths in parallel and series

Calculate the effective area of the system in figure 3.3 for the following flow areas:

$A_1 = A_2 = A_3 = 0.22$ ft^2 (0.02 m^2)
$A_4 = A_5 = A_6 = 0.11$ ft^2 (0.01 m^2)

From the equations above,
$A_{23e} = 0.44$ ft^2 (0.04 m^2)
$A_{456e} = 0.33$ ft^2 (0.03 m^2)
$A_e = 0.17$ ft^2 (0.016 m^2)

3.1.4 Effects of Temperatures and Flow Coefficients

For most calculations involved in smoke control the assumptions of constant temperature and uniform flow coefficient are appropriate, but it may be desired in some cases to consider the effects of these parameters. For parallel and series flow paths, the equations for effective flow area are:

$$A_e = \frac{T_e^{1/2}}{C_e} \sum_{i=1}^{n} C_i A_i T_i^{-1/2} \qquad \text{for parallel paths} \qquad (3.14)$$

and

$$A_e = \frac{T_e^{1/2}}{C_e} \left[\sum_{i=1}^{n} T_i (C_i A_i)^{-2} \right]^{-1/2} \qquad \text{for series paths} \qquad (3.15)$$

where:

A_e = effective flow area of system, ft^2 (m^2)
T_e = absolute temperature in effective flow path, °R (°K)
C_e = flow coefficient for effective path, dimensionless
T_i = absolute temperature in path i, °R (°K)
A_i = flow area of path i, ft^2 (m^2)
C_i = flow coefficient of path i, dimensionless

For the case of two areas in series with the same flow coefficients, the effective area is:

$$A_e = T_e^{1/2} \left(\frac{T_1}{A_1^2} + \frac{T_2}{A_2^2} \right)^{-1/2} \qquad (3.16)$$

Example 3.6 Effective area at elevated temperature

1. What is the effective area of two paths in series both of 0.22 ft^2 (0.02 m^2) area and one at 70°F (21°C) and the other at 100°F (38°C)? Use T_e of 70°F (21°C).

$T_e = T_1 = 70 + 460 = 530°R$ (294 K)
$T_2 = 100 + 460 = 560°R$ (311 K)
$A_1 = A_2 = 0.22\ ft^2$ (0.02 m^2)

From equation (3.16), $A_e = 0.153\ ft^2$ (0.0142 m^2)

For both temperatures the same, the effective area of this system is 0.156 ft^2 (0.0145 m^2) as calculated in example 4.10. Considering the degree of uncertainty associated with flow areas, adjustment of the effective flow area is unnecessary.

2. What is the effective area above if the elevated temperature is 1000°F (538°C)?

$T_e = T_1 = 70 + 460 = 530°R$ (294 K)
$T_2 = 1000 + 460 = 1460°R$ (811 K)
$A_1 = A_2 = 0.22\ ft^2$ (0.02 m^2)

From equation (3.16), $A_e = 0.114\ ft^2$ (0.0105 m^2)

3.2 DRIVING FORCES OF SMOKE MOVEMENT

The driving forces of smoke movement include naturally occurring stack effect, buoyancy of combustion gases, expansion of combustion gases, the wind effect, fan powered ventilation systems, and elevator piston effect. This section discusses these driving forces, and in particular addresses smoke movement due to the stack effect process, either naturally occurring or that of combustion gases. Generally, each driving force is discussed here as acting alone in order to facilitate discussion and lead to an understanding of smoke transport.

3.2.1 Stack Effect

Frequently when it is cold outside, there is an upward movement of air within building shafts, such as stairwells, elevator shafts, dumbwaiters shafts, mechanical shafts, and mail chutes. Air in the building has a buoyant force because it is warmer and therefore less dense than outside air. The buoyant force causes air to rise within building shafts. This phenomenon is called by various names such as stack effect, stack action, and chimney effect. These names come from the comparison with the upward flow of gases in a smoke stack or chimney. However, a downward flow of air can occur in air conditioned buildings when it is hot outside. For this manual, the upward flow will be called normal stack effect, and the downward flow will be called reverse stack effect as illustrated in figure 3.4.

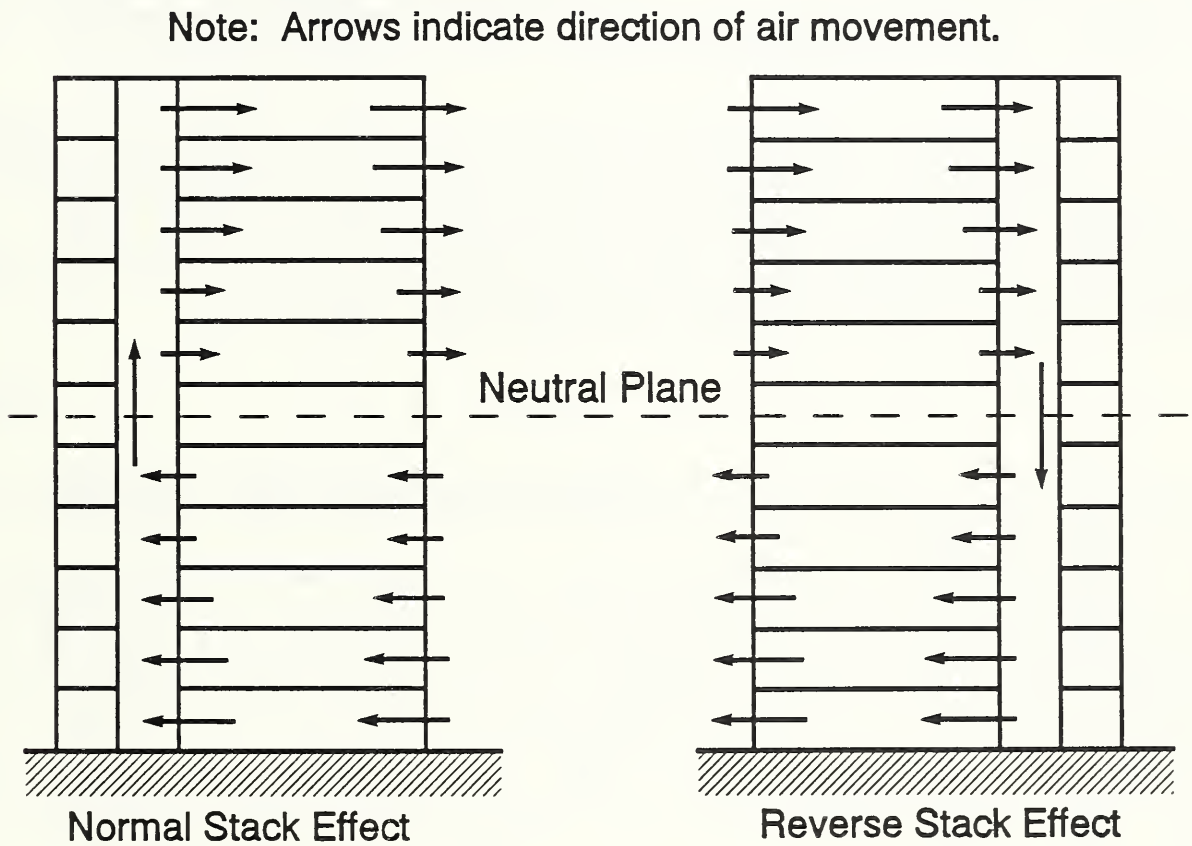


Figure 3.4 Air movement due to normal and reverse stack effect

Most building shafts have relatively large cross sectional areas, and for most flows typical of those induced by stack effect the friction losses are negligible in comparison with pressure differences due to buoyancy. Accordingly, this analysis is for negligible shaft friction, but shaft friction is specifically addressed later. Pressure within a shaft is due to fluid static forces and can be expressed as

$$dP_s = - \rho_s g dz \tag{3.17}$$

where:
P_s = air pressure inside the shaft
g = acceleration of gravity
z = elevation
ρ_s = gas density inside the shaft

For the elevations relevant to buildings, the acceleration of gravity can be considered constant. For constant density, equation (3.17) can be integrated to yield

$$P_s = P_a - \rho_s g z \tag{3.18}$$

where P_a is the pressure at $z = 0$. To simplify the analysis, the vertical coordinate system was selected such that $P_s = P_o$ at $z = 0$. In the absence of wind effects, the outside pressure, P_o, is

$$P_o = P_a - \rho_o g z \tag{3.19}$$

where ρ_o is the density outside the shaft. Pressures inside the shaft and outside the building are graphically illustrated in figure 3.5 for normal stack effect. This figure also shows the pressure of the building spaces, and methods of calculating this are presented later in this section. The pressure difference, ΔP_{so}, from the inside to the outside is expressed as

$$\Delta P_{so} = P_s - P_o = (\rho_o - \rho_s) g z \tag{3.20}$$

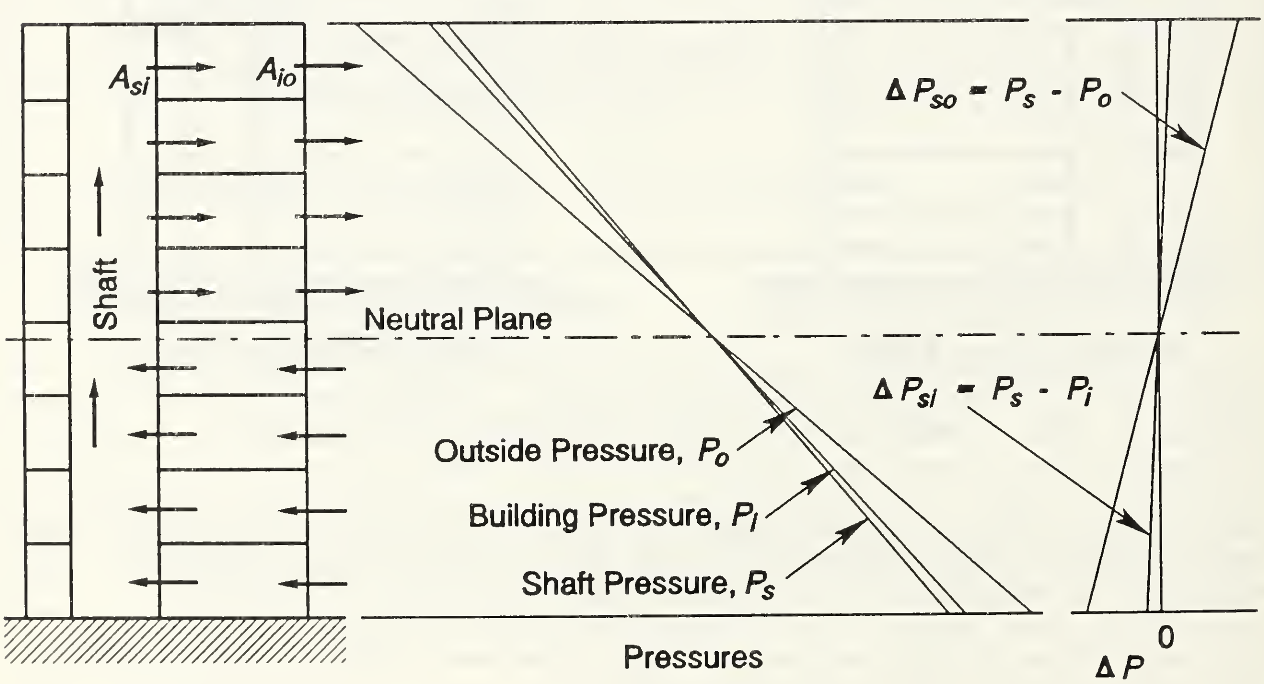


Figure 3.5 Pressures and pressure differences occurring during normal stack effect

Because variations in pressure within a building are very small compared to atmospheric pressure, atmospheric pressure, P_{atm}, can be used in calculating gas density from the ideal gas equation.

$$\rho = \frac{P_{atm}}{R\,T} \tag{3.21}$$

where:

ρ = air density
P_{atm} = absolute atmospheric pressure
R = gas constant of air
T = absolute temperature of air

Values for the gas constant and of standard atmospheric pressure for several systems of units are given in Appendix A. Substituting equation (3.21) into equation (3.20), and rearranging results in the following equation.

$$\Delta P_{so} = \frac{g\,P_{atm}}{R}\left(\frac{1}{T_o} - \frac{1}{T_s}\right) z \tag{3.22}$$

where:

T_o = absolute temperature of outside air
T_s = absolute temperature of air inside the shaft

Equation (3.22) was developed for a shaft connected to the outside. The neutral plane is a horizontal plane located at z = 0 where the pressure inside equals that outside as stated above. If the location of the neutral plane is known, this equation can be used to determine the pressure difference from the inside to the outside regardless of variations in building leakage or the presence of other shafts. Methods of determining the location of the neutral plane are discussed later. Table 3.1 is a comparison of pressure differences due to various driving forces. For standard atmospheric pressure of air, equation (3.22) becomes:

$$\Delta P_{so} = K_s\left(\frac{1}{T_o} - \frac{1}{T_s}\right) z \tag{3.22a}$$

where:

ΔP_{so} = pressure difference from shaft to outside, in H_2O (Pa)
T_o = absolute temperature of outside air, °R (K)
T_s = absolute temperature of air inside shaft, °R (K)
h = distance above neutral plane, ft (m)
K_s = coefficient, 7.64 (3460)

Table 3.1 Comparison of pressure differences due to various driving forces

Driving Force	Location of ΔP	Conditions		ΔP in H_2O (Pa)
Stack Effect [Equation (3.6)]:	Shaft to Outside	Note: For all stack effect examples, T_s = 70°F (21°C), and T_o = 0°F (-18°C).		
			h = 30 ft (9.25 m)	0.07 (17)
			h = 300 ft (92.5 m)	0.66 (160)
			h = 1000 ft (305 m)	2.2 (550)
[Equation (3.9)]:	Shaft to Building	For A_{si}/A_{io} = 1.7:	h = 30 ft (9.25 m)	0.02 (5)
			h = 300 ft (92.5 m)	0.17 (42)
			h = 1000 ft (305 m)	0.57 (140)
		For A_{si}/A_{io} = 7:	h = 30 ft (9.25 m)	0.001 (0.2)
			h = 300 ft (92.5 m)	0.01 (2)
			h = 1000 ft (305 m)	0.04 (10)
Buoyancy of Combustion Gases [Equation (3.11)]:	Fire Room to Adjacent Room at Ceiling	T_f = 1600°F (870°C), T_o = 70°F (21°C), and h = 5.6 ft (1.71 m)		0.06 (15)
		T_f = 1290°F (700°C), T_o = 70°F (21°C), and h = 35 ft (10.7 m)		0.35 (87)
Wind Effect [Equation (3.14)]:	Across the Building (Windward Wall to Leeward Wall)	Note: For all the wind effect examples, ρ_o = 0.075 lb/ft^3 (1.2 kg/m^3), C_{w1} = 0.8, and C_{w2} = -0.8.		
			V = 5 mph (2.24 m/s)	0.02 (5)
			V = 10 mph (4.47 m/s)	0.08 (20)
			V = 25 mph (11.2 m/s)	0.48 (120)
			V = 50 mph (22.4 m/s)	1.9 (470)
Ventilation Systems	Across Barrier of Smoke of Control System	Note: Values based on experience		0.05 to 0.30 (12 to 75)
Elevator Piston Effect [Equations (3.19) and (20)]:	From Elevator Lobby to Building	Note: For all the examples of the upper limit of pressure difference due elevator car motion, ρ = 0.75 lb/ft^3 (1.20 kg/m^3), A_{rs} = 1.60 ft^2 (0.149 m^2), A_{ir} = 0.42 ft^2 (0.039 m^2), A_{oi} = 0.54 ft^2 (0.0502 m^2).		
		For a single car shaft with C_c = 0.83, A_s = 60.4 ft^2 (5.61 m_2), A_a = 19.4 ft^2 (1.80 m^2):		
			V = 400 ft/min (2.03 m/s)	0.08 (20)
			V = 700 ft/min (3.56 m/s)	0.26 (65)
		For a double car shaft with C_c = 0.94, A_s = 120.8 ft^2 (11.22 m_2), A_a = 79.8 ft^2 (7.41 m^2):		
			V = 400 ft/min (2.03 m/s)	0.02 (5)
			V = 700 ft/min (3.56 m/s)	0.05 (12)

Example 3.7 Stack effect in tall building

The neutral plane is located at the mid height of a 600 ft (185 m) tall building with inside and outside temperatures of 70°F (21 C) and 0°F (-18 C). What is the pressure difference at the top of building?

$$T_o = 0 + 460 = 460°R \ (256 \ K)$$
$$T_s = 70 + 460 = 530°R \ (294 \ K)$$

Because of the neutral plane location, h = 300 ft (91.4 m). Using equation (3.6a), the pressure difference due to stack effect is 0.66 in H_2O (164 Pa) from the top of the shaft to the outside.

Note: Figure 3.6 can also be used for this calculation. In using this figure, the term, $\Delta P_{so}/h$, is positive for normal stack effect and it is negative for reverse stack effect.

For the building illustrated in figure 3.5, all of the vertical airflow is in the shaft. Of course, the floors of real buildings have some leakage, and there is some airflow through these floors. The discussion of stack effect to this point has been general, and it applies to buildings with or without leakage through floors. To analyze the pressure differences on building floors, an idealized building model is used which has no leakage between floors. For normal buildings, airflow through floors is much smaller than that through shafts. The following analysis develops some useful equations based on this <u>zero floor leakage idealization</u>.

For the system of flow paths illustrated in figure 3.5, the effective flow area per floor is

$$A_e = \left[\frac{1}{A_{si}^2} + \frac{1}{A_{io}^2} \right]^{-\frac{1}{2}} \qquad (3.23)$$

where:

A_e = effective leakage area between the shaft and the outside, ft^2 (m^2)
A_{si} = per floor leakage area between the shaft and the building, ft^2 (m^2)
A_{io} = per floor leakage area between the building and the outside, ft^2 (m^2)

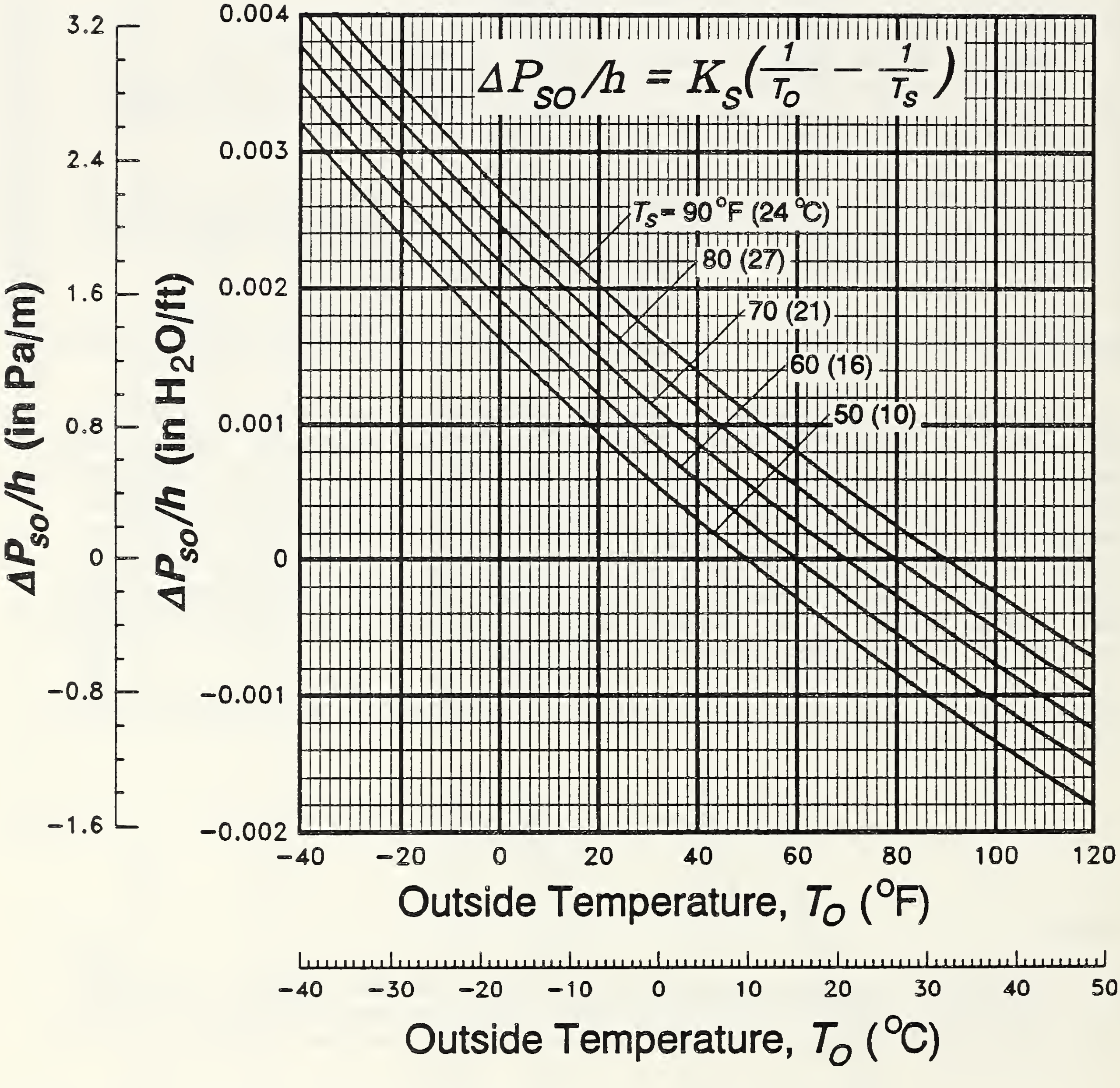


Figure 3.6 Graph of pressure difference due to stack effect

The mass flow rate, $\dot{m}$, at a floor can be expressed as $C\ A_e\ (2\ \rho\ \Delta P_{so})^{½}$, where C is a dimensionless flow coefficient which is generally in the range of 0.6 to 0.7. For paths in series the pressure difference across one path equals the pressure difference across the system times the square of the ratio of the effective area of the system to the flow area of the path in question. Thus the pressure difference from the shaft to the building space is $\Delta P_{si} = \Delta P_{so}\ (A_e/A_{si})^2$. By substituting equation (3.23) into this relation and rearranging, the effective area is eliminated.

$$\Delta P_{si} = \frac{\Delta P_{so}}{1 + (A_{si}/A_{io})^2} \qquad (3.24)$$

In general, the ratio A_{si}/A_{io} varies from about 1.7 to 7. The pressure differences from a shaft to the building space are much less than those from the shaft to the outside, as can be seen from the examples listed in table 3.1. In the event that many windows on the fire floor break due to the fire, the value of A_{io} becomes very large on the fire floor. When this happens, the ratio A_{si}/A_{io} becomes very small, and ΔP_{si} approaches ΔP_{so}. Thus when a large number of windows break on the fire floor, the pressure from the shaft to the building is almost the same as that from the shaft to the outside.

The development of equation (3.24) considered the pressure difference uniform with height at each floor which introduces an error, the maximum value of which can be calculated by equation (3.22) for a value of h equal to the distance between floors. In the examples of table 3.1, if the floors were 10 ft (3.1 m) apart, the maximum error of equation (3.24) is about .01 in H_2O (2.5 Pa). In general, this error is not significant. Equation (3.24) can be rewritten for the pressure, P_i, at the building space.

$$P_i = P_s - \frac{\Delta P_{so}}{1 + (A_{si}/A_{io})^2} \qquad (3.25)$$

The series flow approach to determining building pressures described above can be used for buildings with multiple shafts, if all the shafts are at the same pressures and if all the shafts have the same starting and ending elevations.

Pressure measurements on several buildings (Tamura and Wilson 1966, 1967a, 1967b) verify the stack effect theory presented above for conditions encountered in the field. Further, these studies show that the zero floor leakage idealization generally is appropriate for determining pressure differences on building floors due to stack effect. Additionally, Tamura and Klote (1988) have conducted full scale stack effect experiments at the Canadian ten story Fire Research Tower near Ottawa which verified the stack effect theory for a range of temperatures and of leakage conditions they considered representative of most buildings. Figure 3.7 shows comparisons of measured and calculated pressure differences due to stack effect for outside temperatures of 12°F (-11°C), 27°F (-3°C) and 45°F (7°C). Figure 3.8 shows comparisons of measured and calculated pressure differences for ratios A_{si}/A_{io} of 1.7, 2.4 and 7. Further, this stack effect theory provides a useful approximation for buildings for which all of the shafts do not have the same starting and ending elevations.

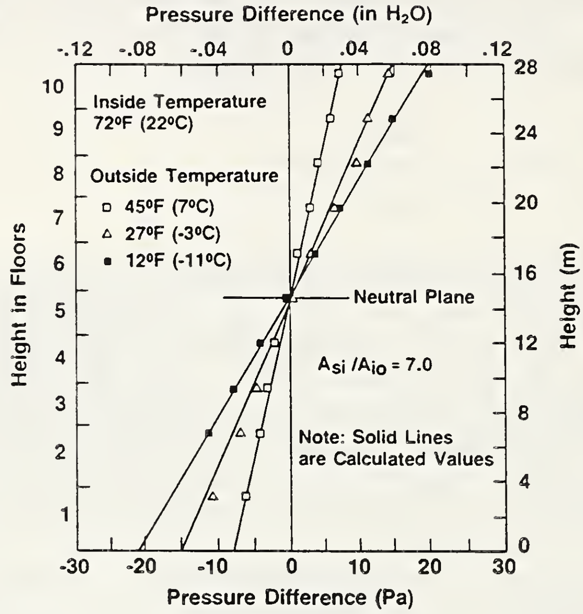


Figure 3.7 Comparison of measured and calculated pressure differences across the outside wall of the Canadian Fire Research Tower for different outside temperatures [Adapted from Tamura and Klote (1988)]

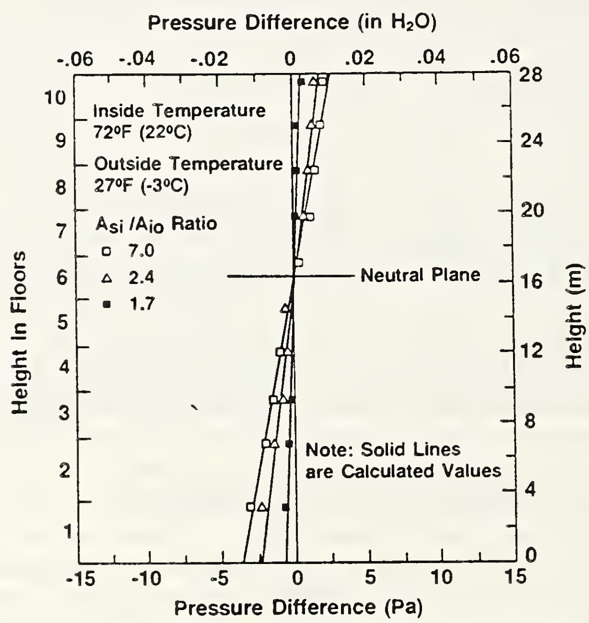


Figure 3.8 Comparison of measured and calculated pressure differences across a shaft enclosure of the Canadian Fire Research Tower for different building leakages [Adapted from Tamura and Klote (1988)]

In unusually tight buildings with exterior stairwells, reverse stack effect has been observed even with low outside air temperatures (Klote 1980). In this situation, the exterior stairwell temperature was considerably lower than the building temperature. The stairwell was the cold column of air and the other shafts within the building were the warm columns of air.

Smoke movement from a building fire can be dominated by stack effect. During normal stack effect (figure 3.4), smoke from a fire below the neutral plane moves with the building air flow into shafts and up the shafts. This upward smoke flow is enhanced by any buoyancy forces on the smoke due to its temperature. Once above the neutral plane, the smoke flows out of the shafts into the upper floors of the building as illustrated in figure 3.9(a). Leakage between floors results in smoke flow to the floor above the fire floor. If leakage between floors is negligible, the floors below the neutral plane, except for the fire floor, will be essentially smoke-free. For significant leakage between floors, smoke flow to the floor directly above the fire floor will be much greater than that to other floors below the neutral plane as is shown in figure 3.9(a).

For a fire above the neutral plane, the building air flows due to normal stack effect tend to restrict the extent of smoke flow. Air flow from the shafts to the fire floor can prevent smoke infiltration of those shafts [figure 3.9(b)], but leakage between floors can result in some smoke movement. If the buoyancy forces of the hot smoke overcome the stack effect forces at the shafts on the fire floor, smoke can infiltrate the shafts and flow to upper floors [figure 3.9(c)]. The air currents of reverse stack effect (figure 3.4) tend to affect

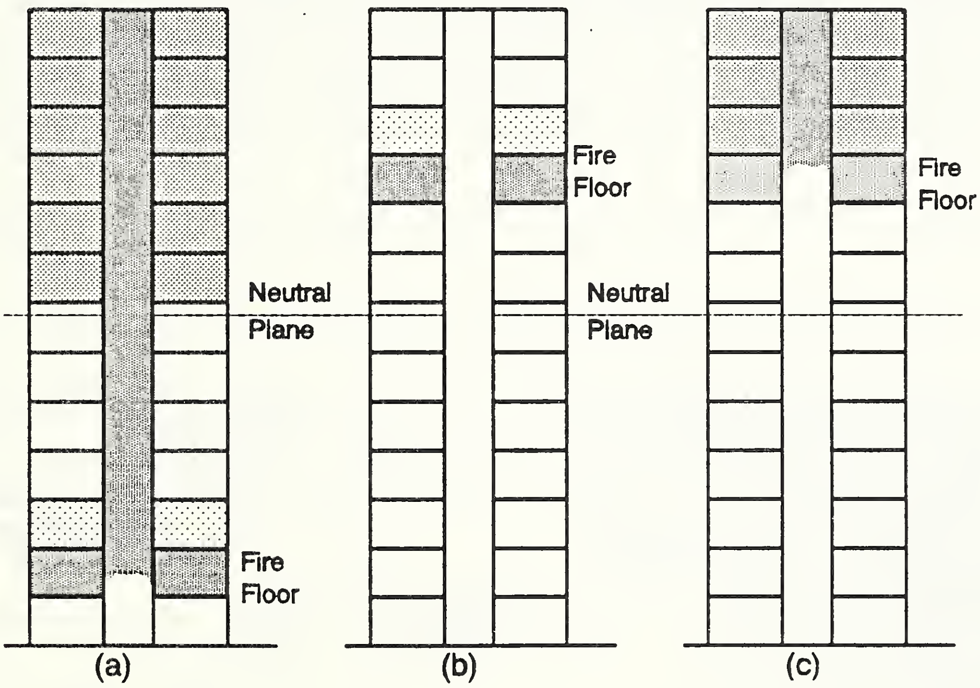


Figure 3.9 Smoke movement in high rise buildings due to normal stack effect: (a) fire below neutral plane, (b) fire above neutral plane, and (c) fire above neutral plane with smoke entering shafts at fire floor due to buoyancy of hot fire gases

smoke movement of relatively cool smoke in the reverse of normal stack effect. In the case of hot smoke, buoyancy forces can be so great that smoke can flow upward even during reverse stack effect. Further information about smoke flow due to stack effect and other driving forces is presented by Klote (1989).

3.2.2 Buoyancy of Combustion Gases

High temperature smoke from a fire has a buoyancy force due to its reduced density. The pressures occurring during a fully involved compartment fire are illustrated in figure 3.10, and these pressures can be analyzed in the same manner as pressures due to stack effect. In the same manner as equation (3.22) was developed for stack effect, the following equation for the pressure difference, ΔP_{fo}, from the fire compartment to its surroundings can be developed

$$\Delta P_{fo} = \frac{g\, P_{atm}}{R} \left(\frac{1}{T_o} - \frac{1}{T_f} \right) h \tag{3.26}$$

where:

T_o = absolute temperature of gases surrounding the fire compartment
T_f = absolute temperature gas within the fire compartment
h = distance above the neutral plane

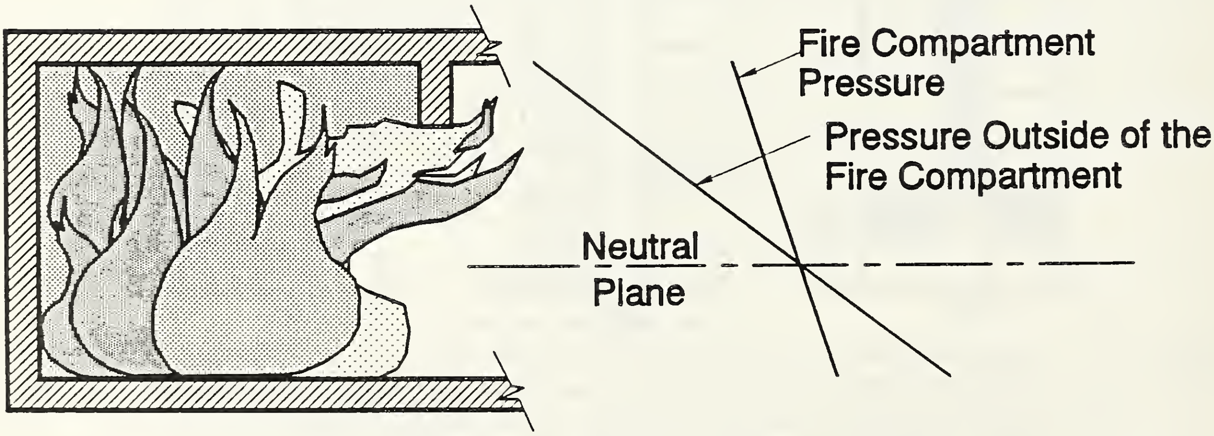


Figure 3.10 Pressures occurring during a fully involved compartment fire

The neutral plane is a horizontal plane where the pressure inside the fire compartment equals that outside. Equation (3.26) is for a constant fire-compartment temperature. For standard atmospheric pressure, the above relation becomes:

$$\Delta P_{fo} = K_s \left(\frac{1}{T_o} - \frac{1}{T_f} \right) h \qquad (3.26a)$$

where:

ΔP_{fo} = pressure difference from fire compartment to surroundings, in H_2O (Pa)
T_o = absolute temperature of outside air, °R (K)
T_f = absolute temperature of gas inside fire compartment, °R (K)
h = distance above neutral plane, ft (m)
K_s = coefficient, 7.64 (3460)

Fang (1980) has studied pressure differences caused by the stack effect of a room fire during a series of full scale fire tests. During these tests, the maximum pressure difference reached was 0.064 in H_2O (16 Pa) across the burn room wall at the ceiling.

Observation of table 3.1 can provide insight on conditions for which buoyancy as opposed to stack effect is likely to be the dominant driving force. Without broken windows, the buoyancy will dominate for large values of A_{si}/A_{io} at almost any location from the neutral plane. For low values of A_{si}/A_{io} at locations far from the neutral plane, stack effect can dominate even when windows are unbroken. When windows are broken, stack effect is even more likely to dominate. Stack effect can only be the dominant driving force during times of significant inside-to-outside temperature difference.

Much larger pressure differences are possible for tall fire compartments where the distance, h, from the neutral plane can be larger as illustrated by the following example.

Example 3.8 Buoyancy pressure in a fire compartment

For a fire-compartment temperature of 1470°F (800°C), what is the buoyancy pressure difference at 6 ft (1.83 m) above the neutral plane.

T_o = 70 + 460 = 530°R (294 K)
T_f = 1470 + 460 = 1930°R (1072 K)
h = 6 ft (1.83 m)

Using equation (3.26a), the buoyancy pressure difference is 0.06 in H_2O (15 Pa). Figure 3.11 can also be used for this calculation.

Example 3.9 Buoyancy pressure difference for very tall fire compartment

If the fire compartment temperature is 1290°F (700°C), what is the pressure difference at 35 ft (10.7 m) above the neutral plane?

T_o = 70 + 460 = 530°R (294 K)
T_f = 1290 + 460 = 1750°R (972 K)
h = 35 ft (10.7 m)

Using equation (3.26a) or figure 3.11, ΔP_{fo} is 0.35 in H_2O (88 Pa). This represents an extremely large fire, and the example is included to illustrate the extent to which equation (3.26a) can be applied.

3.2.3 Expansion of Combustion Gases

In addition to buoyancy, the energy released by a fire can cause smoke movement due to expansion. In a fire compartment with only one opening to the building, air will flow into the fire compartment and hot smoke will flow out of the compartment. Neglecting the added mass of the fuel which is small compared to the airflow and considering the thermal properties of smoke to be the same as those of air, the ratio of the volumetric flows can be simply expressed as a ratio of absolute temperatures.

$$\frac{Q_{out}}{Q_{in}} = \frac{T_{out}}{T_{in}} \tag{3.27}$$

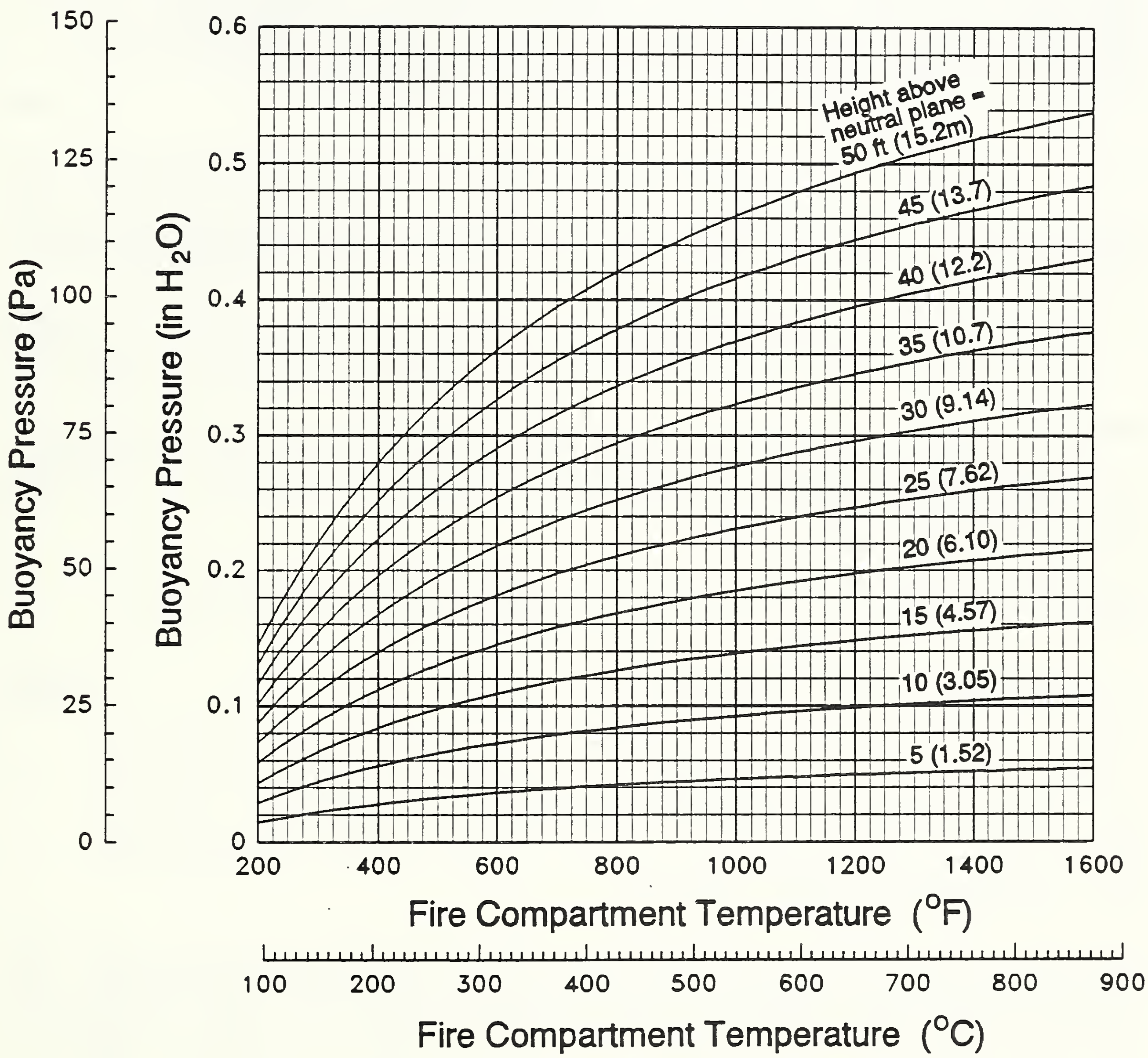


Figure 3.11 Graph of pressures due to buoyancy

where:

Q_{out} = volumetric flow rate of smoke out of the fire compartment, cfm (m^3/s)
Q_{in} = volumetric flow rate of air into the fire compartment, cfm (m^3/s)
T_{out} = absolute temperature of smoke leaving the fire compartment, °R (K)
T_{in} = absolute temperature of air entering the fire compartment, °R (K)

For a smoke temperature of 1110°F (600°C), the gas will expand to about three times its original volume. For a fire compartment with open doors or windows, the pressure difference across these openings due to expansion is negligible because of the large flow areas involved. However, for a fire space without open doors or windows, the pressure differences due to expansion may be important, provided there is sufficient oxygen to support combustion for a significant time. Gas expansion, in such a closed space subject to the exhaust of zoned smoke control, is addressed in Chapter 9.

3.2.4 Wind Effect

Wind can have a pronounced effect on smoke movement. The pressure, P_w, that wind exerts on a surface can be expressed as

$$P_w = \frac{1}{2} C_w \rho_o V^2 \qquad (3.28)$$

where:

C_w = dimensionless pressure coefficient
ρ_o = outside air density
V = wind velocity

For an air density of 0.075 lb/ft^3 (1.20 kg/m^3) this relation becomes

$$P_w = K_w C_w V^2 \qquad (3.28a)$$

where:

P_w = wind pressure on a surface, in H_2O (Pa)
C_w = dimensionless pressure coefficient
V = wind velocity, mph (m/s)
K_w = coefficient, 4.2×10^{-4} (0.600)

Generally, the pressure coefficient, C_w, is in the range of -0.8 to 0.8, with positive values for windward walls and negative values for leeward walls. The pressure coefficient depends on building geometry and local wind obstructions, and the pressure coefficient varies locally over the wall surface. Values of pressure coefficient, $\bar{C}_w$, averaged over the wall area are listed in table 3.2 for rectangular buildings which are free of local obstructions.

The pressure difference from one side of a building to another due to wind effect can be expressed as

$$\Delta P_w = \frac{1}{2} (C_{w1} - C_{w2}) \rho_o V^2 \qquad (3.29)$$

where:

C_{w1} = pressure coefficient for windward wall
C_{w2} = pressure coefficient for leeward wall

For an air density of 0.075 lb/ft^3 (1.20 kg/m^3) this equation becomes

$$\Delta P_w = K_w (C_{w1} - C_{w2}) V^2 \qquad (3.29a)$$

where:

P_w = wind pressure across a building, in H_2O (Pa)
C_{w1} = pressure coefficient for windward wall, dimensionless
C_{w2} = pressure coefficient for leeward wall, dimensionless
V = wind velocity, mph (m/s)
K_w = coefficient, 4.2×10^{-4} (0.600)

Examples of wind induced pressures for wind speeds from 5 to 50 mph (2.24 to 22.4 m/s) are provided in table 3.1. Wind effects are most severe at high wind speeds and when windows are broken.

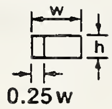
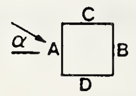
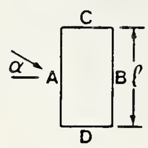
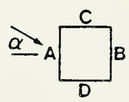
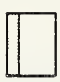
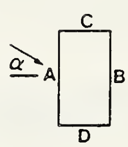
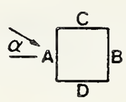
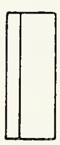
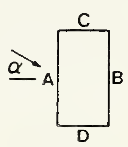
In general, wind velocity increases with elevation above the ground, as is expressed by the power law equation.

$$V = V_o \left(\frac{z}{z_o} \right)^n \qquad (3.30)$$

where:

V = wind velocity, fpm (m/s)
V_o = velocity at reference elevation, fpm (m/s)
z = elevation of velocity, V, ft (m)
z_o = reference elevation, ft (m)
n = wind exponent, dimensionless

Table 3.2 Average pressure coefficients for walls of rectangular buildings [Adapted from MacDonald, (1975)]

Building Height Ratio	Building Plan Ratio	Elevation	Plan	Wind Angle α	$\bar{C}_W$ for Surface A	B	C	D
$\frac{h}{w} \leq \frac{1}{2}$	$1 < \frac{\ell}{w} \leq \frac{3}{2}$			0°	+0.7	-0.2	-0.5	-0.5
				90°	-0.5	-0.5	+0.7	-0.2
	$\frac{3}{2} < \frac{\ell}{w} < 4$			0°	+0.7	-0.25	-0.6	-0.6
				90°	-0.5	-0.5	+0.7	0.1
$\frac{1}{2} < \frac{h}{w} \leq \frac{3}{2}$	$1 < \frac{\ell}{w} \leq \frac{3}{2}$			0°	+0.7	-0.25	-0.6	-0.6
				90°	-0.6	-0.6	+0.7	-0.25
	$\frac{3}{2} < \frac{\ell}{w} < 4$			0°	+0.7	-0.3	-0.7	-0.7
				90°	-0.5	-0.5	+0.7	-0.1
$\frac{3}{2} < \frac{h}{w} < 6$	$1 < \frac{\ell}{w} \leq \frac{3}{2}$			0°	+0.8	-0.25	-0.8	-0.8
				90°	-0.8	-0.8	+0.8	-0.25
	$\frac{3}{2} < \frac{\ell}{w} < 4$			0°	+0.7	-0.4	-0.7	-0.7
				90°	-0.5	-0.5	+0.8	-0.1

Note: h = height to eaves or parapet; ℓ = length = the greater horizontal dimension of a building; w = width = the lesser horizontal dimension of a building

Wind data is recorded by airports and the weather service at heights, z_o, of about 33 ft (10 m) above the ground. This relationship has been extensively used to describe the velocity profile of the wind near the surface of the earth. It assumes that there are no large obstructions near the building that could produce local wind conditions. For buildings with such obstructions, specialized wind tunnel studies are needed to determine the pressure loadings due to the wind.

A value of 0.16 for the wind exponent is appropriate for flat terrain. The wind exponent increases with rougher terrain, and for very rough terrain, such as urban areas, a value of 0.40 is appropriate. In urban areas with a rather constant roof level, the wind gradient can be expressed as

$$V = V_o \left(\frac{z - y}{z_o} \right)^n \qquad (3.31)$$

where:

V = wind velocity, fpm (m/s)
V_o = velocity at reference elevation, fpm (m/s)
z = elevation of velocity, V, ft (m)
z_o = reference elevation, ft (m)
y = average roof height, ft (m)
n = wind exponent, dimensionless

Wind velocity profiles are illustrated in figure 3.12 for flat and very rough terrain. For further information about wind exponents and flow coefficients the reader is referred to texts on wind engineering such as those by Houghton and Carruthers (1976), Kolousek et al. (1984), MacDonald (1975), Sachs (1978), and Simiu and Scanlan (1986).

Example 3.10 Wind velocity and elevation

Estimate the wind velocity near the top of a 600 ft (180 m) building located in an city where the average roof height is 60 ft (18 m). The wind speed measured at a local airport is 10 mph (4.5 m/s).

For very rough terrain, the wind exponent of 0.4 is appropriate. Because the measurement is at an airport, z_o = 33 ft (10 m). Using equation (3.31) the velocity at the top of the building is 31 mph (14 m/s).

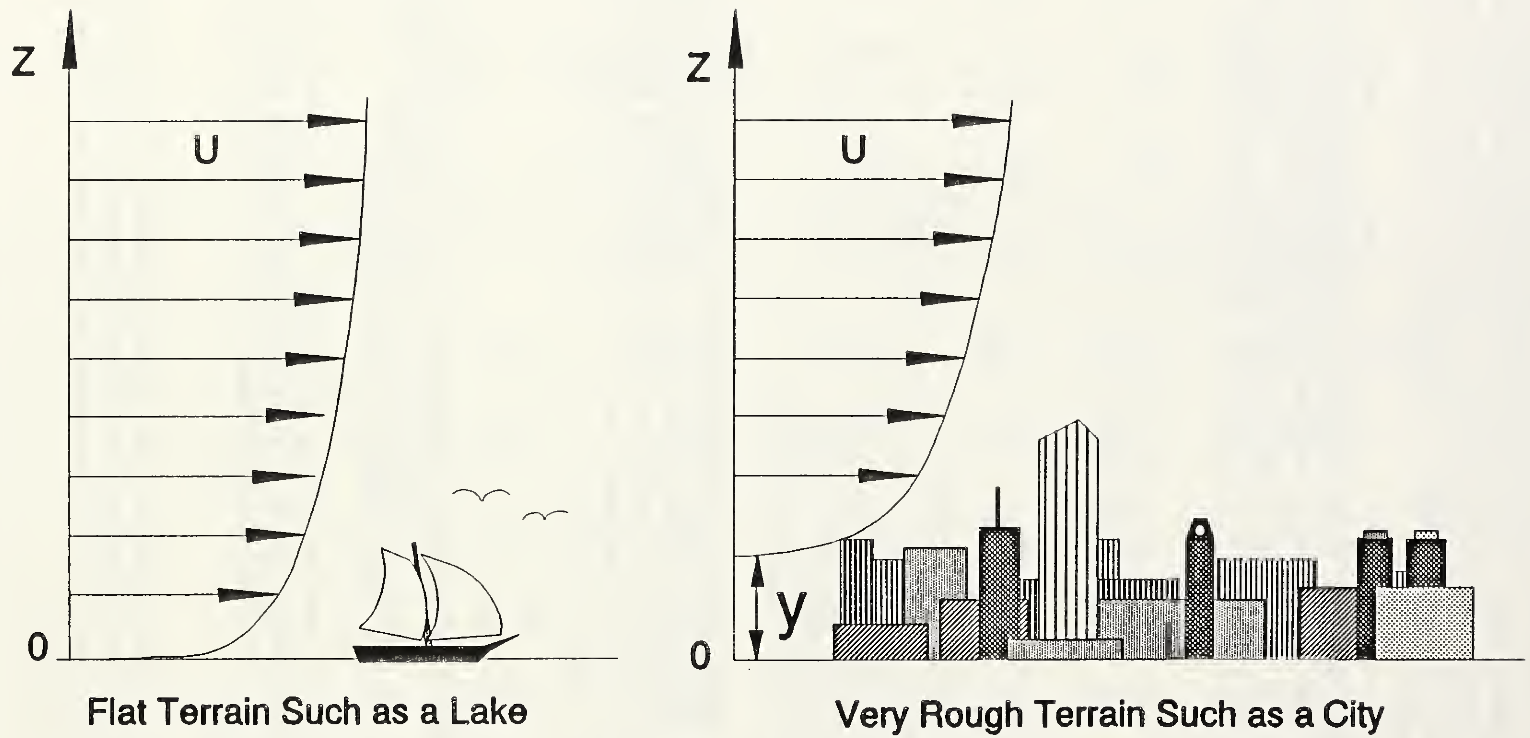


Figure 3.12 Wind velocity profiles for flat and very rough terrain

Example 3.11 Wind pressure on a wall

What is the wind pressure exerted on a wall at the top of the building in example 3.4. The wind velocity is 31 mph (14 m/s), and the pressure coefficient is 0.8.

Using equation (3.28a) or figure 3.13, the wind pressure is .37 in H_2O (92 Pa).

3.2.5 Forced Ventilation Systems

Heating, ventilating and air conditioning (HVAC) systems frequently transport smoke during building fires. When a fire starts in an unoccupied portion of a building, the HVAC system can transport smoke to a space where people can smell the smoke and be alerted to the fire. Upon detection of fire or smoke, the HVAC system should be designed so that either the fans are shut-down or the system goes into a special smoke control mode of operation. The advantages and disadvantages of these approaches are complex, and no simple consensus has been reached regarding a preferred method for various building types. However, if normal HVAC operation continues, the HVAC system will transport smoke to every area the system serves. As the fire progresses, smoke in these spaces will endanger life, damage property and inhibit fire fighting. Although shutting down the HVAC system prevents it from supplying oxygen to the fire, system shut-down does not prevent smoke movement through the supply and return ducts, air shafts, and other building openings due to stack effect, buoyancy, or wind. Installation of smoke dampers can help inhibit this smoke movement. A third alternative fire mode for HVAC systems consists of continued HVAC operation while dumping return air to the outside in an attempt to minimize smoke transport throughout in the building by the HVAC system. While this third approach has not been experimentally or theoretically verified, it seems that it may have the potential to minimize smoke transport through the HVAC system. Computer simulation of smoke movement through HVAC systems is discussed by Klote (1987).

3.2.6 Elevator Piston Effect

When an elevator car moves in a shaft, transient pressures are produced. A downward-moving elevator car forces air out of the section of shaft below the car and into the section of shaft above the car as illustrated in figure 3.14. Klote and Tamura (1986) developed the following analytical equation for the pressure difference, ΔP_{so}, due to elevator piston effect from the outside to the elevator shaft above the car.

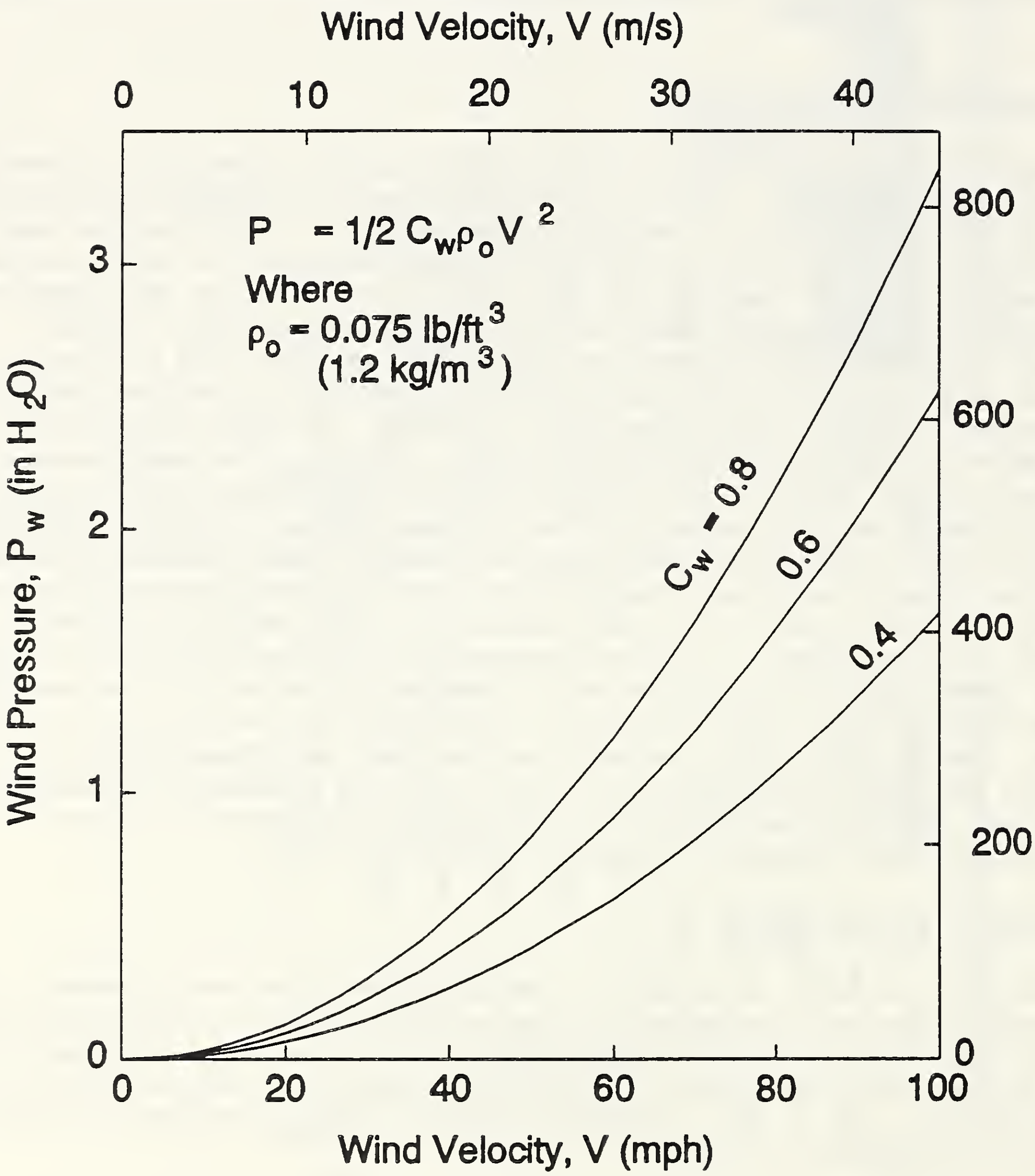


Figure 3.13 Graph of pressure due to wind

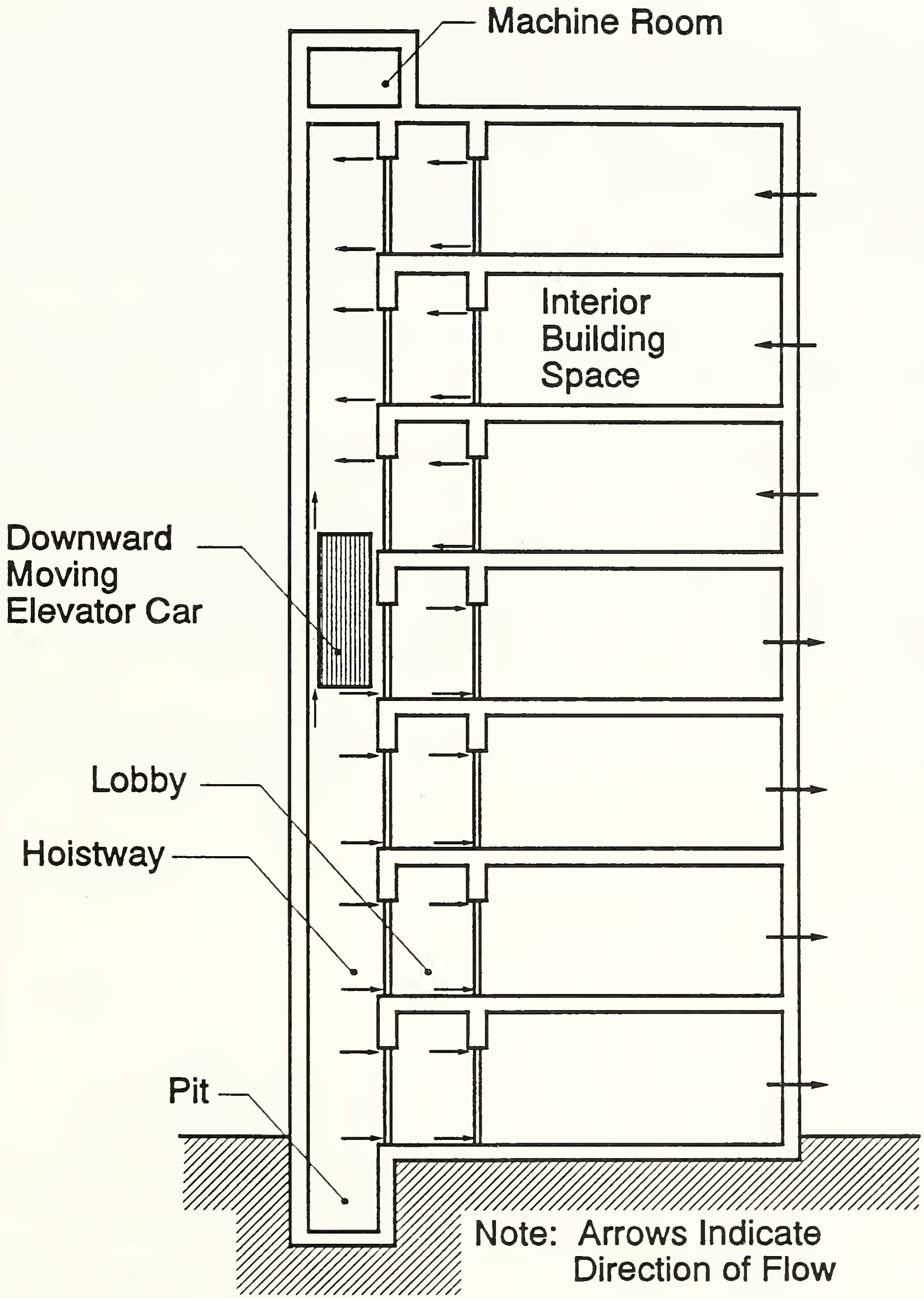


Figure 3.14 Airflow due to downward movement of elevator car

$$\Delta P_{so} = \frac{K_{pe}\ \rho}{2} \left[\frac{A_s\ V}{N_a\ C\ A_e + C_c\ A_a\ [1 + (N_a/N_b)^2]^{\frac{1}{2}}} \right]^2 \qquad (3.32)$$

where:

ρ = air density within the shaft, lb/ft^3 (kg/m^3)
A_s = cross-sectional area of shaft, ft^2 (m^2)
V = velocity of elevator car, fpm (m/s)
N_a = number of floors above the car, dimensionless
N_b = number of floors below the car, dimensionless
C = flow coefficient for building leakage paths, dimensionless
A_e = effective flow area per floor between the shaft and the outside, ft^2 (m^2)
C_c = flow coefficient for flow around the car, dimensionless
A_a = free flow area in shaft around car, or cross-sectional area of shaft less cross-sectional area of the car, ft^2 (m^2)
K_{pe} = coefficient, 1.66×10^{-6} (1.00)

The coefficient, C_c, was evaluated at 0.94 for a two car shaft with only one car moving and at 0.83 for a two car shaft with both cars traveling side-by-side together. The value for the two cars moving together is believed to be appropriate for obtaining approximations of pressures produced by the motion of a car in a single car shaft. For the sake of simplicity in the analysis leading to equation (3.32), buoyancy, wind, stack effect, and effects of the heating and ventilating system were omitted. Omitting stack effect is equivalent to stipulating that the building air temperature and the outside air temperature are equal.

For the system of three series flow paths from the shaft to the outside illustrated in figure 3.14, the effective flow area, A_e, per floor is

$$A_e = \left[\frac{1}{A_{rs}^2} + \frac{1}{A_{ir}^2} + \frac{1}{A_{oi}^2} \right]^{-\frac{1}{2}} \qquad (3.33)$$

where:

A_e = effective flow area, ft^2 (m^2)
A_{rs} = leakage area between the lobby and the shaft, ft^2 (m^2)
A_{ir} = leakage area between the building and the lobby, ft^2 (m^2)
A_{oi} = leakage area between the outside and the building, ft^2 (m^2)

A detailed discussion of effective flow areas is provided later in this text. In a similar manner to the development for stack effect, the pressure difference from the lobby to building interior can be expressed as

$$\Delta P_{ri} = \Delta P_{so}\ (A_e/A_{ir})^2 \qquad (3.34)$$

where:

ΔP_{ri} = pressure difference from the building to the lobby, in H_2O (Pa)
ΔP_{so} = pressure difference from the outside to the shaft, in H_2O (Pa)
A_e = effective area between shaft and the outside, ft^2 (m^2)
A_{ir} = leakage area between the building and the lobby, ft^2 (m^2)

This series flow path analysis does not include the effects of other shafts such as stairwells and dumbwaiters. Provided that the leakage of these other shafts is relatively small compared to A_{oi}, equation (3.33) is appropriate for evaluation of A_e for buildings with open floor plans. Further, equation (3.34) is appropriate for closed floor plans, provided all the flow paths are in series and there is negligible vertical flow in the building outside the elevator shaft. The complicated flow path systems probably require case by case evaluation which can be done by using the effective area techniques presented later in this manual.

To test the above theory, experiments were conducted in a hotel in Toronto, Ontario, Canada. Figure 3.15 shows measured pressure differences across the top floor elevator lobby while a car was descending. Also shown is the calculated pressure difference which is in good agreement with the measurements. This experiment is described in detail by Klote and Tamura (1986).

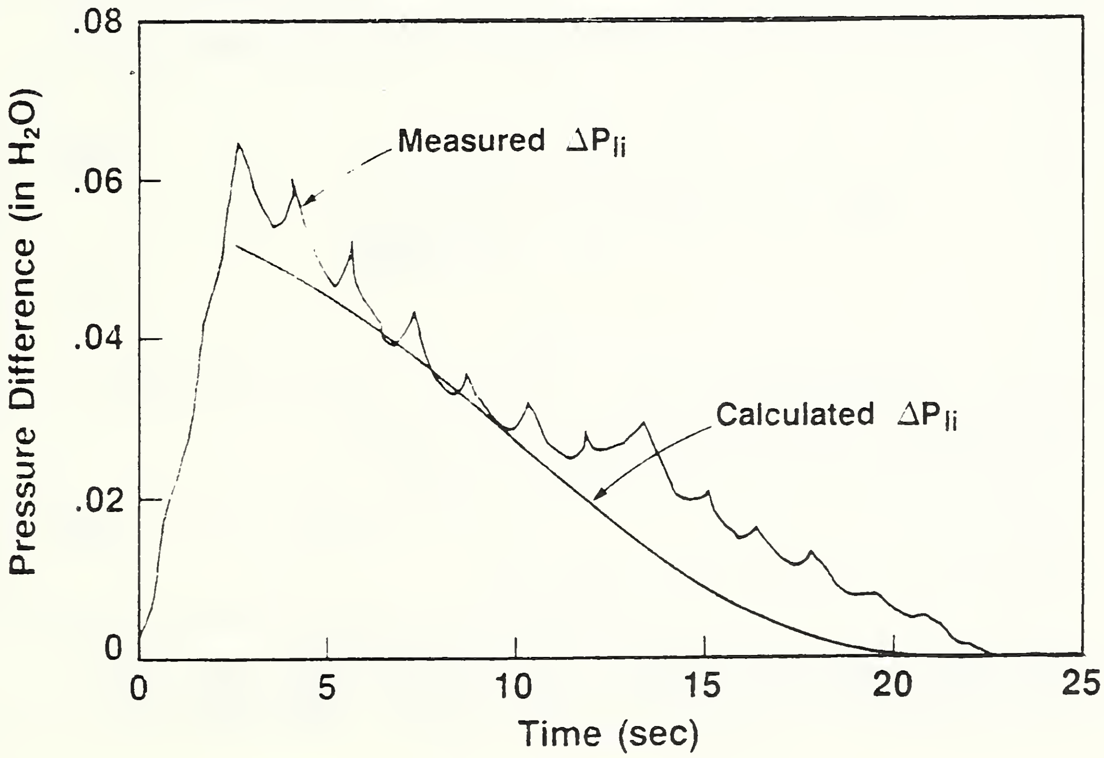


Figure 3.15 Pressure difference, ΔP_{ri}, across elevator lobby of a Toronto hotel due to piston effect

Example 3.12 Pressures due to moving elevator car

What pressure differences are produced by a downward moving elevator car with a velocity of 600 fpm (3.05 m/s) in a single car shaft? The shaft is 20 stories high and the car is at floor 18 (N_a = 2 and N_b = 17). The areas are:

	ft^2	(m^2)
A_{rs}, area between lobby and shaft	1.60	(0.149)
A_{ir}, area between building and lobby	0.42	(0.039)
A_{oi}, area between outside and building	0.54	(0.050)
A_s, cross-sectional area of shaft	60.4	(5.61)
A_a, free flow area around car	19.4	(1.80)

Use C = .65, C_c = .83, and ρ = 0.075 lb/ft^3 (kg/m^3). From equation (3.34), the effective area is 0.325 ft^2 (0.302 m^2). From equation (3.17), the pressure difference from the outside to the shaft, ΔP_{so}, is 0.30 in H_2O (75 Pa). From equation (3.34), the pressure difference from the building to the lobby is .18 in H_2O (45 Pa).

The pressure difference, ΔP_{ri}, can not exceed the upper limit of

$$(\Delta P_{ri})_u = \frac{K_{pe}\,\rho}{2}\left(\frac{A_s\,A_e\,V}{A_a\,A_{ir}\,C_c}\right)^2 \qquad (3.35)$$

where:

$(\Delta P_{ri})_u$ = upper limit of the pressure difference from the building to the lobby, in H_2O (Pa)
ρ = air density within the shaft, lb/ft^3 (kg/m^3)
A_s = cross-sectional area of shaft, ft^2 (m^2)
A_e = effective flow area per floor between the shaft and the outside, ft^2 (m^2)
V = velocity of elevator car, fpm (m/s)
A_a = free flow area in shaft around car, or cross-sectional area of shaft less cross-sectional area of the car, ft^2 (m^2)
A_{ir} = leakage area between the building and the lobby, ft^2 (m^2)
C_c = flow coefficient for flow around the car, dimensionless
K_{pe} = coefficient, 1.66×10^{-6} (1.00)

This relation is for unvented elevator shafts, or for which the vents are closed. The pressure difference, $(\Delta P_{ri})_u$, is strongly dependant upon V, A_s and A_a. For example, figure 3.16 shows the calculated relationship between $(\Delta P_{ri})_u$ and V due to one car moving in a single car shaft, a double car shaft and a quadruple car shaft. As expected the $(\Delta P_{ri})_u$ is much greater for the single car shaft. It follows that the potential for smoke problems due to piston effect in single car shafts is much greater than in multiple car shafts. Comparison of stack effect induced pressure differences indicates that they can be larger than those of other driving forces (table 3.1).

Operation of elevators by the fire service during a fire can result in smoke being pulled into the elevator shaft by piston effect. It seems a safe recommendation that fire fighters should favor the use of elevators in multiple car shafts over ones in single car shafts. Klote (1988a) developed another analysis of piston effect including the influence of elevator smoke control, and experiments conducted by Klote and Tamura (1987) were in good agreement with this theory.

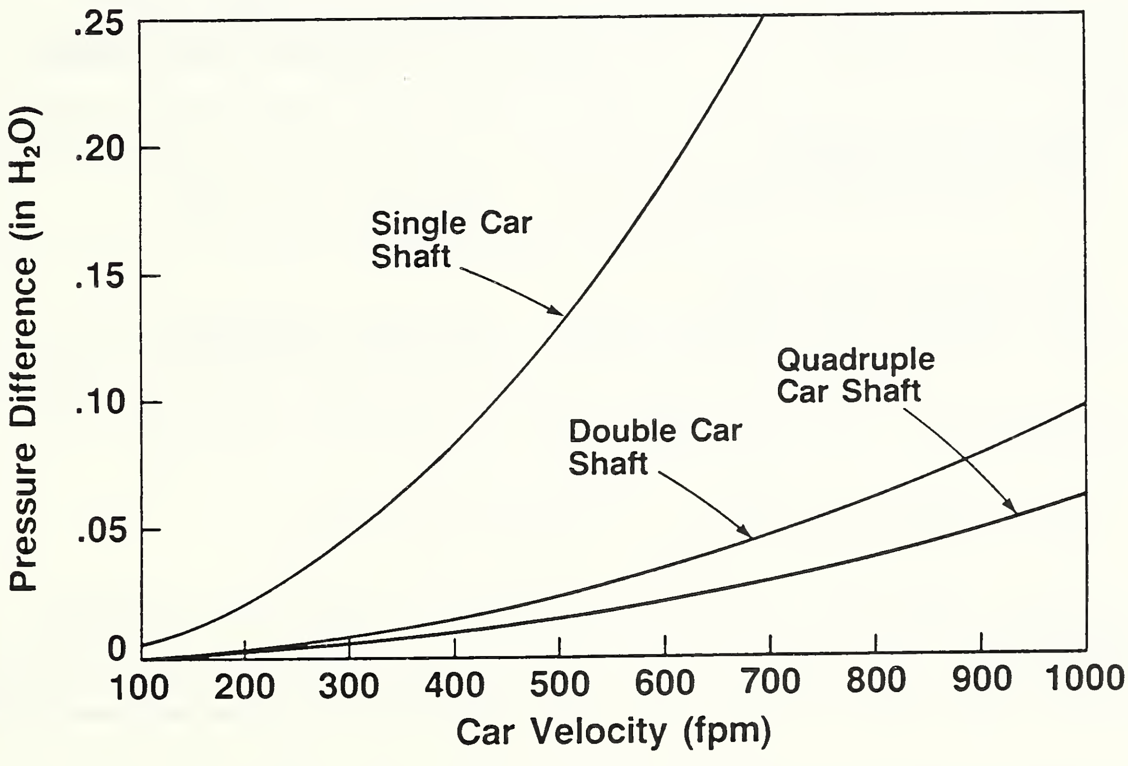


Figure 3.16 Calculated upper limit of the pressure difference, $(\Delta P_{ri})_u$, from the elevator lobby to the building due to piston effect

Example 3.13 Upper limit of pressure due to elevator motion

(A) What is the upper limit of the pressure difference produced by the moving elevator car in a single car shaft from example 3.6? The values used in this calculation are:

V, car velocity	600 fpm (3.05 m/s)
C_c, flow coefficient for flow around elevator car	0.83
ρ, air density in shaft	0.075 lb/ft^3 (1.20 kg/m^3)
A_e, effective area between shaft and outside	0.325 ft^2 (0.0302 m^2)
A_{ir}, area between building and lobby	0.42 ft^2 (0.039 m^2)
A_s, cross-sectional area of shaft	60.4 ft^2 (5.61 m^2)
A_a, free flow area around car	19.4 ft^2 (1.80 m^2)

From equation (3.35), the upper limit of pressure difference from the building to the lobby is 0.19 in H_2O (47 Pa).

(B) What would be the upper limits of pressure difference if the car were in a double car shaft or a quadruple car shaft? For multiple car shafts, C_c = .94 is used. The areas for these shafts are:

<u>For double car shaft</u>

A_s, cross-sectional area of shaft	120.8 ft^2 (11.22 m^2)
A_a, free flow area around car	79.8 ft^2 (7.41 m^2)

<u>For Quadruple car shaft</u>

A_s, cross-sectional area of shaft	241.5 ft^2 (22.44 m^2)
A_a, free flow area around car	200.5 ft^2 (18.63 m^2)

From equation (3.36), the upper limits of pressure difference from the building to the lobby are:

For the double car shaft: 0.035 in H_2O (9.0 Pa).
For the quadruple car shaft: 0.022 in H_2O (5.5 Pa).

Pressure differences, $(\Delta P_{ri})_u$, for other car velocities are shown on figure 3.16.

3.3 LOCATION OF NEUTRAL PLANE

In this section methods of determining the location of the neutral plane are described for a single shaft connected to the outside only. The methods of effective area can be used to extend this analysis to buildings. Using these neutral plane locations, the flow rates and pressures throughout the building can be evaluated to the extent that the series flow model of section 2.1 is applicable.

3.3.1 Shaft with a Continuous Opening

2

The flow and pressures of normal stack effect for a single shaft connected to the outside by a continuous opening of constant width from the top to the bottom of the shaft is illustrated in figure 3.17. The following analysis of this flow and the resulting location of the neutral plane was developed by McGuire and Tamura (1975). The pressure difference from the shaft to the outside is expressed by equation (3.22). The mass flow rate, dm_{in}, through the a differential section, dh, of the shaft below the neutral plane is

$$dm_{in} = C\ A' \sqrt{2\ \rho_o\ \Delta P_{so}}\ dh = C\ A' \sqrt{2\ \rho_o\ b\ h}\ dh \qquad (3.36)$$

where:

$$b = \frac{g\ P_{atm}}{R} \left(\frac{1}{T_o} - \frac{1}{T_s} \right)$$

A′ = area of the opening per unit height

To obtain the mass flow rate into the shaft, this equation can be integrated from the neutral plane (h = 0) to the bottom of the shaft ($h = -H_n$).

$$\dot{m}_{in} = \frac{2}{3}\ C\ A'\ H_n^{3/2} \sqrt{2\ \rho_o\ b} \qquad (3.37)$$

In a similar manner an expression for the mass flow rate from the shaft can be developed, where H is the total height of the shaft.

$$\dot{m}_{out} = \frac{2}{3}\ C\ A'\ (H - H_n)^{3/2} \sqrt{2\ \rho_s\ b}^{\ 2} \qquad (3.38)$$

For steady flow, the mass flow rate into the shaft equals that leaving it. Equating equations (3.37) and (3.38), cancelling like terms, rearranging, and substituting equation (3.21) yields

$$\frac{H_n}{H} = \frac{1}{1 + (T_s/T_o)^{1/3}} \qquad (3.39)$$

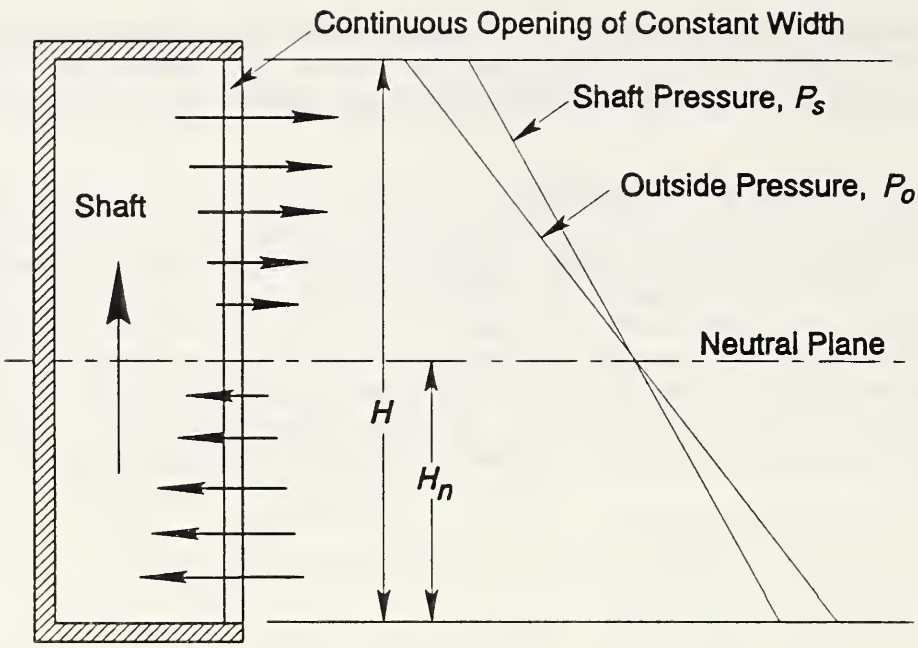


Figure 3.17 Normal stack effect between a single shaft connected to the outside by a continuous opening

where:

H_n = distance from the bottom of the shaft to the neutral plane, ft (m)
H = height of shaft, ft (m)
T_s = absolute temperature of air in shaft, °R (K)
T_o = absolute temperature of outside air, °R (K)

Example 3.14 Location of neutral plane with in structure with uniform leakage

Calculate the location of the neutral plane for a 100 ft (30.5 m) tall building of uniform floor to floor leakage. The inside temperature is 72°F (22°C), and an outside temperature of 0°F (-18°C).

From equation (3.39), the neutral plane is located at a height of 48.8 ft (14.9 m) above the bottom of the building. This is slightly different from the generally accepted approximation of halfway up the shaft.

3.3.2 Shaft With Two Vents

Normal stack effect for a shaft with two openings is illustrated in figure 3.18. The pressure difference from the shaft to the outside is expressed by

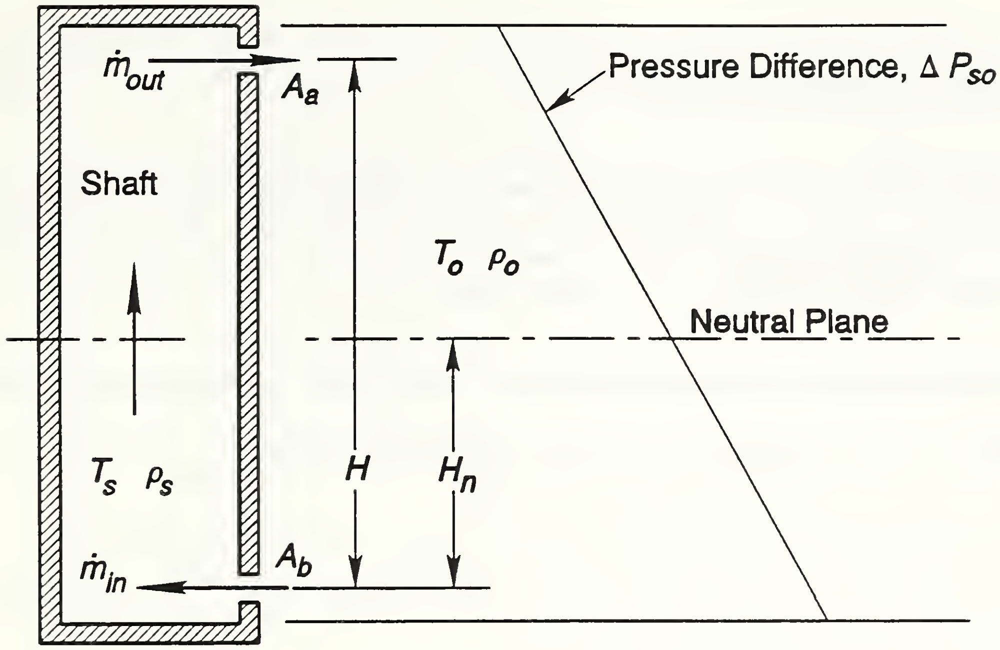


Figure 3.18 Stack effect for a shaft with two openings

equation (3.22). To simplify analysis, the distance, H, between the openings is considered much greater than the height of either opening. Thus the variation of pressure with height for the openings can be neglected, and the mass flow rate into the shaft can be expressed as

$$\dot{m}_{in} = C A_b \sqrt{2 \rho_o b H_n} \tag{3.40}$$

and the mass flow rate out of the shaft is

$$\dot{m}_{out} = C A_a \sqrt{2 \rho_s b (H - H_n)} \tag{3.41}$$

Where A_a and A_b are the areas above and below the neutral plane. Equating these two flows as was done above yields

$$\frac{H_n}{H} = \frac{1}{1 + (T_s/T_o)(A_b/A_a)^2} \tag{3.42}$$

where:

H_n = distance from the bottom of the shaft to the neutral plane, ft (m)
H = height of shaft, ft (m)
T_s = absolute temperature of air in shaft, °R (K)
T_o = absolute temperature of outside air, °R (K)

A_a = area above neutral plane, ft^2 (m^2)
A_b = area below neutral plane, ft^2 (m^2)

The location of the neutral plane is highly dependent on the ratio A_b/A_a. For A_b/A_a that approaches zero, H_n approaches H. This means that if the area at the bottom is very small compared to the area at the top, then the neutral plane is at or near the top area. Equation (3.42) is a strong function of the flow areas and a weak function of temperature.

Example 3.15 Location of neutral plane for shaft with two equal openings

What is the location of the neutral plane in a 100 ft (30.5 m) tall shaft with two equal leakage areas ($A_b = A_a$) at the shaft top and bottom? The inside temperature is 72°F (22°C), and the outside temperature is 0°F (-18°C).

From equation (3.42), the neutral is located 46.4 ft (14.1 m) above the bottom area. This is only a little less than example 3.8 with the continuous opening [48.8 ft (14.9 m)].

Example 3.16 Location of neutral plane for shaft with two unequal openings

What is the location of the neutral plane in a 100 ft (30.5 m) tall shaft with a 4 ft^2 (.37 m^2) opening at the top and a 1 ft^2 (.093 m^2) opening at the bottom? The inside temperature is 72°F (22°C), and the outside temperature is 0°F (-18°C).

From equation (3.42), the neutral is located 93.3 ft (28.4 m) above the bottom area. This illustrates the extent to which non-uniform leakage areas can cause the neutral plane to be far from the building mid-height.

3.3.3 Vented Shaft

The flow and pressures of normal stack effect for a shaft connected to the outside by a vent and a continuous opening are shown in figure 3.19. The following analysis is for a vent above the neutral plane, but a similar one can be made for a vent below the neutral plane. This analysis is an extension of one by McGuire and Tamura (1975) for a top vented shaft. The mass flow into the shaft is expressed by equation (3.37). For simplicity of analysis, the

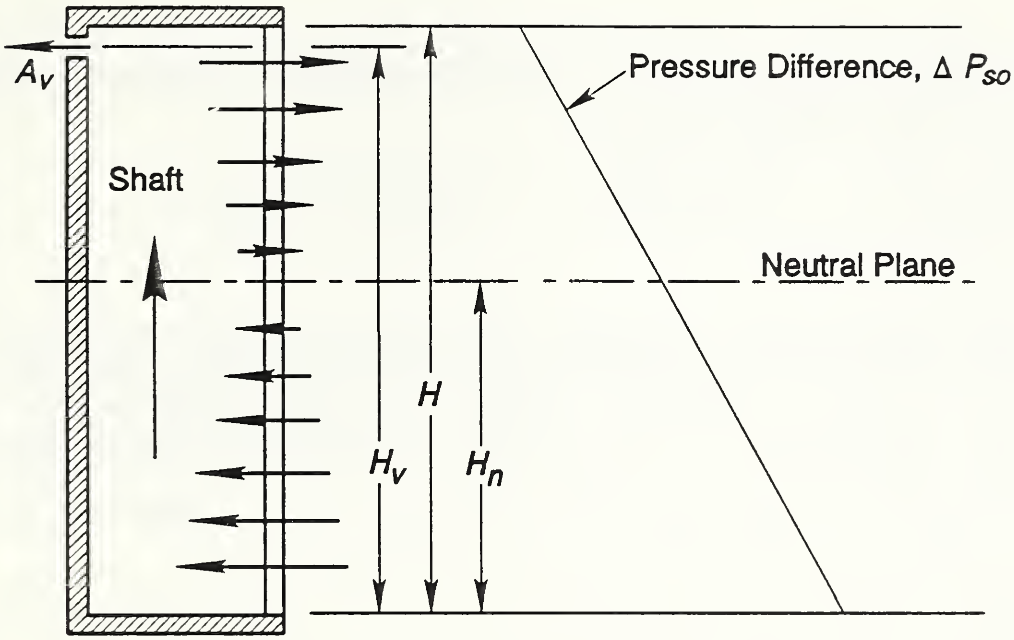


Figure 3.19 Normal stack effect between a single shaft connected to the outside by a vent and a continuous opening

height of the vent is considered small in comparison to the shaft height, H. Thus, a constant pressure difference can be used to describe the flow through the vent. The mass flow out of the shaft is the sum of the flow out of the continuous opening, expressed as equation (3.38), plus the flow out of the vent of area A_v located at an elevation of H_v above the shaft bottom.

$$\dot{m}_{out} = \frac{2}{3} C A' (H - H_n)^{3/2} \sqrt{2 \rho_s b} + C A_v \sqrt{2 \rho_s b (H_v - H_n)} \quad (3.43)$$

Continuity of mass equation for the shaft can be written as

$$\frac{2}{3} C A' (H - H_n)^{3/2} \sqrt{2 \rho_s b} + C A_v \sqrt{2 \rho_s b (H_v - H_n)} = \frac{2}{3} C A' H_n^{3/2} \sqrt{2 \rho_o b} \quad (3.44)$$

Cancelling like terms and incorporating equation (3.21) results in

$$\frac{2}{3} A' (H - H_n)^{3/2} + A_v (H_v - H_n)^{1/2} = \frac{2}{3} A' H_n^{3/2} (T_s/T_o)^{1/2} \quad (3.45)$$

As would be expected, this equation reduces to equation (3.39) for $A_v = 0$. Equation (3.46) can be rearranged as

$$\frac{2 A' H (H - H_n)^{3/2}}{3 A_v H} + \frac{(Hv - H_n)^{1/2}}{H} - \frac{2 A' H H_n^{3/2} T_s^{1/2}}{3 A_v H T_o^{1/2}} = 0 \qquad (3.46)$$

For relatively large vents, the ratio $A'H/A_v$ approaches zero. As $A'H/A_v$ approaches zero, the first and third terms in the above equation approach zero, and the equation is reduced to $H_n = H_v$. Thus the neutral plane is at or near the vent elevation, for a vent area very much greater than the area of the continuous opening (A'H). As with equation (3.42), the above equation is a strong function of the flow areas and a weak function of temperature.

Regardless of whether the vent is above or below the neutral plane, the neutral plane will be located between the height described by equation (3.39) for an unvented shaft and the vent elevation, H_v. Further, the smaller the value of $A'H/A_v$, the closer the neutral plane will be to H_v.

3.4 ANALYSIS OF SMOKE FLOW TO UPPER FLOORS

This section presents a simple method of analysis of smoke flow to the upper floors of buildings with the intent of providing insight into some circumstances when smoke control would be appropriate. This analysis is unique in that it leads to an analytic expression for the concentration of a pollutant on an upper floor of the building.

The mass flow rate is considered steady, even though the concentration of pollutants changes. The location of the neutral plane can be evaluated by the methods previously discussed. This analysis is for floors above the neutral plane and for outside temperatures less than shaft temperatures ($T_a < T_{sh}$ where subscripts a and sh are for outside and shaft).

Because there is no leakage through the floors, the mass flow rate from the stairwell to any floor equals that from the floor to the outside. This mass flow rate can be expressed as

$$\dot{m} = C K A_e \sqrt{2 \rho_{sh} \Delta p} \qquad (3.47)$$

where:

$\dot{m}$ = mass flow rate, lbm/s (kg/s)
C = flow coefficient, dimensionless (approximately 0.65)
A_e = effective flow area between the stairwell to the outside, ft^2 (m^2)
ρ_{sh} = density of gas in shaft, lbm/ft^3 (kg/m^3)
Δp = pressure difference from the stairwell to the outside, in H_2O (Pa)
K = coefficient, 12.9 (1.0)

Equation (3.23) is for the effective flow area of two paths in series where the fluid in both paths is at the same temperature. The analysis can be extended for different temperatures as

$$A_e = \left(\frac{1}{A_{sh}^2} + \frac{T_{fl}}{T_{sh}} \frac{1}{A_a^2} \right)^{-1/2} \tag{3.48}$$

where:

A_e = effective flow area between the stairwell to the outside, ft² (m²)
A_{sh} = area between shaft and building, ft² (m²)
A_a = area between building and outside, ft² (m²)
T_{fl} = gas temperature at floor, °R (K)
T_{sh} = gas temperature in shaft, °R (K)

The pressure difference is expressed by the stack effect equation

$$\Delta p = K_s \left(\frac{1}{T_a} - \frac{1}{T_{sh}} \right) z \tag{3.49}$$

where:

T_a = temperature of outside air, °R (K)
T_{sh} = gas temperature in shaft, °R (K)
z = distance above neutral plane, ft (m)
K_s = coefficient, 7.64 (3460)

The conservation of mass equation for the pollutant on a floor above the neutral plane is

$$\frac{dc_{fl}}{dt} = \frac{\dot{m}}{V_{fl}\ \rho_{fl}} (c_{sh} - c_{fl}) \tag{3.50}$$

where c_{fl} and c_{sh} are the concentrations of the pollutant in the stairwell and on the floor. The solution to this differential equation is

$$c_{fl} = c_{sh}(1 - e^{-\lambda t}) \tag{3.51}$$

where:
c_{fl} = concentration of contaminant on floor above neutral plane
c_{sh} = concentration of contaminant in shaft
t = time, sec (s)

$$\lambda = \frac{\dot{m}}{V_{fl}\ \rho_{fl}}, \ \text{sec}^{-1}\ (\text{s}^{-1}) \tag{3.52}$$

$\dot{m}$ = mass flow rate, lbm/s (kg/s)
V_{fl} = volume of floor, ft³ (m³)
ρ_{fl} = density of gas on floor, lbm/ft³ (kg/m³)

The concentrations, c_{fl} and c_{sh}, can be expressed in any desired units provided that both terms are in the same units. The above equations can be used to estimate the concentrations of toxic gases on any floor above the neutral plane.

Chapter 2 discussed tenability limits for temperature, smoke obscuration, oxygen depletion and numerous toxic gases. On floors far removed from the fire, the hazards due to temperature are believed to be insignificant. A complex analysis could be made including smoke obscuration and many gases. However, the first order model above does not seem to warrant such an exhaustive tenability analysis. In order to obtain a rough idea of the extent to which smoke spread is a concern in a high rise building, only the hazard due to CO is considered. However, this should not be taken to mean that other toxic gases, O_2 depletion or smoke obscuration might not have a significant effect. Equation (2.32) can be written for CO only as

$$FED = \sum \frac{\Delta t\ (\bar{C}_{CO} - 1700)}{80,000} \tag{3.53}$$

where:
$\bar{C}_{co}$ = average concentration of CO over the time interval Δt, ppm
Δt = time interval, min

Example 3.17 CO levels above the neutral plane

If the concentration of CO in a shaft is 1%, calculate the concentrations on a floor above the neutral plane for the following parameters: temperature of outside air, $T_a = 0°F$ (-18°C); temperature of air in shaft, $T_{sh} = 200°F$ (93°C); temperature of air on floor, $T_{fl} = 70°F$ (21°C); leakage area between shaft and building, $A_{sh} = 2\ ft^2$ (0.186 m^2); leakage area between building and outside, $A_a = 3\ ft^2$ (0.279 m^2); volume on floor, $V_{fl} = 20000\ ft^3$ (566 m^3); and height above neutral plane, Z = 60 ft (18.3 m).

Calculate density from the ideal gas law: $\rho_{sh} = P/RT_{sh}$ and $\rho_{fl} = P/RT_{fl}$ where P is atmospheric pressure of 2116 lbf/ft^2 (101,325 Pa), R is the gas constant at 53.34 lbf ft/lbm°R (287.0 J/kg K). The temperatures are: $T_{sh} = 200+460 = 660°R$ (367 K) and $T_{fl} = 70+460 = 530°R$ (294 K). The densities are $\rho_{sh} = 0.0602\ lbm/ft^3$ (0.964 kg/m^3) and $\rho_{fl} = 0.075\ lbm/ft^3$ (1.20 kg/m^3).

From Equation	Term	Value
(3.48)	A_e	1.72 ft^2 (0.160 m^2)
(3.49)	ΔP	0.30 in H_2O (75 Pa)
(3.47)	$\dot{m}$	2.75 lbm/sec (1.25 kg/s)
(3.52)	λ	0.00183 sec^{-1}

Values of C_{CO} and FED are calculated from equations (3.51) and (3.54), and they are tabulated below.

Time (min)	C_{CO} (ppm)	$\overline{C}_{CO}$ (ppm)	FED
0	0	0	0.0000
2	1974	987	0.0000
4	3559	2767	0.0267
6	4830	4195	0.0890
8	5851	5341	0.1800
10	6670	6261	0.2941
12	7328	6999	0.4265
14	7855	7591	0.5738
16	8279	8067	0.7330
18	8618	8449	0.9017
20	8891	8755	1.0781

At about 19 minutes, the value of FED is 1. For this example, the time of death is estimated at about 19 minutes. Other shaft concentrations of CO have a significant effect on the estimated time to death as illustrated in figure 3.20.

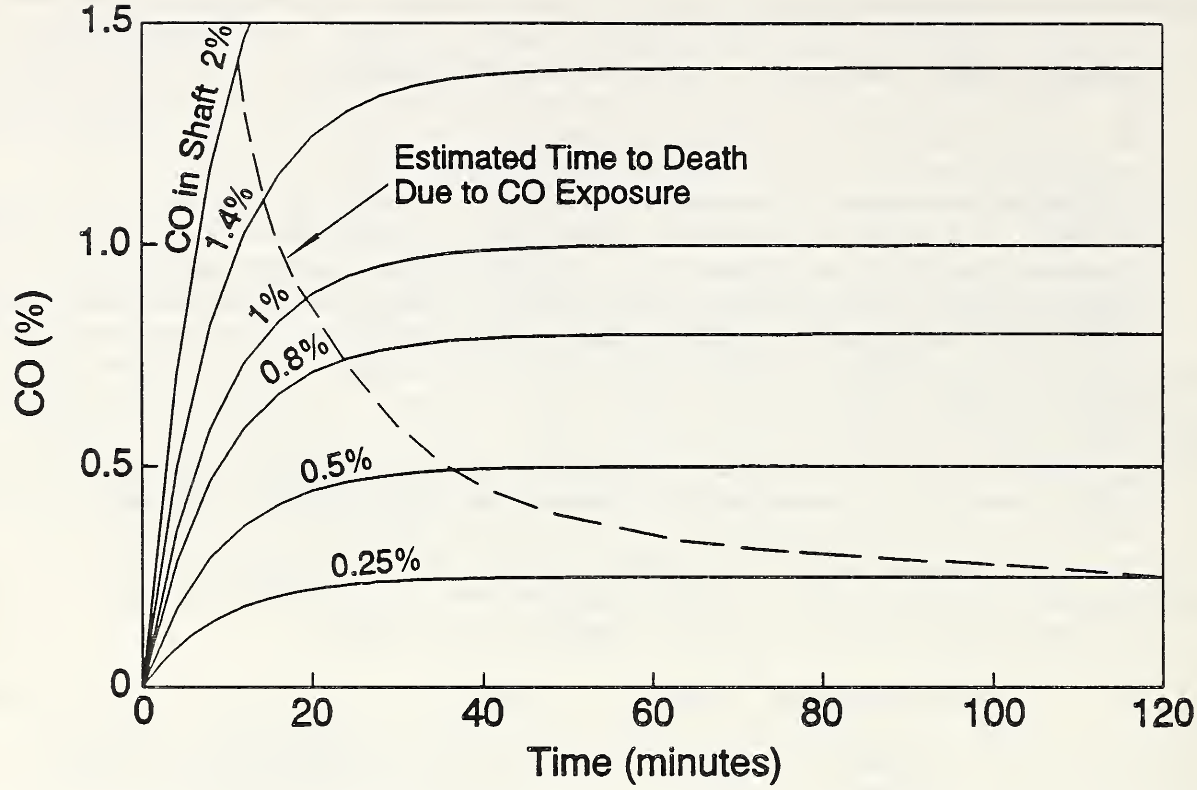


Figure 3.20 Calculated CO concentrations and times to death [See example 3.11]

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Chapter 4. PRINCIPLES AND ANALYSIS APPROACH

4.1 SMOKE MANAGEMENT

The term "smoke management", as used in this manual, includes all methods that can be used singly or in combination to modify smoke movement for the benefit of occupants or firefighters or for the reduction of property damage. The use of barriers, smoke vents, and smoke shafts are traditional methods of smoke management. The effectiveness of barriers are limited to the extent to which they are free of leakage paths. Smoke vents and smoke shafts are limited to the extent that smoke must be sufficiently buoyant to overcome any other driving forces that could be present. In the last few decades, fans have been employed with the intent of overcoming the limitations of traditional approaches. The mechanisms of compartmentation, dilution, air flow, pressurization, and buoyancy are used by themselves or in combination to manage smoke conditions in fire situations. These mechanisms are discussed in the sections below.

4.1.1 Compartmentation

Barriers with sufficient fire endurance to remain effective throughout a fire exposure have a long history of providing protection against fire spread. In such fire compartmentation, the walls, partitions, floors, doors, and other barriers provide some level of smoke protection to spaces remote from the fire. This section discusses the use of passive compartmentation, while the use of compartmentation in conjunction with pressurization is discussed later. Many codes, such as the NFPA 101 "Code for Safety to Life from Fire in Buildings and Structures", provide specific criteria for the construction of smoke barriers including doors and smoke dampers in these barriers. The extent to which smoke leaks through such barriers depends on the size and shape of the leakage paths in the barriers and the pressure difference across the paths.

There is no formalized analytical method for determining the rate of smoke leakage through barriers and the resulting levels of hazard in areas to be protected. There are emerging fire and smoke transport models that can address the smoke leakage through barriers. Recent advances in evaluating smoke leakage through small gaps and construction cracks are addressed later in this chapter. A first order approximation of the leakage can be made using the equation for flow through an opening, typical leakage areas (discussed later), estimates of the dimensions of paths such as gaps around doors, and the procedures for estimating effective flow areas. More accurate calculations await better data and improved calculation procedures. Full appraisal of the impact of such leakage requires knowledge of the smoke toxicity or an assumed design value of acceptable smoke concentration in protected spaces. A formalized approach to smoke compartmentation should include development of appropriate methods of acceptance testing and routine testing. Efforts are needed to advance understanding of the passive capabilities of barriers from the present uncalculated heuristic approach to a sufficient understanding to take proper advantage of this oldest and most fundamental method of smoke management.

4.1.2 Dilution Remote From a Fire

Dilution of smoke is sometimes referred to as smoke purging, smoke removal, smoke exhaust, or smoke extraction. Dilution can be used to maintain acceptable gas and particulate concentrations in a compartment subject to smoke infiltration from an adjacent space. This can be effective if the rate of smoke leakage is small compared to either the total volume of the safeguarded space or the rate of purging air supplied to and removed from the space. Also, dilution can be beneficial to the fire service for removing smoke after a fire has been extinguished. Sometimes, when doors are opened, smoke will flow into areas intended to be protected. Ideally, such occurrences of open doors will only happen for short periods of time during evacuation. Smoke that has entered spaces remote from the fire can be purged by supplying outside air to dilute the smoke.

The following is a simple analysis of smoke dilution for spaces in which there is no fire. At time zero ($t = 0$), a compartment is contaminated with some concentration of smoke and no further smoke flows into the compartment or is generated within it. Also, the contaminant is considered uniformly distributed throughout the space. The concentration of contaminant in the space can be expressed as:

$$\frac{C}{C_o} = e^{-at} \qquad (4.1)$$

This equation can be solved for the dilution rate and the time.

$$a = \frac{1}{t} \log_e \left(\frac{C_o}{C} \right) \qquad (4.2)$$

$$t = \frac{1}{a} \log_e \left(\frac{C_o}{C} \right) \qquad (4.3)$$

where:

C_o = initial concentration of contaminant
C = concentration of contaminant at time, t
a = dilution rate in number of air changes per minute
t = time after smoke stops entering space or time after which smoke production has stopped, minutes
e = constant approximately 2.718

The concentrations C_o and C must be expressed in the same units, and they can be any units appropriate for the particular contaminant being considered. McGuire, Tamura, and Wilson (1971) evaluated the maximum levels of smoke obscuration from a number of fire tests and a number of proposed criteria for tolerable levels of smoke obscuration. Based on this evaluation, they state that the maximum levels of smoke obscuration are greater by a factor of 100 than those relating to the limit of tolerance. Thus, they indicate that a space can be considered "reasonably safe" with respect to smoke obscuration, if the concentration of contaminants in the space is less than about 1% of the concentration in the immediate fire area. It is obvious that such dilution would also reduce the concentrations of toxic smoke components. Toxicity is a more complicated problem, and no parallel statement has been made regarding dilution needed to obtain a safe atmosphere with respect to toxic gases.

In reality, it is impossible to assure that the concentration of the contaminant is uniform throughout the compartment. Because of buoyancy, it is likely that higher concentrations would tend to be near the ceiling. Therefore, exhausting smoke near the ceiling and supplying air near the floor will probably dilute smoke even faster than indicated by equation (4.1) and (4.2). Caution should be exercised in the location of the supply and exhaust points to prevent the supply air from blowing into the exhaust inlet and thus short circuiting the dilution operation.

Example 4.1 Smoke purging after the fire is extinguished

1. After the fire department puts out a fire, they want to clear the smoke quickly so that they can make an inspection to determine if the fire is completely out. If the HVAC system is capable of a dilution rate of six air changes per hour, how long will it take to reduce to smoke concentration to 1% of the initial value?

The dilution rate, a, is 0.1 changes per minute, and C_o/C is 100. From equation (4.3), the time to get the concentration to 1% is 46 minutes. Considering the desire of the fire department to quickly inspect the area, such a long purging time will probably be excessive.

2. If the fire department wants the space to be purged in 10 minutes, what dilution rate is needed?

The time, t, is 10 minutes, and C_o/C is 100. From equation (4.2), the dilution rate is .46 changes per minute or about 28 changes per hour.

Example 4.2 Smoke dilution in a space remote from the fire

A space is isolated from a fire by smoke barriers and self closing doors, so that no smoke enters the compartment when the doors are closed. However, when a door is opened, smoke flows through the open doorway into the space. If the door is closed when the contaminate in the space is 20% of the burn room, what dilution rate is required so that six minutes later the concentration will be 1% of the burn room.

The time, t, is six minutes, and C_o/C is 20. From equation (4.2), the dilution rate is about .5 changes per minute or 30 air changes per hour.

4.1.3 Caution About Dilution Near a Fire

Many people have unrealistic expectations about what dilution can accomplish in the fire space. There is no theoretical or experimental evidence that using a building's heating, ventilation or air conditioning (HVAC) system for smoke dilution will result in any significant improvement in tenable conditions within the fire space. It is well known that 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 fire space will not result in any practical improvement in the tenable conditions in that space. Thus it is recommended that smoke purging systems intended to improve hazard conditions within the fire space or in spaces connected to the fire space by large openings not be used.

4.1.4 Pressurization

Systems using pressurization produced by mechanical fans is referred to as smoke control in this manual and in NFPA 92A (1988a). A pressure difference across a barrier can control smoke movement as illustrated in figure 4.1. Within the barrier is a door. The high pressure side of the door can be either a refuge area or an egress route. The low pressure side is exposed to smoke from a fire. Airflow through the gaps around the door and through construction cracks prevents smoke infiltration to the high pressure side. When the door in the barrier is opened, airflow through the open door results. When the air velocity is low, smoke can flow against the airflow into the refuge area or egress route, as shown in figure 4.2. This smoke backflow can be prevented if the air velocity is sufficiently large, as shown in figure 4.3. The magnitude of velocity necessary to prevent backflow depends on the energy release rate of the fire, as discussed in the next section.

The two "principles" of smoke control can be stated as follows:

- Air pressure differences across barriers can act to control smoke movement.

- Airflow by itself can control smoke movement if the average air velocity is of sufficient magnitude.

Pressurization results in airflows of high velocity in the small gaps around closed doors and in construction cracks, thereby preventing smoke backflows through these openings. Therefore, in a strict physical sense, the two "principles" are equivalent statements. However, considering the "principles" as separate is advantageous for discussing smoke control design options. For a barrier with one or more large openings, air velocity is the appropriate physical quantity for both design and measurement. However, when there are only small cracks, such as those around closed doors, designing to and measurement of air velocities is impractical. In this case, the appropriate physical quantity is pressure difference. Consideration of the two "principles" as separate has the added advantage that it emphasizes the different considerations that need to be given for opened and closed doors.

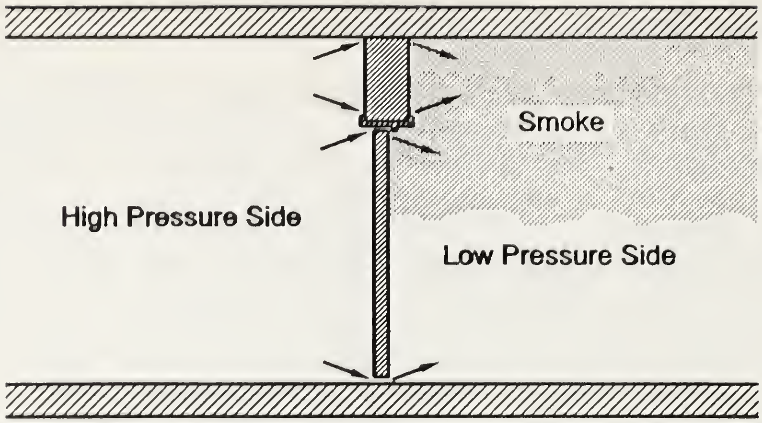

Figure 4.1 Pressure difference across a barrier of a smoke control system preventing smoke infiltration to the high pressure side of the barrier

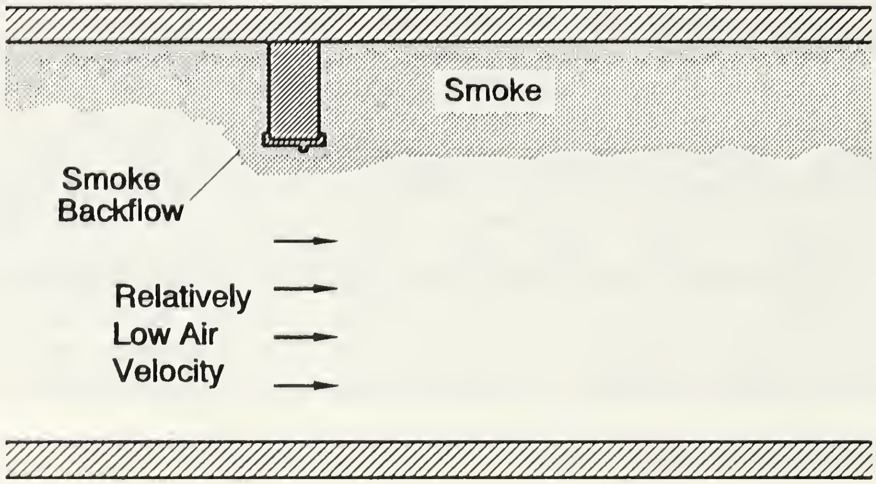

Figure 4.2 Smoke backflow against low air velocity through an open doorway

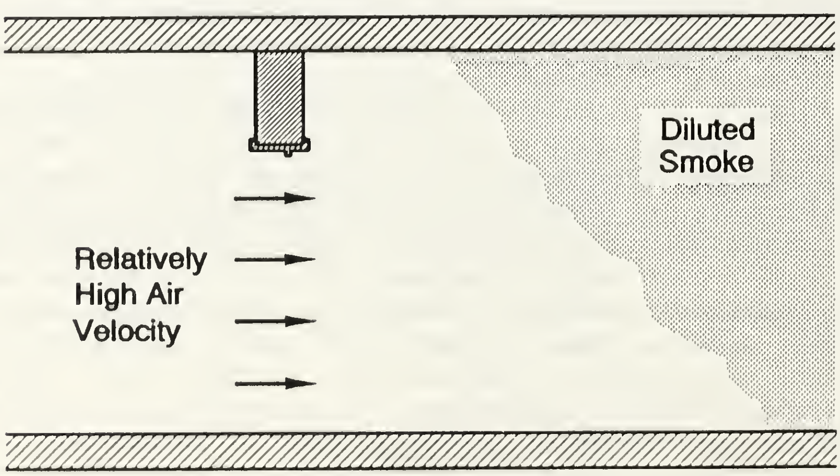

Figure 4.3 No smoke backflow with high air velocity through an open doorway

To assure that expansion pressures are not a problem, pressurization systems should be designed so that a path exists for smoke movement to the outside. This path could be as simple as relying on a top vented elevator shaft, or it can be accomplished by a fan-powered exhaust. It is important that some opening to the outside be provided. The pressurization systems most commonly used are pressurized stairwells and zoned smoke control. Elevator smoke control is less common. Detailed design analysis and general considerations about these pressurization systems are discussed later in this manual.

4.1.5 Airflow

Airflow has been used extensively to manage smoke from fires in subway, railroad and highway tunnels. Large flow rates of air are needed to control smoke flow, and these flow rates can supply additional oxygen to the fire. Because of the need for complex controls, airflow is not used so extensively in buildings. The control problem consists of having very small flows when a door is closed and then having those flows increase significantly when that door opens. Further, it is a major concern that the airflow supplies oxygen to the fire. This section presents the basics of smoke control by airflow which demonstrate why this technique is not recommended, except when the fire is suppressed or in the rare cases when fuel can be restricted with confidence.

Thomas (1970) determined that airflow in a corridor in which there is a fire can almost totally prevent smoke from flowing upstream of the fire. As illustrated in figure 4.4, the smoke forms a surface sloped into the direction of the oncoming airflow. Molecular diffusion is believed to result in transfer of trace amounts of smoke producing no hazard but just the smell of smoke upstream. There is a minimum velocity below which smoke will flow upstream, and Thomas developed the following empirical relation for this critical velocity:

$$V_k = K \left(\frac{gE}{W \rho c T} \right)^{1/3} \tag{4.4}$$

where:

V_k = critical air velocity to prevent smoke backflow
E = energy release rate into corridor
W = corridor width
ρ = density of upstream air
c = specific heat of downstream gases
T = absolute temperature of downstream gases
K = constant on the order of 1
g = acceleration of gravity

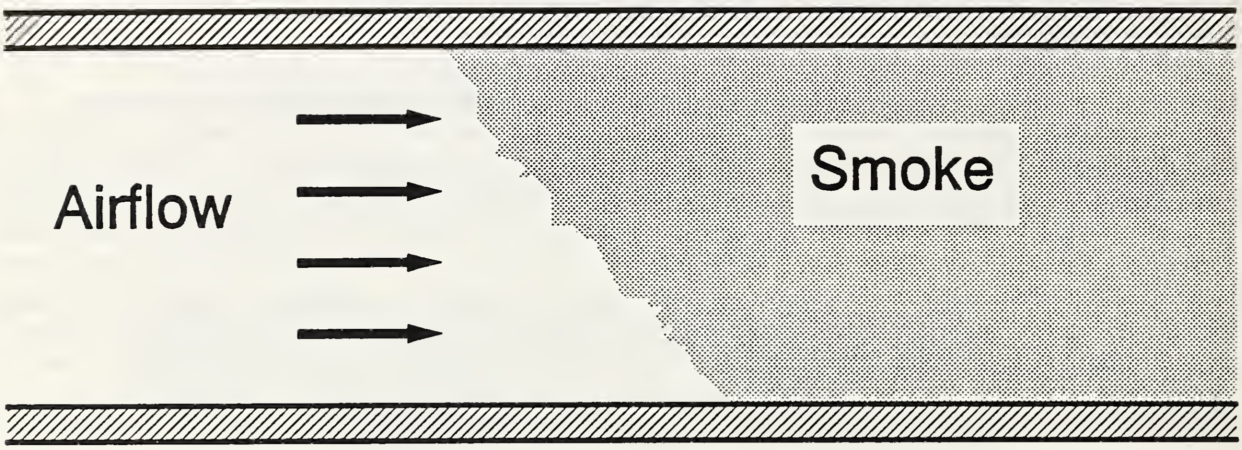

Figure 4.4 Airflow preventing smoke backflow in corridor

The downstream properties are considered to be sufficiently far downstream of the fire for the properties to be uniform across the section. The critical air velocity can be evaluated at $\rho = 0.081$ lb/ft^3 (1.3 kg/m^3), c = 0.24 Btu/lb °F (1.005 kJ/kg °C), T = 81 °F (27 °C), and K = 1.

$$V_k = K_v \left(\frac{E}{W} \right)^{1/3} \qquad (4.4a)$$

where:

V_k = critical air velocity to prevent smoke backflow, fpm (m/s)
E = energy release rate into corridor, Btu/hr (W)
W = corridor width, ft (m)
K_v = coefficient, 5.68 (0.0292)

This relation can be used when the fire is located in the corridor or when the smoke enters the corridor through an open doorway, air transfer grille, or other opening. The critical velocities calculated form equations (4.4) and (4.4a) are approximate because an approximate value of K was used. However, the critical velocities from this relation are indicative of the kind of air velocities required to prevent smoke backflow from fires of different sizes. Equation (4.4a) can be evaluated from figure 4.5. Examples 4.3 and 4.4 illustrate the flows needed for different fires.

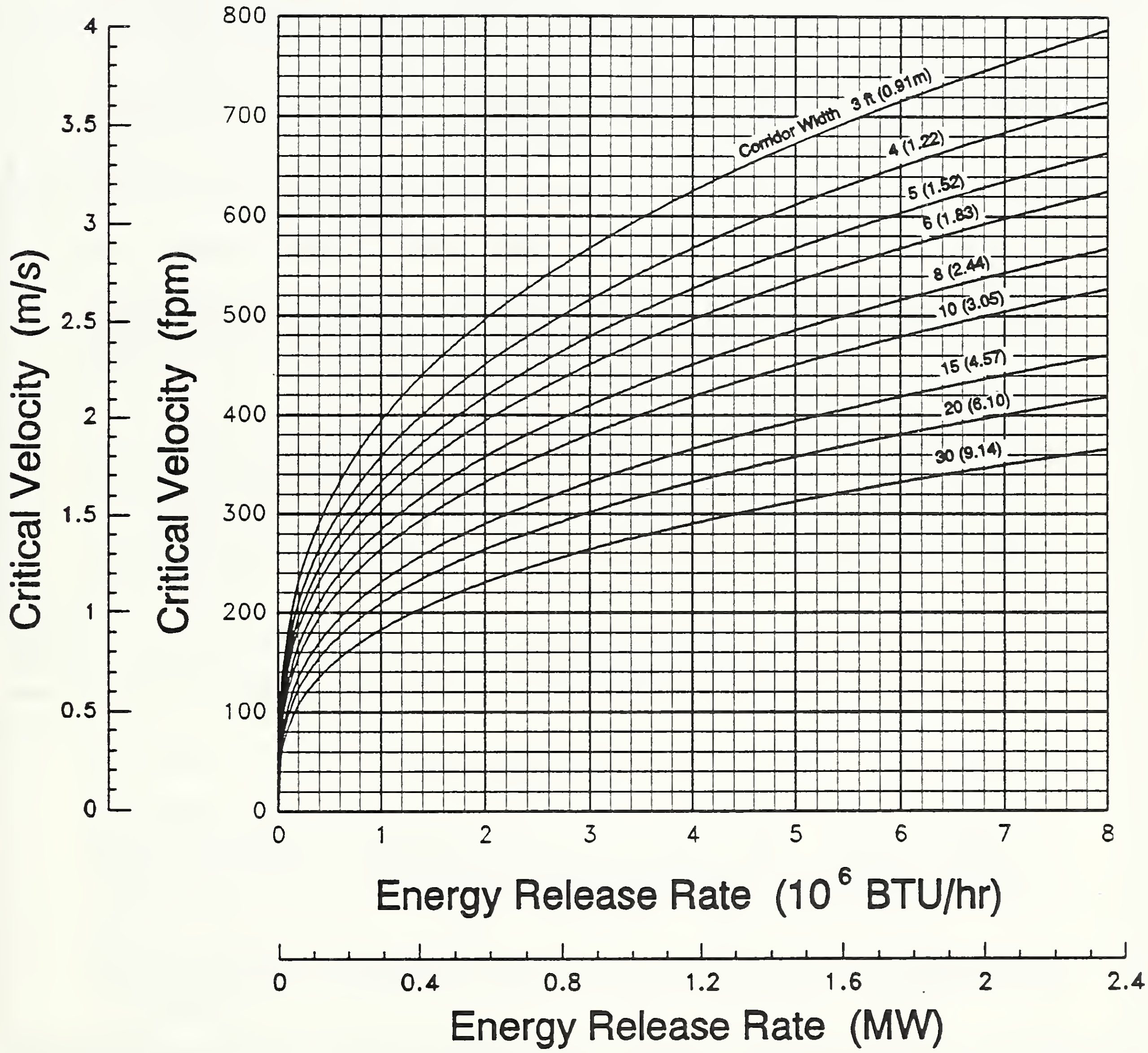

Figure 4.5 Critical velocity to prevent smoke backflow in a corridor

The equation of Thomas can be used to estimate the air flow rate necessary to prevent smoke backflow through an open door in a boundary of a smoke control system. However, the oxygen supplied is a concern. Huggett (1980) evaluated the oxygen consumed for combustion of numerous natural and synthetic solids. He found that for most materials that are involved in building fires, the energy released per unit of mass of oxygen consumed is approximately 5630 Btu/lb (13.1×10^6 J/kg). Air is 23.3% oxygen by weight. Thus if all the oxygen in a pound of air is consumed, 1300 Btu of heat is liberated. Stated in the SI system: if all the oxygen in a kg of air is consumed, 3.0 MJ of heat is liberated. As can be seen from example 4.3, the air needed to prevent smoke backflow can support an extremely large fire. In most locations of commercial and residential buildings, sufficient fuel (paper, cardboard, furniture, etc.) is present to support very large fires. Even when the amount of fuel is normally very small, short term fuel loads (during building renovation, material delivery, etc.) can be significant. Therefore, the use of airflow for smoke control is not recommended, except when the fire is suppressed or in the rare cases when fuel can be restricted with confidence.

Example 4.3 Airflow to prevent smoke backflow from a small fire

An energy release rate of 0.5×10^6 Btu/hr (150 kW) can be thought of as the size of a large wastebasket fire. What flow rate of air is needed to prevent smoke backflow from such a fire in a corridor 4 ft (1.22 m) wide and 9 ft (2.74 m) high?

From equation (4.4a) or figure 4.5, the critical velocity is 286 fpm (1.45 m/s). The cross-sectional area of the corridor is 4 x 9 = 36 ft^2 (1.22 x 2.74 = 3.34 m^2). The flow rate is the cross sectional area times the velocity which is about 10,000 cfm (4.7 m^3/s).

Example 4.4 Airflow to prevent smoke backflow from a large fire

An energy release rate of 5.1×10^6 Btu/hr (1.5 MW) would result in a large portion of the corridor being completely involved in fire. What flow rate of air is needed to prevent smoke backflow from such a fire in the corridor of example 4.3?

From equation (4.4a) or figure 4.5, the critical velocity is 616 fpm (3.13 m/s). The flow rate is about 22,000 cfm (10.4 m^3/s).

Example 4.5 Airflow through a doorway and fire growth

1. Thomas indicated that his relation for critical velocity can be used to obtain a rough estimate for doorways. A room fully involved in fire could have an energy release rate on the order of $8x10^6$ Btu/hr (2.4 MW). What estimate of critical velocity is obtained from the Thomas equation for a door 3 ft (0.9 m) wide?

From equation (4.4a) or figure 4.5, the critical velocity is about 800 fpm (4 m/s). If the door has an of area 20 ft^2 (1.9 m^2), this would amount to a flow of 16000 cfm (7.6 m^3/s).

2. Consideration of a smaller fire such as the wastebasket fire of example 4.5 may be appropriate for many situations. What flow rate does the Thomas relation indicate is needed to prevent backflow for the above door?

$$E = 0.5x10^6 \text{ Btu/hr (150 kW)}, \quad W = 3 \text{ ft (0.9 m)}$$

From equation (4.4a) or figure 4.5, the critical velocity of about 300 fpm (1.5 m/s). For a door area of 20 ft^2 (1.9 m^2), this would amount to a flow of 6000 cfm (2.8 m^3/s).

3. What size fires can the airflows above support? Consider that all of the oxygen in the air is consumed, and that the air density is 0.075 lb/ft^3 (1.2 kg/m^3).

Approximately 1300 Btu of energy is released when the oxygen in a pound of air is consumed. 16,000 cfm can support the following size fire:

$$\left(16000\ \frac{ft^3}{min}\right)\left(0.075\ \frac{lb\ air}{ft^3}\right)\left(\frac{60\ min}{hr}\right)\left(\frac{1300\ Btu}{lb\ air}\right) =$$

$$94x10^6 \text{ Btu/hr (28 MW)}$$

For 6000 cfm, the energy release rate would be $35x10^6$ (10 MW). These fires are very large. Airflow intended to prevent smoke backflow can cause a fire to grow significantly if there is sufficient material to burn. Therefore, the use of airflow for smoke control is not recommended, except when the fire is suppressed or in the rare cases when fuel can be restricted with confidence.

4.1.6 Buoyancy

Buoyancy of hot combustion gases is employed in both fan-powered and non-powered venting systems. Such fan-powered venting for large spaces is commonly employed for atriums and covered shopping malls. Another concern is that the sprinkler flow will cool the smoke reducing buoyancy and thus system effectiveness. There is no question that sprinkler flow does cool smoke, but it is unknown as to what extent that cooling reduces effectiveness of fan-powered venting. Further research is needed in this area. However, the existing information can be used to develop new design information for fan-powered venting systems. NFPA 92B (1991) provides methods of design analysis for smoke management systems in large spaces such as atriums and shopping malls.

4.2 AIRFLOW AND PRESSURE DIFFERENCE

For a crack, gap or other opening with a pressure difference across it, a flow will result from the higher pressure to the lower pressure. Many different equations have been used to express the relation between fluid flow rate and pressure difference with regard to air and smoke flow in buildings. This section contains a discussion of some of the more common equations, as well as, a detailed discussion of flows through the gaps around doors. The flow through a crack or other opening can be represented by a general function:

$$Q = f(\Delta P) \qquad (4.5)$$

where:

Q = volumetric flow rate through the path
ΔP = pressure difference across path
f = general functional relation

The particular from of the function f depends on the geometry of the opening and Reynolds number. The Reynolds number is:

$$R_e = \frac{D_h \ V}{\nu} \qquad (4.6)$$

where:

R_e = Reynolds number, dimensionless
D_h = hydraulic diameter of flow path
V = average velocity in flow path
ν = kinematic viscosity

For commonly used English units, this equation can be expressed as

$$R_e = \frac{1.389 \times 10^{-3} \ D_h \ V}{\nu} \qquad (4.6a)$$

where:

R_e = Reynolds number, dimensionless
D_h = hydraulic diameter of flow path, in
V = average velocity in flow path, ft/min
ν = kinematic viscosity, ft^2/sec

Values of kinematic viscosity are listed in Appendix A tables A10 and A11. The hydraulic diameter is four times the cross-sectional area of the path divided by the "wetted perimeter" of the path. For example, the hydraulic diameter of a circle is the diameter of the circle, and the hydraulic diameter of a square is the side of the square. For the long rectangular gaps around doors, the hydraulic diameter is the gap thickness ($D_h = a$, where a is the gap thickness). The Reynolds number is usually thought of a the ratio of kinetic forces to viscous forces. Later sections discuss different approaches that apply for flow dominated by viscous forces, kinetic forces, or both.

The pressure difference above can be expressed as

$$\Delta P = P_i - P_o + \rho g(Z_i - Z_o) \tag{4.7}$$

where:

P_i = pressure at path inlet
P_o = pressure at path outlet
ρ = density gas in path
Z_i = elevation of the path inlet
Z_o = elevation of the path outlet
g = acceleration of gravity

Equations (4.5) and (4.7) are for constant density in the flow path, and for flows where the values of the inlet pressure, outlet pressure, inlet elevation, and outlet elevation are all constants. This representation is not appropriate for inlet and outlet pressures that vary considerably with the elevation as is often the case for flows of hot fire gases. However, for smoke control design, analysis of flows is limited to normal building and outside temperatures. Thus, this representation is appropriate for smoke control analysis, as well as, general considerations of air flow in buildings.

4.2.1 Flow Dominated by Dynamic Forces

For large Reynolds numbers, flow is directly proportional to the square root of the pressure difference across the path:

$$Q = K_o CA \sqrt{\frac{2\,\Delta P}{\rho}} \tag{4.8}$$

where:

Q = volumetric flow rate through the path, cfm (m^3/s)
C = dimensionless flow coefficient
A = flow area (also called leakage area), ft^2 (m^2)
ΔP = pressure difference across path, in H_2O (Pa)
ρ = density gas in path, lb/ft^3 (kg/m^3)
K_o = coefficient, 776. (1.00)

The flow area can differ from the cross sectional area of the path as is discussed later in this chapter. Dynamic forces dominate flow with Reynolds numbers greater than about 2000 or 4000 depending on path geometry. At these large Reynolds numbers, the flow becomes turbulent. For turbulent flow the velocity at a given point fluctuates rapidly in an apparent random manner.

Equation (4.8) has been applied so extensively to orifice flow meters that it is sometimes referred to as the "orifice" equation. However, this equation is also commonly used for analysis of air flow in buildings and for analysis of smoke control systems. Further, this equation is the flow equation used in the computer program for analysis of smoke control system (ASCOS) which is discussed later. Because equation (4.8) is based on Bernoulli's equation, it strictly applies to steady, frictionless, incompressible flows. However, the flow coefficient was introduced to account for friction losses due to viscosity and for dynamic losses. The flow coefficient depends on the Reynolds number and the geometry of the flow path. In the context of flows through gaps around doors and through construction cracks, the coefficient is generally in the range of 0.6 to 0.7. For standard air density of $\rho = 0.075$ lb/ft^3 (1.20 kg/m^3) and for C = 0.65, the flow equation above can be expressed as:

$$Q = K_f A \sqrt{\Delta P} \qquad (4.8a)$$

where:

Q = volumetric flow rate through the path, scfm (sm^3/s)
A = flow area (also called leakage area), ft^2 (m^2)
ΔP = pressure difference across path, in H_2O (Pa)
K_f = coefficient, 2610 (0.839)

Equation (4.8a) gives flow at standard temperature of 70°F (21°C) and standard atmospheric pressure of 14.7 psi (101 kPa). Frequently, volumetric flows are adjusted to standard volumetric flow rates. The mass flow rate is divided by the standard density to obtain the standard volumetric flow rate. This is convenient, because it allows engineers to think in terms of the familiar volumetric flow rates. Further, these standard flows can be treated as mass flows rates, because they only deviate from mass flow rates by a constant.

Equations (4.8) and (4.8a) are extensively used for analysis of smoke control systems in this manual. For normally constructed buildings, these equations are recommended for all smoke control calculations. By a normally constructed building it is meant one that has at least tight wall and floor leakage and that does not have gasketed or sealed interior doors. Tight leakage of walls and floors is discussed in the section on flow areas. The rest of the flow equations presented in this section are included for the unusual cases of very tight construction.

Example 4.6 Flow calculated by the "orifice" equation

1. Calculate the volumetric flow through a path by the orifice equation for the following values:

$A = 1\ ft^2\ (0.0929\ m^2)$
$C = 0.65$
$\Delta P = 0.05$ in H_2O (12.4 Pa)
$\rho = 0.081\ lb/ft^3\ (1.30\ kg/m^3)$

From equation (4.8), the flow rate is 560 cfm (.26 m^3/s).

2. Calculate the above flow for standard density of 0.075 lb/ft^3 (1.20 kg/m^3).

Using either equations (4.8), (4.8a) or figure 4.6, the flow is 580 cfm.

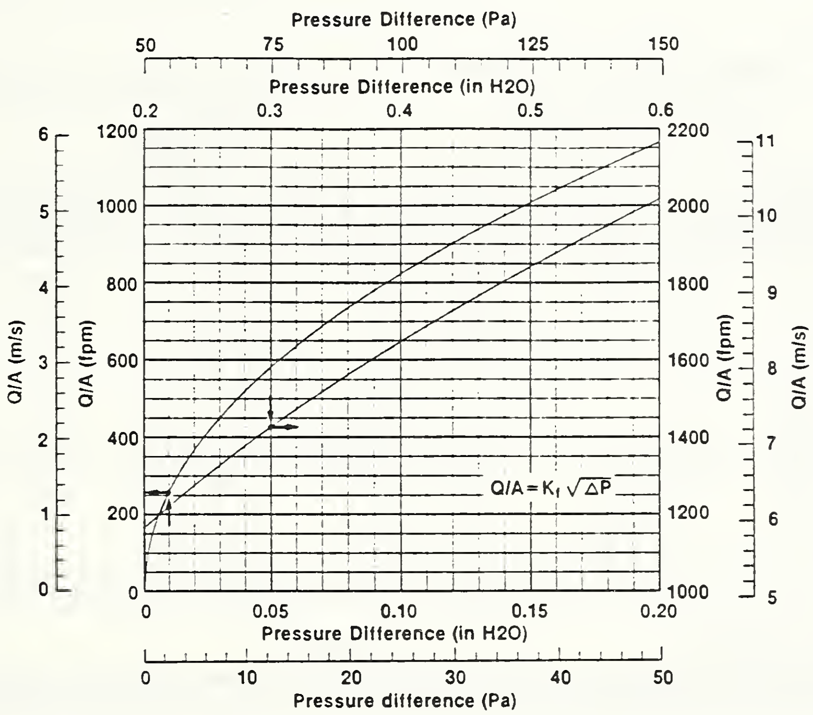

Figure 4.6 Airflow due to pressure difference for standard density [0.075 lb/ft^3 (1.20 kg/m^3)] and for C = 0.65

4.2.2 Flow Dominated by Viscous Forces

For low Reynolds number, flow is directly proportional to the pressure loss. Viscous forces dominate flow with Reynolds numbers below about 100 to 1000 depending on particular path geometry. Plane Poiseuille flow is an exact solution to the Navier-Stokes equations for the flow of a viscous fluid between two parallel and infinitely long plates. The velocity distribution between the plates is parabolic as illustrated in figure 4.7. The fluid velocity varies only in the direction perpendicular to the flow, and this type of flow is referred to as laminar flow. The average velocity, V, for plane Poiseuille flow is proportional to pressure loss (dP/dx).

$$V = - \frac{a^2}{12\,\mu} \frac{dP}{dx} \qquad (4.9)$$

where:

a = distance between plates (gap thickness)
μ = absolute viscosity
P = pressure

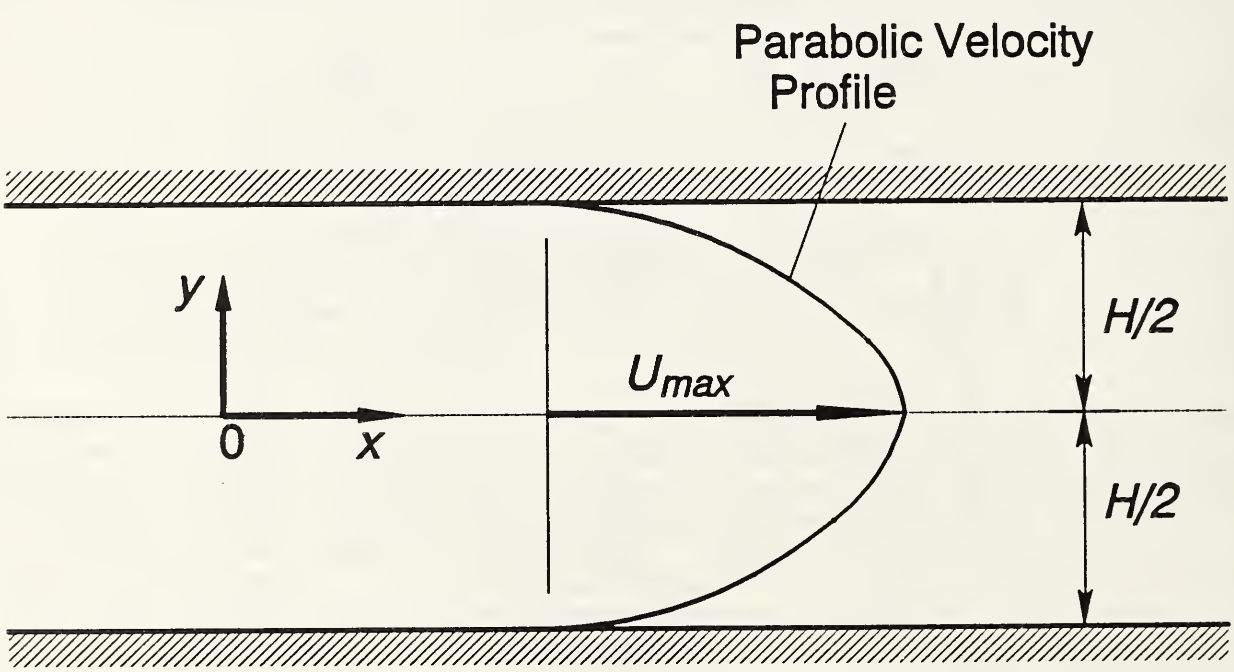

Figure 4.7 Parabolic velocity profile for Poiseuille flow between two parallel plates

Real gaps in buildings are not infinitely long, and some distance is needed for the parabolic flow profile to become established as illustrated in figure 4.8. The pressure losses (dP/dx) over this inlet length are greater than those of fully developed parabolic flow. Further, there are inlet and outlet losses due to flows just outside the gap. These deviations from plane Poiseuille can be significant and are accounted for in methods of analysis presented later.

4.2.3 Exponential Flow Equation

In order to accommodate the flows which are between viscous dominated and kinetic dominated, the following exponential relation has been used extensively in analysis of air flows through buildings.

$$Q = C_e (\Delta P)^n \tag{4.10}$$

where

Q = volumetric flow, cfm (m^3/s)
C_e = flow coefficient for exponential flow equation, $ft^3\ min^{-1}\ (in\ H_2O)^{-n}$ ($m^3\ s^{-1}\ Pa^{-n}$)
ΔP = pressure difference across the path, in H_2O (Pa)
n = flow exponent, dimensionless

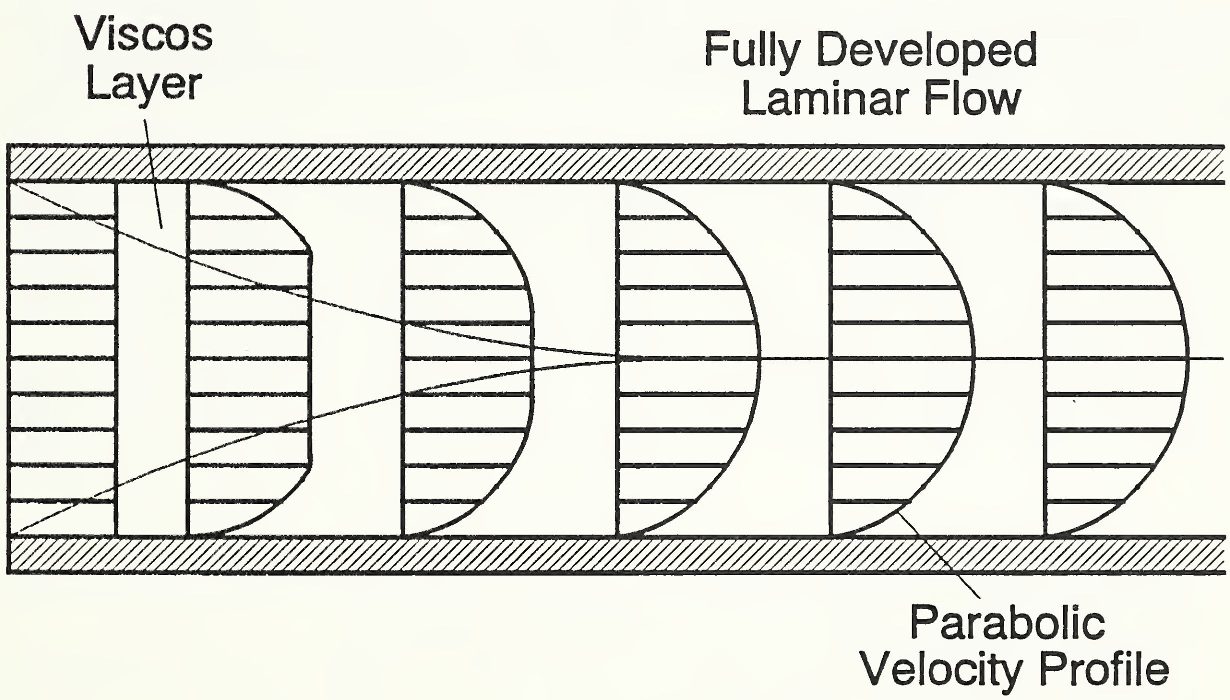

Figure 4.8 Development laminar flow in a gap

As would be expected from the above discussion, the flow exponent, n, varies from 0.5 to 1. Equation (4.10) only approximates the relation between flow and pressure difference, and the values of C_e and n used depends on the range of ΔP. This equation has proven itself useful for evaluation of flows through many small cracks in buildings at low levels of pressure difference. However, this equation is not directly related to the geometry of the flow path as are equations (4.8) and (4.9). The values of C_e for particular flow paths must be determined empirically.

For analysis of building airflow, the exponents of interior paths are generally taken at 1/2, and exponents of exterior walls are considered to be about 0.6 or .65. Considering that the pressure differences of most concern in smoke control design are across interior paths, use of 1/2 for all flow exponents would seem appropriate. The manual by Klote and Fothergill (1983) used equations (4.8) and (4.8a) for all smoke control analysis because it was believed that a value of n = 1/2 was sufficiently accurate for design analysis. Klote and Bodart (1985) reevaluated this use of 1/2 for the all flow exponents. They experimentally determined flow coefficients and exponents for the leakage paths of the French Fire Research Tower using regression analysis. Computer flow simulations with the experimentally determined exponents (n not equal to 1/2) and with all flow exponents at 1/2 were in good agreement. It can be concluded that use of 1/2 for all exponents in normally constructed building yields acceptable results for smoke control design purposes.

4.2.4 Flow Through Gaps

Gross and Haberman (1988) developed a generalized approach to determining the leakage through gaps of different geometry such as those of door assemblies. They developed a functional relationship between the following two nondimensional groups.

$$NQ = R_e \left(\frac{a}{x} \right) \qquad (4.11)$$

and

$$NP = \frac{\Delta P \, D_h^2}{\rho \, \nu^2} \left(\frac{D_h}{x} \right)^2 \qquad (4.12)$$

where:

NQ = dimensionless flow rate
NP = dimensionless pressure difference
R_e = Reynolds number, dimensionless [equation (4.6)]
a = thickness of gap in direction perpendicular to flow
x = depth of gap in flow direction
ΔP = pressure difference across gap
D_h = hydraulic diameter; D_h = 2a
ρ = density of gas in gap
ν = kinematic viscosity

For commonly used English units, equation (4.12) can be expressed as

$$NP = \frac{1.16\ \Delta P\ D_h^{\ 2}}{\rho\ \nu^2} \left(\frac{D_h}{x}\right)^2 \tag{4.12a}$$

where:

x = depth of gap in flow direction, in
ΔP = pressure difference across gap, in H_2O
D_h = hydraulic diameter, in; $D_h = 2a$
ρ = density of gas in gap, lb/ft^3
ν = kinematic viscosity, ft^2/sec

Gross and Haberman used an analytical method of Miller and Han (1971) to account for the pressure losses in the entrance region before fully developed flow is achieved in a straight-through slot. Their relation for flow verses pressure difference is shown in figure 4.9. Three regions of flow through the straight-through slot were identified, and equations for these regions are:

Region 1 (Viscous dominated region - for $NP \leq 250$):
$$NQ = 0.01042\ NP \tag{4.13}$$

Region 2 (Transition region - for $250 < NP < 10^6$):
$$NQ = 0.016984\ NP^{\alpha} \tag{4.14}$$
where $\alpha = 1.01746 - .044181\ Log_{10}(NP)$

Region 3 (Kinetic dominated region - for $NP \geq 10^6$):
$$NQ = 0.555\ NP^{\frac{1}{2}} \tag{4.15}$$

The equations for regions 1 and 3 were developed by Gross and Haberman, and the exponents are as expected considering that region 1 is dominated by viscous forces and region 3 is dominated by kinetic forces. Region 2 is a transition between the other two regions. Gross and Haberman's analysis for region 2 is complicated, and equation (4.14) is an approximation to the Gross and Haberman analysis developed by Forney (1988). Forney's approximation is within 6% of the more complicated analysis. Forney's approximation has the advantage that at the end points it is continuous with the expressions for the other two regions. This is particularly attractive for computer applications. Equations (4.6) and (4.11) can be combined to obtain a relation for volumetric flow rate through a straight-through slot.

$$Q = \frac{K_q\ \nu\ x\ L\ NQ}{D_h} \tag{4.16}$$

where

Q = volumetric flow rate, cfm (m^3/s)
NQ = nondimensional flow
x = depth of gap in flow direction, in (m)
D_h = hydraulic diameter, in (m); D_h = 2a
L = length of gap, ft (m)
ν = kinematic viscosity, ft^2/sec (m^2/s)
K_q = coefficient, 60 (1.00)

Frequently, slots around doors have one or more bends. For single and double bend slots, the nondimensional flow, NP, can be obtained by multiplying values for a straight-through slot by flow factors, F_1 and F_2 (where F_1 is for single bend slots, and F_2 is for a double bend slots). These flow factors are presented in table 4.1 and figure 4.10.

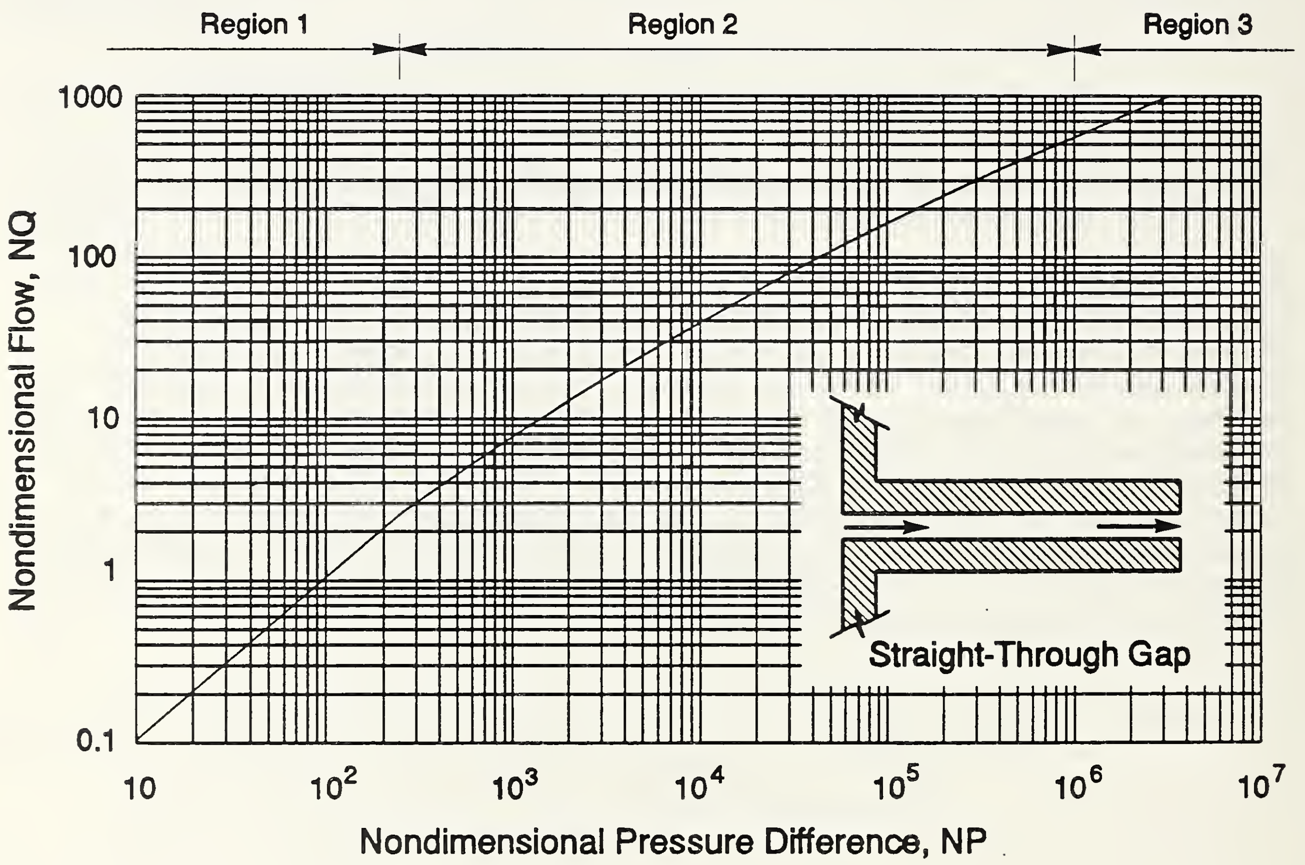

Figure 4.9 Relation between flow and pressure difference for straight-through gap [adapted from Gross and Haberman (1988)]

Table 4.1 Flow factors for single and double bend gaps

Nondimensional Pressure Difference, NP	Flow Factor For Single Bend Slot, F_1	Flow Factor For Double Bend Slot, F_2
Less than or equal to 4000	1.000	1.000
7000	0.981	0.939
10000	0.972	0.908
15000	0.960	0.880
20000	0.952	0.862
40000	0.935	0.826
100000	0.910	0.793
200000	0.890	0.772
400000	0.872	0.742
1000000	0.848	0.720
2000000	0.827	0.700

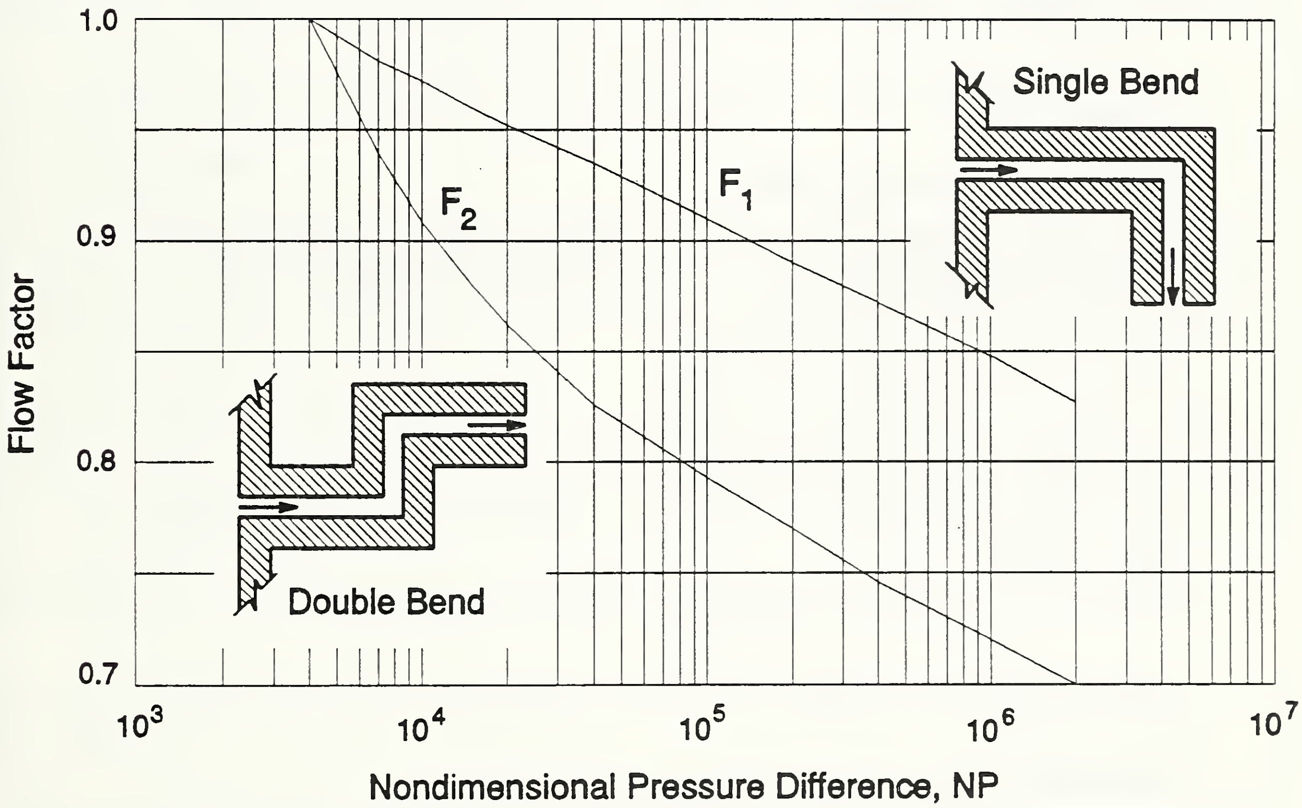

Figure 4.10 Flow factors for single and double bend slots [adapted from Gross and Haberman (1988)]

Example 4.7 Gross and Haberman method for flow through door gaps

A door has the dimensions shown in figure 4.11. What is the flow through the gaps between the door and the door frame at a pressure difference of 0.15 in H_2O (24.9 Pa)? Use the following properties of air at 70 °F (21 °C):

ρ = 0.075 lb/ft^3 (1.20 kg/m^3)
ν = 1.64x10^{-4} ft^2/sec (1.52x10^{-5} m^2/s)

For the slot at the door bottom:

a = 0.50 in (0.0127 m) D_h = 2a = 1.00 in (0.0254 m)
L = 3 ft (0.914 m) x = 1.75 in (0.0445 m)
ΔP = 0.15 in H_2O (37.3 Pa)

From equation (4.12), NP = 28.2x10^6.

From equation (4.15), NQ = 2950

From equation (4.16), Q = 152. cfm (.0718 m^3/s) flow through slot at door bottom

For slots at top and sides:

a = 0.12 in (0.00305 m) D_h = 2a = 0.24 in (0.00610 m)
L = 17 ft (5.18 m) x = 2.37 in (0.0602 m)
ΔP = 0.15 in H_2O (37.3 Pa)

From equation (4.12), NP = 51000.

From equation (4.14), NQ = 109.8

From equation (4.16), Q = 181 cfm (.0855 m^3/s) if the slot had been straight

From figure 4.10, F_1 = 0.93 for a single bend slot

Q = 181 (0.93) = 168 cfm (0.0792 m^3/s) flow through slots at top and sides

Total flow: 152 + 168 = 320 cfm (0.151 m^3/s)

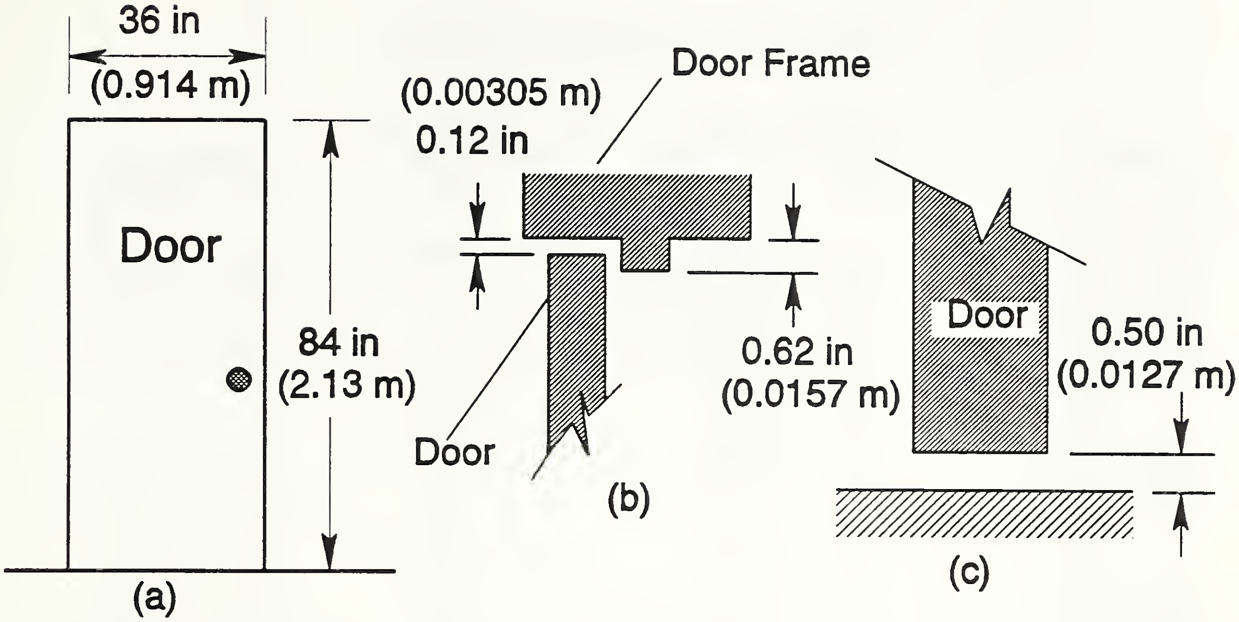

Figure 4.11 Dimensions for Example 4.7: (a) front of door, (b) gap at top and sides, and (c) gap at bottom

4.3 FLOW AREAS

In the design of smoke control systems, airflow paths must be identified and evaluated. Some leakage paths are obvious, such as gaps around closed doors, open doors, elevator doors, windows, and air transfer grilles. Construction cracks in building walls and floors are less obvious but no less important.

The flow area of most large openings, such as open windows, can be calculated easily. However, flow areas of cracks are more difficult to evaluate. The area of these leakage paths is dependent on workmanship, for example how well a door is fitted or how well weather stripping is installed. Table 4.2 lists the flow areas of doors with various gap sizes. These flow areas are intended for use with equation (4.8a), or with equation (4.8) for C = 0.65. The leakage flow rates of door assemblies can be measured and rated at ambient temperature and elevated temperatures in accordance UL 1784 (1990).

Typical leakage areas for walls and floors of commercial buildings are listed in table 4.3. These data are based on a relatively small number of tests performed by the National Research Council of Canada as referenced in the table. It is believed that actual leakage values are primarily dependent on workmanship rather than construction materials, and, in some cases, the flow areas in particular buildings may vary from the values listed. Considerable data concerning building components is also provided in Chapter 23 of the ASHRAE Handbook of Fundamentals (1989).

Table 4.2 Flow areas of doors[1]

Width in (m)	Gap Thickness at Top and Sides in (m)	Gap Thickness at Bottom in (m)	Flow Area[2] ft^2 (m^2)
36 (.914)	.02 (.000508)	.02 (.000508)	.005 (.0005)
36 (.914)	.02 (.000508)	.25 (.00635)	.079 (.0073)
36 (.914)	.02 (.000508)	.50 (.0127)	.155 (.0144)
36 (.914)	.02 (.000508)	.75 (.0191)	.230 (.0214)
36 (.914)	.08 (.00203)	.25 (.00635)	.169 (.0157)
36 (.914)	.08 (.00203)	.50 (.0127)	.244 (.0227)
36 (.914)	.08 (.00203)	.75 (.0191)	.320 (.0297)
36 (.914)	.12 (.00305)	.25 (.00635)	.242 (.0225)
36 (.914)	.12 (.00305)	.50 (.0127)	.317 (.0295)
36 (.914)	.12 (.00305)	.75 (.0191)	.392 (.0364)
36 (.914)	.16 (.00406)	.25 (.00635)	.310 (.0288)
36 (.914)	.16 (.00406)	.50 (.0127)	.385 (.0358)
36 (.914)	.16 (.00406)	.75 (.0191)	.461 (.0428)
44 (1.12)	.02 (.000508)	.02 (.000508)	.005 (.0005)
44 (1.12)	.02 (.000508)	.25 (.00635)	.096 (.0089)
44 (1.12)	.02 (.000508)	.50 (.0127)	.188 (.0175)
44 (1.12)	.02 (.000508)	.75 (.0191)	.280 (.0260)
44 (1.12)	.08 (.00203)	.25 (.00635)	.186 (.0173)
44 (1.12)	.08 (.00203)	.50 (.0127)	.278 (.0258)
44 (1.12)	.08 (.00203)	.75 (.0191)	.370 (.0344)
44 (1.12)	.12 (.00305)	.25 (.00635)	.259 (.0241)
44 (1.12)	.12 (.00305)	.50 (.0127)	.351 (.0326)
44 (1.12)	.12 (.00305)	.75 (.0191)	.443 (.0412)
44 (1.12)	.16 (.00406)	.25 (.00635)	.327 (.0304)
44 (1.12)	.16 (.00406)	.50 (.0127)	.419 (.0389)
44 (1.12)	.16 (.00406)	.75 (.0191)	.511 (.0475)

[1] This table is for doors 7 ft (2.13 m) high, 1.75 in (0.0445 m) thick, and with a door stop protruding 0.62 in (0.0157 m) from the frame.

[2] Flow area should not be confused with the geometric area of the gaps. The flow area is for use in equation (4.10a) or in equation (4.10) with C = 0.65. The flow area was calculated from $A = (Q/CK_o)(\rho/2\Delta P)^{½}$ with C = .65, $\rho = 0.075\ lb/ft^3$ ($1.20\ kg/m^3$), ΔP = 0.15 in H_2O (37.3 Pa), and Q calculated by the method of Gross and Haberman.

Table 4.3 Typical leakage areas of for walls and floors of commercial buildings

Construction Element	Tightness	Area Ratio[1]
Exterior Building Walls (includes construction cracks, cracks around windows and doors)	Tight[2]	0.7×10^{-4}
	Average[2]	0.21×10^{-3}
	Loose[2]	0.42×10^{-3}
	Very Loose[3]	0.13×10^{-2}
Stairwell Walls (includes construction cracks but not cracks around windows or doors)	Tight[4]	0.14×10^{-4}
	Average[4]	0.11×10^{-3}
	Loose[4]	0.35×10^{-3}
Elevator Shaft Walls (includes construction cracks but not cracks around doors)	Tight[4]	0.18×10^{-3}
	Average[4]	0.84×10^{-3}
	Loose[4]	0.18×10^{-2}
Floors (includes construction cracks and gaps around penetrations)	Tight[5]	0.66×10^{-5}
	Average[6]	0.52×10^{-4}
	Loose[5]	0.17×10^{-3}

---

[1] For a wall the area ratio is the area of the leakage through the wall divided by the total wall area. For a floor the area ratio is the area of the leakage through the floor divided by the total area of the floor.

[2] Values based measurements of Tamura and Shaw (1976a).

[3] Values based measurements of Tamura and Wilson (1966).

[4] Values based measurements of Tamura and Shaw (1976b).

[5] Values extrapolated from average floor tightness based on range of tightness of other construction elements.

[6] Values based measurements of Tamura and Shaw (1978).

For open stairwell doorways, Cresci (1973) found that stationary vortices form in the doorways and that the resulting flow through open doorways was considerably below the flow calculated using the geometric area of the doorway as the flow area in equation (4.8). Based on this research, it is recommended that the flow area of an open stairwell doorway be half that of the geometric area (door height times width) of the doorway. An alternate approach for open stairwell doors is to use the geometric area as the flow area and use a reduced flow coefficient. Because it does not allow the direct use of equation (4.8a), this alternate approach is not used in this manual.

The determination of the flow area of a vent is not always straightforward, because the vent surface is usually covered by a louver and screen. Thus the flow area is less than the vent area (vent height times width). Because the slats in louvers are frequently slanted, calculation of the flow area is further complicated. Manufacturers' data should be sought for specific information.

4.4 SYMMETRY

The concept of symmetry is useful in simplifying problems and thereby easing solutions. Figure 4.12 illustrates the floor plan of a multistory building that can be divided in half by a plane of symmetry. Flow areas on one side of this plane are equal to corresponding areas on the other side. If the flows and pressures are solved for one side, those on the other side are also known. To apply symmetry to a building, every floor must be such that it can be divided in the same manner by the plan of symmetry. If wind effects are included in the analysis, the wind direction must be parallel to the plane of symmetry. It is not necessary that the building be geometrically symmetric, as shown in figure 4.12; it must be symmetric only with respect to flow.

4.5 DOOR OPENING FORCES

The door opening forces due to the pressure differences produced by a smoke control system must be considered in any design. Unreasonably high door opening forces can result in occupants having difficulty or being unable to open doors to refuge areas or escape routes. This is addressed in the next section.

Figure 4.13 is a diagram of the forces on a door in a smoke control system. The sum of the moments about the hinge is

$$M_r + K_d A \Delta P (W/2) - F(W - d) = 0 \qquad (4.17)$$

Example 4.8 Flow area of stair

1. What is the leakage area between an interior stairwell and the building if the stairwell walls are of average tightness? The stairwell door is 7 ft (2.13 m) by 3 ft (0.914 m), with a 0.08 in (0.00203 m) gap on the sides and top, and with a 0.25 in (.00635 m) gap at the bottom. The stairwell is 8 ft (2.44 m) by 18 ft (5.49 m) with a floor to ceiling height of 10 ft (3.05 m).

<u>For the stairwell walls</u>:

Wall area is 2(8+18)10 = 520 ft^2 (48.3 m^3)

From table 4.3 for stairwell wall of average tightness, the ratio of the leakage area the wall area is 0.11×10^{-3}.

The leakage area of the wall is 0.11×10^{-3} (520) = 0.057 ft^2 (0.0053 m^2)

<u>For the gaps around the door</u>:

From table 4.2, the flow area of this door is 0.169 ft^2 (.0157 m^2)

<u>Total flow area</u>:

0.057 + 0.169 = 0.226 ft^2 (.0210 m^2) flow area between the stairwell and the building on a per floor basis.

2. What would the flow area be if the construction tightness were loose and the door undercut 0.75 in (0.0191 m)?

<u>For the stairwell walls</u>:

From table 4.3 for stairwell wall of loose tightness, the ratio of the leakage area the wall area is 0.35×10^{-3}.

The leakage area of the wall is 0.35×10^{-3} (520) = 0.182 ft^2 (0.0169 m^2)

<u>For the gaps around the door</u>:

From table 4.2, the flow area of this door is 0.320 ft^2 (.0297 m^2)

<u>Total flow area</u>:

0.182 + 0.320 = 0.502 ft^2 (.0466 m^2) flow area between the stairwell and the building on a per floor basis. This is about double the flow area of the first part illustrating the extent to which flow areas can vary.

where:

F = total door opening force, lb (N)
M_r = moment of the door closer and other friction, lb ft (N m)
W = door width, ft (m)
A = door area, ft^2 (m^2)
ΔP = pressure difference across the door, in H_2O (Pa)
d = distance from the doorknob to the knob side of the door, ft (m)
K_d = coefficient, 5.20 (1.00)

The moment to overcome the door closer and friction consists of all moments about hinge due to the door closer or friction forces such as friction in the hinges or rubbing of the door against the door frame. The force at the knob needed to overcome hinge friction is about 0.5 to 2 lb (2.3 to 9 N). Some poorly fitted doors rub against the frames resulting in extremely high door opening forces. Ideally, such poor workmanship will be identified and corrected during building commissioning. The component force, F_r, at the knob to overcome the door closer and other friction is

$$F_r = M_r/(W - d)$$

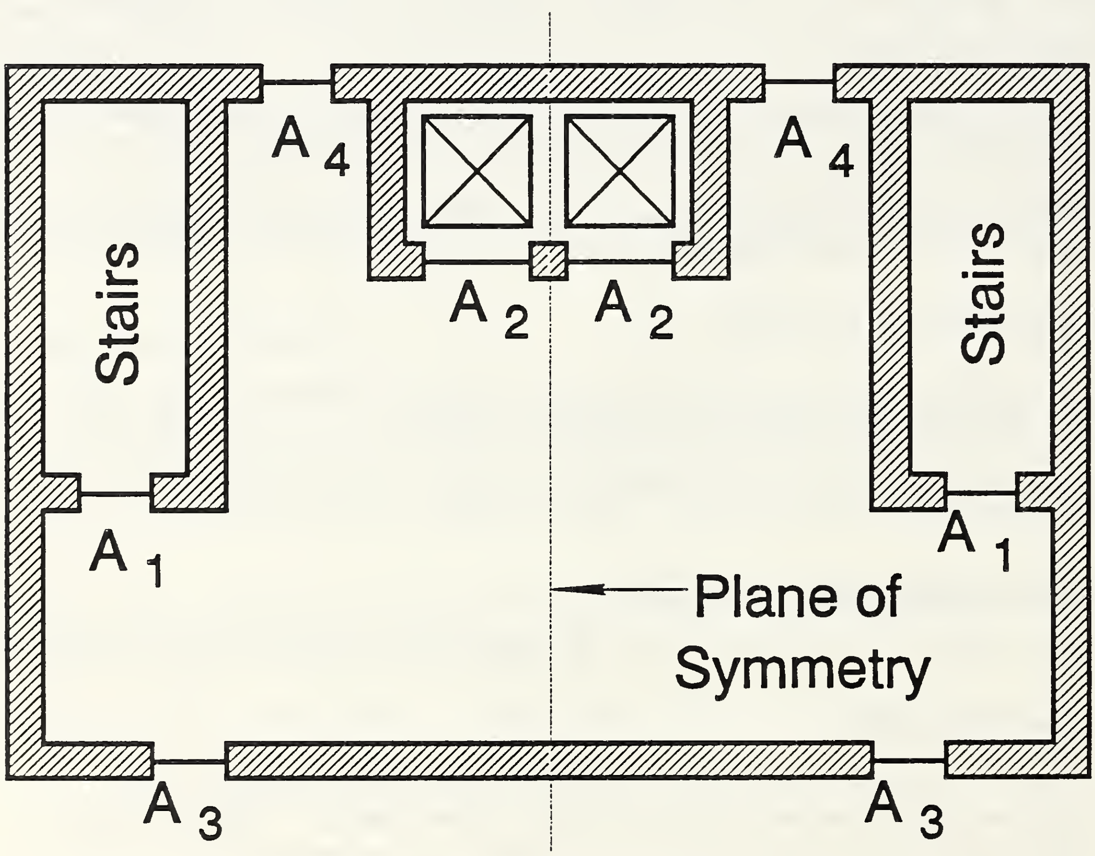

Figure 4.12 Building floor plan illustrating symmetry concept

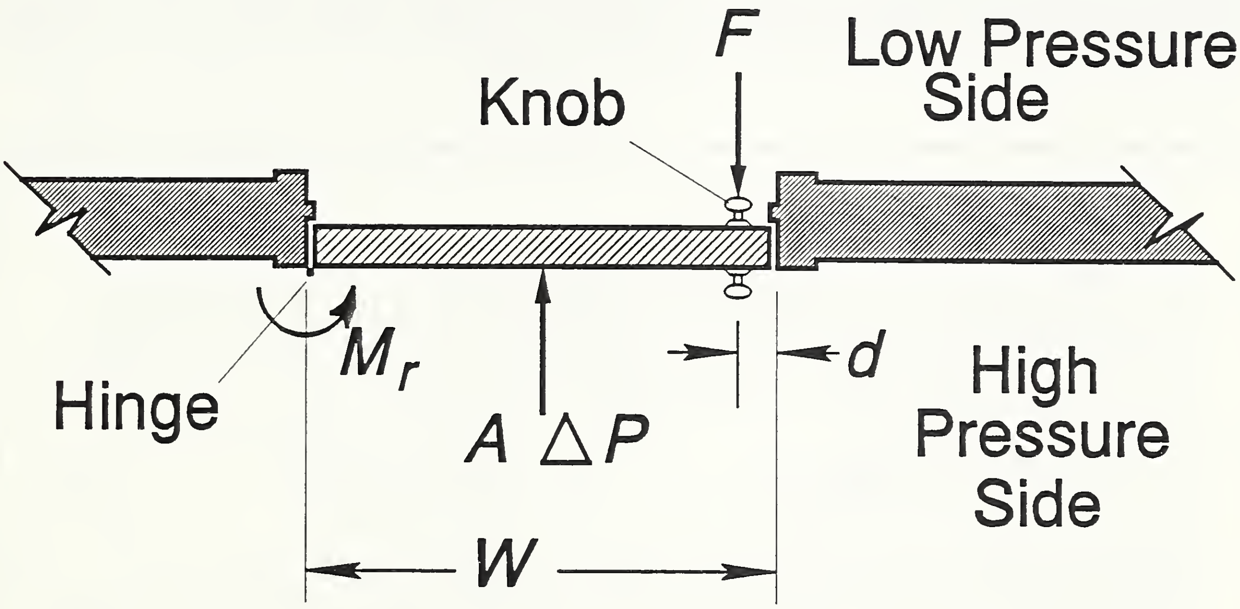

Figure 4.13 Diagram of forces on a door in a smoke control system

This can be substituted into equation (4.17) to obtain

$$F = F_r + \frac{K_d \; W \; A \; \Delta P}{2(W - d)} \qquad (4.18)$$

where:

F = total door opening force, lb (N)
F_r = force to overcome the door closer and other friction, lb (N)
W = door width, ft (m)
A = door area, ft^2 (m^2)
ΔP = pressure difference across the door, in H_2O (Pa)
d = distance from the doorknob to the knob side of the door, ft (m)
K_d = coefficient, 5.20 (1.00)

This relation assumes that the door-opening force is applied at the knob. This force to overcome the door closer is usually greater than 3 lb (13 N) and, in some cases, can be as large as 20 lb (90 N). Caution should be exercised in evaluating the 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. For this discussion, the force to overcome the door closer and other friction is that force at the very beginning of the opening process. The pressure difference component of door opening force can be determined from figure 4.14 for a door 7 ft (2.13 m) high with a knob located 3 in (0.076 m) from the edge.

Example 4.9 Door opening force

1. What is the door opening force for a door 7 ft by 3 ft (2.13 m by 0.91 m) subject to a pressure difference of 0.25 in H_2O (62 Pa)? The force to overcome the door closer and other friction is 10 lb (44 N), and the knob is 3 in from the door edge.

$W = 3$ ft (2.13 m)	$d = 0.25$ ft (0.076 m)
$\Delta P = 0.25$ in H_2O (62 Pa)	$F_r = 10$ lb (44 N)
$A = 3 \times 7 = 21$ ft^2 (1.95 m^2)	$K_d = 5.2$ (1.00)

From equation (4.18), the door opening force is 25 lb (110 N). Alternately, figure 4.14 gives 15 lb (66 N), and adding this to the door closer force gives 25 lb (110 N).

2. What is the pressure difference across a door that has a 30 lb (133 N) door opening force and a frictional and door closer force of 5 lb (22 N)? The door is the same size as in part 1 above.

Equation (4.18) can be solved for the pressure difference

$$\Delta P = \frac{2(W - d)(F - F_r)}{K_d \ W \ A}$$

$F = 30$ lb (133 N)
$F_r = 5$ lb (22 N)

From this equation, ΔP is 0.42 in H_2O (104 Pa).

4.6 DESIGN 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 NFPA 92A (1988a). The maximum allowable pressure difference should be a value that does not result in excessive door opening forces. The force that a particular person can exert to open a door depends on that person's strength, the location of the

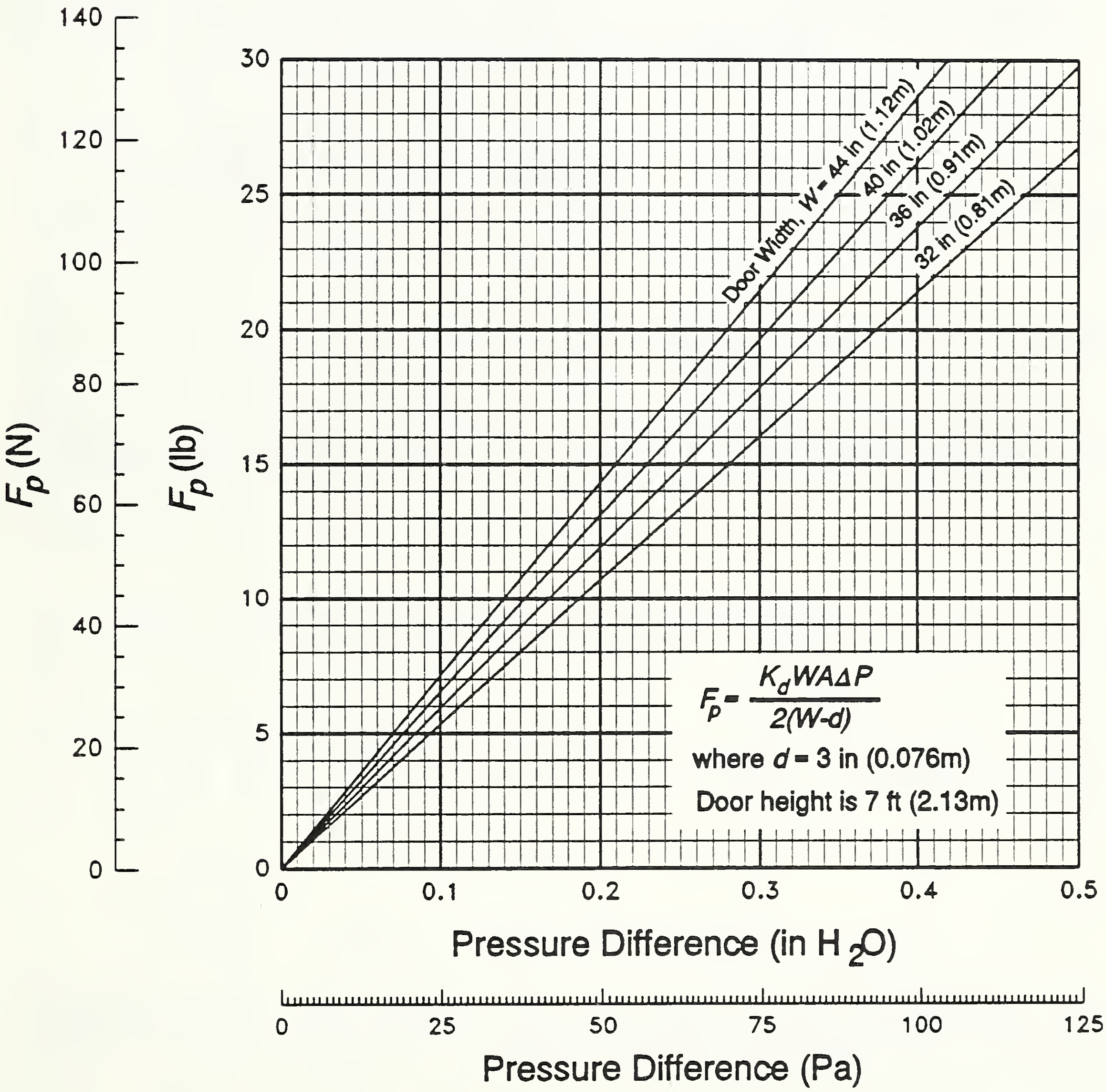

Figure 4.14 Door opening forces due to pressure difference

knob, the coefficient of friction between floor and shoe, and whether the door requires a push or a pull.

Read and Shipp (1979) studied door opening forces, and they present strength data for the very young (age 5 to 6 years) and the elderly (age 60 to 75 years). From these tables 4.4 and 4.5, the five percentile pushing force for the very young females is only 6.5 lb (29 N), and the five percentile pushing force for the elderly females is only 20 lb (91 N). The five percentile push

Table 4.4 Functional strength values for age group 5-6 years [Adapted from Read and Shipp (1979)]

Function	Gender	Mean lb (N)	Maximum lb (N)	Minimum lb (N)	Fifth Percentile lb (N)
Push	M	20 (90)	26 (155)	7.2 (32)	8.1 (36)
	F	16 (73)	28 (126)	10 (46)	6.5 (29)
Pull	M	27 (120)	41 (184)	18 (82)	17 (77)
	F	19 (86)	32 (141)	11 (48)	8.7 (39)

Note: Subjects used only one hand. Suddenly applied "jerk" pushes and pulls or two handed forward leaning pushes would have resulted in greater forces.

Table 4.5 Functional strength values for age group 60-75 years [Adapted from Read and Shipp (1979)]

Function	Gender	Mean lb (N)	Maximum lb (N)	Minimum lb (N)	Fifth Percentile lb (N)
Push	M	53 (237)	121 (540)	21 (92)	23 (101)
	F	36 (162)	70 (309)	19 (83)	20 (91)
Pull	M	69 (306)	177 (786)	23 (102)	23 (102)
	F	45 (201)	91 (407)	22 (100)	21 (95)

Note: Subjects used only one hand. Suddenly applied "jerk" pushes and pulls or two handed forward leaning pushes would have resulted in greater forces.

force of healthy male adults is 45 lbs (200 N). These forces are gradually applied, and a "jerk" method of suddenly applying the force results in a peak force of 175 lb (780 N). These push forces are one handed and the subjects are not leaning forward, the push force increases to 146 lb (652 N) for a forward leaning two handed push.

Section 5-2.1.4.3 of the Life Safety Code (NFPA 1988b) states that the force required to open any door in a means of egress shall not exceed 30 lb (133 N). Based on the data of Read and Shipp, it seems that this 30 lb (133 N) limiting force is appropriate for most occupancies, but care should be exercised when building occupants are likely to have low levels of pushing and pulling strength. For a 30 lb (133 N) limitation on door opening force, the maximum allowable pressure differences are listed in table 4.6.

The fire effect of buoyancy of "hot" smoke can be incorporated in the selection of the minimum design pressure difference. Unless otherwise stated, the minimum design pressure differences used in this manual incorporate buoyancy and are based on the idealization that the mass flow through the leakage paths is constant for the duration of the fire. A method for handling variable mass flow through these paths is presented in Chapter 9.

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). NFPA 92A (1988a) suggests minimum design pressure differences, and these values are listed in table 4.7. The values for nonsprinklered spaces are those that will not be overcome by the buoyancy forces of hot gases. These values for sprinklered buildings were calculated from equation (3.11a) for a gas temperature of 1700 °F (927 °C), 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 in H_2O (7.5 Pa).

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 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.

4.7 WEATHER DATA

The state-of-the-art of smoke control is such that little consideration has been given to the selection of weather data specifically for the design of smoke control systems. However, design temperatures for heating and cooling during winter and summer are recommended in the ASHRAE Handbook, Fundamentals Volume, Chapter 24 (1989). For example, this source provides 99 percent and 97.5 percent winter design temperatures. These values represent the temperatures that are equaled or exceeded in these portions of the heating season.

Table 4.6 Maximum allowable pressure difference across doors in inches of water (Pascals) [Adapted from NFPA 92A (1989)]

Door Closer Force lb (N)	Door Width, in (m) 32 (.813)	36 (.914)	40 (1.02)	44 (1.12)	46 (1.17)
6 (26.7)	0.45 (112.)	0.40 (99.5)	0.37 (92.1)	0.34 (84.6)	0.31 (77.1)
8 (35.6)	0.41 (102.)	0.37 (92.1)	0.34 (84.5)	0.31 (77.1)	0.28 (69.7)
10 (44.5)	0.37 (92.1)	0.34 (84.5)	0.30 (74.6)	0.28 (69.7)	0.26 (64.7)
12 (53.4)	0.34 (84.5)	0.30 (74.6)	0.27 (67.2)	0.25 (62.2)	0.23 (57.2)
14 (62.3)	0.30 (74.6)	0.27 (67.2)	0.24 (59.7)	0.22 (45.7)	0.21 (52.2)

Note: Total door opening force is 30 lb (133 N), and the door height is 7 ft (2.13 m). For other size doors or other door opening forces, the maximum allowable pressure difference can be calculated in the same manner as example 4.15 part 2.

Table 4.7 Suggested Minimum Pressure Design Difference[1] [Adapted from NFPA 92A (1989)]

Building Type[2]	Ceiling Height ft (m)	Design Pressure Difference[3] in H_2O (Pa)
AS	Any	0.05 (12.4)
NS	9 (2.7)	0.10 (24.9)
NS	15 (4.6)	0.14 (34.8)
NS	21 (6.4)	0.18 (44.8)

[1] For design purposes, a smoke control system should maintain these minimum pressure differences under likely conditions of stack effect or wind.
[2] AS for sprinklered and NS for nonsprinklered.
[3] The pressure difference measured between the smoke zone and adjacent spaces, while the affected areas are in the smoke control mode.

The heating season usually consists of three winter months (the exact definition of heating season is available in the ASHRAE Handbook).

Extreme temperatures can be considerably lower than the winter design temperatures. For example, the ASHRAE 99 percent design temperature for Tallahassee, Florida is 27 °F (-3 °C), but the lowest temperature observed there was -2 °F (-19 °C) by the National Climatic Center (1979). Temperatures are generally below the design values for short periods of time, and because of the thermal lag of building materials, these short intervals of low temperature usually do not result in problems with respect to heating systems. However, a smoke control system is subjected to all the forces of stack effect that exist at the moment it is being operated. If the outdoor temperature is below the winter design temperature for which it was designed, then problems from stack effect may result. A similar situation can happen during the summer with respect to reverse stack effect. Further research is needed concerning the selection of appropriate design temperature data for smoke control systems.

Wind data is needed for a wind analysis of a smoke control system. At present, no formal method of such an analysis exists. The approach most generally taken is to design the smoke control system to minimize any effects of wind. This approach is followed in this manual. The development of wind data for design of smoke control systems is an area for future effort.

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Chapter 5. COMPUTER ANALYSIS

The computer program described in this chapter provides a means to calculate the airflows and pressure differences throughout a building in which a smoke control system is operating. This program, entitled Analysis of Smoke Control System (ASCOS), has been previously published (Klote 1982). The program is in the public domain, and it is available from the National Institute for Standards and Technology's Fire Research Bulletin Board System. The following description is presented here as a convenience to the reader, and the appendices contain a program listing and examples.

A number of computer programs applicable to smoke control have been developed. Some calculate steady state airflow and pressures throughout a building (Sander 1974; and Sander and Tamura 1973). Other programs go beyond this to calculate the smoke concentrations that would be produced throughout a building in the event of a fire (Yoshida et al. 1979; Butcher et al. 1969; Barrett and Locklin 1969; Evers and Waterhouse 1978; and Wakamatsu 1977).

In general, most of these programs are capable of analyzing smoke control systems. However, the program described in this chapter has been specifically written for analysis of smoke control systems and is an extension of a program specifically written for analysis of pressurized stairwells and elevators (Klote 1981). While the basic theory of this program is the same as that of the stairwell and elevator program, it has been extended to include analysis of (1) stairwells with vestibules, (2) elevators with elevator lobbies, (3) zoned smoke control systems, and (4) pressurized corridors. The data input has been designed to minimize the quantity of required data and still maintain a high level of generality in the model. The output consists of the pressure differences across all of the building shafts, as well as the flows and pressures throughout the building.

This program was originally intended as a research tool to investigate the feasibility of specific smoke control systems and to determine the interaction between these systems and the rest of the building. The predecessor (Klote 1981) of this program has already been used to analyze pressurized stairwells without vestibules and to evaluate factors affecting the performance of these systems (Klote 1980). This program has been used to analyze example problems in subsequent chapters.

It is believed that the computer program discussed in this chapter may be useful for smoke control design. As of this writing, ASHRAE is sponsoring a research project to evaluate various algorithms for smoke control analysis. It is anticipated that the resulting algorithm will become the basis of the next generation of smoke control analysis programs.

5.1 PROGRAM CONCEPT

In this computer program, a building is represented by a network of spaces or nodes, each at a specific pressure and temperature. The stairwells and other shafts are modeled by a vertical series of spaces, one for each floor. Air flows through leakage paths from regions of high pressure to regions of low pressure. These leakage paths are doors and windows that may be opened or closed. Leakage can also occur through partitions, floors, and exterior walls and roofs. The airflow through a leakage path is a function of the pressure difference across the leakage path.

In this model, air from outside the building can be introduced by a pressurization system into any level of a shaft or even into other building spaces. This allows simulation of stairwell pressurization, elevator shaft pressurization, stairwell vestibule pressurization, and pressurization of any other building space. In addition, any building space can be exhausted. This allows analysis of zoned smoke control systems where the fire zone is exhausted and other zones are pressurized. The pressures throughout the building and steady flow rates through all the flow paths are obtained by solving the airflow network, including the driving forces such as wind, the pressurization system, and inside-to-outside temperature difference.

5.2 ASSUMPTIONS AND LIMITATIONS

1. Each space is considered to be at one specific pressure and one specific temperature.

2. The flows and leakage paths are assumed to occur at mid-height of each level.

3. The net air supplied by the air handling system or by the pressurization system is assumed to be constant and independent of building pressure.

4. The outside air temperature is assumed to be constant.

5. The barometric pressure at ground level is assumed to be standard atmospheric pressure (101325 Pa).

The results of the program are not very sensitive to changes in atmospheric pressure. For altitudes considerably different from sea level, a more accurate value of barometric pressure can be substituted by changing an assign statement in the subroutine INPUT and one in the subroutine CORR.

5.3 EQUATIONS

The calculations in ASCOS are all in SI units. Accordingly, no units are given for the equations in this section. When input data is in English units, input data is converted to SI units for solution, and output data is converted to English units. Appendix C contains a detailed description of the data input method.

5.3.1 Mass Flow

$$\dot{m} = SCA \sqrt{2\rho \, |\Delta P|} \qquad (5.1)$$

where:

$\dot{m}$ = mass flow rate
S = sign of
C = flow coefficient
A = flow area
ρ = density of air in flow path
ΔP = pressure difference across flow path

The pressure difference is

$$\Delta P = P_{(i)} - P_{(j)} - \frac{g\bar{P}}{R\bar{T}} (h_{(i)} - h_{(j)})$$

where:

$P_{(i)}$ = pressure at space i
$P_{(j)}$ = pressure at space j
$h_{(i)}$ = height of point i
$h_{(j)}$ = height of point j
g = acceleration of gravity
R = gas constant
$\bar{T}$ = $(T_{(i)} + T_{(j)})/2$
$\bar{P}$ = $(P_{(i)} + P_{(j)})/2 + P_b$

P_b is a constant used to convert an average gauge pressure to the average absolute pressure, $\bar{P}$. The flow coefficient is dimensionless, and for smoke control analysis it is generally taken to be in the range of 0.6 to 0.7. Because of the large number of flow calculations performed during the computer analysis, equation (5.1) is rewritten in the program as $\dot{m} = C'(\Delta P)^{\frac{1}{2}}$. Using the ideal gas law, the adjusted flow coefficient, C', can be expressed as

$$C' = C\ A \sqrt{\frac{2\ P_{atm}}{R\ T}} \qquad (5.2)$$

where:

P_{atm} = absolute barometric pressure at ground level
= absolute temperature of air in flow path

5.3.2 Conservation of Mass

In this manual the term "building compartment" refers to a space in a building other than in a shaft. For building compartment i

$$\sum_{j=1}^{N_c} \dot{m}_{(i,j)} + \sum_{k=1}^{N_o} \dot{m}_{o(i,k)} + \dot{m}_{f(i)} = 0 \qquad (5.3)$$

and for shafts

$$\sum_{i=N_1}^{N_2} \left[\sum_{j=1}^{N_c} \dot{m}_{(i,j)} + \sum_{k=1}^{N_o} \dot{m}_{o(i,k)} + \dot{m}_{f(i)} \right] = 0 \qquad (5.4)$$

where:

$\dot{m}_{(i,j)}$ = mass flow rate from space j to space i. For building compartments this flow can be either horizontal or vertical; however, for shafts this flow can only be horizontal.

$\dot{m}_o(_{i,j})$ = mass flow rate from direction k outside of the building to space i.

$\dot{m}_{f(i)}$ = net mass flow rate of air due to the air handling system or due to a pressurization system.

N_c = number of building spaces connected to space i.

N_o = number of connections to the outside from space i.

N_1 is the space number at the bottom level of the shaft and the spaces in the shaft are numbered consecutively up to N_2, which is the space number at the top of the shaft.

5.3.3 Shaft Pressures

The following relationship is used to calculate the gauge pressure, P_i, at floor i of a shaft in terms of P_{i-1} at floor i - 1.

$$P_{(i)} = P_{(i-1)} - P_z - P_f \qquad (5.5)$$

where:

P_z = hydrostatic pressure difference

P_f = pressure loss due to friction

The following equation is used to calculate the hydrostatic pressure difference.

$$P_z = \frac{g\bar{P}}{R\bar{T}} (h_{(i)} - h_{(i-1)}) \qquad (5.6)$$

where:

$h_{(i)}$ = height of point i

$h_{(i-1)}$ = height of point i-1

g = acceleration of gravity

R = gas constant

$$\overline{T} = \frac{T_{(i)} - T_{(i-1)}}{2}$$

$$\overline{P} = \frac{P_{(i)} - P_{(i-1)}}{2} + P_b$$

P_b is a constant used to convert an average gauge pressure to an average absolute pressure, $\overline{P}$. The following equation is used to calculate the pressure loss due to friction.

$$P_f = S \left(\frac{\dot{m}_u}{C_s} \right)^2 \quad (5.7)$$

where:

$\dot{m}_u$ = upward mass flow from i-1 to i in shaft
C_s = shaft flow coefficient
S = sign of $\dot{m}_u$

Shaft flow coefficients are discussed in detail later in this chapter.

5.3.4 Outside Pressures

Outside pressures can be entered by the user or can be calculated by the following method.

$$P_{o(i)} = P_{h(i)} + C_w \, P_{w(i)} \quad (5.8)$$

where:

$P_{o(i)}$ = outside gauge pressure at height $h_{(i)}$ above absolute pressure at ground level
$P_{h(i)}$ = hydrostatic pressure difference between $h_{(i)}$ and ground level
$P_{w(i)}$ = dynamic pressure due to the wind at height $h_{(i)}$
C_w = pressure coefficient

Because the outside temperature is constant

$$P_{h(i)} = P_{atm} \exp \left(- \frac{g \, h_{(i)}}{R \, T_{out}} \right) - P_b \quad (5.9)$$

where:

P_{atm} = absolute barometric pressure at ground level
T_{out} = outside absolute temperature

When the outside pressures are calculated by the computer, the wind velocity, V, at height, h, above ground is assumed to be described by the power law.

$$V = V_o \left(\frac{h}{h_o}\right)^n$$

where:

V_o = wind velocity at height h_o
n = wind exponent

The equation for the dynamic pressure at height h(i) is obtained by substituting the velocity from the power law into the usual relation for wind dynamic pressure, equation (2.3).

$$P_w = \frac{\rho V_o^{\,2}}{2} \left[\frac{h_{(i)}}{h_o}\right]^{2n} \qquad (5.10)$$

where ρ is the outside air density. Values for C_w and n, as well as practical engineering information about wind effects are provided in Chapter 3.

5.4 PROGRAM DESCRIPTION

This program is written in ANSI-1977 FORTRAN and a program listing is provided in appendix F. The following is a detailed description of the main program and the major subroutines.

5.4.1 Main Program

The main program calls the subprograms that read the data, calculate the adjusted flow coefficients, calculate the initial values of pressures and solve for the pressures according to the logic illustrated in the flow chart of figure 5.1.

5.4.2 INPUT Subroutine

This routine reads the data that are necessary for a flow analysis of the smoke control system, including an analysis of the rest of the building. These data consist of the following:

1. Outside temperature.

2. Temperature throughout the building.

3. Outside pressures. These can be entered or calculated as described earlier.

4. Description of the flow network including flow coefficients and flow areas for all connections and the net airflows to each space due to the air conditioning system or due to a pressurization system.

In addition to reading data, this subroutine provides temperature and pressure data, as well as, a complete description of the flow network. The routine also calculates initial estimates of the hydrostatic pressure differences. When data are entered in engineering units, the subroutine UNITS is called which converts all units to the SI system.

5.4.3 CORR Subroutine

This routine calculates adjusted flow coefficients for all flow paths using equation (3.2). Two sets of these coefficients are calculated for each flow path to allow for flow in either direction.

5.4.4 INIT Subroutine

This routine calculates initial estimates of the building pressures by a technique used by Sander (1974). In this technique, mass flows are considered linear functions of pressure difference; therefore, the flow equations can be expressed and solved in matrix form. In this estimate, shaft pressures are considered hydrostatic, and the resulting pressures form a starting point for the iterative solution that follows.

5.4.5 BLDGP Subroutine

The iterative solution for the building pressures and flows consists of the three subroutines, BLDGP, SHAFTP, and PZAD. The subroutine BLDGP operates on the building compartments sequentially. The sum of all the mass flows into compartment i is calculated. If the absolute value of this sum is less than a convergence limit, then equation (3.3) is considered satisfied and the computer proceeds to the next compartment or returns to the main program. However, if the absolute value of the sum is greater than the convergence limit, then an improved estimate of the pressure at compartment i is obtained by the <u>regula falsi</u> method (Carnahan, Luther, and Wilkes 1969). When none of the pressures need to be modified, this routine passes a convergence signal to the main program.

5.4.6 SHAFTP Subroutine

The structure of this routine is very similar to that of BLDGP, except that it operates on shafts sequentially. The sum of all the mass flows into shaft i is calculated. If the absolute value of this sum is less than the convergence limit, then equation (5.4) is also considered satisfied and the computer proceeds to the next shaft or returns to the main program. However, if the absolute value of the sum is greater than the convergence limit, then improved estimates of the shaft pressure are calculated. This is done by changing the pressures at the bottom of the shaft and then recalculating the shaft pressure by equation (5.5). Again, the regula falsi method is used, and if none of the shaft pressures requires modification, a convergence signal is passed to the

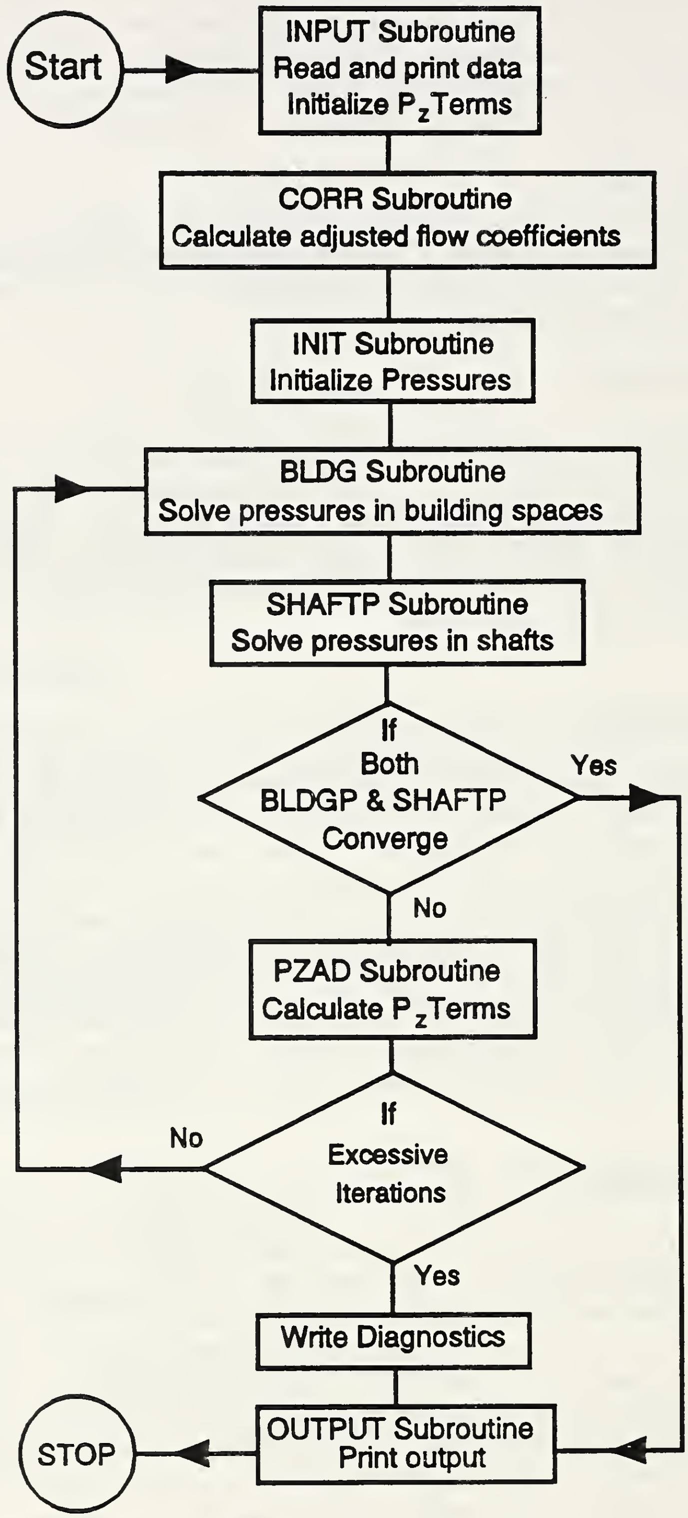

Figure 5.1 Flow chart for main program logic

main program. It can be seen from figure 5.1 that if convergence is achieved in both BLDGP and SHAFTP, then the subroutine OUT will print the solution. Otherwise, the hydrostatic pressure differences are adjusted in the subroutine PZAD.

5.4.7 PZAD Subroutine

This routine calculates hydrostatic pressure differences by equation (5.6) using the most recent pressure estimates.

5.4.8 OUT Subroutine

This routine prints mass flows and pressures for the flow network, as well as the pressure differences across each shaft. If the data input was in engineering units, then appropriate variables are converted to the engineering system before output.

5.5 CALCULATION OF SHAFT COEFFICIENTS

The ASCOS program requires that the shaft flow coefficient be supplied as input for each shaft in a building. This section is presented as an aid to calculation of this coefficient. The shaft flow coefficient, C_s, is defined by the following equation:

$$C_s = \frac{\dot{m}}{\sqrt{P_f}} \qquad (5.11)$$

where $\dot{m}$ is the mass flow through the shaft and P_f is the pressure loss in the direction of the mass flow.

5.5.1 Straight Shafts

The pressure losses in straight shafts are similar to those in ducts, and they can be analyzed in the same manner. For a round duct, the pressure los due to friction is expressed by the Darcy equation

$$P_f = f \frac{L}{D} \frac{\rho V^2}{2} \qquad (5.13)$$

where f is the friction factor, L is the duct length, D is the duct diameter, ρ is the gas density inside the duct, and V is the average velocity in the duct. The friction factor can be obtained from the traditional Moody diagram, or it can be evaluated by the Colebrook equation

$$\frac{1}{\sqrt{f}} = -2 \operatorname{Log}_{10} \left(\frac{\epsilon}{3.7\,D} + \frac{2.51}{R_e \sqrt{f}} \right) \qquad (5.14)$$

where R_e is the Reynolds number (VD/υ where υ is the kinematic viscosity) and ϵ is the absolute roughness of the inside surface of the duct. The ASHRAE handbook of fundamentals (1989) lists values of ϵ for common duct materials and constructions. Equation (5.14) can be solved for f by the Newton-Raphson method[1]. An equation for C_s of round duct is obtained by combining equations (5.11) and (5.12) (using the relation $\dot{m} = \rho V A$ where A is the cross-sectional area of the duct).

$$C_s = \frac{A^{5/4}}{\pi^{1/4}} \sqrt{\frac{4 \rho}{f L}} \tag{5.15}$$

Values of C_s are listed in tables 5.1 and 5.2 for Engineering units and SI units for galvanized steel duct [ϵ = 0.0003 ft (0.09 mm)] and concrete [ϵ = 0.01 ft (3.0 mm)]. The shaft flow coefficient is a weak function of absolute roughness. The values listed for galvanized steel can be used for smooth duct [ϵ = 0.0001 ft (0.03 mm)] to duct of average roughness [ϵ = 0.0005 ft (0.15 mm)] with errors less than about 5 percent. Duct flow theory has an inherent uncertainty of a few percent. Construction tolerances and deviations from ideal conditions can result in additional errors. The relative significance of friction losses is generally small compared to that of the pressure differences due to stack effect. For these reasons, the 5 percent uncertainty seems appropriate for smoke control design.

For a noncircular duct, the effective diameter is the diameter of a round duct that has the same pressure loss at the same flow rate as that through the noncircular duct. This is different from the commonly used hydraulic diameter concept. A duct of the hydraulic diameter has the same pressure loss at the same average velocity as that in the noncircular duct. Huebscher (1948) developed the following relation for the effective diameter of rectangular duct

$$D_e = 1.30 \frac{(ab)^{0.625}}{(a + b)^{0.250}} \tag{5.16}$$

where:

D_e = effective diameter of a rectangular duct for equal length, fluid resistance, and airflow, in (mm)
a = length of one side of duct, in (mm)
b = length of adjacent side of duct, in (mm)

---

[1]As suggested by George Walton of NIST, the efficiency of this numerical solution is significantly improved by substituting $x=f^{-1/2}$ and solving for x.

Table 5.1 Shaft coefficients, C_s, in English units

	Interior Surface of Shaft	
Diameter (inches)	Galvanized Steel	Concrete
6.	0.11×10^4	0.78×10^3
8.	0.24	0.17×10^4
10.	0.43	0.31
12.	0.70	0.50
14.	0.11×10^5	0.76
16.	0.15	0.11×10^5
18.	0.21	0.15
20.	0.27	0.20
22.	0.35	0.25
24.	0.44	0.32
26.	0.55	0.40
28.	0.67	0.48
30.	0.80	0.58
32.	0.95	0.69
34.	0.11×10^6	0.81
36.	0.13	0.94
38.	0.15	0.11×10^6
40.	0.17	0.12
45.	0.23	0.17
50.	0.31	0.22
60.	0.50	0.36
70.	0.74	0.54
80.	0.11×10^7	0.77
90.	0.14	0.11×10^7
100.	0.19	0.14
125.	0.34	0.25
150.	0.54	0.40
200.	0.12×10^8	0.85
300.	0.33	0.25×10^8
400.	0.70	0.52
500.	0.12×10^9	0.93
750.	0.35	0.27×10^9
1000.	0.74	0.57

Note: Units of C_s are scfm/(in $H_2O)^{1/2}$ where scfm is standard cubic feet per minute at 70°F and one atmosphere. This table is for floor to floor heights of L = 10 ft. For other values of L, multiply C_s by $(10/L)^{1/2}$.

Table 5.2 Shaft coefficients, C_s, in SI units

Diameter (mm)	Interior Surface of Shaft: Galvanized Steel	Interior Surface of Shaft: Concrete
150.	0.32×10^2	0.23×10^2
200.	0.69	0.49
250.	0.13×10^3	0.90
300.	0.20	0.15×10^3
350.	0.31	0.22
400.	0.44	0.32
450.	0.60	0.43
500.	0.79	0.57
550.	0.10×10^4	0.74
600.	0.13	0.93
650.	0.16	0.11×10^4
700.	0.19	0.14
750.	0.23	0.17
800.	0.27	0.20
850.	0.32	0.23
900.	0.37	0.27
950.	0.43	0.31
1000.	0.49	0.36
1100.	0.64	0.46
1200.	0.80	0.58
1500.	0.14×10^5	0.10×10^5
1800.	0.23	0.17
2000.	0.31	0.22
2200.	0.39	0.29
2500.	0.55	0.40
3000.	0.88	0.65
4000.	0.19×10^6	0.14×10^6
5000.	0.33	0.25
7500.	0.96	0.71
10000.	0.20×10^7	0.15×10^7
15000.	0.58	0.43
20000.	0.12×10^8	0.92
25000.	0.22	0.16×10^8

Note: Units of C_s are sL s^{-1} $Pa^{-\frac{1}{2}}$ where sL is standard liters at 21°C and one atmosphere. This table is for floor to floor heights of L = 3 m. For other values of L, multiply C_s by $(3/L)^{\frac{1}{2}}$.

Heyt and Diaz (1975) developed an equation for the effective diameter of oval ducts

$$D_e = \frac{1.55\ A^{0.625}}{P^{0.250}} \qquad (5.17)$$

where A is the cross-sectional area of the oval duct defined by:

$$A = \pi b^2/4 + b(a - b)$$

and the perimeter, P, is calculated as

$$P = \pi b\ 2(a - b)$$

where:

P = perimeter of oval duct, in (mm)
A = cross-sectional area of oval duct, in^2 (mm^2)
a = major dimension of oval duct, in (mm)
b = minor dimension of oval duct, in (mm)

Example 5.1 Calculate the C_s of a duct

Calculate C_s for a galvanized steel duct measuring 12 by 36 in (305 by 914 mm) with a floor to floor length of 15 ft (4.57 m).

From equation (5.16),

$$D_e = 1.30\ \frac{(12x16)^{0.625}}{(12+16)^{0.250}} = 21.9.\ \text{in (556 mm)}$$

From table 5.1, $C_s = 0.342x10^5$ for a floor to floor length of 10 ft.

As indicated in the note at the bottom of table 5.1, the shaft flow coefficient is adjusted for the 15 ft (4.57 m) length of duct as follows

$$C_s = 0.342x10^5\ (10/15)^{½} = 0.28x10^5\ (0.84x10^3)$$

Note: Table 5.2 would be used for calculations in SI units

5.5.2 Stairwells

Based on the research of Tamura and Shaw (1976) and Achakji and Tamura (1988), the shaft coefficient for stairwells may be expressed as

$$C_s = K_{sw} \frac{A^{5/4}}{L^{1/2}} \qquad (5.18)$$

where:

A = horizontal cross-sectional area of stairwell, ft^2 (m^2)
L = distance from one floor to the next, ft (m)
K_{sw} = proportionality constant (table 5.3 and 5.4)

Table 5.3 K_{sw} in English Units

Stair Treads	Stairwell Occupancy Conditions	K_{sw}
open	no occupancy	500
open	high density	380
closed	no occupancy	460
closed	medium density	350
closed	high density	290

Note: Units of K_{sw} are scfm $ft^2/(in\ H_2O)^{1/2}$. Medium occupant density is based on 1 person per 11 ft^2, and high density is based on 1 person per 5.5 ft^2.

Table 5.4 K_{sw} in SI Units

Stair Treads	Stairwell Occupancy Conditions	K_{sw}
open	no occupancy	160
open	high density	120
closed	no occupancy	150
closed	medium density	110
closed	high density	95

Note: Units of K_{sw} are sL m^2 s^{-1} $Pa^{-1/2}$ where sL is standard liters at 21°C and one atmosphere. Medium occupant density is based on 1 person per m^2, and high density is based on 2 persons per m^2.

Example 5.2 Calculate the C_s of a Stairwell

Calculate C_s for a stairwell measuring 8 by 19 ft (2.4 by 5.8 m) with a floor to floor length of 11 ft (3.4 m).

From table 5.3, K_{sw} = 290 in English units

Using equation (5.18)

$$C_s = 290 \frac{(8x19)^{5/4}}{(10)^{1/2}} = 49,000 \ (1500)$$

Note: Table 5.4 would be used for calculations in SI units

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Chapter 6. AIR MOVING EQUIPMENT AND SYSTEMS

The National Board of Fire Underwriters examined the NFPA fire data from January 1936 to April 1938 to determine the extent of the smoke hazards due to heating, ventilating and air conditioning (HVAC) systems (NBFU 1939). Of 25 fires recorded, 19 had combustion of parts of the air moving system. Ducts, duct linings, and filters burned. In five cases of no fire in the HVAC system, smoke was distributed by the system. This report has had a major impact on the materials and construction of modern HVAC systems as is apparent from examination of current standards such as NFPA 90A (NFPA 1989). The report recommended that HVAC systems be shut down during fire situations to prevent them from spreading smoke and supplying combustion air to the fire. System shut-down became the standard response to fire. However, operation of the HVAC system in a smoke control mode has become a common alternative in recent years as discussed in later chapters.

The information in this chapter is provided as a broad and general background of air moving systems. The material was selected to aid in the understanding of the smoke control systems discussed in later chapters. This information should help fire protection engineers, firefighters, and code officials to communicate with HVAC designers and to recognize and understand HVAC equipment. Because energy conservation is a major concern, energy efficiency of systems and equipment are addressed in this chapter. This chapter is not an exhaustive treatment of the fire safety requirements of HVAC systems, and the design of such systems should be done by experienced professionals. More detailed information about these HVAC systems and equipment is available from the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE 1987), and the Sheet Metal and Air Conditioning Contractors National Association (SMACNA 1988).

The simplest systems consist of a fan in a housing, such as a roof mounted atrium exhaust fan. Most systems are more complicated with ductwork and some of the following components: supply air outlets, return air inlets, fresh air intakes, humidifiers, filters, heating and cooling coils, preheat coils, and dampers. Ductwork is constructed of a variety of materials including steel, aluminum, concrete, and masonry. Ductwork of fiberglass, gypsum and fabrics are used with some restrictions. Discussions of fans and dampers are provided later. The air moving systems that are discussed later are primarily intended for maintaining comfort conditions. Exhaust systems for toilets, laboratories and kitchens are not discussed, but they generally are less complicated and use many of the same components.

6.1 HVAC LAYOUT

In large buildings, the heating and cooling loads often vary considerably from one location to another. Heat is transferred to or from the spaces near the exterior walls depending on outdoor weather conditions. Solar radiation effects each of the exterior zones differently. It is common to divide a building into four perimeter zones and a core zone as is shown in figure 6.1. The perimeter zones can be conditioned by a variety of means including fan

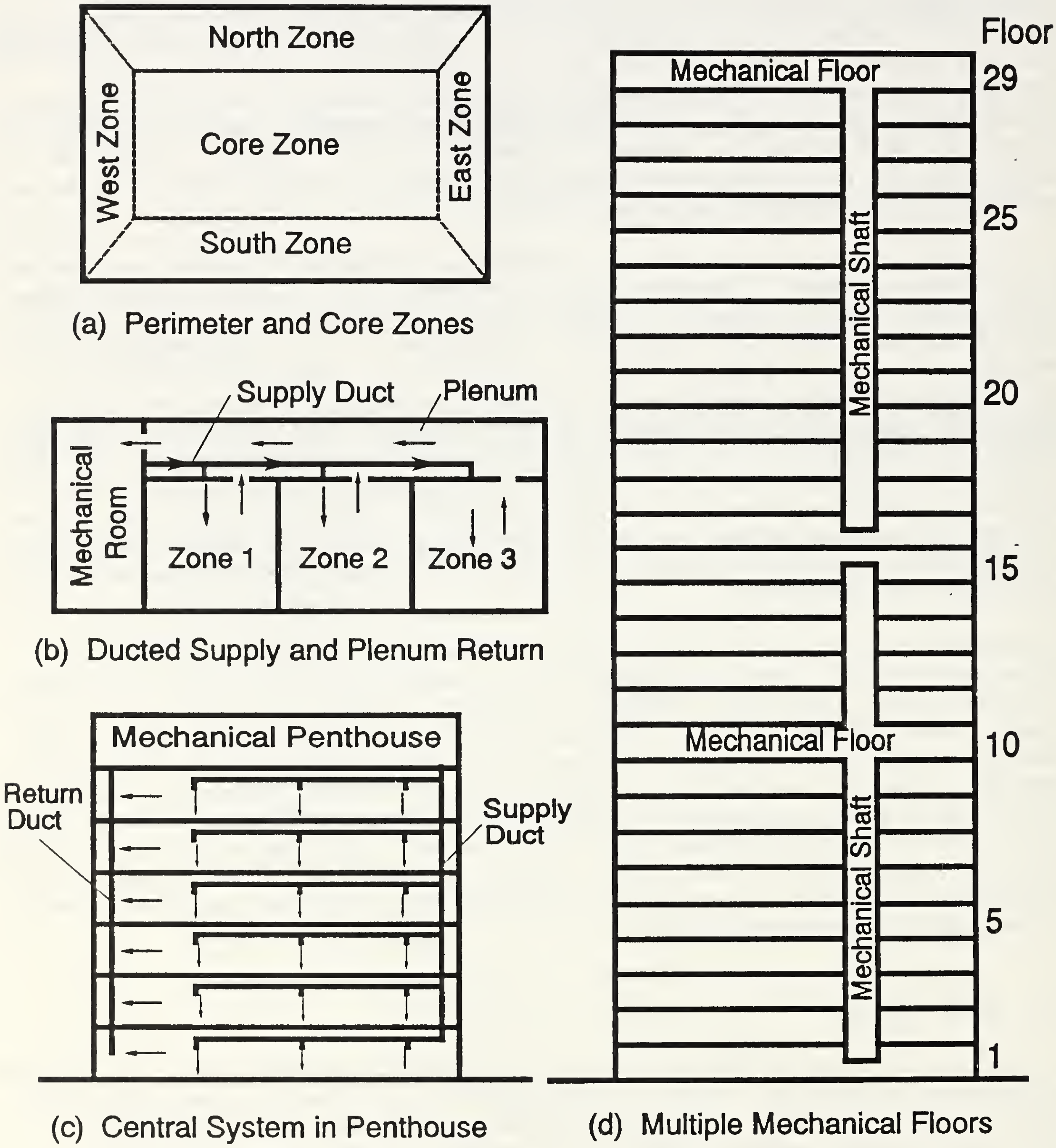

Figure 6.1 Some HVAC arrangements

coil units, air conditioners and heat pumps. Generally, fan coil units are supplied with hot and cold water to allow both heating and cooling. Often air conditioners and heat pumps are located through-the-wall. Both fan coil units and through-the-wall equipment can receive ventilation air directly from the outside or from a ducted ventilation system. In large commercial buildings, ventilation air is needed to control the odors due to cooking, smoking, perspiration and other processes[1]. The perimeter zones may be served by ducted forced air systems, and the core zone is usually served by such forced air systems. Some types of forced air systems are capable of satisfying a wide range of needs simultaneously and are used to serve both perimeter and core zones. The different types of forced air systems are discussed later.

Distribution on a floor is often through ducts located above a suspended ceiling. Return air is often pulled through the plenum space above the ceiling as shown in figure 6.1(b). The return may be ducted above the ceiling as well. Mechanical equipment of a forced air system may be located on each floor (figure 6.1(b)), on one floor (figure 6.1(c)), or on several floors (figure 6.1(d)).

The arrangements above are but a few of those possible. There may be several forced air systems on each floor. There may be several units located in a penthouse, each serving its own vertical portion of the building. Sometimes several air systems are used and the areas served are selected on the basis of having similar heating and cooling demands. These demands depend on occupancy, the presence of heat releasing equipment, electrical lighting levels, and heat transferred to or from the outside. For a complicated building (such as hospitals, laboratories, and hotels), the duct systems can be intertwined to such a level that considerable study is needed to understand which systems serve which areas.

6.2 FORCED AIR SYSTEMS

Four common types of forced air systems are:

- constant volume, single zone systems,
- constant volume systems with terminal reheat,
- variable air volume (VAV) systems, and
- dual duct systems.

There are numerous variations on these systems. Generally, the heat source for heating coils is hot water. However, other sources such as steam or electrical resistance heating are possible. Cooling coils can be supplied with chilled water or with refrigerant. The source of heating or cooling has significant effects on system economics but little effect on air flow. The forced air systems discussed in the following sections can be completely built up in the field, factory fabricated subsections can be field assembled, or completely factory fabricated systems can be installed.

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[1]In small buildings and residences, such odor control is achieved by naturally occurring air infiltration through construction gaps and cracks.

6.2.1 Constant Volume, Single Zone

Figure 6.2 is a representation of a single fan, constant volume system. The term "constant volume" is used in the HVAC industry to indicate that the system produces constant or nearly constant volumetric flow rate of air. This system is used in residences and some small commercial applications. In this example return air from the living quarters is drawn in at one location, flows through filter, fan and coils, and is distributed back to the residence. This system does not have the capability of providing fresh outside air. These systems are intended for applications where there is sufficient natural air leakage through cracks in walls and around windows and doors for odor control.

Single zone systems are so called because they serve only one HVAC control zone. For example, a residential system is controlled by a thermostat to maintain the temperature in the living quarters. Generally, the residential system has a two position control system allowing only on and off operation to maintain temperature and humidity conditions.

Frequently in commercial buildings, constant volume systems have two fans and are capable of providing ventilation air as illustrated in figure 6.3(a). The return fan permits lower supply fan speeds and quieter operation. The return air fan provides positive return and exhaust from the conditioned space. During cold weather, many large commercial buildings have so much heat generated by equipment and people that cooling is required. To save energy, cold outside air can be used for this cooling. The system of dampers and controls which maximizes the use of outdoor air for cooling is called an economizer.

For systems with an economizer, the humidifier and cooling coils need to be protected from freezing. Thus, the preheat coil is used to temper the outside air to 38 to 45°F (3 to 7°C) when the outside air is below freezing. The preheat coil and reheat coil can be used when heating is required. The reheat coil used with the cooling coil allows precise humidity control.

When the supply fan and return fan have the same flow rate, the system is said to be in a "balanced condition." Many designers size the exhaust fan at about 80 or 90% of the flow of the supply fan to provide slight building pressurization [about 0.05 in H_2O (12 PA)]. The intent is to prevent normal infiltration of airborne dirt, odors and pollen from the outside into the building. Figure 6.3(b) is a line diagram illustrating the same system as that of figure 6.3(a). In the rest of this chapter, line diagrams will be used to illustrate systems. The components of the following systems are the same as those shown in figure 6.3(a) and (b).

6.2.2 Constant Volume, Terminal Reheat

The constant volume, terminal reheat system is intended to serve many HVAC control zones as illustrated in figure 6.4. This system can have an economizer as can all the following systems. The supply fan provides cooled air to each zone where it is reheated to the temperature required to maintain comfort condition with that zone. The air flow rate through the system is

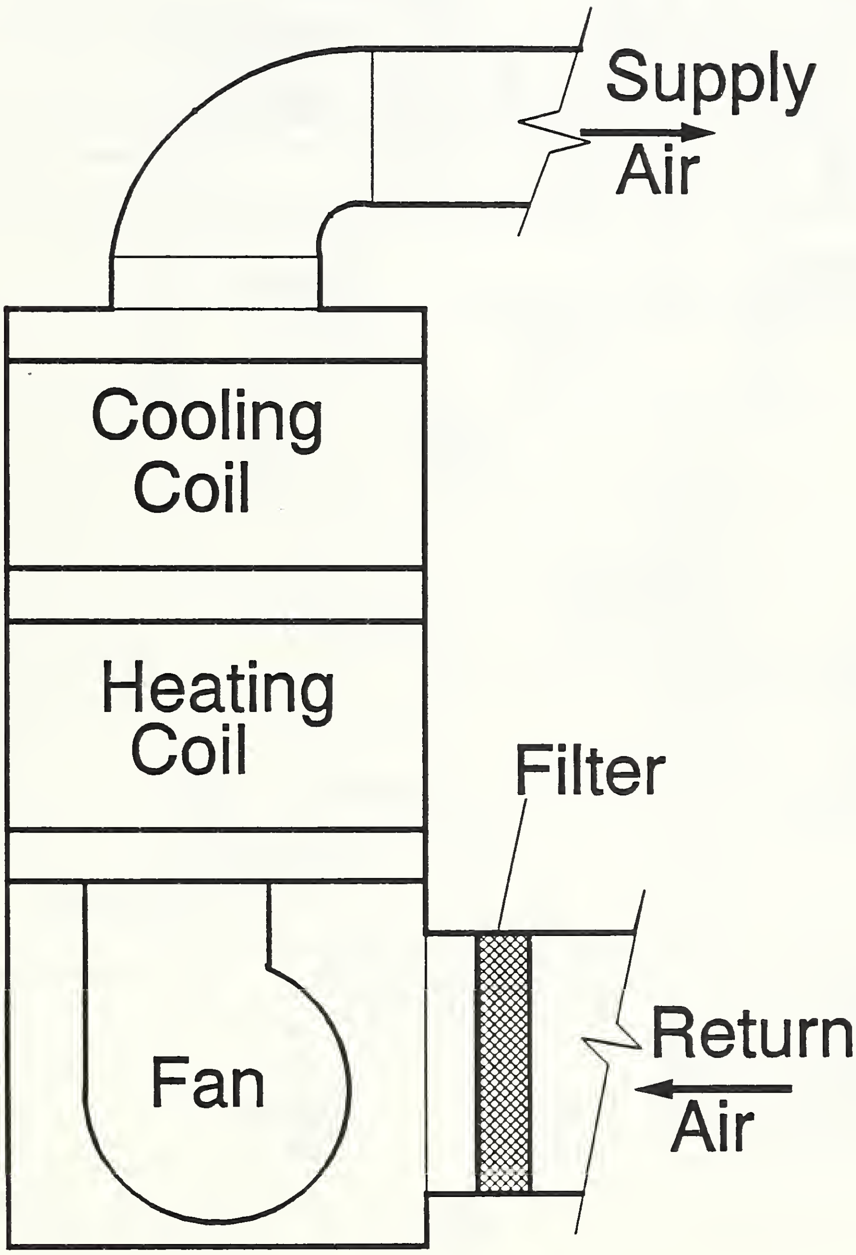

Figure 6.2 Single fan system

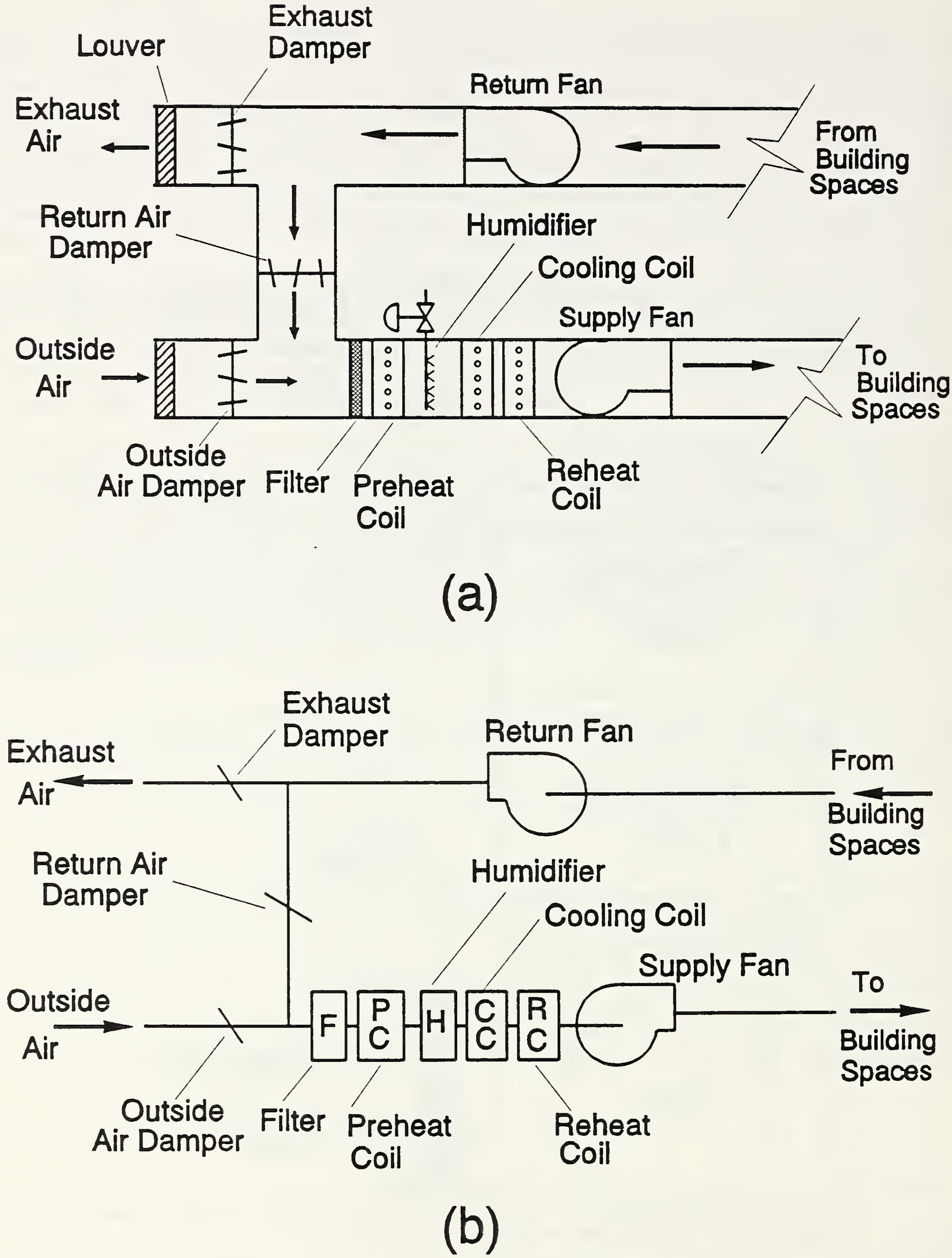

Figure 6.3 Constant volume, single zone system

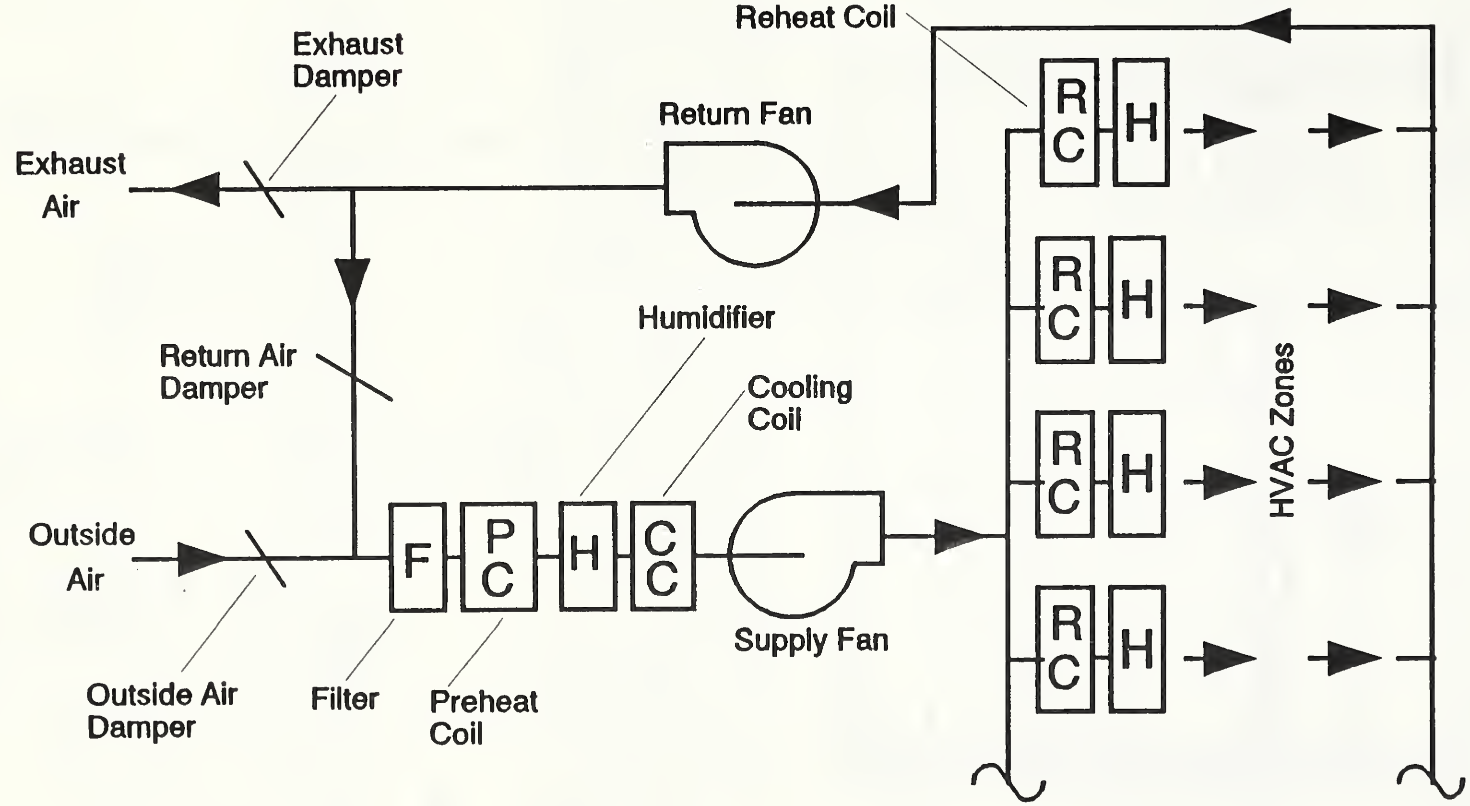

Figure 6.4 Constant volume system with terminal reheat

constant, and control is achieved by varying the heat input to each reheat coil. This system is capable of achieving a high level of temperature and humidity control for each zone. However, terminal reheat is not very energy efficient.

6.2.3 Variable Air Volume

The variable air volume system varies the supply rate of conditioned air to the space to maintain comfort conditions. Additionally, the temperature of the supply air may be varied. There are many approaches for achieving variable flow. In the system depicted in figure 6.5, flow to each zone is controlled by a damper or other flow control device in the VAV unit. This unit is sometimes referred to as the VAV terminal box. Generally, the supply and return fans are capable of variable flow rates and are controlled by the static pressure sensors. Some of the approaches that are used to achieve variable flow rates through fans are variable pitch inlet vanes, discharge dampers, variable pitch motor sheaves, eddy current couplings, variable speed DC motors, and variable frequency AC motor speed controllers. As with constant volume systems, VAV systems can be designed to provide building pressurization.

6.2.4 Dual Duct

The dual duct system conditions all the air at a central location and distributes it to the conditioned spaces through two supply ducts. One duct conveys cold air, and the other warm air (figure 6.6). A mixing box supplying each zone combines the two air streams in the proper proportions to achieve comfort conditions. These systems have been used in multi-room buildings to accommodate highly variable heating and cooling loads. Dual duct system can be constant volume or VAV. Operating costs of VAV dual duct systems are less than those of the constant volume systems.

6.3 FANS

There are two general fan classifications: centrifugal and axial. Figure 6.7 illustrates the basic parts of a centrifugal fan. Flow within a centrifugal fan is primarily in a radial direction to the impeller. Figure 6.8 illustrates the basic parts of an axial fan. Flow within an axial fan is parallel to the shaft.

6.3.1 Centrifugal Fans

Centrifugal fans used in the HVAC industry are generally classified by impeller design (figure 6.9):

- forward curved,
- backward curved, and
- airfoil.

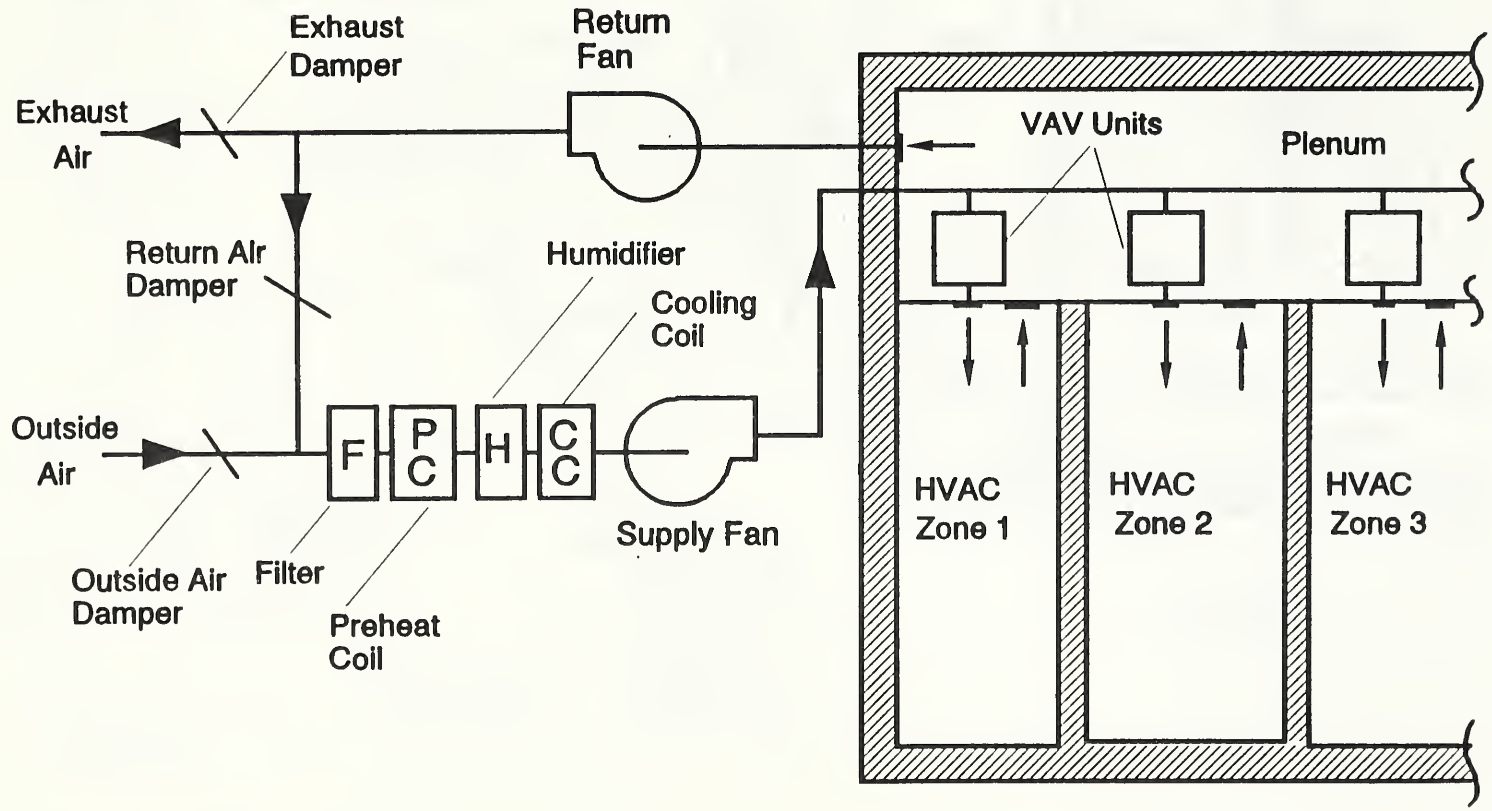

Figure 6.5 Variable air volume (VAV) system

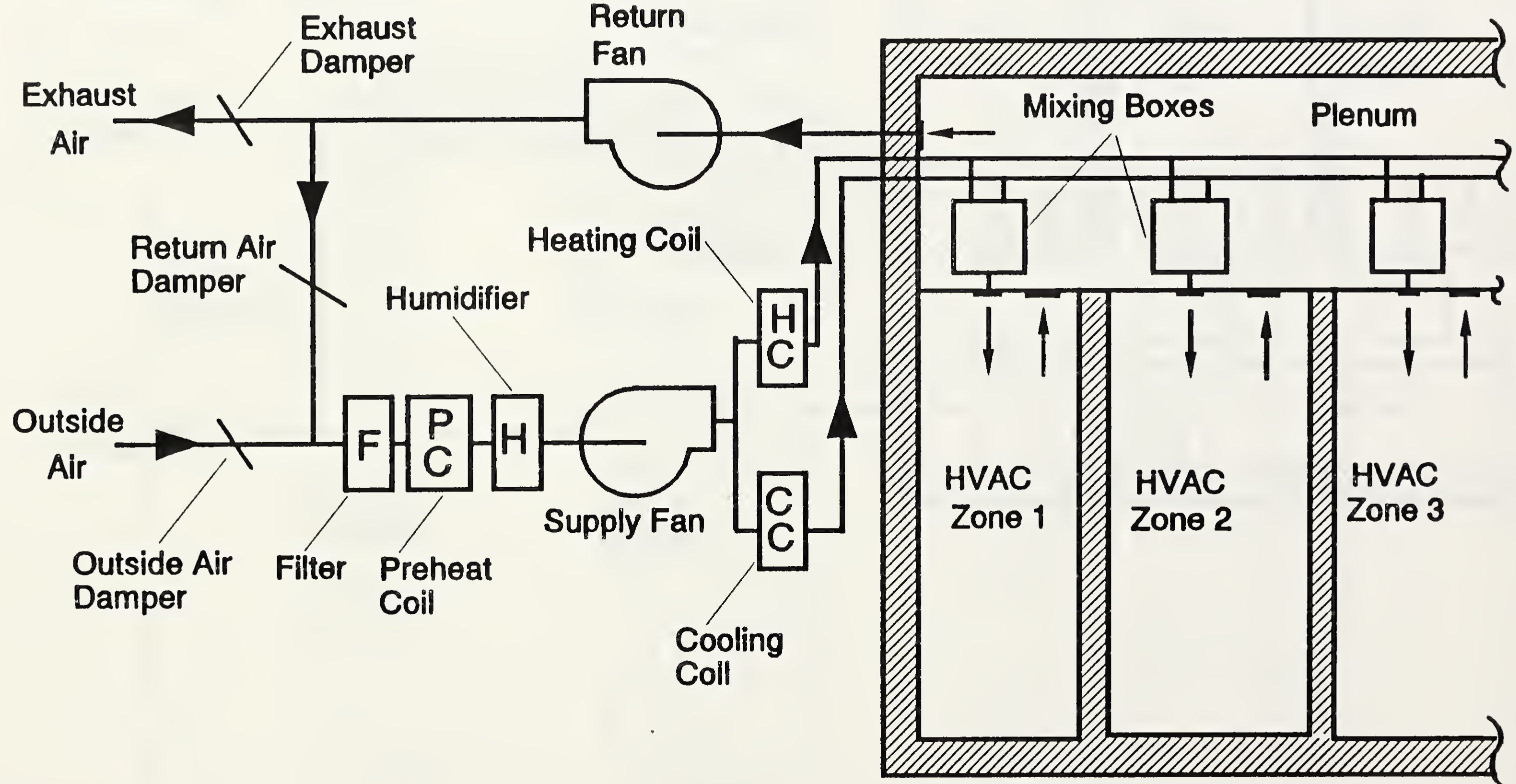

Figure 6.6 Dual-duct system

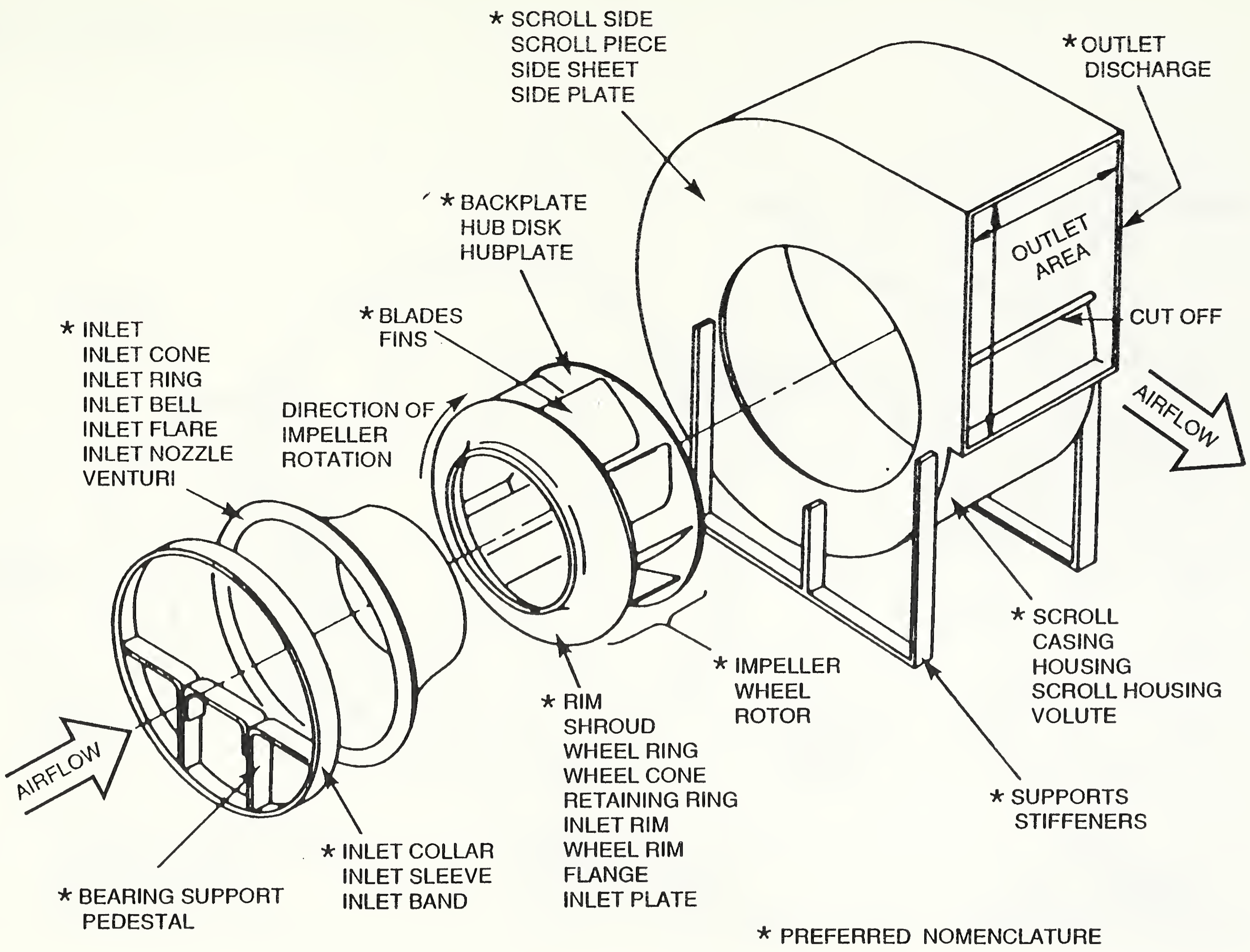

Figure 6.7 Centrifugal fan components

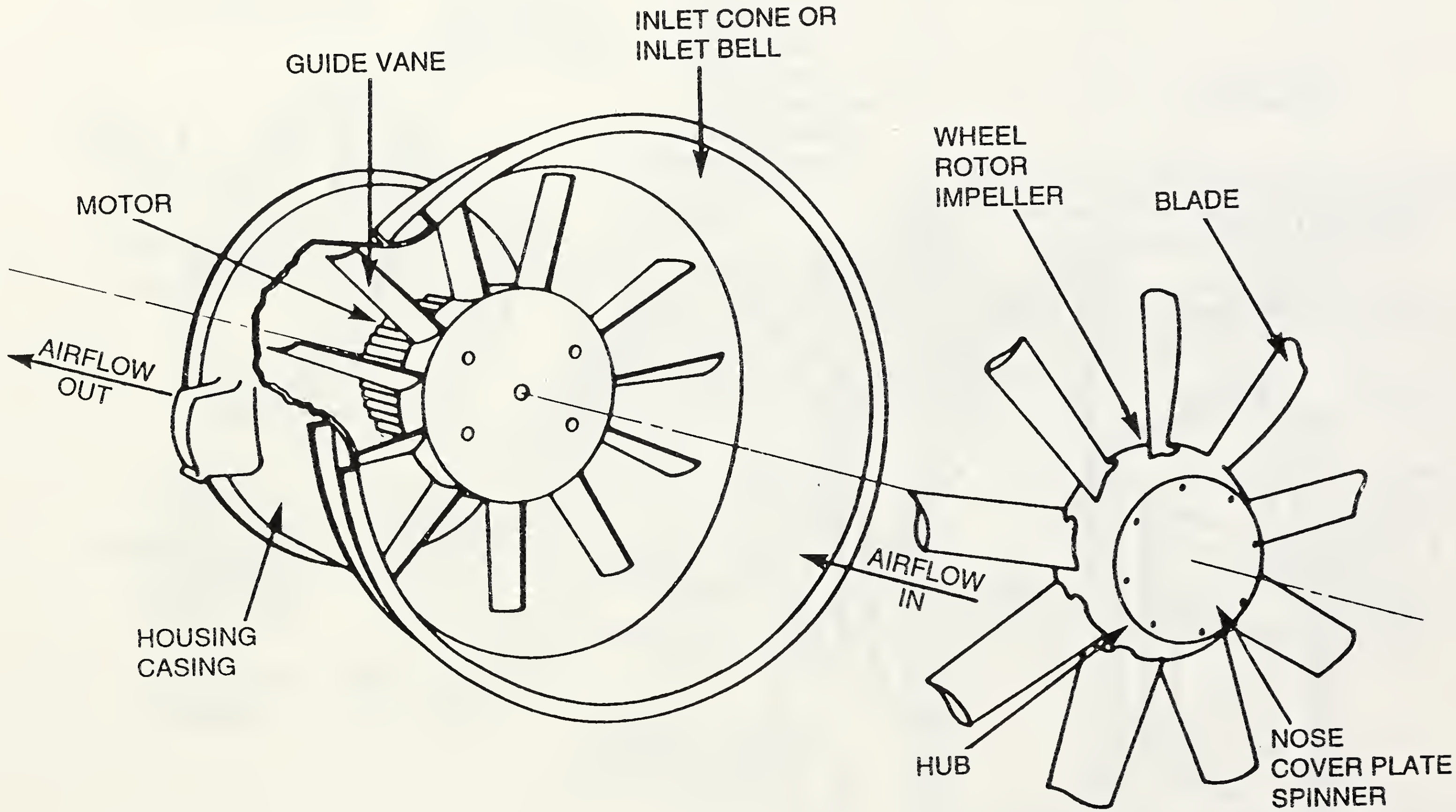

Figure 6.8 Axial fan components

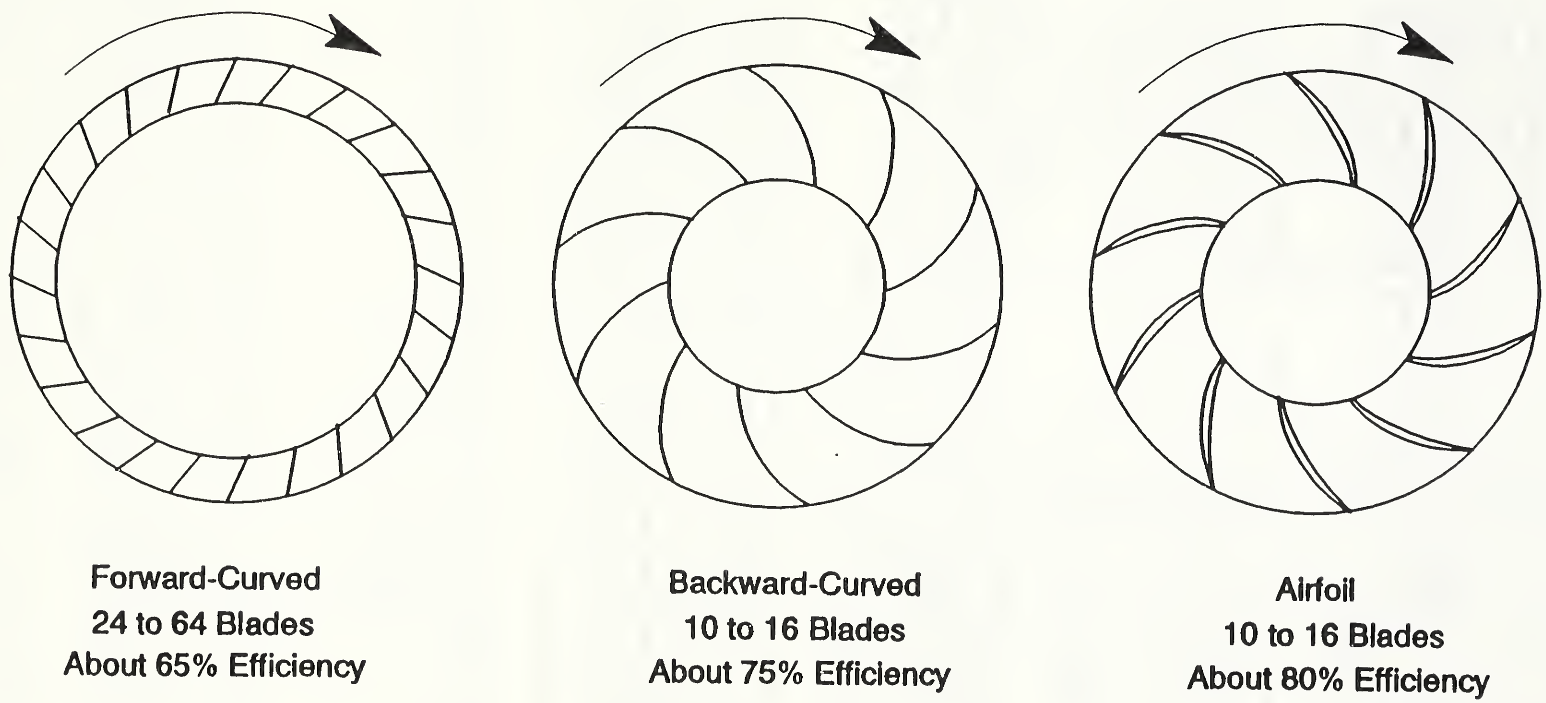

Figure 6.9 Centrifugal fan impeller types

Forward curved centrifugal fans rotate at a relatively low speed and are generally used to produce high flow rates and low static pressures. Backward curved fans rotate at about twice the speed of forward curved fans and have a higher efficiency. The higher rotational speed requires more expensive fan construction. Both forward and backward curved impeller blades are single width stamped from sheet metal. Airfoil fans are basically backward curved fans with blades of varying thickness to improve fan efficiency. Airfoil blades are designed using the same airfoil technology that is used to design airplane wings.

Required performance and economics are major factors in the selection of a fan type for a particular application. However, the following generalizations can be made concerning application. Forward curved fans are used for low pressure HVAC applications including residential furnaces and packaged air conditioning equipment. Airfoil and backward curved fans are used for general purpose HVAC applications, and airfoil fans are usually limited to large systems where the energy savings are significant.

Tubular centrifugal fans (figure 6.10) are an exception to the classification by impeller type. Generally these fans have single width impeller blades, and straightening vanes to direct air parallel to the shaft. Tubular centrifugal fans are primarily used for low pressure HVAC applications particularly as return air fans. These fans have significant space savings over other centrifugal fans.

Backward impeller rotation is a common problem with systems with centrifugal fans. It is important to note that backward rotation of centrifugal fans results in reduced flow in the normal direction. This problem is often not recognized, because of the mistaken belief that backward rotation of these fans results in backward flow. The normal direction airflow and the direction of rotation of centrifugal fans is shown on figure 6.7.

6.3.2 Axial Fans

The common types of axial fans used in buildings are (figure 6.11):

- propeller fans,
- tubeaxial fans, and
- vaneaxial fans.

For propeller fans, a variety of impeller designs are employed with the intent of achieving high flow rates at low pressures. The impellers of propeller fans have two or more blades and are usually of inexpensive construction (for example these blades are often stamped from sheet metal). Propeller fans are used for low pressure, high flow rate applications including kitchen exhaust, toilet exhaust, stairwell pressurization, and space ventilation.

Tubeaxial fans have a higher efficiency and can operate at higher pressures than propeller fans. Vaneaxial fans have still higher efficiencies and operating pressures. Blades of tubeaxial and vaneaxial fans can be single thickness or airfoil design. Adjustable pitch blades are used on some

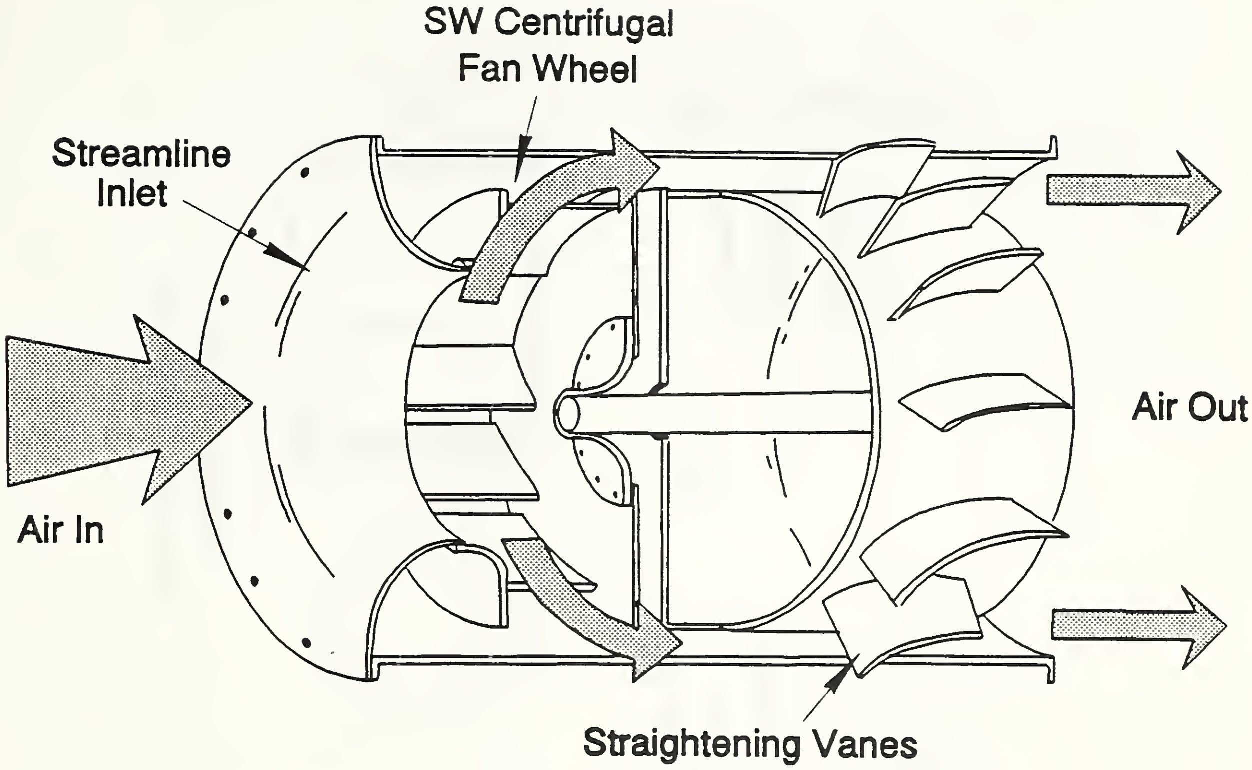

Figure 6.10 Tubular centrifugal fan [from SMACNA (1983)]

vaneaxial fans to obtain high efficiency. Both tubeaxial and vaneaxial fans have the advantages of straight through flow and compact installation. Tubeaxial fans are used for low to medium pressure HVAC applications, and vaneaxial fans are used for low to high pressure HVAC applications.

Unlike centrifugal fans, backward rotation of an axial fan normally results in backward flow. This backward flow is at a reduced air flow rate. More information about both centrifugal and axial fans is provided by Jorgensen (1983) and ASHRAE (1988).

6.4 DAMPERS

In air moving systems, dampers are used to:

- balance airflow,
- control airflow,
- resist the passage of fire, or
- resist the passage of smoke.

Balancing dampers are used in supply ducts and return ducts to adjust the airflow to the design values. These dampers can be of simple construction (figure 6.12) or of multi-blade construction (figure 6.13). Multi-blade

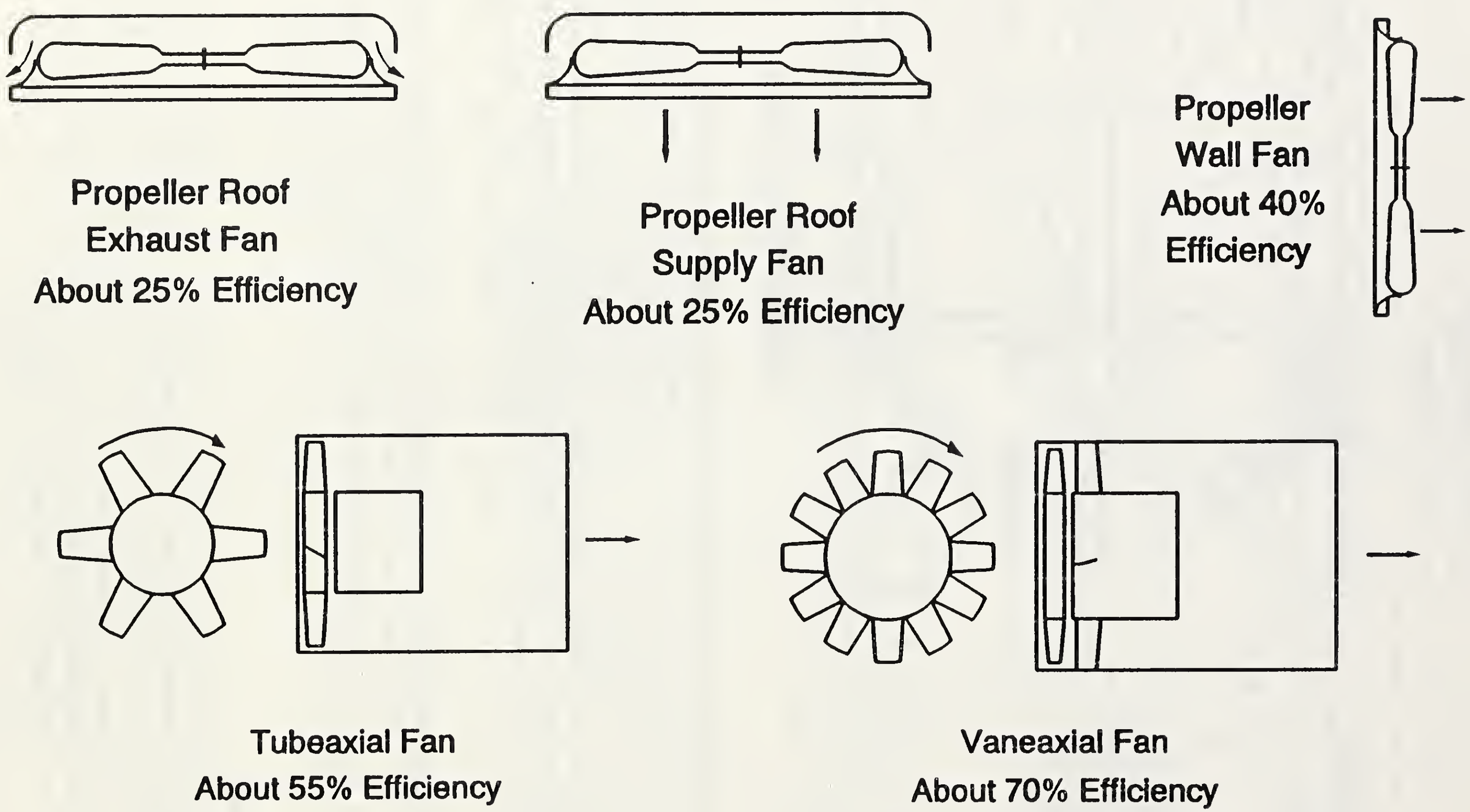

Figure 6.11 Types of axial fans

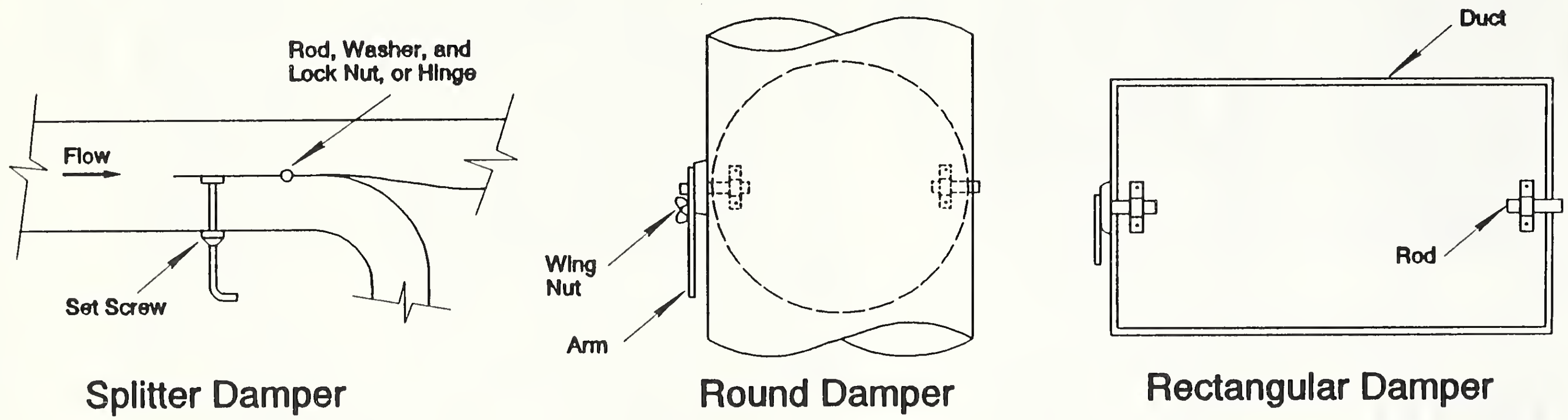

Figure 6.12 Damper types used for balancing

dampers operated by electric motors or pneumatic pistons to vary the flow rate are called control dampers. Dampers used to resist the passage of fire are called fire dampers, and these can be multi-blade dampers (figure 6.13) or curtain dampers (figure 6.14). Dampers used to resist the passage of smoke are called smoke dampers, and these can also be either multi-blade or curtain. Combination dampers can be used to balance airflow, control airflow, resist the passage of fire, and resist the passage of smoke.

6.4.1 Fire Dampers

In the United States, fire dampers are usually constructed and labeled in accordance with standard UL 555 (UL 1990). Additionally, ceiling dampers are used in fire resistance rated floor-ceiling assemblies to limit radiative heat transfer. Generally, multi-blade fire dampers are held open by a fusible link and are spring loaded. In a fire situation, hot gases cause the link to come apart allowing a spring to slam the blades shut. In place of fusible links, some manufacturers use other heat responsive devices. Curtain fire dampers are held open by a fusible link, and they close by gravity of a spring when the link comes apart.

6.4.2 Smoke Dampers

In the United States, smoke dampers are usually constructed and classified for leakage in accordance with standard UL 555S (UL 1983). As a convenience to the reader, a general description of the standard follows. UL 555S contains requirements for leakage rated dampers intended for use in heating, ventilating, and air conditioning systems. It includes construction requirements and tests for cycling, temperature degradation, dust loading exposure, salt-spray exposure, air leakage, and operation under airflow. These dampers are classified as 0, I, II, III, or IV leakage rated at ambient or elevated temperatures of 250°F (121°C) or at an higher in increments of 100°F (56°C) above 250°F (121°C). Thus they can also be tested at 350°F (177°C), 450°F (232°C), 550°F (287°C), etc. The maximum leakage rates for the different classifications are listed in table 6.1. Class 0 dampers with zero leakage under this standard are commonly used in 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 can have some leakage without adversely affecting smoke control system performance. Thus a designer might select class II, III or even IV smoke dampers for such an application. However, a designer might choose class I dampers for applications that require a very tight damper like a return air damper (figure 6.3).

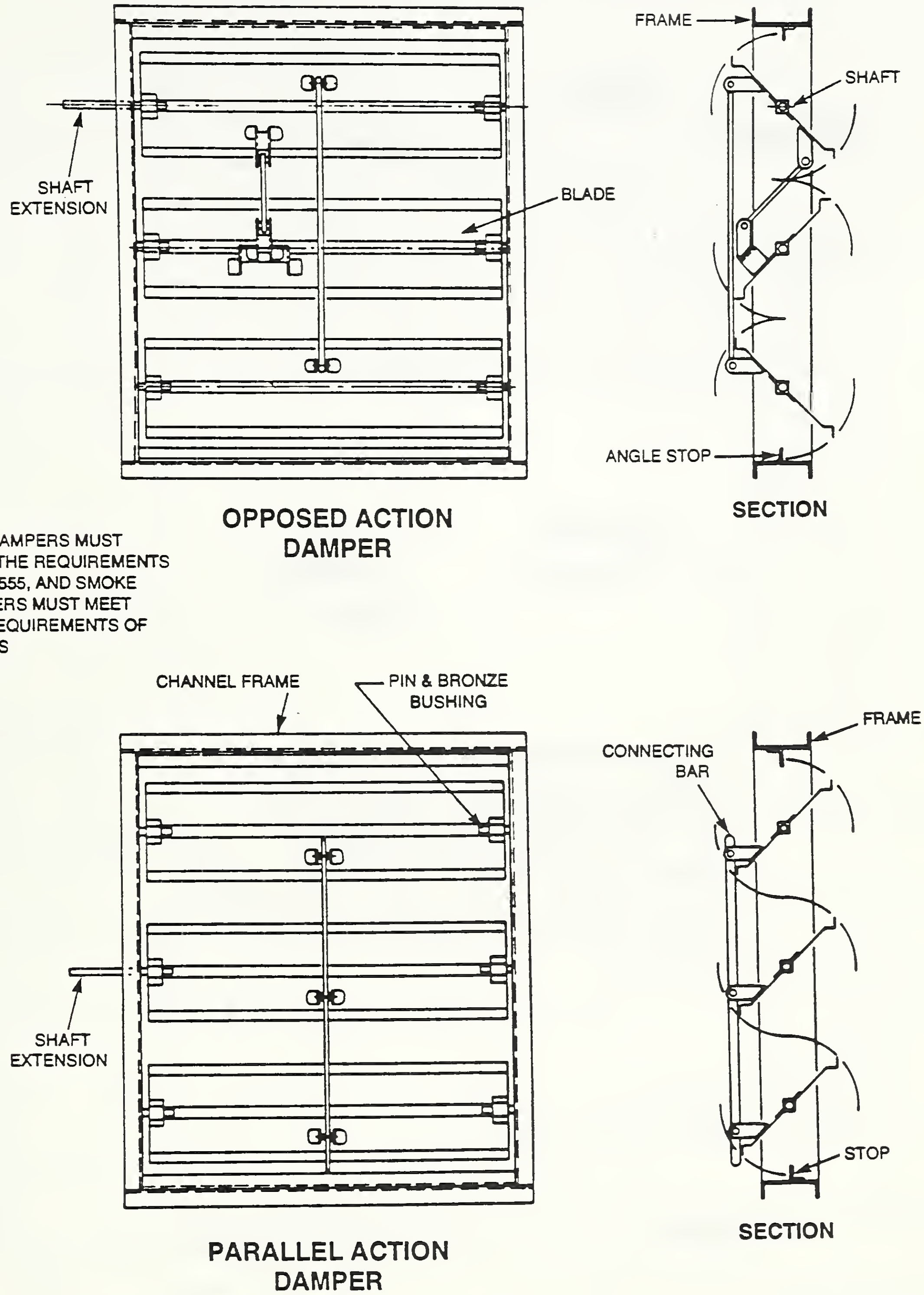

Figure 6.13 Multi-blade construction used for balancing, control, fire, and smoke dampers [adapted from SMACNA (1981)]

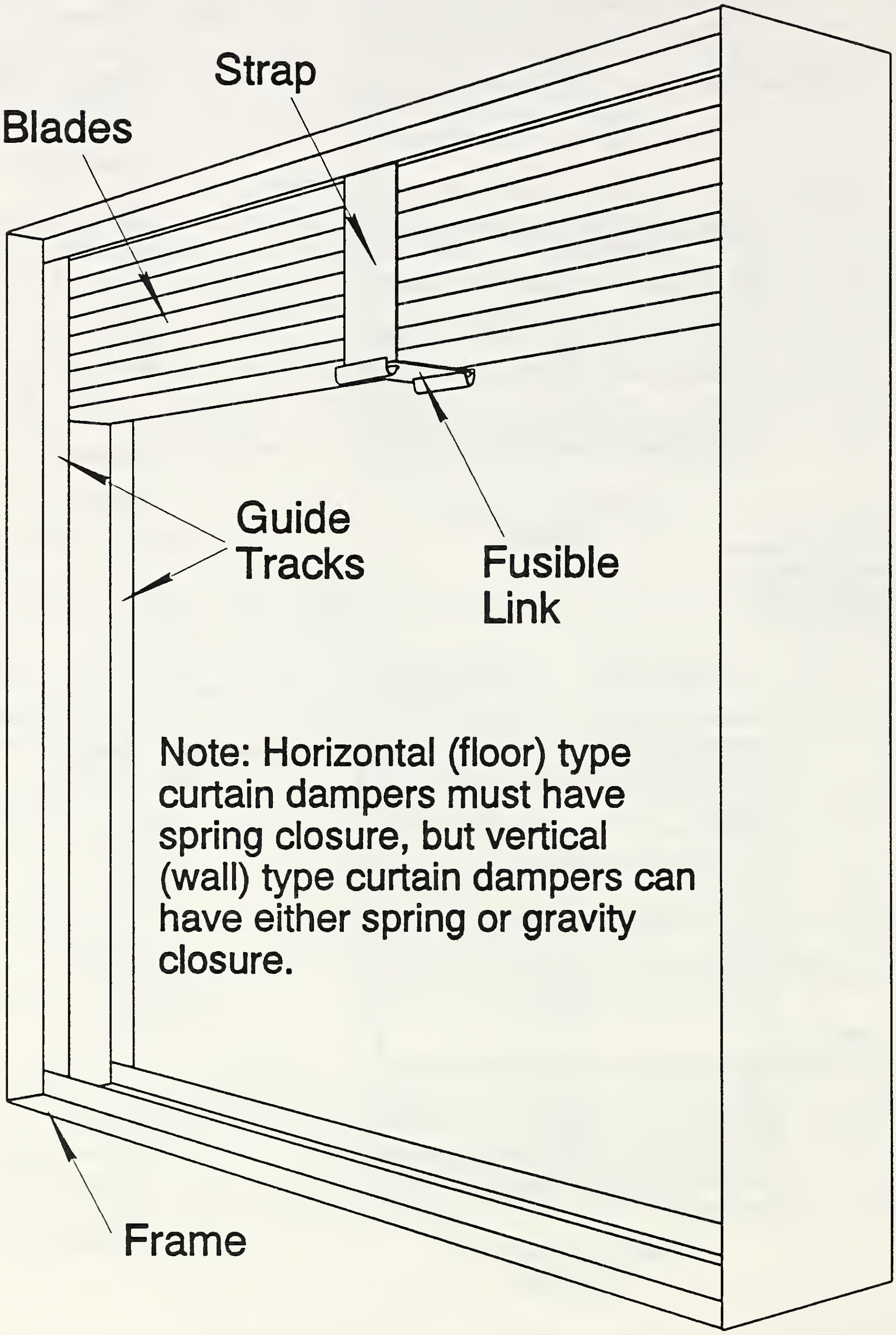

Figure 6.14 Curtain fire damper

Table 6.1 Leakage classifications for smoke dampers [adapted from UL 555S (UL 1983)]

Classification	Leakage, cfm/ft² At 1.0 Inches Water (0.249 kPa)	At 4.0 Inches Water (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 (1.99 kPa)	At 12 Inches Water (2.99 kPa)
0	0	0
I	11	14
II	28	35
III	112	140
IV	168	210

Note: 1 cfm/ft^2 = 0.00508 $m^3/(s\ m2)$

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Chapter 7. STAIRWELL PRESSURIZATION

Many pressurized stairwells are designed and built with the goal of providing a smoke-free escape route in the event of a building fire. A secondary objective is to provide a smoke-free staging area for fire fighters. On the fire floor, the design objective is to maintain a pressure difference across a closed stairwell door to prevent smoke infiltration into the stairwell.

Stairwells usually are pressurized by a single dedicated fan, but more than one dedicated fan can be used. Also, a fan normally used for some other purpose can be used to pressurize a stairwell in a fire situation. HVAC system fans have been so used with modulating dampers controlled by differential pressure sensors. However, many smoke control designers feel that the same fans should not be used for both the HVAC system and stairwell pressurization, because the dampers and controls needed only for the stairwell pressurization system may be damaged during HVAC system maintenance or modification. Accordingly, it is not surprising that most stairwell pressurization systems have dedicated fans. In this chapter, only systems with dedicated fans will be discussed. However, this material can be adapted by the designer who must design a system without dedicated fans.

The methods of analysis presented in this chapter consider the pressurized stairwell as part of a building system of connected flow paths. The performance of a pressurized stairwell depends on the flow areas from the stairwell to the building, on any flow areas from the stairwell directly to the outside, and on the other flow areas in the building. Air flows from a pressurized stairwell to the building, and then through other paths to the outside. These other paths include elevator shafts, toilet exhausts, kitchen exhausts, and leakage areas in the exterior walls of building. The methods of analysis presented in this chapter are for buildings where these other areas are significant for system performance. For buildings with unusually tight exterior walls or underground buildings, special building venting or exhaust may be necessary. Analysis of these special cases can be done with the ASCOS program (Chapter 5).

The methods of analysis of this chapter are for buildings where the only pressurization system is the pressurized stairwell. When other pressurization systems are present, the total building flow network including all the pressurization systems must be analyzed. For example, consider a building with two pressurized stairwell and a zoned smoke control system, where all three of these smoke control systems are intended to operate at the same time during a fire. Analysis of these systems must consist of analysis of all of the systems operating at the same time. Designs for the separate systems operating alone can not be "just added" together to get a realistic design for the three systems operating together. Later chapters present example calculations of multiple systems operating together.

7.1 PRESSURIZATION SYSTEMS

It is impossible to provide detailed design methods for the almost infinite number of possible stairwell pressurization systems. The intent of this book is to discuss, in general, some systemic considerations and alternatives and to provide detailed analyses of a few systems. For the analysis of other systems, designers can, in many cases, use the same principles employed in this manual to perform their own analyses.

7.1.1 Single and Multiple Injection

A single injection system is one that has pressurization air supplied to the stairwell at one location. The most common injection point is at the top as illustrated in figure 7.1. With this system, there is the potential for smoke feedback into the pressurized stairwell through the pressurization fan intake. Therefore, the capability of automatic shutdown in such an event should be considered.

For tall stairwells single injection systems can fail when a few doors near the air supply injection point are open. All of the pressurization air can be lost through these open doors, and the system will then fail to maintain positive pressures across doors further from the injection point. To prevent this, some smoke control designers limit the height of single injection stairwells to eight stories; however, other designers feel this limit can be extended to twelve stories. Careful design is recommended for single injection stairwells in excess of eight stories.

There is the potential for failure of a bottom injection system when the exterior door is opened. Some of the supply air can short circuit the system by flowing directly out the opened doorway. It is recommended that supply inlets be at least one floor above or below exterior doors.

Figures 7.2 and 7.3 are two examples of many possible multiple injection systems that can be used to overcome the limitations of single injection systems. In figures 7.2 and 7.3, the supply duct is shown in a separate shaft. However, systems have been built that have eliminated the expense of a separate duct shaft by locating the supply duct in the stairwell itself. If the duct is located inside the stairwell, care must be taken that the duct does not become an obstruction to orderly building evacuation.

Many multiple injection systems have been built with supply air injection points on each floor. These represent the ultimate in preventing loss of pressurization air through a few open doors; however, that many injection points may not be necessary. There is some difference of opinion as to how far apart injection points can be safely located. Some designers feel that injection points should not be more than three floors apart, while others feel that a distance of eight stories is acceptable. For designs with injection points more than three stories apart, the designer should determine by computer analysis that loss of pressurization air through a few open doors does not lead to loss of stairwell pressurization.

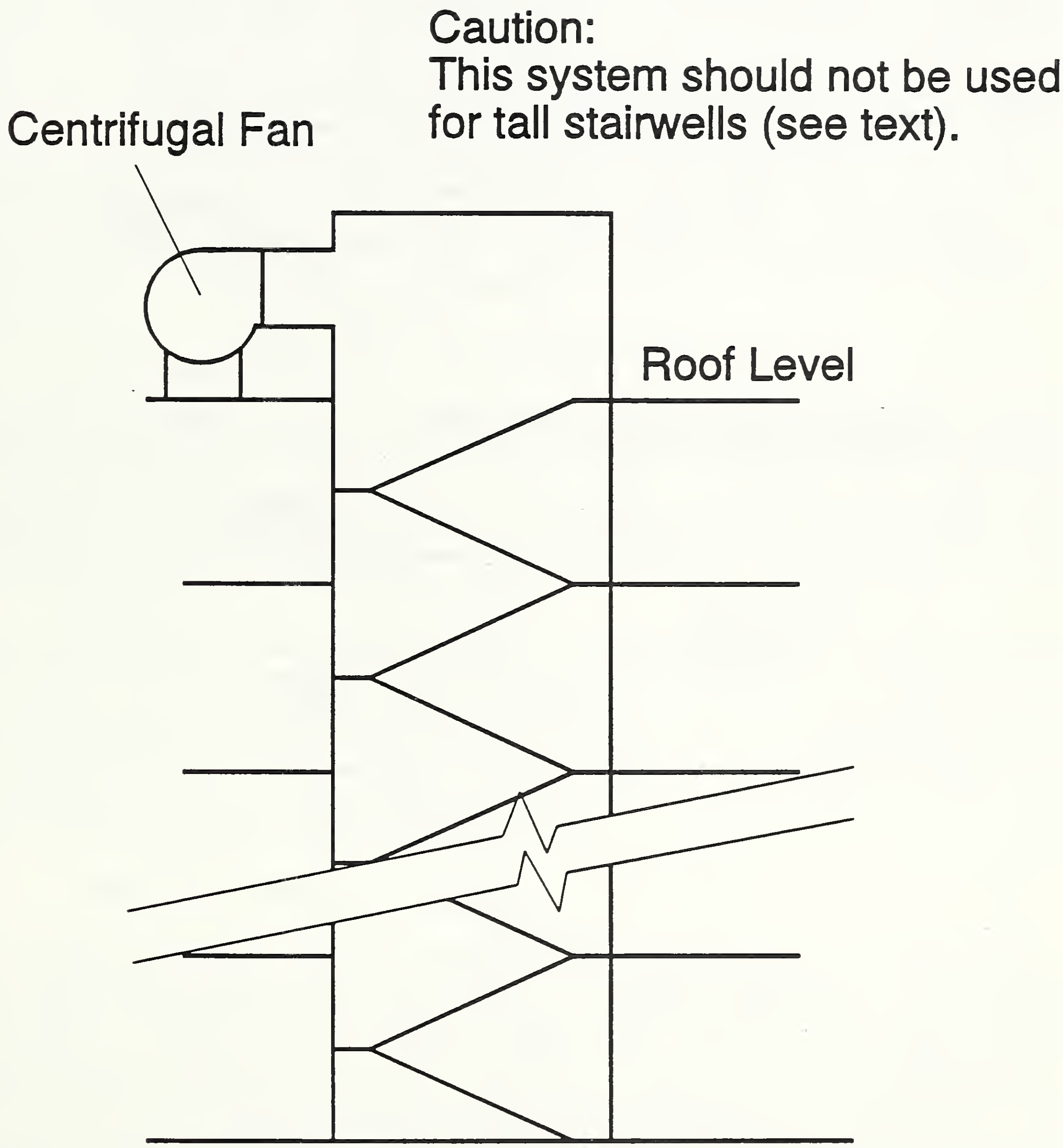

Figure 7.1 Stairwell pressurization by top injection

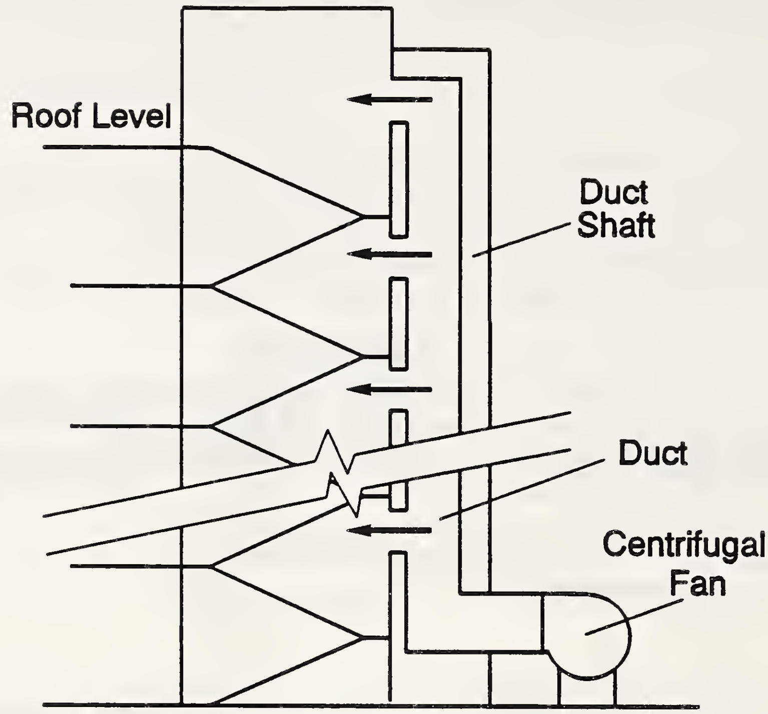

Figure 7.2 Stairwell pressurization by multiple injection with the fan located at ground level

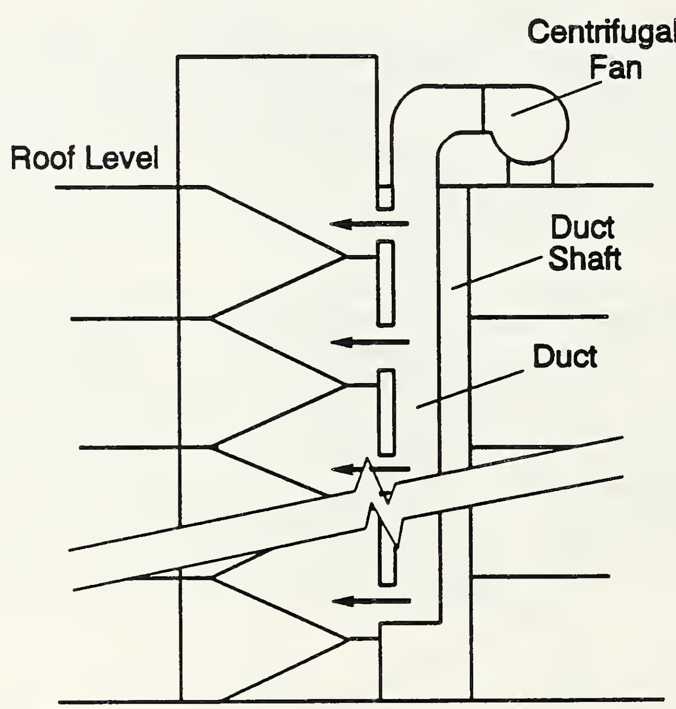

Figure 7.3 Stairwell pressurization by multiple injection with roof mounted fan

7.1.2 Compartmentation

An alternative to multiple injection is compartmentation of the stairwell into a number of sections, as illustrated in figure 7.4. The stairwell is divided into a number of sections or compartments, each compartment being from one to about eight floors high. The compartments are separated by walls with normally closed doors. Each compartment has at least one supply air injection point. The main advantage of compartmentation is that it allows satisfactory pressurization of stairwells that are otherwise too tall for satisfactory pressurization.

When the 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 the 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 operate successfully when the maximum number of doors between compartments are 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 space at the location of the compartmentation doors.

7.1.3 Vestibules

A number of pressurized stairwells have been built with vestibules, which can be either pressurized or not pressurized. Vestibules provide an additional barrier around a stairwell and, to some extent, a vestibule can reduce the possibility of an open-door connection existing between the stairwell and the building. An evacuation analysis can be performed to determine the extent to which both vestibule doors are likely to be opened simultaneously.

Analysis of a pressurized stairwell with an unpressurized vestibule can be performed using the same methods employed for analyzing a system without a vestibule, except that the effective leakage areas from the stairwell to the building would be used. These effective areas can be determined by methods presented in Chapter 3. No formal method of design analysis has been developed for pressurized stairwells with pressurized vestibules, and this topic is beyond the scope of this manual.

7.1.4 Supply Air Intakes

In the pressurization systems illustrated in figures 7.1, 7.2, and 7.3, centrifugal fans supply pressurization air to the stairwell. A shield around the intake should be considered to reduce adverse effects of wind on the fan performance. This is especially important for propeller fans which are more susceptible to wind effects than are other types of fan. Roof mounted-propeller fans should have wind shields as illustrated in figure 7.5. Because the horizontal component of wind is generally about ten times greater than the vertical component, wall-mounted propeller fans are extremely susceptible to

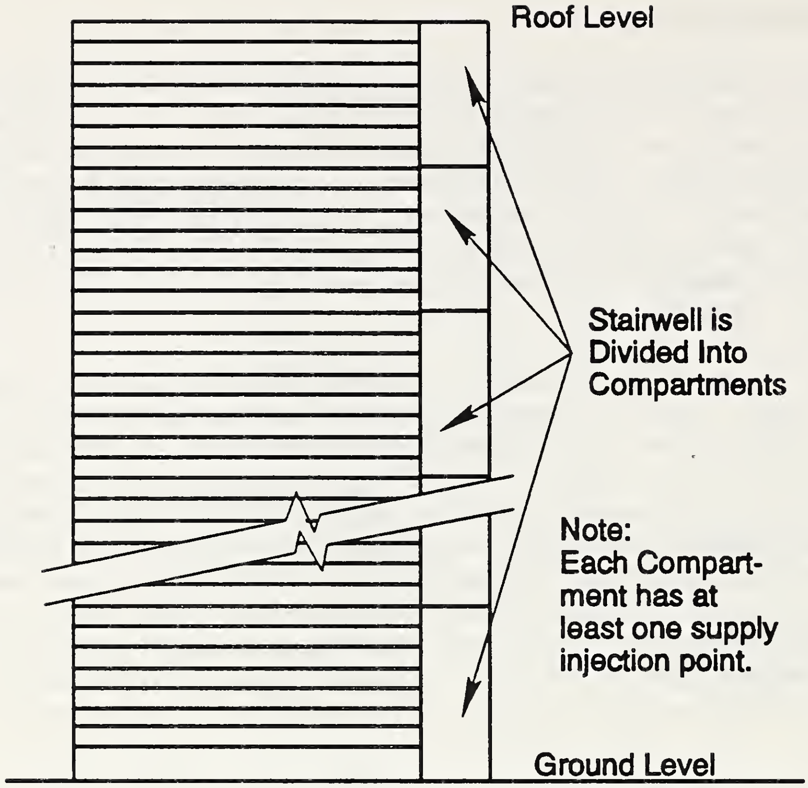

Figure 7.4 Compartmentation of a pressurized stairwell

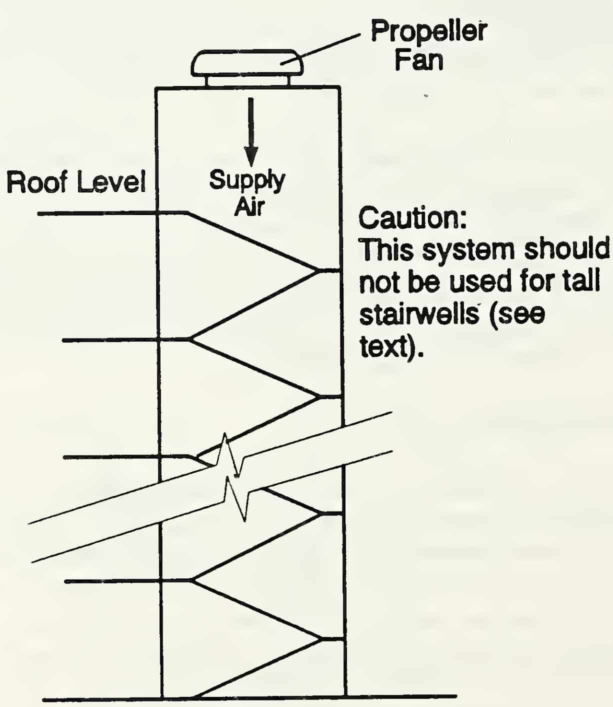

Figure 7.5 Stairwell pressurization by roof mounted propeller fan

wind effects. Alternatives to wall-mounted propeller fans should be used when possible. When wall-mounted propeller fans are used, they should have wind shields.

Outdoor smoke movement that might result in smoke feedback into supply air inlets depends on location of fire, location of points of smoke leakage from the building, wind speed and direction, and on the temperature difference between the smoke and the outside air. At present, no formal method of analysis has been developed for this complex outdoor airflow. However, some general recommendations can be made. The supply air intake should be separated from exhausts, outlets from smoke shafts and roof smoke and heat vents, or open vents from elevator shafts or other building openings that might expel smoke during a fire. These smoke outlets include the outlets from a zoned smoke control system. Ideally, this separation should be as great as is practically possible. Because hot smoke rises, consideration should be given to locating supply air intakes below such critical openings. A commonly used approach is to have all the supply air intakes near the bottom of the building and smoke outlets above roof level. Another approach is to have the supply air intakes on one side of the building and the smoke outlets on the other side and the roof.

7.2 PRESSURE PROFILES

The pressure differences across a stairwell normally vary over the height of the stairwell. Analysis of the pressure profiles of unpressurized shafts was presented in Chapter 3. The analysis of pressure differences in stairwells presented in this chapter is slightly more complicated in that pressurization is incorporated.

To facilitate analysis, the following discussion is limited to buildings that have the same leakage areas on each floor. Figure 7.6 shows pressure profiles for pressurized stairwells located in three buildings with different leakage characteristics, all of which have the same stairwell and outside temperatures. These profiles represent 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 of a pressurized stairwell is a straight line. The slope of that straight line depends on the temperature difference between the stairwell and the outside, and on the building leakage areas. This relation is discussed later in this Chapter.

Figure 7.6 shows typical pressure profiles of pressurized stairwells in a building with leakage between the floors and in a building without leakage between floors which are similar, except at the top and the bottom of the buildings. The extent of the deviation depends on the magnitude of the leakage area between floors. The pressure profiles depend on the leakage areas of the stairwell, the elevator shaft, and the exterior walls, as well as the temperatures of the building, the stairwell, and the outside air. Analysis of such a building is complicated and is generally feasible only with the aid of a computer.

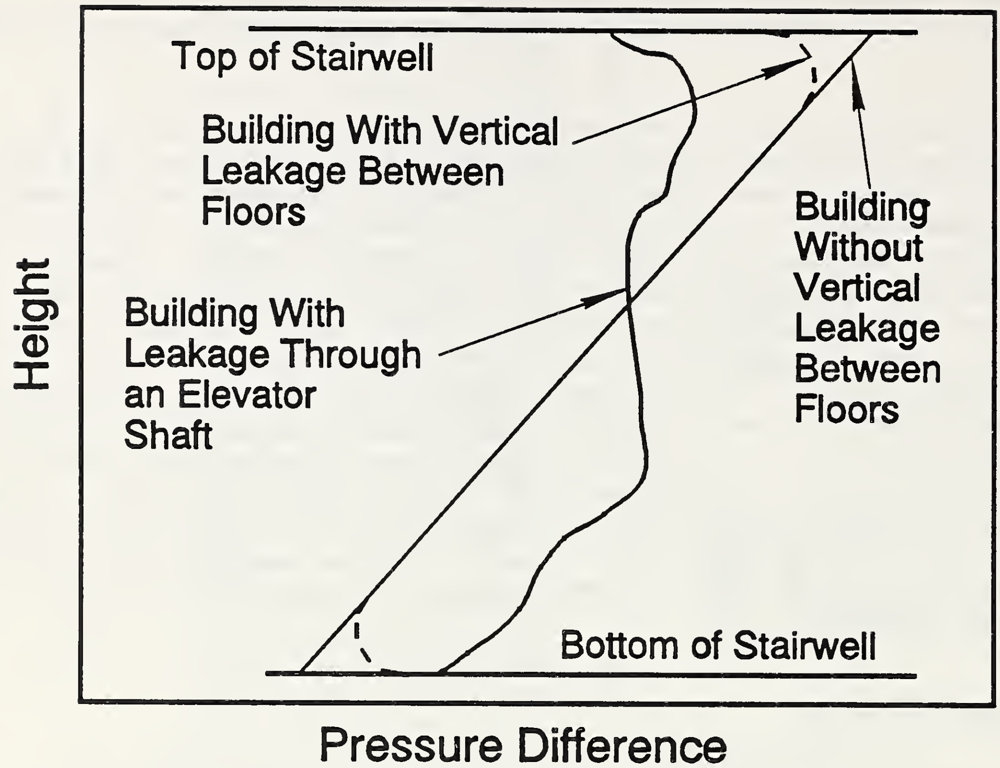

Figure 7.6 Pressure profile for pressurized stairwells in three buildings with different leakage characteristics

The pressure difference across a stairwell at one height can be much larger than at another height. Therefore, in addition to being concerned with the average pressure difference across a stairwell, a designer should also be concerned with both the minimum and the maximum pressure differences.

7.3 STAIRWELL ANALYSIS

In this section, a method of analysis is presented for a pressurized stairwell in a building without vertical leakage between floors. This is the same zero floor leakage idealization that was used for the analysis of stack effect in Chapter 3. The performance of pressurized stairwells in buildings without elevators may be closely approximated by the method of analysis developed in this section.

Neglecting the effects of leakage through floors and other shafts, increases the spread between the minimum and maximum pressure differences. In this sense the analysis is conservative. This analysis considers only one pressurized stairwell in a building, however, it can be extended to any number of stairwells by use of the concept of symmetry, discussed in Chapter 4. The initial analysis does not include consideration of open stairwell doors, but they are addressed later in this chapter.

This analysis is for buildings where the leakage areas are the same for each floor of the building and where the only significant driving forces are the stairwell pressurization system and the temperature difference between the indoors and outdoors.

7.3.1 Pressures

For many applications of pressurized stairwells, the vertical flows within the stair shaft are low enough so that friction losses can be neglected. This is particularly true of the simple stairwell system which has closed doors. Therefore, the absolute pressure in the stairwell is considered hydrostatic.

$$P_S = P_{Sb} - K_\rho \, \rho_S \, y \qquad (7.1)$$

where:
P_S = absolute air pressure in stairwell at elevation y, in H_2O (Pa)
P_{Sb} = absolute air pressure in stairwell at stairwell bottom, in H_2O (Pa)
ρ_S = air density within the stairwell, lb/ft^3 (kg/m^3)
y = distance above stairwell bottom, ft (m)
K_ρ = constant, 0.192 (9.8)

For the case where the wind velocity is essentially zero, the outside air pressure, P_O, is also hydrostatic and can be expressed in the same manner.

$$P_O = P_{Ob} - K_\rho \, \rho_O \, y \qquad (7.2)$$

where:
P_O = absolute air pressure at elevation y, in H_2O (Pa)
P_{Ob} = absolute air pressure at stairwell bottom, in H_2O (Pa)
ρ_O = air density outside the stairwell, lb/ft^3 (kg/m^3)

The pressure difference from the stairwell to the outside can be expressed as $\Delta P_{SO} = P_S - P_O$, and substituting equations (7.1) and (7.2) this is

$$\Delta P_{SO} = \Delta P_{SOb} + K_\rho \, y(\rho_O - \rho_S) \qquad (7.3)$$

where:
ΔP_{SO} = pressure difference at elevation y, in H_2O (Pa)
ΔP_{SOb} = pressure difference at the bottom of the stairwell, in H_2O (Pa)

The above analysis assumes no change in densities, ρ_S and ρ_O, with height resulting in a slight over-prediction of pressure difference. The magnitude of this over-prediction increases with height, and for a 100 story building the resulting error would be less than 4 percent. For purposes of this manual, this over-prediction is insignificant. By substituting the ideal gas law into equation (7.3), ΔP_{SO} can be expressed as a function of temperature.

$$\Delta P_{SO} = \Delta P_{SOb} + by \quad (7.4)$$

where

$$b = K_s \left(\frac{1}{T_O} - \frac{1}{T_S} \right) \quad (7.5)$$

and where:

b = temperature factor, in H_2O/ft (Pa/m)
T_O = absolute temperature of outside air, °R (K)
T_S = absolute temperature of stairwell air, °R (K)
K_s = coefficient, 7.64 (3460)

The effective flow area from the stairwell through the building to the outside is expressed on a per floor basis as

$$A_{SBOe} = \frac{A_{SB}\ A_{BO}}{\sqrt{A_{SB}^2 + A_{BO}^2}} \quad (7.6)$$

where:

A_{SBOe} = effective flow area between the stairwell and the outside, ft^2 (m^2)
A_{SB} = flow area between the stairwell and the building, ft^2 (m^2)
A_{BO} = flow area between the building and the outside, ft^2 (m^2)

The areas in this equation are those of the entire floor. In such a case, the pressure difference, ΔP_{SB}, between the stairwell and the building can be expressed as:

$$\Delta P_{SB} = \Delta P_{SBb} + \frac{by}{1 + (A_{SB}/A_{BO})^2} \quad (7.7)$$

The pressure differences ΔP_{SO} and ΔP_{SB} are related as follows:

$$\Delta P_{SB} = \frac{\Delta P_{SO}}{1 + (A_{SB}/A_{BO})^2} \quad (7.8)$$

which can be rewritten as

$$\Delta P_{SO} = \Delta P_{SB}\ [1 + (A_{SB}/A_{BO})^2] \quad (7.8a)$$

7.3.2 Pressurization Air

For the case where a stairwell is positively pressurized throughout (i.e., the direction of air flow is from the stairwell to the outside over the entire stairwell height), the flow from the stairwell to the outside can be written in differential form as:

$$dQ = CA_{he} \sqrt{\frac{2\ \Delta P_{SO}}{\rho}}\ dy \qquad (7.9)$$

The term A_{he} is the distributed effective flow area per unit height which is uniform vertically. This distributed flow area is expressed as

$$A_{he} = \frac{N\ A_{SBOe}}{H} \qquad (7.10)$$

where:
A_{he} = distributed effective flow area per unit height, ft (m)
H = stairwell height, ft (m)
N = number of floors

Substituting this and equation (7.4) into equation (7.9) gives:

$$dQ = \frac{N\ C\ A_{SBOe}}{H} \sqrt{2(\Delta P_{SOb} + by)/\rho}\ \ dy \qquad (7.9a)$$

This can be integrated from y = 0 to y = H to give the total flow, Q_{SBO}, from the stairwell to the building and to the outside.

$$Q_{SBO} = \frac{2}{3}\ N\ C\ A_{SBOe} \sqrt{\frac{2}{\rho}} \left[\frac{\Delta P_{SOt}^{3/2} - \Delta P_{SOb}^{3/2}}{\Delta P_{SOt} - \Delta P_{SOb}} \right] \qquad (7.11)$$

Where ΔP_{SOt} is the pressure difference between the stairwell and the outside at the stairwell top (y = H). Because the ΔP_{SB} is a linear function of ΔP_{SO} as expressed in equation (7.8), equation (7.11) can be written in terms of the pressure from the stairwell to the building. For C = 0.65, this becomes

$$Q_{SB} = K_q\ \frac{N\ A_{SB}}{\sqrt{\rho}} \left[\frac{\Delta P_{SBt}^{3/2} - \Delta P_{SBb}^{3/2}}{\Delta P_{SBt} - \Delta P_{SBb}} \right] \qquad (7.11a)$$

where:

Q_{SB} = volumetric flow rate of air from stairwell to building, cfm (m^3/s)
ρ = density of air in stairwell, lb/ft^3 (kg/m^3)
A_{SB} = flow area between the stairwell and the building when stairwell doors are closed, ft^2 (m^2)
N = number of floors
ΔP_{SBt} = pressure difference between the stairwell and the building at the stairwell top when all the stairwell doors are closed, in H_2O (Pa)
ΔP_{SBb} = pressure difference between the stairwell and the building at the stairwell bottom when all the stairwell doors are closed, in H_2O (Pa)
K_q = coefficient, 475. (0.613)

Because there is no vertical flow in the building, $Q_{SB} = Q_{SBO}$. This is the flow rate of supply air to the stairwell necessary to maintain the pressure differences, ΔP_{SBb} at the stairwell bottom and ΔP_{SBt} at the top.

In a building with vertical air leakage, the exact evaluation of the system would require that the effect of three or more columns of air at different temperatures be included. Such an analysis is cumbersome and for practical purposes a computer is needed. For this reason, the method of analysis presented in this section is based on a building without vertical leakage. In order to make this analysis conservative when applied to buildings with vertical leakage, the stairwell temperature is replaced by the building temperature. Thus equation (7.5) becomes:

$$b = K_s \left(\frac{1}{T_O} - \frac{1}{T_B} \right) \qquad (7.12)$$

where:

T_O = absolute temperature of outside air, °R (K)
T_B = absolute temperature of the air in the building, °R (K)
K_s = coefficient, 7.64 (3460)

For a building temperature of 70°F (21°C) and for winter conditions, the temperature factor, b, can be obtained from figure 7.7.

7.3.3 Average Pressure Difference

The average pressure difference can be defined as a pressure difference uniform over the stairwell height that would result in the same total flow as a nonuniform pressure profile. The flow from the stairwell can be expressed as:

$$Q = N A_e C \sqrt{2 \overline{\Delta P}/\rho} \qquad (7.13)$$

where $\overline{\Delta P}$ is the average pressure difference across the flow path. Equations (7.11), (7. 11a), and (7.12) can be combined and solved for ΔP to give:

$$\overline{\Delta P} = \frac{4}{9} \left(\frac{\Delta P_t^{3/2} - \Delta P_b^{3/2}}{\Delta P_t - \Delta P_b} \right)^2 \qquad (7.14)$$

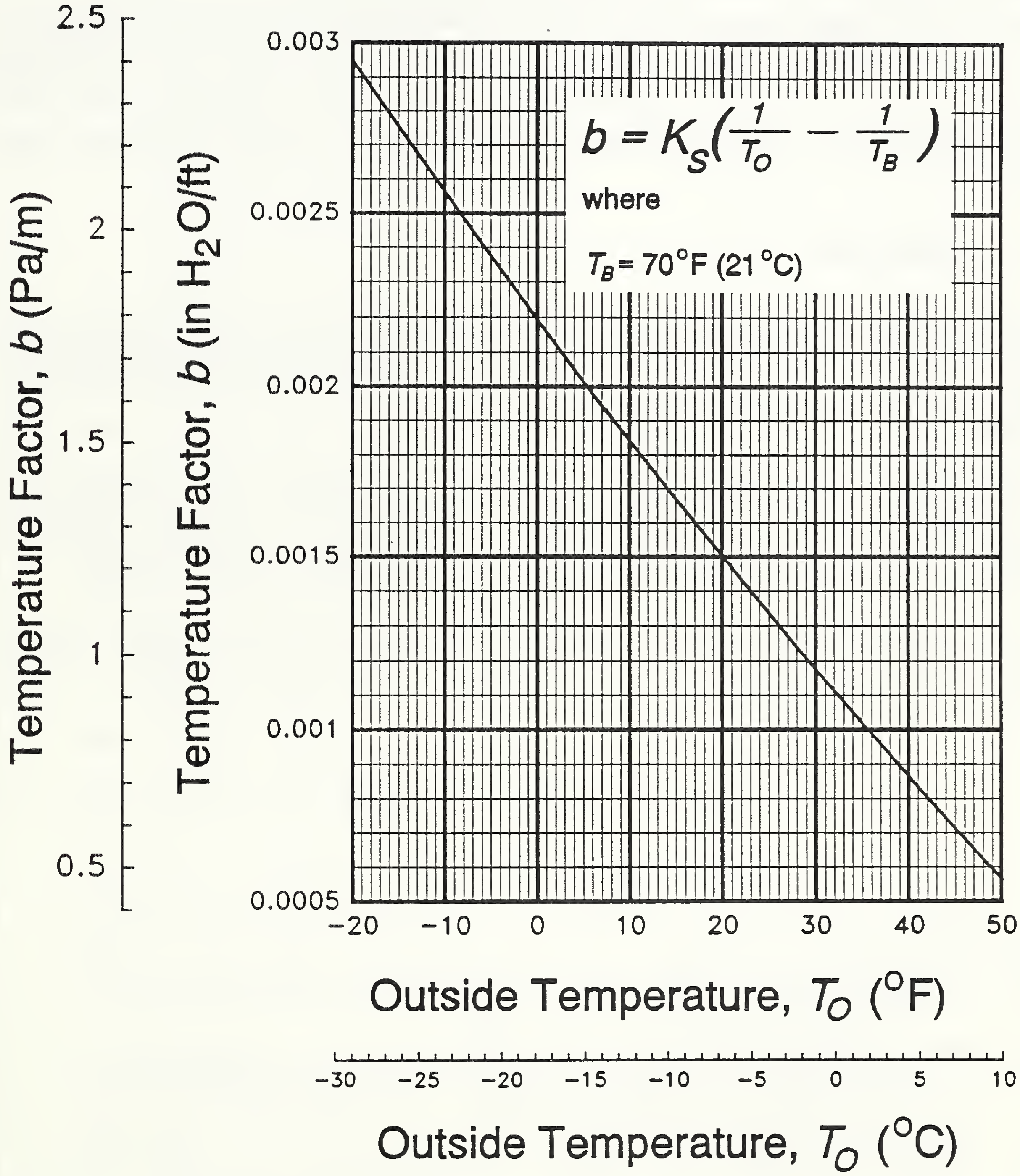

Figure 7.7 Temperature factor

The subscripts SB and SO have been eliminated from this equation, because it is applicable to flow from the stairwell to either the building or the outside. When applying equation (7.14) to flow from the stairwell to the building; $A_e = A_{SB}$, $\Delta P_b = \Delta P_{SBb}$, and $\Delta P_t = \Delta P_{SBt}$. When applying the equation to flow from the stairwell to the outside; $A_e = A_{SBOe}$, $\Delta P_b = \Delta P_{SOb}$, and $\Delta P_t = \Delta P_{SOt}$. Equation (7.14) can be approximated by:

$$\overline{\Delta P} = \frac{1}{2} (\Delta P_t + \Delta P_b) \qquad (7.15)$$

The maximum error in this relation is approximately 6 percent and occurs when $\Delta P_b = 0$.

7.4 HEIGHT LIMIT

As stated before, two problems with pressurized stairwells are that the minimum pressure difference may be too low to prevent smoke infiltration and that the maximum pressure difference may be too high making door opening forces difficult. These problems are most likely to exist in tall buildings during periods of extreme outside temperature.

In some cases, satisfactory pressurization of a stairwell can be impossible even when all the stairwell 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.

For a building without vertical leakage, equation (7.5) can be substituted into equation (7.7) and solved for the height limit, Hm, below which satisfactory pressurization is possible.

$$Hm = K_m \frac{(\Delta P_{max} - \Delta P_{min})}{\left| \frac{1}{T_O} - \frac{1}{T_B} \right|} \left[1 + \left(\frac{A_{SB}}{A_{BO}} \right)^2 \right] \qquad (7.16)$$

where:

Hm = height limit, ft (m)
ΔP_{max} = maximum allowable pressure difference between the stairwell and the building, in H_2O (Pa)
ΔP_{min} = minimum allowable pressure difference between the stairwell and the building, in H_2O (Pa)
T_O = outside design temperature, °R (K)
T_B = building temperature, °R (K)
A_{SB} = flow area between the stairwell and the building, ft^2 (m^2)
A_{BO} = flow area between the building and the outside, ft^2 (m^2)
K_m = coefficient, 0.131 (0.000289)

T_S was replaced by T_B in equation (7.16), so that the equation would yield conservative values of Hm for buildings with vertical leakage. In such buildings, the actual pressure profiles depend on three or more columns of air at different temperatures. If the stairwell temperature is between the outside temperature and the building temperature, then equation (7.16) will yield conservative results.

The absolute value of the temperature term is used in equations (7.16) so that the equation will apply to both winter conditions ($T_B > T_O$) and summer conditions ($T_O > T_B$). In many cases, A_{SB} is much smaller than A_{BO}, and, in such cases, equation (7.16) can be simplified to

$$Hm = K_m \frac{(\Delta P_{max} - \Delta P_{min})}{\left| \frac{1}{T_O} - \frac{1}{T_B} \right|} \tag{7.17}$$

The units for this equation are the same as those for equation (7.16). For a building temperature of 70°F (21°C) and for winter conditions, the height limit, Hm, can be obtained from figure 7.8.

Example 7.1 Evaluate the possibility of stair pressurization

Is it possible to pressurize a 150 ft (46 m) stairwell if the outside design temperature is 0°F (-18°C)? The minimum and maximum allowable pressure difference are:

ΔP_{min} = 0.05 in H_2O (12.4 Pa)
ΔP_{max} = 0.40 in H_2O (100. Pa)

Then $\Delta P_{max} - \Delta P_{min}$ = 0.40 - 0.05 = 0.35 in H_2O (87. Pa)

From figure 7.8 or equation (7.17) for T_O = 0°F (-18°C),
Hm = 160 ft (49 m)

Because Hm is greater than the height of the stairwell, satisfactory pressurization of the stairwell is possible. If Hm had been less than the stairwell height, it would not necessarily mean that satisfactory pressurization is impossible, because the estimate of Hm from equation (7.17) (Fig. 7.8) is conservative.

In such a case, a more exact analysis indicated that satisfactory pressurization was not possible at extreme outside temperatures, stairwell compartmentation may be used (see section 7.1.2). (Note that this example has nothing to do with single or multiple injection.)

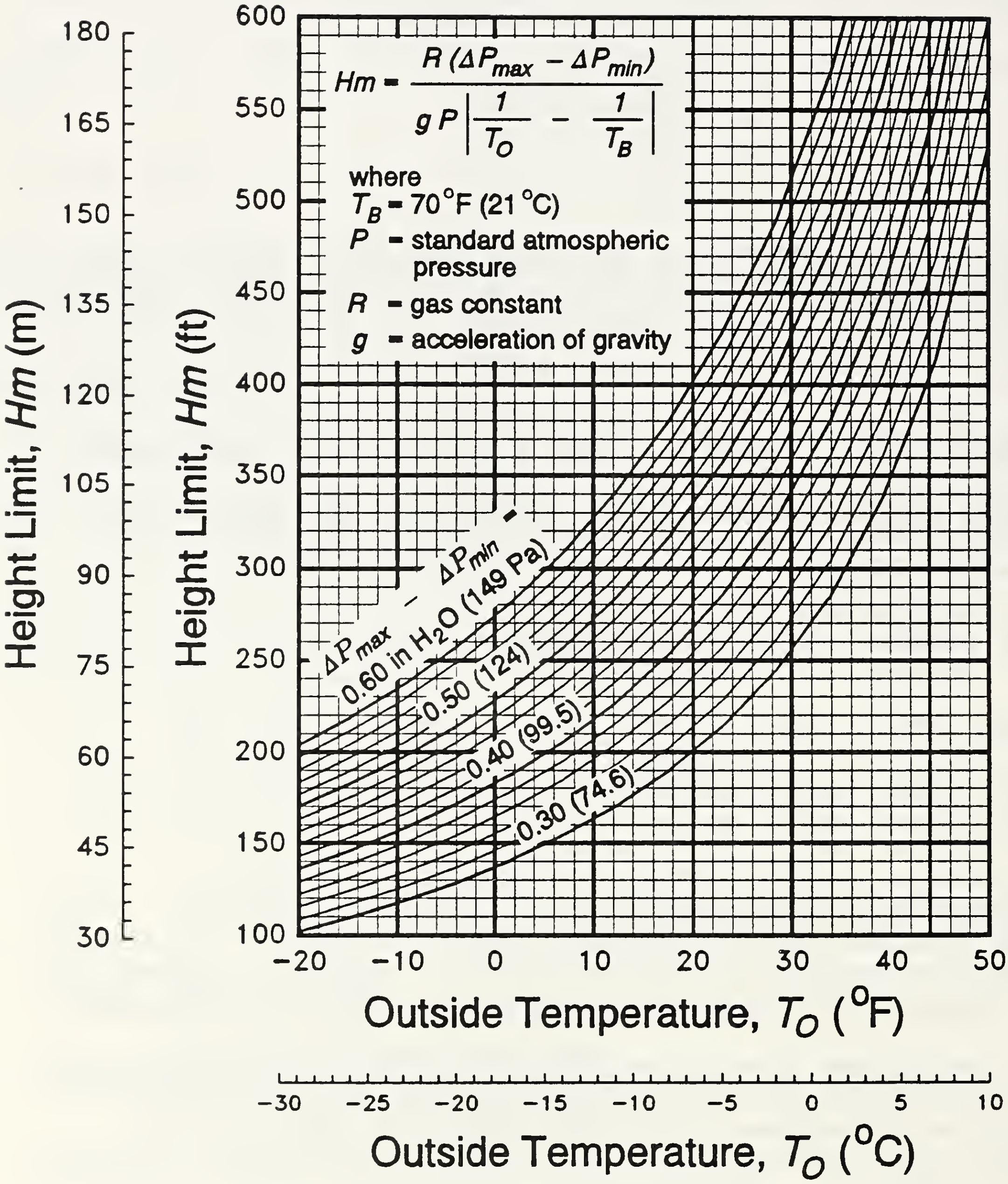

Figure 7.8 Height limit for a pressurized stairwell in a building without vertical leakage

7.5 SIMPLE STAIRWELL SYSTEMS

A simple stairwell system is one for which no design provisions have been made to overcome the drop in pressurization when one or more stairwell doors are opened. Analysis of the simple stairwell system forms a foundation for the analysis of systems with open doors.

Some of the stairwell doors must be opened during evacuation if the stairwell is being used. No consensus exists concerning appropriate applications of simple stairwell systems. A possible criterion for such an application is that smoke leakage during times of low pressurization will not adversely affect the use of the stairwell during evacuation. In a lightly populated building (for example telephone exchanges, luxury apartments), the stairwell doors may only be open for a few short intervals during a fire evacuation. Applications of the simple stairwell have so far been based on engineering judgement, because no formal method of analysis has been developed for evaluation of effects of intermittent smoke infiltration. Such an analysis would need to consider tenability conditions, evacuation analysis and flow analysis.

The simple stairwell system can use single or multiple injection. One or more fans are used, which can be a centrifugal, axial or propeller. When all the stairwell doors are closed, the system must maintain satisfactory pressurization. When stairwell doors are open, the pressure difference across closed stairwell doors usually drops to low levels [in the range of 0.01 in H_2O (3 Pa)]. These low levels are not sufficient to prevent smoke infiltration into the stairwell, and simple stairwell systems are only appropriate for applications for which stairwell doors are closed for almost all of the time during fire evacuation.

Example 7.2 is for two twenty story stairwells in the same building. Symmetry is used so that calculations are needed for only one stairwell. The same approach can be used for three or more stairwells. The flow rate of pressurization air is highly dependant on the leakage area. Because, these areas can only be roughly estimated in most situations, a safety factor is used in order to size the supply air fan. The supply system must be capable of adjustment, so that acceptable levels of pressurization can be obtained during system commissioning. The calculations of Example 7.2 are based on winter design temperatures. This is appropriate when the inside-to-outside design temperature difference for winter is greater than the outside-to-inside design temperature difference for summer. Otherwise, summer design data should be used. Examination of the weather data in ASHRAE Handbook of Fundamentals (1989), shows that winter design data is appropriate for design of simple systems for most locations around the world where data is provided. There are some exceptions where summer data should be used (such as Yuma, AZ; El Centro, CA; and New Delhi, India). For a design analysis, weather data should be examined to determine if summer or winter data should be used.

Example 7.2 Simple stairwell pressurization

Caution: the system does not take into account the effect the drop in pressurization when doors are opened. The design parameters for this simple system are: A_{SB} = 0.32 ft^2 (0.030 m^2), N = 20, H = 200 ft (61 m), T_0 = 14°F (-10°C) or 474°R (263 K), T_B = 70°F (21°C) or 530°R (294 K), ΔP_{max} = 0.40 in H_2O (100 Pa), and ΔP_{min} = 0.05 in H_2O (12.4 Pa). This analysis is of two stairwells in a building, and the concept of symmetry is used so that analysis of only one is necessary. Therefore, the flow area, A_{BO}, used in these calculations is half the estimated value for the whole building. The leakage area from the building to the outside is estimated at 2.54 ft^2 (0.236 m^2). Therefore, A_{BO} = 2.54/2 = 1.27 ft^2 (0.118 m^2).

Calculate the height limit from equation (7.16).

$$Hm = 0.131 \frac{(0.40 - 0.05)}{\left| \frac{1}{474} - \frac{1}{530} \right|} \left[1 + \left(\frac{0.32}{1.27} \right)^2 \right] = 219 \text{ ft (67 m)}$$

The height limit is greater than the height of the stairwell, so the equations presented in this chapter can be used for analysis. Calculate the temperature factor from equation (7.5).

$$b = 7.64 \left(\frac{1}{474} - \frac{1}{530} \right) = 0.00170 \text{ in } H_2O/\text{ft (1.39 Pa/m)}$$

Set ΔP_{SBb} = 0.05 in H_2O (12.4 Pa), and calculate the pressure difference at the top of the stairwell from equation (7.7).

$$\Delta P_{SBt} = 0.05 + \frac{0.0017\ (200)}{1 + (0.32/1.27)^2} = 0.37 \text{ in } H_2O \text{ (92 Pa)}$$

Calculate the flow from the stairwell to the building from equation (7.11a), using ρ = 0.075 lb/ft^3 (1.20 kg/m^3).

$$Q_{SB} = 475 \frac{20\ (.32)}{(0.075)^{1/2}} \left(\frac{0.40^{3/2} - 0.05^{3/2}}{0.40 - 0.05} \right) = 7{,}700 \text{ cfm (3.6 m}^3\text{/s)}$$

This flow rate is highly dependent on building leakage areas. Because these areas are difficult to determine, a safety factor, SF, should be used. For normal levels of uncertainty, SF = 1.5 is suggested. The design flow for each stairwell is then

$$Q = SF\ Q_{SB} = (1.5)\ (7700) = 11{,}600 \text{ cfm (5.5 m}^3\text{/s)}$$

The pressurization system must be designed so that the flow rate of the supply fan can be adjusted during system commissioning to accommodate the actual building leakage.

7.6 SYSTEMS WITH OPEN DOORS

As discussed in the preceding section, when any stair door opens in the simple stairwell pressurization systems, the pressure differences across closed doors drops significantly. However, opening the exterior stairwell door results in the largest pressure drop. This is because the airflow through the exterior doorway goes directly to the outside, while airflow through other open doorways must also go through other building paths to reach the outside. The increased flow resistance of the building means that less air flows through other doorways than flows through the open exterior doorway. The flow through the exterior doorway can be three to ten times that through other doorways, and the relative flow through the exterior doorway is greatest for tightly constructed buildings. Thus the exterior stairwell door is the greatest cause of pressure fluctuations due to door opening and closing.

For densely populated buildings, it can be expected that many stairwell doors will be open during fire evacuation. Accordingly, stairwell pressurization systems in such buildings should be designed to operate with some number of open doors. This design number of open doors depends heavily on the evacuation plan, and specific guidance about this number is beyond the scope of this manual.

Four types of systems intended to maintain acceptable levels of pressurization with all doors closed and with some doors opened are discussed in this section:

- System with "constant-supply" air rate and an exterior stairwell door that opens automatically upon system activation (Canadian System).
- System with "constant-supply" air rate and a barometric damper.
- System with variable-supply air rate.
- System using stairwell pressurization in combination with either fire floor venting or fire floor exhaust.

The following is a discussion of these systems, and further information about their relative advantages of the above systems is the subject of an ongoing research project at the National Research Council of Canada. Field tests of these different systems for stairwell pressurization were conducted by Butcher, Cottle, and Baily (1971), Dias (1978), and Tamura (1990a, 1990b, and 1990c).

7.6.1 Canadian System

The system with "constant-supply" air rate and an exterior stairwell door that opens automatically upon system activation is essentially the same as that in the Supplement to the National Building Code of Canada (1985). The supply air rate is not actually constant, but it varies to some extent with the pressure across the fan. For centrifugal fans this variation in flow rate can be small. However, the term "constant-supply" is used to differentiate this system from the ones with variable-supply air rates. Supply air can be introduced at one location, or the system can be multiple injection as illustrated in figure 7.9.

By eliminating opening and closing of the exterior stairwell door during system operation, the Canadian system eliminates the major source of pressure fluctuations. This system is simple to design and relatively inexpensive. Accordingly this system is recommended whenever it can meet the design requirements.

7.6.2 Systems with Barometric Dampers

This system has sufficient supply air when a design number of doors are open. When all the doors are closed, part of the supply air is relieved through a vent to prevent excessive pressure buildup. This excess air can be vented to the building or to the outside. Exterior vents can be subjected to adverse effects of the wind, so wind shields are recommended. Barometric dampers that close when the pressure drops below a specified value can be used to minimize air losses through a vent when doors are open. Figure 7.10 illustrates a system vented to the building at each floor. In systems built with vents between the stairwell and the building, the vents typically have one or more fire dampers in series with the barometric damper. As an energy conservation feature, these fire dampers are normally closed and open when the pressurization system is activated. This arrangement can reduce the possibility of annoying damper chatter that frequently occurs with barometric dampers.

7.6.3 Systems with Variable-Supply Air Rate

Systems with variable-supply air can be used to provide overpressure relief. The variable flow rate can be achieved by a using one of the many fans commercially available for variable flow rate. Alternatively, a fan bypass arrangement of ducts and dampers can be used to vary the flow rate of supply air to the stairwell. The variable flow fans are controlled by one or more static pressure sensors that sense the pressure difference between the stairwell and the building. When doors are opened, the stairwell pressure drops and the flow rate of supply air is increased to achieve at least the minimum design pressurization. When all the doors are closed, the stair pressure increases and the flow rate is reduced to prevent excessive pressure differences.

In the bypass system, the flow rate of air into the stairwell is varied by modulating bypass dampers, which also are controlled by one or more static pressure sensors that sense the pressure difference between the stairwell and

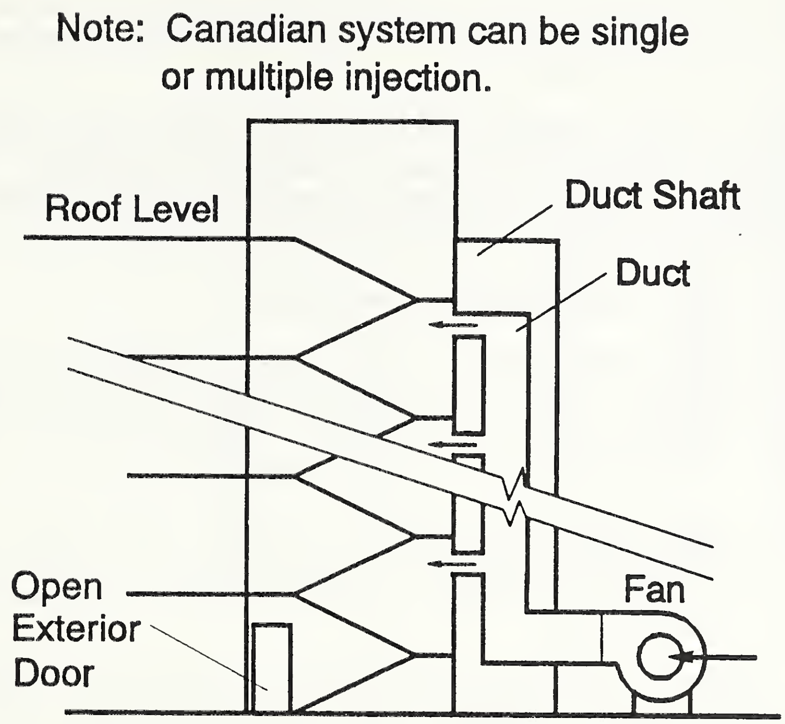

Figure 7.9 Canadian system has exterior door that opens automatically on system activation

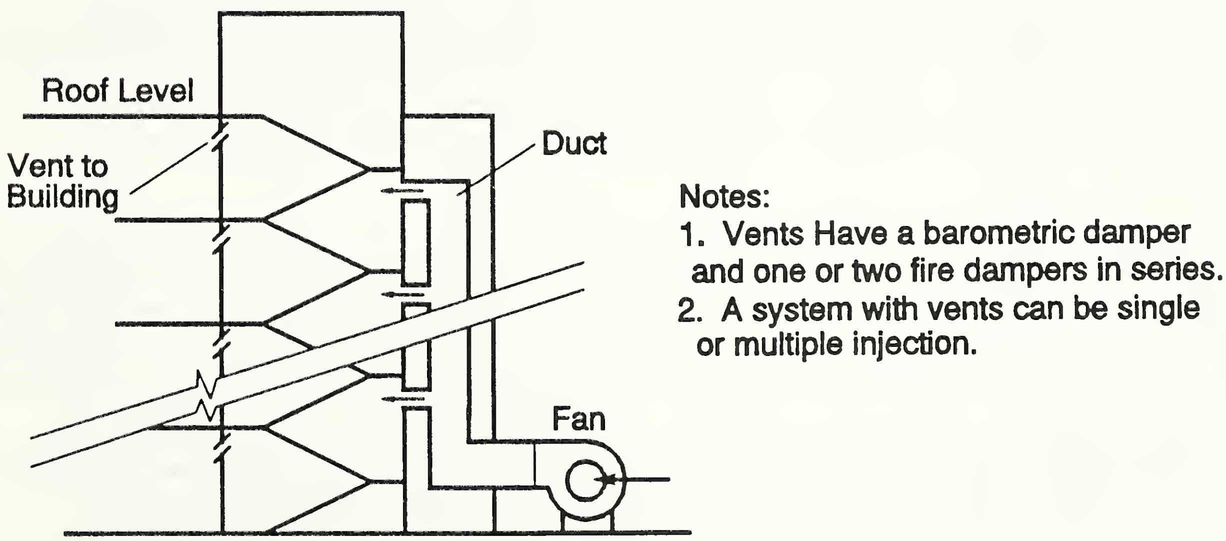

Figure 7.10 Stairwell pressurization with vents to the building at each floor

the building. The system operates in essentially the same way as the variable flow fan systems to prevent excessive pressure differences and the provide at least the minimum design pressure.

The response times of these systems depend on the particular components used for the pressurization system including the feedback controls. Figures 7.11 and 7.12 show response times of systems tested at the experimental fire tower of the National Research Council of Canada (Tamura 1990b).

7.6.4 System with Fire Floor Venting and Exhaust

Smoke venting and smoke exhaust of the fire floor can improve the performance of a pressurized stairwell. This smoke removal may or may not be part of a zoned smoke control system (Chapter 9). Smoke removal can be accomplished by exterior wall vents, smoke shafts, and fan powered exhaust.

Besides providing a path for smoke removal, exterior wall vents allow an increased pressure difference across the closed stairwell door on the fire floor. Venting the fire floor can also aid fire fighters in smoke purging after the fire has been put out.

Smoke shafts are similar to external wall vents, except that smoke from the fire floor is vented through a shaft. The venting is aided by buoyancy forces of hot smoke. Smoke shafts should be constructed in accordance with local codes; specific engineering data regarding sizing of smoke shafts is available from Tamura and Shaw (1973).

7.7 ANALYSIS OF SYSTEMS WITH OPEN DOORS

The analytical approach developed for simple stairwell systems can be extended to pressurized stairwells with open doors provided that the friction looses due to airflow in the stairwell are negligible. Friction losses can be minimized by having a multiple injection system designed to minimize vertical airflow in the stairwell. Because the pressure losses due to friction are insignificant, the pressure differences described by equations (7.4), (7.7), (7.8), and (7.12) apply for both summer and winter conditions as is illustrated in figure 7.13.

When all the doors are closed, the pressure differences are linear as illustrated in figure 7.13 (a) and (b). As expected, the pressure differences increase with elevation in winter and decrease with elevation in summer. When a door to the outside is opened, the pressure difference across it increases as shown in figure 7.13 (c) and (d). This means that the flow through an open exterior doorway can be very large. This is especially true during the summer, when the pressure difference is greatest at the shaft bottom where most exterior doors are located [figure 7.13 (d)]. When doors are opened to the building, the pressure difference across the open doorway drops significantly as illustrated in figure 7.13 (c) and (d). However, the flow through the large area of an opened doorway can be very large, as can be seen from the examples discussed later.

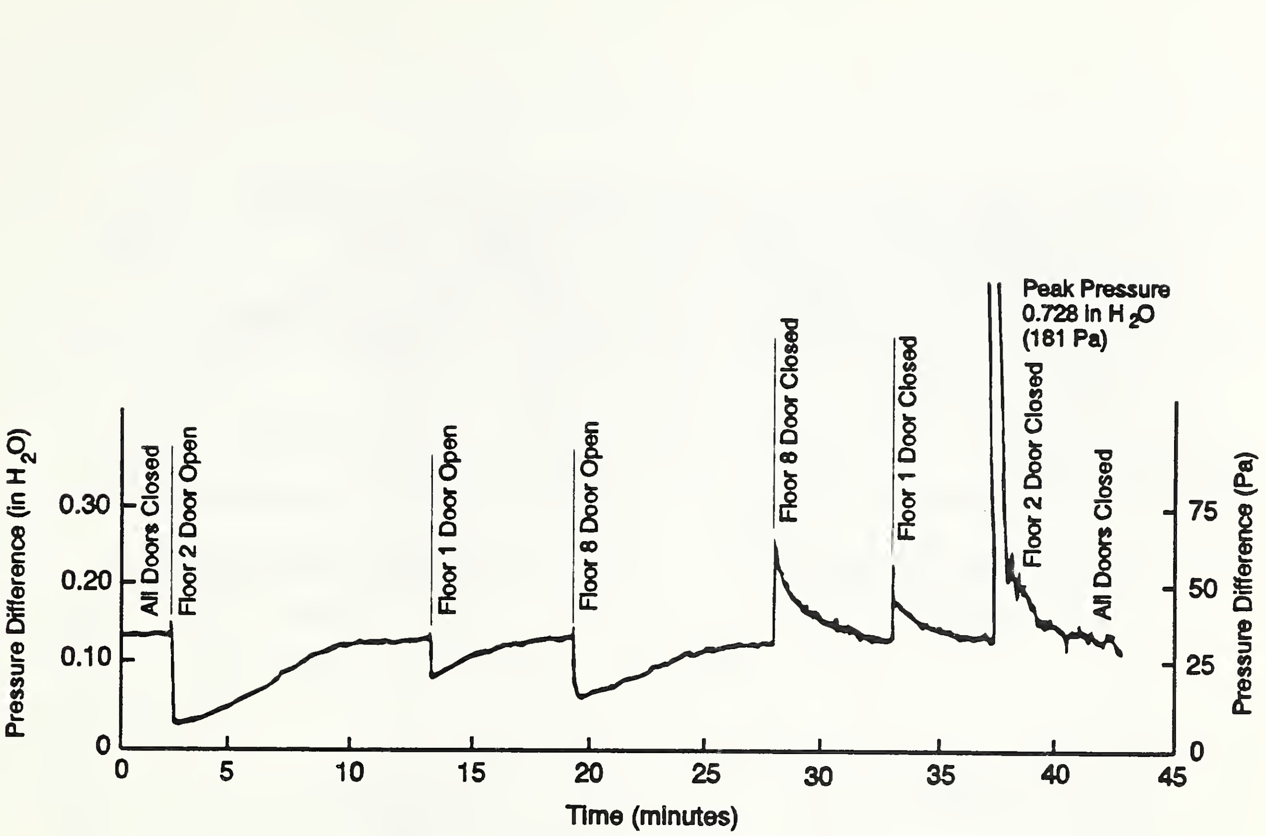

Figure 7.11 Response time of stairwell pressurization system with variable-supply air fan system [adapted from Tamura (1990b)]

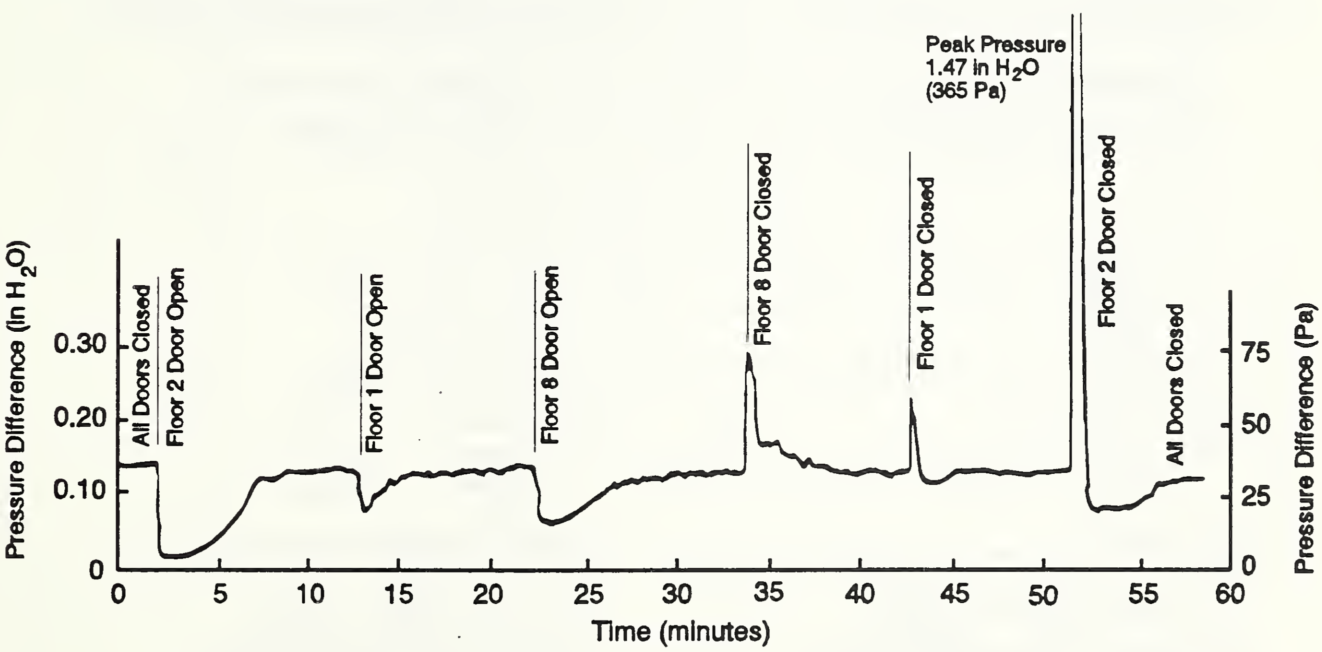

Figure 7.12 Response time of stairwell pressurization system with bypass system [adapted from Tamura (1990b)]

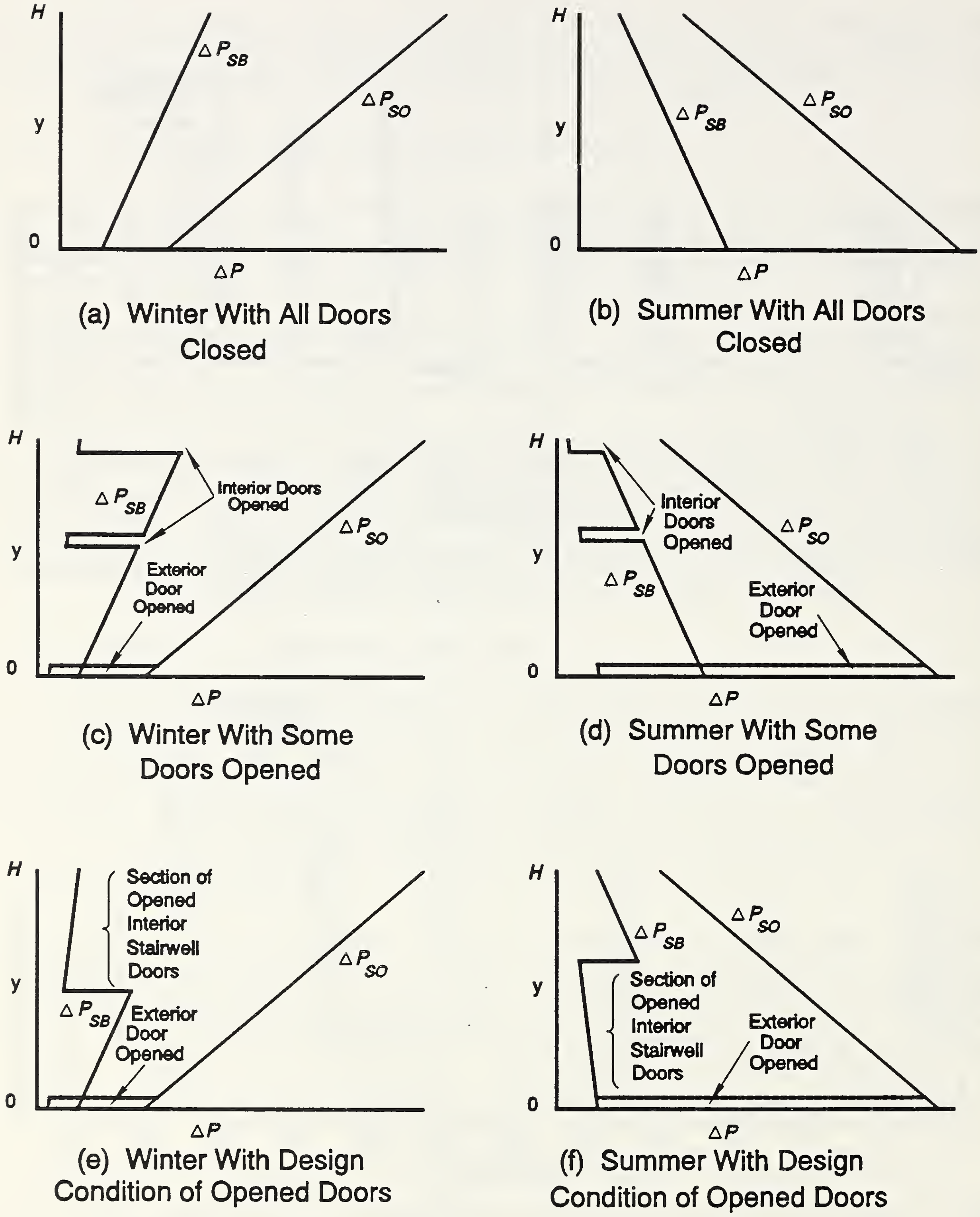

Figure 7.13 Pressure differences with closed and opened stairwell doors

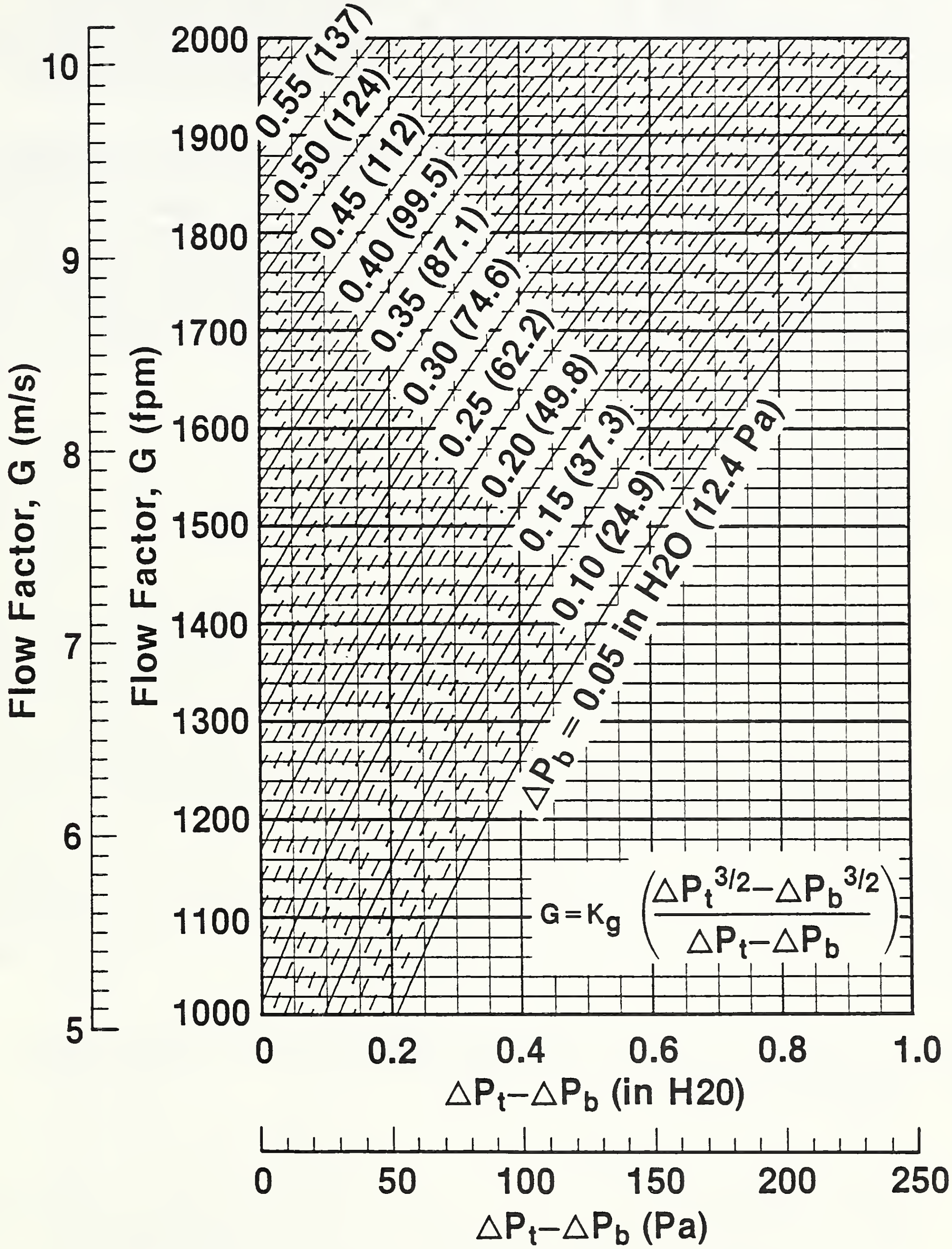

Figure 7.14 Flow factor

In the winter, the pressure difference across opened doors increases with elevation. The greatest amount of pressurization air is needed when the design number of opened doors are located in a section at the top of the stairwell, as illustrated in figure 7.13 (e). This forms a conservative winter design condition. The conservative summer design condition is for the opened doors to form a section at the bottom of the stairwell as in figure 7.13 (f).

Equations (7.11) applies when the effective flow area between the stairwell and the building is the same for each floor. When some doors and opened and others closed, this flow area varies from floor to floor. Equations (7.11) and (7.11a) can be applied piecewise to vertical stairwell sections, where the values of A_{SB} are the same at each floor, and where the values of A_{BO} are the same at each floor. Both of these areas are used to calculate the pressure differences, and the effective flow area. Equation (7.11) and (7.11a) can be written in a general form for $C = 0.65$ and $\rho = 0.075$ lb/ft (1.20 km/m) as

$$Q = G\ N\ A_e \tag{7.18}$$

where:
Q = volumetric flow rate from the section, cfm (m/s)
N = number of floors in section
A_e = effective flow area per floor from stairwell, ft^2 (m^2)
G = the flow factor, fpm (m/s)

$$G = K_g \left(\frac{\Delta P_t^{3/2} - \Delta P_b^{3/2}}{\Delta P_t - \Delta P_b} \right) \tag{7.19}$$

where:
ΔP_b = pressure difference at the bottom of the section, in H_2O (Pa)
ΔP_t = pressure difference at the top of the section, in H_2O (Pa)
K_g = coefficient, 1740 (0.559)

The two equations above can be used to calculate either Q_{SB} or Q_{SO}. When calculating Q_{SB}, A_e and the two pressure differences are from the stairwell to the building. When calculating Q_{SO}, A_e and the two pressure differences are from the stairwell to the outside. The flow factor, G, can be obtained from figure (7.14).

Flows directly to the outside are handled differently from those to the building. For the doors, vents or other openings directly to the outside, the flow can be expressed as

$$Q_{SO} = K_o C A_{SO} \sqrt{\frac{2\ \Delta P_{SO}}{\rho}} \tag{7.20}$$

where:

Q_{SO} = volumetric flow rate from stairwell to outside, cfm (m^3/s)
C = dimensionless flow coefficient
A_{SO} = flow area between stairwell and outside, ft^2 (m^2)
ΔP_{SO} = pressure difference from stairwell to outside, in H_2O (Pa)
ρ = density gas in path, lb/ft^3 (kg/m^3)
K_o = coefficient, 776. (1.00)

The pressure difference is not always constant over the opening, therefore the pressure difference, ΔP_{SO}, should be evaluated at the mid-height of the opening.

Design calculations for a ten story Canadian system are presented as Examples 7.3, 7.4 and 7.5. Analysis in these examples is only of one stairwell, but it can be thought of as being applicable to any number by application of symmetry. The flow area, A_{BO}, is on a per stairwell basis. Example 7.3 and Example 7.4 show calculations of the pressurization air for a winter design temperature of 14°F (-10°C) and a summer design temperature of 94°F (34°C). It is an unusual occurrence that the total pressurization air calculated for both design temperatures is the same [17,500 cfm (8.26 m^3/s)]. As expected from observation of figure 7.13 (e) and (f), the flow through the open exterior doorway is greater for summer than winter [9,200 cfm (4.3 m^3/s) in summer and 6,800 cfm (3.2 m^3/s) in winter]. For a taller stairwell, the flow through the exterior doorway in summer would be even greater.

As with the simple stairwell system, safety factors are needed to size the supply air fan or fans. These safety factors account for deviations in flow areas from the values used in design calculations. The leakage from the stairwell to the building is dependant on two flow areas, A_{SB} and A_{BO}. The flow through an open exterior doorway is dependant on only one flow area, A_{SO}. Thus, it seems that the safety factor should be greater for flows from the stairwell to the building than for flows directly to the outside. This approach to safety factors is illustrated in Example 7.5. In this example, the supply air is injected at each floor to minimize the effect of pressure losses due to friction. If analysis of the pressure losses due to friction is desired, the computer approach discussed in the next section is recommended.

Example 7.3 Winter Analysis Stairwell With Opened Doors

A Canadian stairwell pressurization system (see text for description) is to be designed for interior doors on 8 of its 10 floors opened. The other design parameters are: A_{BO} = 1.27 ft^2 (0.118 m^2), A_{SB} = 0.32 ft^2 (0.030 m^2) with stairwell door closed, A_{SB} = 10.5 ft^2 (0.975 m^2) with stairwell door opened, T_O = 14°F (-10°C) or 474°R (263 K), T_B = 70°F (21°C) or 530°R (294 K), ΔP_{max} = 0.40 in H_2O (100 Pa), and ΔP_{min} = 0.05 in H_2O (12.4 Pa). Because the design temperatures are the same as for example 7.2, the temperature factor is 0.00170 in H_2O/ft (1.39 Pa/m). In order to assure that the stairwell is adequately pressurized at all levels, the pressure difference at bottom of the stairwell door to the building is selected as 0.05 in H_2O (12.4 Pa), when that door is closed. Symmetry can be used to extend this analysis for any number of stairwells in a building. As with Example 7.2, A_{BO} is estimated on a per stairwell basis.

Closed Door Section

The winter design condition consists of a section of opened doors from the stairwell top down, with the rest of the doors forming a section of closed doors near the bottom of the stairwell. For the section of closed doors, the flow from the stairwell to the building will be evaluated, and the following values are used: N = 2, $\Delta P_b = \Delta P_{SB}$ at y = 0, $\Delta P_t = \Delta P_{SB}$ at y = 20 ft (6.1 m), and $A_e = A_{SB}$. As selected ΔP_b is 0.05 in H_2O (12.4 Pa). From equation (7.7), $\Delta P_t = 0.05 + (0.0017 \times 20)/(1+ (0.32/1.27)^2) = 0.082$ in H_2O (20.4 Pa). From equation (7.19), $G = 1740[(0.082^{3/2} - 0.05^{3/2})/(0.082 - 0.05)] = 669$ fpm (3.40 m/s). From equation (7.18), $Q_{SB} = G\ N\ A_{SB} = 669\ (2)\ (0.32) = 400$ cfm (0.2 m^3/s).

Opened Door Section

For the section of opened doors, the flow from the stairwell to the outside will be evaluated, and the following values are used: N = 8, $\Delta P_b = \Delta P_{SO}$ at y = 20 ft (6.1 m), $\Delta P_t = \Delta P_{SO}$ at y = 100 ft (30.5 m), and $A_e = A_{SBOe}$. First, ΔP_{SOb} must be evaluated. From equation (7.8a), $\Delta P_{SOb} = 0.05\ [1+(0.32/1.27)^2] = 0.053$ in H_2O (13.2 Pa). The pressure differences, ΔP_b and ΔP_t, are calculated from equation (7.4) as follows: $\Delta P_b = 0.053 + 0.0017(20) = 0.087$ in H_2O (21.7 Pa) and $\Delta P_t = 0.053 + 0.0017(100) = 0.223$ in H_2O (55.5 Pa). From equation (7.19), $G = 1740\ [(0.223^{3/2} - 0.087^{3/2})/(0.223 - 0.087) = 1020$ fpm (5.18 m/s). From equation (7.6), $A_{SBOe} = [10.5(1.27)/(10.5^2 + 1.27^2)^{½}] = 1.26$ ft (0.117 m^2) From equation (7.18), $QSO = G\ N\ A_{SBOe} = 1020\ (8)\ 1.26 = 10{,}300$ cfm (4.9 m^3/s)

Exterior Stairwell Door

Estimate the flow through the opened exterior doorway with air density of 0.075 lb/ft^3 (1.20 kg/m^3) and at y = 5 ft (1.5 m). The pressure difference is calculated from equation (7.8a) as $\Delta P_{SO} = 0.053 + 0.0017(5) = 0.062$ in H_2O (15.4 Pa). From equation (7.20), $Q_{SO} = 776(.65)(10.5)[2(0.062)/0.075]^{½} = 6800$ cfm (3.2 m^3/s).

Total Flow Needed During Winter

The total flow needed to pressurize the stairwell in winter is the sum of these separate flows: 400+10,300+6800 = 17,500 cfm (8.26 m^3/s). The flows must also be evaluated at summer design temperatures, a safety factor needs to be applied, and flows must be distributed so that shaft friction losses are not a problem. These calculations are done in the following examples.

Example 7.4 Summer Analysis Stairwell With Opened Doors

This analysis is of the Canadian stairwell pressurization system of example 7.3 except that it is for summer design temperature of 94°F (34°C) or 554°R (308 K). From equation (7.12), b = 7.64[(1/554)-(1/530)] = -0.000625 in H_2O/ft (-0.510 Pa/m). The pressure difference at top of the stairwell door to the building is selected as 0.05 in H_2O (12.4 Pa), when that door is closed.

Opened Door Section

The summer design condition for opened doors is that they are located on the first eight floors. The following values are used: N = 8, $\Delta P_b = \Delta P_{SO}$ at y = 0, $\Delta P_t = \Delta P_{SO}$ at y = 80 ft (24.4 m), and $A_e = A_{SBOe}$. From equation (7.8a), $\Delta P_{SOt} = 0.05\ [1 + (0.32/1.27)^2]$ = 0.053 in H_2O (13 Pa). From equation (7.4), $\Delta P_{SOb} = \Delta P_{SOt} - bH$ = 0.053 - (-0.000625)(100) = 0.116 in H_2O (28.9 Pa). By definition, $\Delta P_b = \Delta P_{SOb}$ = 0.116 in H_2O (28.9 Pa). From equation (7.4), ΔP_t = 0.116 + (-0.000625)80 = 0.066 (16.4 Pa). From equation (7.19), G = 1740 $[(0.066^{3/2} - 0.116^{3/2})/(0.066 - 0.116)$ = 785 fpm (4.00 m/s). From Example 7.3, A_{SBOe} = 1.26 ft (0.117 m^2). From equation (7.18), Q = 785 (8) (1.26) = 7,900 cfm (3.7 m^3/s).

Closed Door Section

This section calculates the flow through gaps and other leakage paths at the top two floors of the stairwell. The following values are used: N = 2, $\Delta P_b = \Delta P_{SB}$ at y = 80 ft (24.4 m), $\Delta P_t = \Delta P_{SB}$ at y = 100 ft (30.5 m), and $A_e = A_{SB}$. ΔP_{SBt} was selected to be 0.05 in H_2O (12.5 Pa). From above, ΔP_{SO} at 80 ft (24.4 m) is 0.066 in H_2O (16.4 Pa). Using equation (7.8), ΔP_{SBb} = 0.062 in H_2O (15.5 Pa). From equation (7.19), G = 1740 $[(0.050^{3/2} - 0.062^{3/2})/(0.050 - 0.062)$ = 617 fpm (3.13 m/s). From equation (7.18), Q = 617 (2) (0.32) = 400 cfm (0.2 m^3/s).

Exterior Stairwell Door

Estimate the flow through the opened exterior doorway with air density of 0.075 lb/ft^3 (1.20 kg/m^3) and at y = 5 ft (1.5 m). The pressure difference is calculated from equation (7.8a) as ΔP_{SO} = 0.116 - 0.000625(5) = 0.113 in H_2O (28.1 Pa). From equation (7.20), Q_{SO} = 776(.65)(10.5)$[2(0.113)/0.075]^{½}$ = 9,200 cfm (4.3 m^3/s).

Total Flow Needed During Summer

The total flow needed to pressurize the stairwell in summer is the sum of these separate flows: 7,900 + 400 + 9,200 = 17,500 cfm

(8.26 m^3/s). It is an unusual result that this flow is the same as the flow needed for the winter from Example 7.3. In Example 7.5 a safety factor is applied to the flows, and the flows are distributed.

Example 7.5 Safety Factors and Distribution

Size the fan(s) for the stairwell of examples 7.3 and 7.4. A safety factor of 1.5 will be used for flows from the stairwell to the building and of 1.1 for the flow through the exterior doorway.

Winter: 1.5(400 + 10,300) + 1.1(6,800) = 23,500 cfm (11.1 m^3/s)

Summer: 1.5(7,900 + 400) + 1.1(9,200) = 12,500 + 10,100 = 22,600 cfm (10.7 m^3/s)

The supply air flow rate is 23,500 cfm (11.1 m^3/s), which is the largest. The pressurization system must be designed so that the flow rate of the supply air can be adjusted during system commissioning to accommodate the actual building leakage.

To minimize friction losses, air is injected at each floor. Even though the supply air rate is based on the winter flows, the distribution is based on summer conditions. The flow at each floor except the ground floor is 12,500(23,500/22,600)(1/10) = 1300 cfm (0.6 m^3/s). The flow at the ground floor is 23,500 - 9(1300) = 11,800 cfm (5.6 m^3/s).

7.8 ANALYSIS USING THE COMPUTER PROGRAM ASCOS

The preceding sections were based on the simplifying assumptions of no pressure loss in shafts due friction and no vertical flow in the building. The computer program ASCOS accounts for pressure loss due to friction and for vertical flows between floors and vertical flows in other shafts. Further, this program allows pressurization and exhaust of floors or portions of floors. This program can be used for analysis of stairwell pressurization systems operating in conjunction with other smoke control systems. Example 7.6 is an analysis of two pressurized stairwells in a building with fire floor exhaust.

Table 7.1 Design Parameters for Example 7.6

Design number of open doors from stairwell to building	6
Number of stories	15
Height between stories	12.0 ft (3.66 m)
Outside winter design temperature	14°F (-10°C)
Outside summer design temperature	93°F (34°C)
Building design temperature	70°F (21°C)
Winter stairwell temperatures	45°F (7°C)
Summer stairwell temperature	82°F (28°C)
Flow area per stairwell between the building and the outside	1.13 ft^2 (0.105 m^2)
Flow area between floors of the building per stairwell	0.850 ft^2 (0.0790 m^2)
Flow area between the stairwell and the building on each floor with stairwell doors closed	0.323 ft^2 (0.030 m^2)
Flow area of open stairwell doorways (half the geometric area of the open door, see chapter 4)	10.5 ft_2 (0.975 m^2)
Flow area between the building and the elevator shaft per stairwell per floor	0.670 ft^2 (0.0622 m^2)
Flow area of the vent from the top of the elevator shaft to the outside at the penthouse level, per stairwell (for the difference between vent area and flow area of a vent see chapter 4)	1.50 ft^2 (0.139 m^2)
Shaft flow coefficient, C_S, for stairwell (see Chapter 5)	7.0 x 10^4 scfm/(in H_2O) (2100 sL s^{-1} $Pa^{-½}$)
Shaft flow coefficient, C_S, for elevator shaft (see Chapter 5)	2.4 x 10^5 scfm/(in H_2O) (7200 sL s^{-1} $Pa^{-½}$)

Example 7.6 Computer analysis of a pressurized stairwell

This is an example of a building with two stairwells and an elevator shaft with two elevator cars. The building and both stairwells are 15 stories each. Each stairwell is pressurized by a centrifugal fan supplying air at the second story. The stairwell systems are the Canadian design, which have an exterior door open automatically upon system activation. Additionally, the fire floor is exhausted at 1800 cfm (0.85 m^3/s). The minimum allowable pressure difference between stairwell and building on the fire floor is 0.10 in H_2O (24.9 Pa). The maximum allowable pressure difference at this location is 0.30 in H_2O (74.6 Pa). The design parameters are listed in table 7.1

For the summer design temperatures, the "worst case" with respect to pressurization was taken to be a fire on the top floor with the open exterior doors on floors 1, 2, 3, 4, 5, and 6. This case was selected based on the expected pattern of pressures as illustrated in figure 7.13 (f). Several runs of the computer program were made to determine that 17000 cfm (8.02 m^3/s) of pressurization air is needed to produce 0.10 in H_2O (24.9 Pa) across the top stairwell door. The data input and computer output at this level of pressurization are listed in Appendix D as run 1. None of the pressure differences across closed stairwell doors is greater than the maximum allowable value. It can be observed from the computer output that the pressure profiles differ somewhat from those of figure 7.13 (f). It is possible that some other combination of fire floor and six open doors would require more supply air to the stairwell. A check of several other computer runs was made, and none was found to need more supply air. This leads us to believe that the "worst case" above requires the most or nearly the most supply air.

Consideration of Figure 7.13 (e) leads to a "worst case" for the winter. This case was taken to be a fire on the first floor with the open exterior doors on floors 10, 11, 12, 13, 14 and 15. Analysis of this case is listed as run 2 in Appendix D. This analysis was made at the supply air rate from run 1, and the pressure difference across the fire floor is 0.185 in H_2O (46 Pa), which is in the acceptable range. None of the pressure differences across the closed stairwell doors is greater than the maximum allowable value.

There is concern that at the supply air rate above, excessive pressures could result when all interior doors are closed. Other runs (not listed in Appendix D) were made at this level of pressurization with all interior doors closed for both summer and winter temperatures. In the summer the pressure differences across the closed interior doors ranged from 0.14 to 0.21 in H_2O (35 to 52 Pa), and in the winter it ranged from 0.20 to 0.27 in H_2O (50 to 67 Pa). These values are acceptable.

In the summer, 8447 cfm (4.00 m^3/s) went out the exterior doorway and the rest of the pressurization air went to the building. The flow to the building is 17000 - 8447 = 8553 cfm (4.04 m^3/s). Safety factors can be applied in a manner similar to that of example 7.5. The design flow rate of supply air for the stairwell is 1.5(8553) + 1.1(8447) = 22,100 cfm (1.04 m^3/s). The pressurization system must be designed so that the flow rate of the supply air flow rate can be adjusted during system commissioning to accommodate the actual building leakage.

7.9 REFERENCES

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Chapter 8. ELEVATOR SMOKE CONTROL

This chapter addresses two very different kinds of elevator smoke control systems. One has the objective of providing smoke protection for the elevator system so that it can be used for fire evacuation. Most elevators worldwide do not have smoke protection, fire protection, and other features necessary for them to be considered as a means of fire evacuation. Elevator systems not specifically designed and built for fire evacuation should not be used in fire situations (Sumka, 1987). However, the use of elevators for fire evacuation is a topic that has received considerable attention in recent years. Because the concept of elevator evacuation is so new, this chapter provides a general overview of the topic in addition to the smoke control considerations.

The other kind of elevator smoke control system addressed in this chapter is intended to prevent smoke flow to other floors by way of the hoistway (elevator shaft). The problems that can result from smoke migration through elevator shafts are illustrated by the fire at the MGM Grand Hotel (Best and Demers 1982). The fire occurred on the ground floor, but smoke migrated to the upper floors where the majority of the fatalities occurred. The hoistways at this hotel did not have any special smoke protection, and they were one of the major paths of smoke migration to the upper floors.

8.1 PISTON EFFECT

The transient pressures produced when an elevator car moves in a shaft are a concern for elevator smoke control. Such piston effect can pull smoke into a normally pressurized elevator lobby or hoistway. Analysis of the air flows and pressures produced by elevator car motion in a pressurized hoistway was developed by Klote (1988), based on the continuity equation for the contracting control volume in hoistway above a moving elevator car. Piston effect experiments (Klote and Tamura 1987) were conducted on an elevator of a hotel in Mississauga, Ontario, Canada. This elevator served each floor of the 15 story building, and the hoistway was pressurized by a vane axial fan. Figure 8.1 is a comparison of measured and calculated pressure differences due to an elevator car ascending from the ground floor to the top floor. The general trends of the calculations are in agreement with the measurements. On the ground floor, piston effect causes a rapid drop in pressure followed by a gradual pressure increase as the car moves away from the ground floor. Intuitively, a reduction in pressure is expected below an ascending car. This pressure reduction decreases as the car moves away due to the effect of increasing leakage area of the shaft below the car. On the top floor, piston effect due to the ascending car causes a gradual pressure increase with distance traveled until the car gets close to that floor. On a middle floor (the 8th) the pressure increases as the car approaches, drops suddenly as the car passes and increases after it travels away. For the ground and 8th floors, the extremes of the calculated curves deviate from those of the measured curves by only about 0.004 in H_2O (1 Pa), and for the 15th floor the extremes deviate by about 0.03 in H_2O (8 Pa).

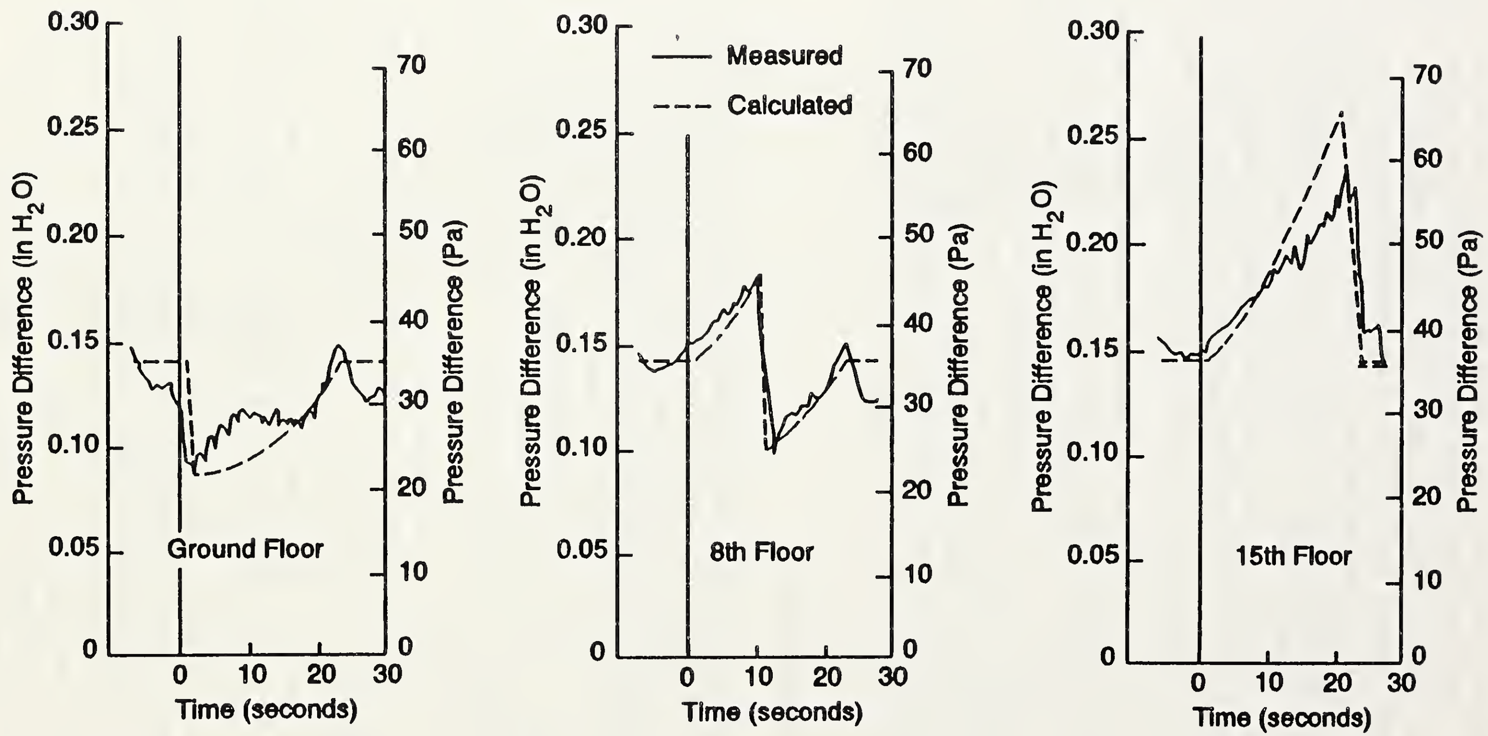

Figure 8.1 Comparison of measured and calculated due to the piston effect of an ascending car

From the analysis by Klote, expressions were developed for the critical pressure difference at which piston effect cannot overcome the elevator pressurization system for both systems intended to prevent smoke migration through the hoistway and for systems intended for elevator evacuation.

8.1.1 Prevention of Smoke Migration

The elevator pressurization systems discussed in this section are intended to prevent smoke migration through the hoistway. Further, this section is limited to elevators without enclosed lobbies. The critical pressure difference, ΔP_{crit}, is from the shaft to the building.

$$\Delta P_{crit} = \frac{K_{pe}\,\rho}{2}\left(\frac{A_s\,A_e\,V}{A_a\,A_{si}\,C_c}\right)^2 \qquad (8.1)$$

where:

ΔP_{crit} = critical pressure difference, in H_2O (Pa)
ρ = air density in hoistway, lb/ft^3 (kg/m^3)
A_s = cross sectional area of the hoistway, ft^2 (m^2)
A_{si} = leakage area between the lobby and the building, ft^2 (m^2)
A_a = free area around the elevator car, ft^2 (m^2)
A_e = effective area between the hoistway and the outside, ft^2 (m^2)
V = elevator car velocity, ft/min (m/s)
C_c = flow coefficient for flow around car, dimensionless
K_{pe} = coefficient, 1.66×10^{-6}, (1.00)

The flow coefficient, C_c, was determined experimentally (Klote and Tamura, 1986a) at about 0.94 for a multiple car hoistway and 0.83 for a single car hoistway. The effective area from the elevator to the outside is

$$A_e = \left(\frac{1}{A_{si}^2} + \frac{1}{A_{io}^2}\right)^{-\frac{1}{2}} \qquad (8.2)$$

where A_{io} is the leakage area between the outside and the building in ft^2 (m^2).

Example 8.1 Piston Effect and Pressurization to Prevent Smoke Migration

An hoistway with two cars is pressurized to a minimum of 0.05 in H_2O (12.4 Pa) from the hoistway to the building. This system is to prevent smoke movement through the elevator shaft, and there is no enclosed elevator lobby. Will the pressure difference due to elevator piston effect be a problem? The parameters are: A_{si} = 1.52 ft^2 (0.141 m^2), A_{io} = 2.26 ft^2 (0.210 m^2), A_s = 121 ft^2 (11.2 m^2), A_a = 80 ft^2 (7.43 m^2), ρ = 0.075 lb/ft^3 (1.20 kg/m^3), V = 500 ft/min (2.54 m/s), C_c = 0.94.

From equation (8.2), A_e = 1.26 ft^2 (0.117 m^2).
From equation (8.1), ΔP_{crit} = 0.028 in H_2O (6.9 Pa).
The hoistway is pressurized at a level above ΔP_{crit}.
Therefore, piston effect will not pull smoke into the elevator shaft.

8.1.2 Elevator Evacuation

For elevator pressurization systems intended for fire evacuation, the elevator lobby is enclosed to help protect people waiting for the elevator during a fire emergency. The critical pressure difference, ΔP_{crit}, is from the shaft elevator lobby and the building.

$$\Delta P_{crit} = \frac{K_{pe}\ \rho}{2}\left(\frac{A_s\ A_e\ V}{A_a\ A_{ir}\ C_c}\right)^2 \qquad (8.3)$$

where A_{ir} is the leakage area between the building and the lobby in ft^2 (m^2). The equation for ΔP_{crit} is the same as that for the same as the upper limit of the pressure difference [Equation (3.20)] due to piston effect in an unpressurized hoistway. The effective area between the hoistway and the outside is

$$A_e = \left(\frac{1}{A_{sr}^2} + \frac{1}{A_{ir}^2} + \frac{1}{A_{io}^2}\right)^{-\frac{1}{2}} \qquad (8.4)$$

where:
A_{sr} = leakage area between the lobby and the shaft, ft^2 (m^2)
A_{io} = leakage area between the outside and the building, ft^2 (m^2)

Example 8.2 Piston Effect and Elevator Evacuation

1. An hoistway has two cars and is pressurized to a minimum of 0.05 in H_2O (12.4 Pa) from the elevator lobby to the building. Will the pressure difference due to elevator piston effect be a problem? The parameters are: A_{sr} = 1.60 ft^2 (0.149 m^2), A_{ir} = 0.42 ft^2 (0.039 m^2), A_{io} = 0.54 ft^2 (0.0502 m^2), A_s = 121 ft^2 (11.2 m^2), A_a = 79.8 ft^2 (7.43 m^2), ρ = 0.075 lb/ft^3 (1.20 kg/m^3), V = 500 ft/min (2.54 m/s), C_c = 0.94.

From equation (8.4), A_e = 0.325 ft^2 (0.0302 m^2).
From equation (8.3), ΔP_{crit} = 0.024 in H_2O (6.0 Pa).
The hoistway is pressurized at a level above ΔP_{crit}.
Therefore, piston effect will not pull smoke into the elevator lobby.

2. If the hoistway in the example above is for a single car, will piston effect be a problem? The parameters are the same as above, except A_s = 60.4 ft^2 (5.61 m^2), A_a = 19.4 ft^2 (1.80 m^2), and C_c = 0.83. The effective area is the same.

From equation (8.3), ΔP_{crit} = 0.13 in H_2O (33 Pa).
The hoistway is pressurized at a level below ΔP_{crit}.
Therefore, piston effect may pull smoke into the elevator lobby. Possible solutions include a slower car speed, use of another elevator with multiple cars in the hoistway, and a higher level of hoistway pressurization.

8.2 SMOKE CONTROL FOR PREVENTION OF SMOKE MIGRATION

These systems consist of supplying air to the hoistway with the intent of producing a pressure difference sufficient to prevent smoke flow into the hoistway in the event of a fire. Upon fire detection, the general procedure is for elevator cars to be taken out of normal service and automatically recalled to the ground floor. A recent modification of this is the capability for recall to an alternate floor in the event of a fire on the ground floor. In some localities, the elevator doors remain open after the car reaches the ground floor or the alternate floor. In other localities, the elevator doors are closed after sufficient time to allow passengers to leave the car. The fire service has elevator keys allowing them to operate elevators for rescue and for transportation of personnel and equipment to fight the fire.

As with pressurized stairwells, factors that must be considered are shaft friction, outside-to-inside temperature difference, and pressure fluctuations due to doors opening and closing. The method of analysis of pressurized stairwells presented in Chapter 7 can be used for pressurized elevators by redefining the subscript S in the analysis from stairwell to hoistway. This analysis is then applicable to buildings without vertical leakage and to shafts with negligible pressure loss due to friction. Of course, this analysis can only be used where the elevator pressurization system is the only system using pressurization or operating in the building. Further, the effect of any exhaust system must be negligible. Accordingly, such analysis would be similar to the examples of Chapter 7. The computer program ASCOS can be used for analysis of systems without these simplifying conditions, as is done with the following examples. Analysis of an elevator smoke control system should include all major building flow paths including stairwells (Example 8.3).

Example 8.3 Elevator Pressurization to Control Smoke Flow

A 14 story hoistway is to be pressurized to prevent smoke from flowing through it in a fire situation. The minimum allowable pressure difference is 0.05 in H_2O (12.4 Pa). This is the same elevator as for Example 8.2, which shows that we do not have to be concerned with piston effect. The hoistway has two cars, and this analysis uses symmetry so that only one stairwell and half the hoistway are analyzed. The design parameters are listed in table 8.1.

Several runs of the computer program ASCOS were made to determine that 8550 cfm (4.04 m^3/s) is needed to maintain at least the minimum pressure difference for winter temperatures. For this condition, the pressure difference from the hoistway to the building ranges from 0.05 to 0.192 in H_2O (12.4 to 47.8 Pa) as listed in run 1 of Appendix E. This flow rate of supply air was used for summer temperatures, and the pressure difference across the hoistway were in the range 0.091 to 0.206 in H_2O (22.6 to 51.3 Pa) as shown in the computer output for run 2 of Appendix E. Thus this flow rate is acceptable for both design seasons.

A safety factor of 1.5 is applied to the results of the computer analysis, and the flow rate must be doubled to account for both halves of the elevator. Thus, the supply into the hoistway is sized at 1.5(2)(8550) = 25,700 cfm (12.1 m^3/s). The elevator pressurization system must be designed so that the flow rate into the hoistway can be adjusted during system commissioning to accommodate the actual building leakage.

8.3 SMOKE CONTROL FOR ELEVATOR EVACUATION

Throughout most of the world, there are signs next to elevators indicating that they should not be used in fire situations and that stairwells should be used for fire evacuation. These elevators are not intended as means of fire egress, and they should not be used for fire evacuation. However, some people can not use stairwells because of physical disabilities, and for these people fire evacuation is a serious problem (Pauls, 1988; Pauls and Juillet, 1989). This section discusses smoke control systems that can be used to provide smoke protection for elevators as a part of an overall elevator protection scheme to

Table 8.1 Design parameters for Example 8.3

Number of stories	14
Height between stories	12.0 ft (3.66 m)
Outside winter design temperature	14°F (-10°C)
Outside summer design temperature	93°F (34°C)
Building design temperature	70°F (21°C)
Winter stairwell temperatures	45°F (7°C)
Summer stairwell temperature	82°F (28°C)
Flow area per stairwell between the building and the outside from floors 2 through 14	1.13 ft^2 (0.105 m^2)
Flow area per stairwell between the building and the outside on the first floor	20 ft^2 (6.10 m^2)
Flow area between floors of the building per stairwell	0.850 ft^2 (0.0790 m^2)
Flow area between the stairwell and the building on each floor with stairwell doors closed	0.323 ft^2 (0.030 m^2)
Flow area of open stairwell doorways (half the geometric area of the open door, see chapter 4)	10.5 ft_2 (0.975 m^2)
Flow area between the building and the hoistway per stairwell per floor	0.670 ft^2 (0.0622 m^2)
Shaft flow coefficient, C_S, for stairwell (see Chapter 5)	7.0 x 10^4 scfm/(in H_2O) (2100 sL s^{-1} $Pa^{-½}$)
Shaft flow coefficient, C_S, for hoistway (see Chapter 5)	2.4 x 10^5 scfm/(in H_2O) (7200 sL s^{-1} $Pa^{-½}$)

allow fire evacuation by elevators. The information in this chapter is based a joint project of the National Institute of Standards Technology (NIST) in the United States and the National Research Council of Canada (NRCC) to evaluate the feasibility of using elevators for the evacuation of the handicapped during a fire (Klote and Tamura 1987, 1986a and 1986b; and Tamura and Klote 1988, 1987a, 1987b, and 1987c). Before this joint project, Klote (1984, 1983) conducted field tests of several elevator pressurization systems. It should be emphasized that conventional elevators do not have any protection scheme for fire evacuation, and fire evacuation by these conventional elevator systems is not recommended.

8.3.1 Concerns about Elevator Evacuation

This section provides a description of many concerns about elevator evacuation, and the next section discusses these concerns along with one approach to deal with them. The 1976 edition of the Life Safety Code (NFPA 1976) listed the following "problems" involved with the use of elevators as fire exits[1]:

- "Persons seeking to escape from a fire by means of an elevator may have to wait at the elevator door for some time, during which they may be exposed to fire, smoke or developing panic.

- Automatic elevators respond to the pressing of buttons in such a way that it would be quite possible for an elevator descending from floors above a fire to stop automatically at the floor involved in the fire and open automatically, exposing occupants to fire and smoke.

- Modern elevators cannot start until doors are fully closed. A large number of people seeking to crowd into an elevator in case of emergency might make it impossible to start.

- Any power failure, such as the burning out of electric supply cables during a fire, may render the elevators inoperative or might result in trapping persons in elevators stopped between floors. Under fire conditions there might not be time to permit rescue of trapped occupants through emergency escape hatches or doors."

It is common for elevators serving more than three floors to descend automatically to the ground floor in the event of a fire. Fire fighters have keys to control elevators manually during building evacuation and fire fighting. However, smoke infiltration into hoistways frequently threatens lives and hinders use of elevators by fire fighters.

In addition, there are three other concerns. First, water from sprinklers or fire hoses could short out or cause other problems with electrical power and control wiring for the elevator. Second, shaft pressurization could result in elevator doors jamming open, limiting movement of the car. Third, piston

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[1]This edition of the Life Safety Code was the last edition to list these "problems".

effect could pull smoke into the elevator lobby or the hoistway, and a method of preventing this has already been presented in this chapter.

8.3.2 Conceptual Solution for Elevator Evacuation

In order to overcome the concerns discussed in the preceding section, an elevator system used as a fire exit needs to have the following attributes:

- Elevator control must assure safe and efficient evacuation
- Reliable electric power must be supplied
- Elevator controls, control wiring and electrical power must be protected against fire or water damage
- Elevator lobbies, hoistway, and elevator machinery room must be protected against fire and smoke

As previously stated, elevator cars are controlled so that they go to the ground floor in the event of a fire alarm. In the event of fire on the ground floor, the elevator cars go to an alternate floor. The fire department or other authorized personnel can then use the elevators for evacuation. Firefighters, police, and uniformed guards have positions of authority in our society. With the elevators controlled by such authority figures, the likelihood of a large number of people crowding into the elevator and making it impossible to close the doors will probably be reduced. Of course, there may be other approaches to elevator control that could allow orderly evacuation by elevators.

Reliability of electric power consists of assuring a source of power and assuring continued distribution of power to where it is used. Considerable experience exists in assuring the supply of electrical power for critical functions in hospitals, communication facilities, computer facilities and the like. For these applications, a major concern is providing back up power when power supplied by the local utility is interrupted. These applications operate most or all of the time, and they need highly reliable power for all the time that they operate. Fire evacuation by elevators is different in that this mode of elevator operation is only needed during a building fire. At most, the fire evacuation mode of an elevator would be expected to operate for a few hours per year. Thus, the probability of simultaneously having a fire and having the utility company power interrupted is relatively small. However, the probability of having a power distribution failure during a fire is relatively high. This is because fire frequently damages electrical distribution within buildings. Therefore, the power distribution to the elevator and associated smoke control fans should be such that it is highly unlikely that a fire could interrupt electrical power to this equipment.

There are numerous applications of electric power and electronic systems being designed and built to function when in contact with water. Street lighting and traffic lights operate during rain, and swimming pool lighting operates underwater. In fact, some elevators operate on building exteriors where they are subjected to rain and the other elements. It is beyond the scope of this manual to examine specific approaches to making these systems resistant to water, however, it is obvious that the technology exists to make elevator systems function when they are subject water.

Considerable information is available concerning the fire resistance of walls, partitions, floors, doors, etc. The ability to design and build elevator lobbies and hoistways that can withstand severe building fire has existed for years. Smoke protection for elevator systems is the topic of the next section.

Elevator doors jam open when the force of the door opener is insufficient to overcome the force of friction. The friction force increases with the pressure difference from the hoistway to the lobby. In tall buildings, elevator doors frequently jam open during extremely cold weather. This is caused by stack effect induced pressure differences. Elevator mechanics commonly adjust the door closing forces to prevent door jamming. During elevator smoke control operation, the possibility of door jamming may decrease or increase. If the leakage area of the elevator lobby doors is less than that of the elevator doors, the pressure difference across the elevator doors can be less than that normally occurring. In field tests conducted by Klote (1984), no door jamming was encountered at pressure differences as high as 0.3 in H_2O (75 Pa). When door jamming was encountered in an elevator without smoke control, it was found that only a small additional force applied by the palms of the hands was sufficient to prevent jamming. Fire fighters can be taught to overcome door jamming this way, and elevator doors could be fitted with grips or handles to aid in this effort.

8.3.3 Smoke Control Considerations

Smoke control systems for elevator evacuation must provide smoke protection for elevator lobbies, hoistways, and machinery rooms. Protection of lobbies is essential so that people will have a safe place to wait for the elevator. Protection of the machinery room is important to prevent damage to elevator machinery. Figure 8.2 illustrates a system that pressurizes the hoistway directly and indirectly pressurizes the elevator lobby and the machinery room.

Pressurization air can also be supplied to the elevator lobbies. Examination of the relative leakage areas of the elevator system provides insight into both hoistway and lobby approaches to pressurization. Considering the leakage from the elevator lobby to the outside to be negligible, the

$$\frac{\Delta P_{sr}}{\Delta P_{ir}} = \left(\frac{A_{ir}}{A_{sr}} \right)^2$$

where:
ΔP_{sr} = pressure difference from hoistway to lobby, in H_2O (Pa)
ΔP_{ir} = pressure difference from lobby to building, in H_2O (Pa)
A_{ir} = leakage area between the building and the lobby in ft^2 (m^2)
A_{sr} = leakage area between the lobby and the shaft, ft^2 (m^2)

For elevator doors with wide gaps that are common in most buildings, Tamura and Shaw (1976) showed that the leakage area of the gaps is generally in the range of 0.5 to 0.7 ft^2 (0.05 to 0.07 m^2). Based on general experience with building leakages, A_{ir}/A_{sr} is about 0.4 for construction of average tightness and about 0.1 for tight construction. From equation (4), $\Delta P_{sr}/\Delta P_{ir}$ is therefore 0.16 and 0.01 for average and tight construction. Thus, the pressure in the elevator lobby can be expected to be close to the pressure in the hoistway, provided that the construction is not unusually leaky. Pressurization air can be supplied to the elevator lobbies (figure 8.3). However, from the above discussion it seems that this direct lobby pressurization does not result in any significant improvement in pressurization over supplying the air into the hoistway as illustrated in figure 8.2.

Direct lobby pressurization has some advantage over direct hoistway pressurization in purging small amounts of smoke from the lobby. Part of the pressurization air to an elevator smoke control system goes from the hoistway to the outside, and the rest goes from the lobby through the building to the outside. With direct lobby pressurization, both these amounts flow through the lobby. Such an increased flow rate tends to better purge any small amounts of smoke that would get into the lobby before smoke control activation or when a person is entering the lobby. The relative benefit of this improved purging compared to its cost has not been evaluated. The following discussions have been focused arbitrarily on the hoistway pressurization systems.

8.3.4 Pressure Fluctuations due to Open Doors

Elevator systems must be designed to maintain design pressure differences under the likely conditions of opened and closed doors. Klote and Tamura (1986a) showed that opening a large flow path from the pressurized spaces to the outside can result in a significant loss in pressurization. For example opening the elevator doors, elevator lobby doors, and exterior doors resulted in a pressure drop from 0.13 in H_2O (32 Pa) to 0.03 in H_2O (7 Pa) for a system without features to resist pressure fluctuation.

During a fire, it is expected that several exterior doors will be propped open, and the elevator doors will open and close as elevators are used for evacuation. Further, stairwell doors are likely to be opened and closed as people use them for evacuation. It is envisioned that lobby doors will close automatically upon smoke control system activation. However, lobby doors can be inadvertently blocked and the closing mechanism can fail. It is anticipated that occupants will close any such opened lobby doors to prevent being exposed to smoke. Doors may not be closed on floors where there is no smoke danger or there are no people waiting in the elevator lobby. The smoke control system should be designed to maintain pressurization when some elevator lobby doors are open on floors away from the fire. The examples presented later deal with pressure fluctuations due to doors opening and closing.

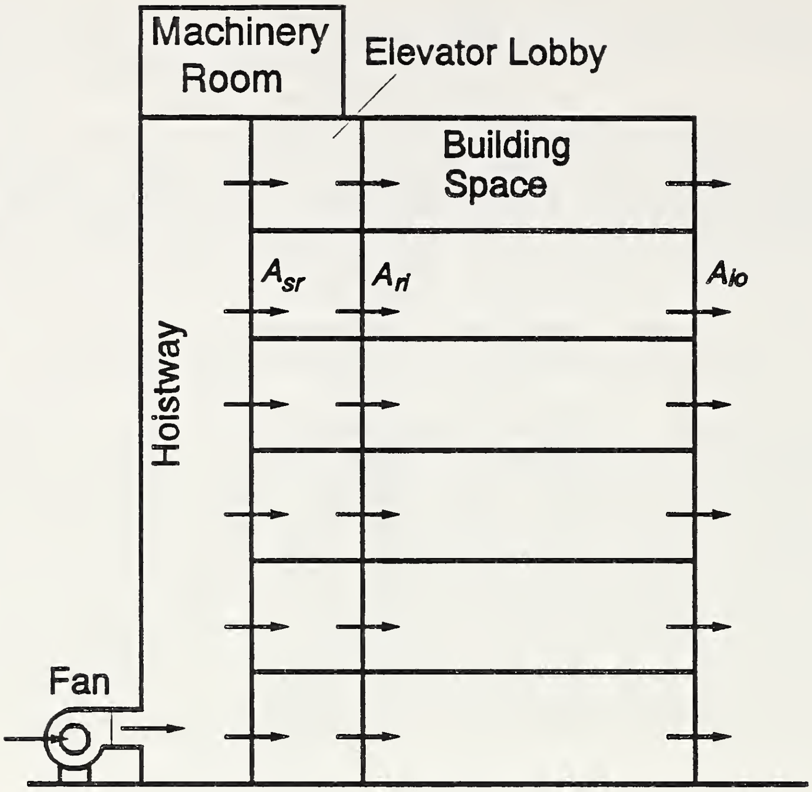

Figure 8.2 Elevator smoke control by shaft pressurization

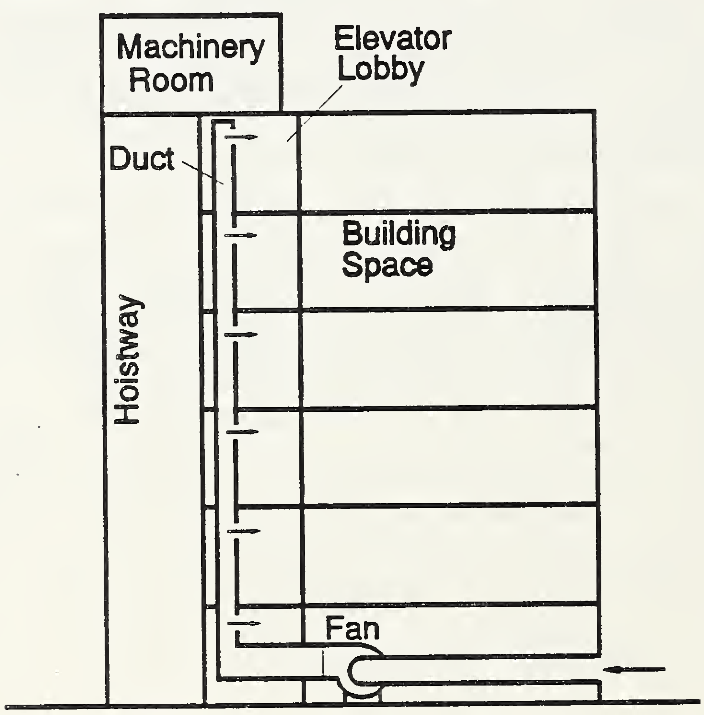

Figure 8.3 Elevator smoke control by lobby pressurization

8.3.5 Smoke Control Systems

Elevator smoke control systems can incorporate features to deal with pressure fluctuations due to opening and closing doors. These features include pressure relief vents, vents with barometric dampers, variable-supply air fans, fire floor venting, and fire floor exhaust.

Pressure Relief Vent System

This system has a "constant-supply" air rate fan and a pressure relief vent to the outside as illustrated in figure 8.4. The area of this vent is fixed, and sized for operation in the smoke control system. The vent can be fitted with automatic dampers, if it is desired for it to be normally closed. The supply rate varies to some extent with the pressure across the fan, but the term "constant-supply" is used to differentiate this fan from one that has a "variable-supply" rate. The vent must be large enough that the maximum allowable pressure difference is not exceeded when all doors are closed. When paths to the outside are opened, air flows through them and the hoistway pressure drops. This system must maintain at least the minimum allowable pressure difference when some design combination of paths is open.

Barometric Damper System

This system is similar to the one above, except that the vent has a barometric damper which closes when the pressure drops below a specified value. The use of these dampers minimizes air losses when paths from the hoistway are opened, and the pressurization fan can be sized smaller than for the above system. A normally closed automatic damper in parallel with the barometric damper can prevent damper chatter caused by the wind.

Variable-Supply Air System

Variable-supply air can be achieved by using one of many fans commercially available for variable flow rate. Alternatively, a fan bypass arrangement of ducts and dampers can be used to vary the flow rate of supply air to the hoistway. The variable flow fans are controlled by one or more static pressure sensors that sense the pressure difference between the lobby and the building. There are two approaches for use of the sensors. The air flow rate can be controlled by the average of all signals from the sensors or it can be controlled by the signal from the fire floor.

Using the average of all the signals has the advantage that no information is required about where the fire is located. Using the fire floor sensor signal requires information about the fire location. This information can come from smoke detectors, heat detectors, or sprinkler water flow indicators. Using the fire floor signal has the advantage that the system maintains a set pressure difference at this most critical location.

System with Fire Floor Venting or Exhaust

Smoke venting and smoke exhaust of the fire floor can improve system performance. The venting or exhaust increases the pressure difference from the lobby to the fire floor. The vents can be exterior wall vents or non-powered smoke shafts. Figure 8.5 shows a fan-duct system intended to exhaust the fire floor. Upon detection of fire or smoke, the damper opens on the fire floor and the exhaust fan is activated. The detection system must be configured to identify the fire floor.

8.3.6 Design Analysis

There are many different approaches that can be taken to the design of the systems discussed above. The design of an elevator smoke control system includes selection of a system for dealing with pressure fluctuations, determining appropriate values for leakage areas and other parameters, as well as calculating the performance of the smoke control system. The objective of the design analysis is to determine a flow rate of pressurization air that will result in acceptable pressurization with a minimum and a maximum design number of large open paths from the hoistway to the outside. The maximum design number of large paths should consist of one on the first floor plus some others on upper floors. The first floor path consists of open elevator doors, elevator lobby doors and exterior doors. The paths on the other floors consist of an open elevator lobby door and an open stairwell door. This results in large paths to the outside, because the exterior stairwell door is open. Two design approaches are outlined below, and these can be considered as examples of application of engineering principles to system design. Examples 8.4 and 8.5 illustrate these two approaches.

Analysis of Pressure Relief Vent Systems:

1. Calculate the flow rate of pressurization air that results in the minimum allowable pressure difference when the maximum design number of large paths are open from the hoistway to the outside. This flow rate is for either summer or winter design conditions, whichever flow rate is largest.

2. Calculate the pressure differences resulting from the flow rate of step 1 when the minimum design number of large paths are open.

3. If the pressure differences from step 2 are less than or equal to the maximum allowable pressure difference, the system can maintain acceptable pressurization. If not, another system or another variation of this system should be considered.

4. Apply a safety factor to the flow rate calculated above.

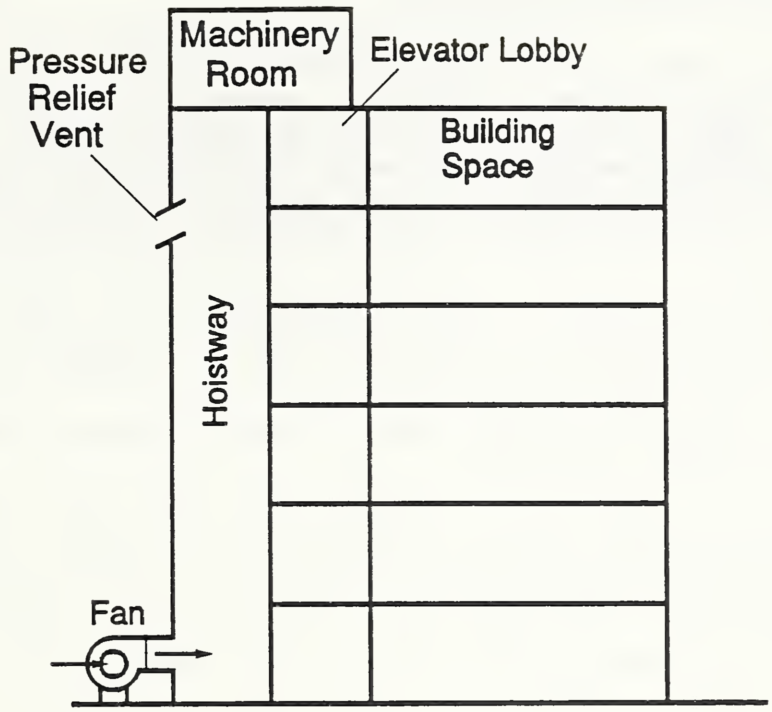

Figure 8.4 Elevator smoke control with a pressure relief vent

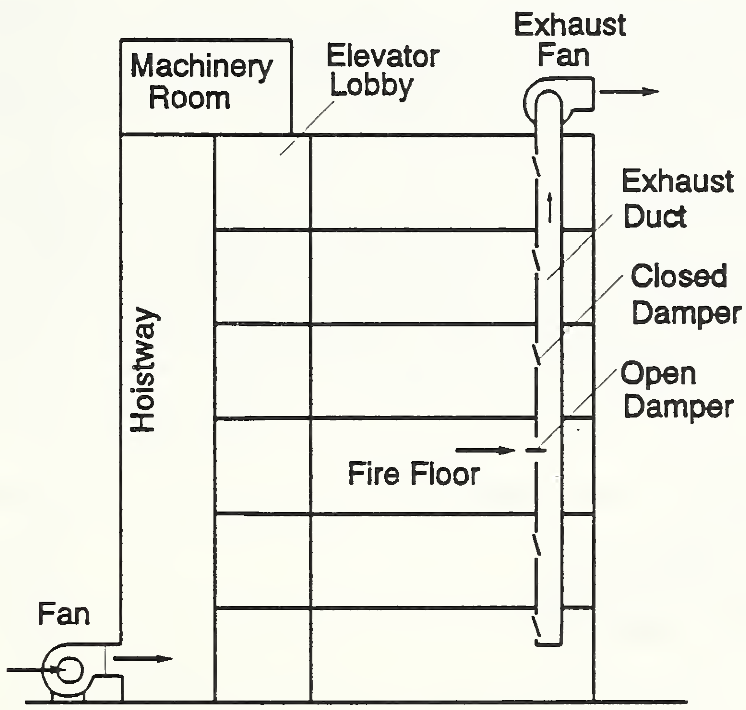

Figure 8.5 Elevator smoke control with fire floor exhaust

Analysis of Variable-Supply Air Systems:

1. Calculate the flow rate of pressurization air that results in the maximum allowable pressure difference across any closed elevator lobby door when the lobby door is open on the fire floor. This calculation should be made for summer and winter design conditions with the fire floor being on the top or second floor. The smallest of these flow rates is the value that should not be exceeded.

2. Calculate the flow rate of pressurization air that results in the minimum allowable pressure difference when the maximum design number of large paths are open from the hoistway to the outside. This flow rate is for either summer or winter design conditions, whichever flow rate is largest.

3. If the flow rate from step 1 is greater than that from step 2, the system can maintain acceptable pressurization. If not, another system or another variation of this system should be considered.

4. Apply a safety factor to the flow rate calculated above.

Table 8.2 Design parameters for Examples 8.4 and 8.5

Flow Areas:	ft^2	m^2
First floor exterior wall (exterior doors closed)	0.940	0.0873
First floor exterior wall (exterior doors opened)	22.0	2.04
Exterior walls (except on 1st floor)	0.540	0.0502
Stairwell to building (stair door closed)	0.270	0.0251
Stairwell to building (stair door opened)	10.5	0.975
Building floor	0.270	0.0251
Building to elevator lobby (lobby doors closed)	0.42	0.0390
Building to elevator lobby (lobby doors opened)	22.0	2.04
Elevator lobby to hoistway (elevator door closed)	1.60	0.149
Elevator lobby to hoistway (elevator door opened)	8.00	0.743
Pressure relief vent from hoistway to outside at 8th floor (Example 8.4 only)	24.0	2.23
Other Parameters:		
Height between building floors	10.0 ft	0.929 m
Number of floors	11	11
Building air temperature	70°F	21°C
Winter outside temperature	5°F	-15°C
Summer outside temperature	90°F	32°C

Example 8.4 Pressure Relief Vent System

An eleven-story building with a typical floor plan shown in figure 8.6 was selected arbitrarily for this example. Because the building is symmetric, only half of each floor was analyzed. The minimum and maximum allowable pressure differences from the lobby to the building are 0.05 and 0.34 in H_2O (12 and 85 Pa). The other design parameters are listed in table 8.2. An value of 24 ft^2 (2.23 m^2) for the relief vent area is selected arbitrarily. Pressurization air is supplied to the hoistway at the second floor.

The minimum number of large paths open is zero - All doors are closed. The maximum number of large paths open is three, the first floor path plus paths on the top two floors. Table 8.3 lists the arrangement of doors for the ASCOS computer analysis (Chapter 5). Runs 1 and 2 are the maximum number of paths open (step 1), and runs 3 and 4 are the minimum paths open (step 2). The pressure differences for these runs are listed in tables 8.4 and 8.5. For winter conditions, the ASCOS program was executed a few times to determine that 33,400 cfm (15,800 L/s) of pressurization air is needed to maintain at least the minimum allowable pressure difference when the maximum design number of large paths are open (run 1). At this flow rate with the maximum design number of large paths open in summer (run 2), the pressure differences are all greater than the minimum allowable pressure difference. At this same rate of pressurization, the pressure differences with the minimum paths open (runs 3 and 4) are all below the maximum allowable pressure difference.

For the design analysis, 33,400 cfm (15,800 L/s) of pressurization air is sufficient to maintain acceptable pressurization under design conditions of large open paths from the hoistway to the outside. A safety factor is suggested to account for differences between the estimated leakage areas of this analysis and those of the actual building. If a safety factor of 25% were used, the supply fan would be sized far about 42,000 cfm (19,800 L/s). The system should be designed so that the flow rate can be adjusted in the field as appropriate.

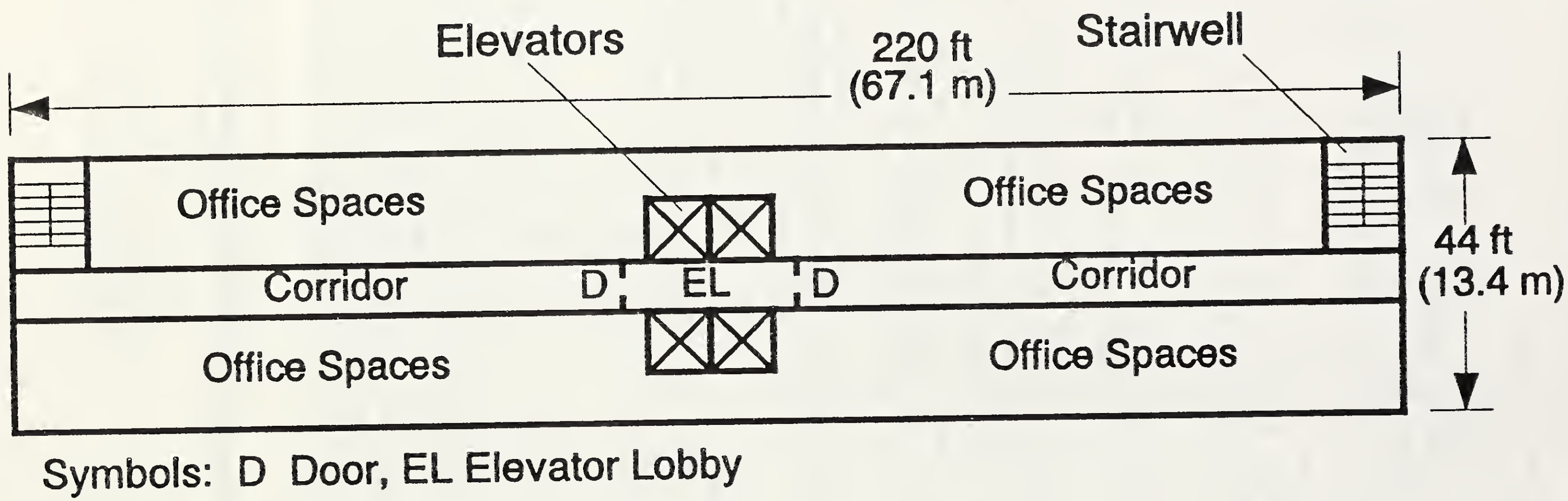

Figure 8.6 Typical floor plan (above first floor) of example building

Table 8.3 Arrangement of doors for computer analysis of Example 8.4

Run	Season	1st Floor Exterior Door Open	Elevator Doors Open on Floors:	Elevator Lobby Doors Open on Floors:	Stairwell Doors Open on Floors[1]:
1	Winter	Yes	1	1, 8, 9, 10, 11	8, 9, 10, 11
2	Summer	Yes	1	1, 8, 9, 10, 11	8, 9 10, 11
3	Winter	No	None	None	None
4	Summer	No	None	None	None

[1]Exterior stairwell door on the ground floor is closed when no other stair doors are opened, and it is open when any other stair door is opened.

Table 8.4 Computer calculated pressure differences for Example 8.4 in English Units

Pressure Difference in inches H_2O from Elevator Lobby to Building on Floors:

Run	1	2	3	4	5	6	7	8	9	10	11
1	Open	0.08	0.07	0.07	0.06	0.06	0.06	0.05	0.05	Open	Open
2	Open	0.15	0.13	0.12	0.11	0.10	0.09	0.08	0.08	Open	Open
3	0.16	0.16	0.15	0.14	0.13	0.12	0.11	0.11	0.11	0.12	0.12
4	0.24	0.22	0.20	0.19	0.17	0.15	0.14	0.12	0.12	0.12	0.12

Example 8.5 Variable-Supply Air System

The same building is used as in Example 8.4. The flow rate of the variable-supply air fan is controlled by a sensor on the fire floor to maintain a set point of 0.05 in H_2O (12 Pa). The system maintains the set point when the elevator lobby door is closed on the fire floor. However, when the elevator lobby door is open on the fire floor, the flow rate of pressurization air increases in an attempt to reach the set point, and high pressure differences can result across elevator lobby doors on other floors. These high pressures should not exceed the maximum allowable pressure difference. As with the previous example, the maximum allowable pressure difference is 0.34 in H_2O (85 Pa). Again, pressurization air is supplied to the hoistway at the second floor.

The maximum design number of large paths open is the same as the first example. Initially the minimum number of large paths open was also zero. However, step 3 of the analysis indicated that this system would not maintain acceptable pressurization. The system was modified such that the minimum number of large paths open is the one on the first floor. This means that the elevator lobby doors and the exterior doors must be opened automatically or remain opened upon system activation. The data presented in the rest of this analysis is for this second system with these doors opened on activation.

The conditions of open and closed doors are listed in table 8.5 for six computer runs, and the resulting pressurization flows and pressure differences are listed in tables 8.7 and 8.8. For each run, the ASCOS program was executed a few times to find the flow rate of pressurization air that produced the desired pressure difference. Computer runs 1, 2, 3, and 4 were made for step 1. From these runs, the pressurization flow rate should not exceed 19,800 cfm (9300 L/s). Runs 5 and 6 are for step 2, and they indicate that the flow rate must be at least 8,500 cfm (4000 L/s). Thus, the system can maintain acceptable pressurization (step 3). Using the same safety factor as the first example, the fan should be sized to deliver 11,000 cfm (8,200 L/s). The system should be designed so that the flow rate can be adjusted in the field as appropriate.

Table 8.5 Computer calculated pressure differences for Example 8.4 in SI Units

Pressure Difference in pascals from Elevator Lobby to Building on Floors:

Run	1	2	3	4	5	6	7	8	9	10	11
1	Open	20	17	17	15	15	15	12	12	Open	Open
2	Open	37	32	30	27	25	22	20	20	Open	Open
3	40	40	37	35	32	30	27	27	27	30	30
4	60	55	50	47	42	37	35	30	30	30	30

Table 8.6 Arrangement of doors for Example 8.5

Run	Season	1st Floor Exterior Door Open	Elevator Doors Open on Floors:	Elevator Lobby Doors Open on Floors:	Stairwell Doors Open on Floors:
1	Winter	Yes	1	1, 2	None
2	Winter	Yes	1	1, 11	None
3	Summer	Yes	1	1, 2	None
4	Summer	Yes	1	1, 11	None
5	Winter	Yes	1	1, 10, 11	10, 11
6	Summer	Yes	1	1, 10, 11	10, 11

Table 8.7 Computer calculated pressure differences for Example 8.5 in English Units

Pressure Difference in inches H_2O from Elevator Lobby to Building on Floors:

Run	Flow Rate[1] (cfm)	1	2	3	4	5	6	7	8	9	10	11
1	19,800	Open	Open	0.29	0.32	0.32	0.33	0.33	0.34	0.34	0.34	0.34
2	20,200	Open	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.33	Open
3	22,000	Open	Open	0.32	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34
4	20,200	Open	0.34	0.32	0.32	0.31	0.31	0.31	0.31	0.30	0.28	Open
5	8,500	Open	0.05	0.05	0.06	0.06	0.07	0.08	0.08	0.08	Open	Open
6	8,500	Open	0.05	0.05	0.04	0.04	0.04	0.03	0.03	0.03	Open	Open

[1] Flow rate of pressurization air into the hoistway at the second floor

Table 8.8 Computer calculated pressure differences for Example 8.5 in SI Units

Run	Flow Rate[1] (cfm)	Pressure Difference in inches H_2O from Elevator Lobby to Building on Floors: 1	2	3	4	5	6	7	8	9	10	11
1	9300	Open	Open	72	80	80	82	82	85	85	85	85
2	9500	Open	85	85	85	85	85	85	85	85	82	Open
3	10400	Open	Open	80	85	85	85	85	85	85	85	85
4	9500	Open	85	80	80	77	77	77	77	75	70	Open
5	4000	Open	12	12	15	15	17	20	20	20	Open	Open
6	4000	Open	12	12	10	10	10	7	7	7	Open	Open

[1]Flow rate of pressurization air into the hoistway at the second floor

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Chapter 9. ZONED SMOKE CONTROL

The stairwell systems and elevator systems discussed in previous chapters were primarily intended to prevent smoke infiltration into these shafts. However, smoke can flow through cracks in floors and through unpressurized shafts to damage property and threaten life at locations remote from the fire. The concept of zoned smoke control discussed in this chapter is intended to limit this type of smoke movement within a building.

9.1 SMOKE CONTROL ZONES

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.

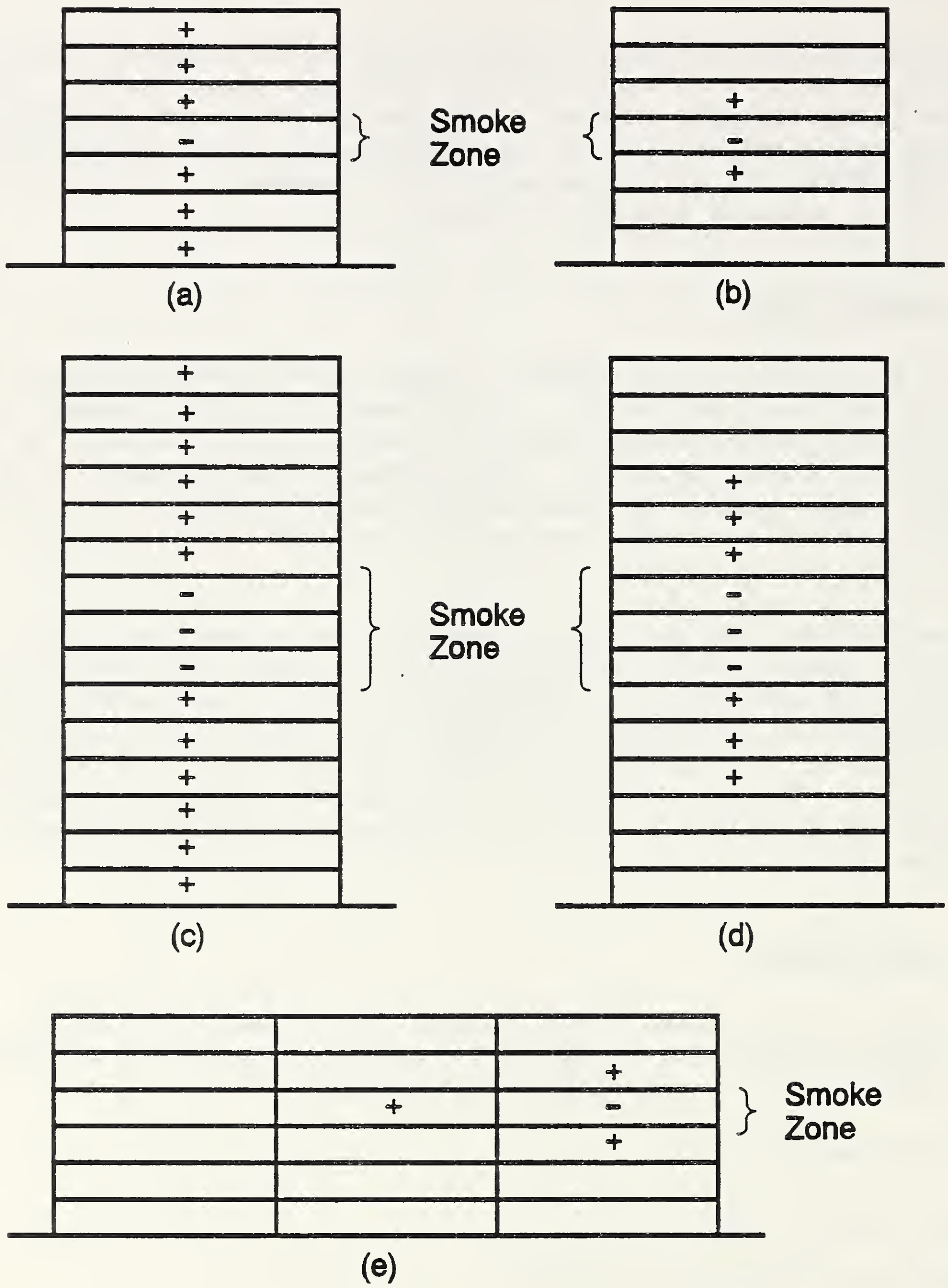
Frequently, each floor of a building is chosen to be a separate smoke control zone. However, a smoke control zone can consist of more than one floor, or a floor can consist of more than one smoke control zone. Some arrangements of smoke control zones are illustrated in figure 9.1. When a fire occurs, all of the nonsmoke 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 9.1 (b), the system is sometimes called a "pressure sandwich."

9.2 SMOKE ZONE VENTING

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 the 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 nonsmoke 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.



Note:
In the above figures, the smoke zone is indicated by a minus sign and pressurized spaces are indicated by a plus sign. A smoke zone can consist of one floor as in (a) and (b) or of more than one floor as in (c) and (d). All the nonsmoke zones in a building may be pressurized as in (a) and (c), or only the nonsmoke zones adjacent to the smoke zone may be pressurized as in (b), (d) and (e). A smoke zone may be part of a floor as in (e).

Figure 9.1 Some arrangements of smoke control zones

Smoke purging, consisting of equal air supply and exhaust rates, is not considered here, because it does not produce pressure differences that control smoke movement. It is generally believed that such purging at the airflows available with HVAC systems cannot significantly reduce smoke concentrations in a zone where a large fire is located. Dilution away from the fire is discussed in Chapter 4.

9.3 EXTERIOR WALL VENTS

Exterior wall vents can consist of windows or panels that open automatically when the smoke control system is activated. The system considered here consists of a vented smoke zone without any mechanical exhaust and adjacent zones that are pressurized.

In order to minimize adverse effects of wind, the area of wall vents should be evenly distributed among all the exterior walls. For buildings that are much longer than wide, the vents can evenly divided between the two long sides. Exterior wall venting is most appropriate for buildings with open floor plans and least suitable when the floor plan is divided into many compartments. Because the flow of hot gases through a wall vent can be substantial, precautions should be taken in the design of exterior walls to minimize the possibility of exterior fire spread to floors above the vent.

9.3.1 Vent Areas

The following is a method for evaluating the size of exterior wall vents presented in essentially the same form as originally developed by Tamura (1978a). In this analysis, each floor consists of a smoke zone. For the analyses presented in this and the following section, the effects of fire are indirectly incorporated in the selection of minimum design pressure difference (Chapter 4). For this system, the fire floor (smoke zone) is vented to the outside, supply and exhaust fans serving the fire floor are shut off, and the floors above and below the fire floor are pressurized.

Air flows from adjacent floors to the fire floor and through the vent to the outside, as illustrated in figure 9.2. Because the supply and exhaust fans are shut off on the fire floor, the total air flow rate through the wall vents equals the total flow rate into the vented floor from the surrounding smoke control zones:

$$A_v \sqrt{P_F - P_O} = A_e \sqrt{P_B - P_F} \qquad (9.1)$$

where:
A_v = flow area of the exterior vent, ft^2 (m^2)
A_e = effective flow area of the enclosure of the smoke zone to the other zones, ft^2 (m^2)
P_F = smoke zone pressure, in H_2O (Pa)
P_O = outside pressure, in H_2O (Pa)
P_B = building pressure on nonsmoke zones, in H_2O (Pa)

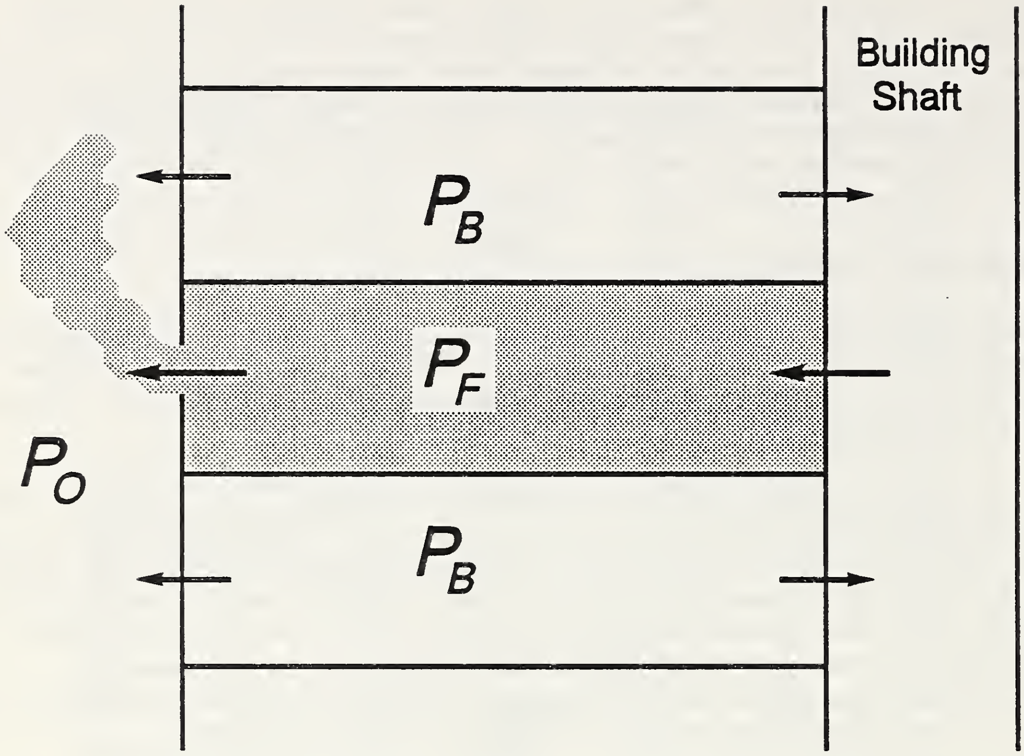


Figure 9.2 Flow pattern with venting of smoke zone

The effective flow area, A_e, includes the flow areas of the walls of vertical shafts, floor constructions, and duct openings (return and exhaust) of the smoke zone. Effective flow areas are discussed in detail in Chapter 4. Rearranging equation (9.1) yields

$$\frac{P_B - P_F}{P_F - P_O} = \left(\frac{A_v}{A_e} \right)^2 \tag{9.2}$$

But: $P_B - P_O = (P_B - P_F) - (P_F - P_O)$

Let: $\Delta P_{BO} = P_B - P_O$
$\Delta P_{BF} = P_B - P_F$
$\Delta P_{FO} = P_F - P_O$

where:
ΔP_{BO} = pressure difference from the nonsmoke zones to the outside, in H_2O (Pa)
ΔP_{BF} = pressure difference from the nonsmoke zones to the smoke zone, in H_2O (Pa)
ΔP_{FO} = pressure difference form the smoke zone to the outside, in H_2O (Pa)

Then: $\Delta P_{BO} = \Delta P_{BF} + \Delta P_{FO}$
$\Delta P_{FO} = \Delta P_{BO} - \Delta P_{BF}$

Substituting the above into equation (9.2) and rearranging yields

$$\frac{\Delta P_{BF}}{\Delta PB_O} = \frac{(A_v/A_e)^2}{1 + (A_v/A_e)^2} \tag{9.3}$$

A plot of equation (9.3) is shown in figure 9.3. This shows that for particular values of ΔP_{BO} and A_e, the pressure difference, ΔP_{BF}, across the boundary of the smoke zone increases as the vent area, A_v, increases. For large values of A_v, ΔP_{BF} approaches ΔP_{BO}.

Opening a stairwell door on a floor of a nonsmoke zone increases the pressure difference across the closed stairwell door on the fire floor (smoke zone). This can be explained by use of the concept of the effective flow area (Chapter 4), and it is left to the reader as an exercise. Opening doors in a stairwell on both a nonsmoke zone floor and the smoke zone floor results in considerable airflow to the smoke zone, which is accompanied by reduced pressure difference across the boundary of the smoke zone.

Example 9.1 Vent Areas and Pressure Differences

1. If the ratio of A_v/A_e is 1, what is the ratio of $\Delta P_{BF}/\Delta P_{BO}$?

From equation 9.3, $\Delta P_{BF}/\Delta P_{BO} = 0.5$. Thus, the pressure difference across the boundary of the smoke zone is only half that from the building to the outside.

2. If A_v/A_e is 2, what is $\Delta P_{BF}/\Delta P_{BO}$?

From equation 9.3, $\Delta P_{BF}/\Delta P_{BO} = 0.8$. This is much better.

3. If A_v/A_e is 3, how does $\Delta P_{BF}/\Delta P_{BO}$ change?

From equation 9.3, $\Delta P_{BF}/\Delta P_{BO} = 0.9$.

9.3.2 Pressurization Air Flow Rates

The effective flow area, A_e, of the enclosure of the smoke zone to the other zones usually consists of sum of the flow areas between the smoke zone and many other nonsmoke zones. The is expressed as

$$A_e = \sum_{i=1}^{n} A_{BFi} \tag{9.4}$$

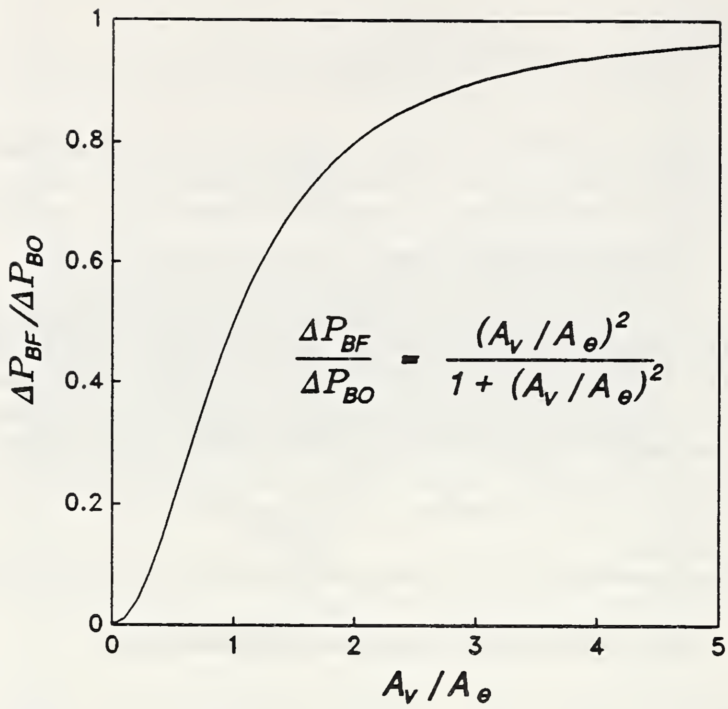


Figure 9.3 Variation of pressure difference with size of exterior wall vents

where:

A_e = effective flow area of the enclosure of the smoke zone to the other zones, ft^2 (m^2)
n = number of adjacent nonsmoke zones
A_{BFi} = flow area between nonsmoke zone i and the smoke zone, ft^2 (m^2)

Considering steady flow conditions, the mass flow rate of pressurization air entering a nonsmoke zone equals the flow rate of air leaving the zone:

$$\dot{m}_{ti} = \dot{m}_{BFi} + \dot{m}_{BOi} \tag{9.5}$$

where:
$\dot{m}_{ti}$ = mass flow rate of pressurization air into zone i, lb/s (kg/s)
$\dot{m}_{BFi}$ = mass flow rate from zone i to the smoke zone, lb/s (kg/s)
$\dot{m}_{BOi}$ = mass flow rate from zone i to the outside, lb/s (kg/s)

The flow rate from zone i to the smoke zone can be expressed in the form of equation (4.8a):

$$\dot{m}_{BF}i = K_m \, C \, A_{BFi} \sqrt{2 \rho \Delta P_{BF}} \tag{9.6}$$

where:

$\dot{m}_{BF}i$ = mass flow rate from zone i to the smoke zone, lb/s (kg/s)
C = dimensionless flow coefficient
A_{BFi} = flow area between nonsmoke zone i and the smoke zone, ft^2 (m^2)
ρ = density of air in flow path, in H_2O (Pa)
ΔP_{BF} = pressure difference from the nonsmoke zones to the smoke zone, in H_2O (Pa)
K_m = coefficient, 12.9 (1.00)

Similarly, the mass flow rate to the outside is

$$\dot{m}_{BO}i = K_m \, C \, A_{BOi} \sqrt{2 \, \rho \, \Delta P_{BO}} \qquad (9.7)$$

where:

$\dot{m}_{BO}i$ = mass flow rate from zone i to the outside, lb/s (kg/s)
C = dimensionless flow coefficient
A_{BOi} = flow area between nonsmoke zone i and the outside, ft^2 (m^2)
ρ = density of gas in flow path, in H_2O (Pa)
ΔP_{BO} = pressure difference from the nonsmoke zones to the outside, in H_2O (Pa)
K_m = coefficient, 12.9 (1.00)

For an unsprinklered fire, the gases leaving the smoke zone are likely to be relatively hot. However, the flows in question are both from the nonsmoke zones, which are probably near building temperature. Considering the very approximate nature of flow area estimates, the errors involved in using volumetric flow rates at standard conditions are not significant. Equations of the form of equation (4.8b) can be used

$$Q_{BFi} = K_f \, A_{BFi} \sqrt{\Delta P_{BF}} \qquad (9.8)$$

where:

Q_{BFi} = volumetric flow rate from zone i to the smoke zone, cfm (m^3/s)
A_{BFi} = flow area between nonsmoke zone i and the smoke zone, ft^2 (m^2)
ΔP_{BF} = pressure difference from the nonsmoke zones to the smoke zone, in H_2O (Pa)
K_f = coefficient, 2610 (0.839)

and

$$Q_{BOi} = K_f \, A_{BOi} \sqrt{\Delta P_{BO}} \qquad (9.9)$$

where:

Q_{BOi} = volumetric flow rate from zone i to the outside, cfm (m^3/s)
A_{BOi} = flow area between nonsmoke zone i and the outside, ft^2 (m^2)
ΔP_{BO} = pressure difference from the nonsmoke zones to the outside, in H_2O (Pa)
K_f = coefficient, 2610 (0.839)

The pressure difference from the nonsmoke zones can be obtained from equation (9.3) as

$$\Delta P_{BO} = \Delta P_{BF} \left[\frac{1 + (A_v/A_e)^2}{(A_v/A_e)^2} \right] \quad (9.10)$$

where:

ΔP_{BO} = pressure difference from the nonsmoke zones to the outside, in H_2O (Pa)
ΔP_{BF} = pressure difference from the nonsmoke zones to the smoke zone, in H_2O (Pa)
A_v = flow area of the exterior vent of the fire floor, ft^2 (m^2)
A_e = effective flow area of the enclosure of the smoke zone to the other zones, ft^2 (m^2)

The approach to estimation of supply air to nonsmoke zones is:

- Estimate flow areas using information in Chapter 4.
- Select a value of A_v (Suggest using $A_v/Ae = 2$).
- Establish appropriate value for ΔP_{BF} (Can use NFPA 92A (1988) suggested values).
- Calculate ΔP_{BO} from equation (9.10).
- Calculate flow rates using equations (9.4) through (9.9) as appropriate.
- Use a safety factor to account for deviations from estimated and actual flow areas.

Example 9.2 Supply Air and Exterior Wall Vents

The smoke zone of a zoned smoke control system is to have exterior wall vents and two adjacent nonsmoke zones. Supply and return are shut off to the smoke zone, and the adjacent zones are pressurized. The nonsmoke zones have the same flow areas: $A_{BO1} = A_{BO2} = 4.5$ ft^2 (0.42 m^2) and $A_{BF1} = A_{BF2} = 3.0$ ft^2 (0.28 m^2). Use $A_v/A_e = 2$, and $\Delta P_{BF} = 0.10$ in H_2O (25 Pa). How much pressurization air is needed?

From equation (9.4), $A_e = 3.0 + 3.0 = 6.0$ ft^2 (0.56 m^2).
From equation (9.10), $\Delta P_{BO} = 0.10((1+2^2)/(2^2)) = 0.13$ in H_2O (31 Pa
From equation (9.8), $Q_{BF1} = 2610(3)(.1)^{½} = 2500$ cfm (1.2 m^3/s)
From equation (9.9). $Q_{BO1} = 2610(4.5)(.13)^{½} = 4200$ cfm (2.0 m^3/s)

Including a safety factor or 1.5, the supply rate of pressurization air into zone 1 is 1.5(2500 + 4200) = 10,000 cfm (4.7 m^3/s).

9.4 SMOKE SHAFTS

A smoke shaft is a vertical shaft intended to be a path for smoke movement from the fire floor to above the level of the roof. Generally, the driving force of smoke movement is buoyancy, although the flow through some smoke shafts is aided by mechanical fans. This mechanical exhaust is addressed in the next section. A smoke shaft can serve one floor, a group of floors, or all the floors in a building. Smoke shafts have openings above the roof level and on the floors they serve. These openings are fitted with normally closed dampers. In a fire situation, only the damper on the fire floor and the top outside damper open to vent smoke outside. Smoke shafts should be constructed in accordance with local codes. Tamura and Shaw (1973) provide information concerning sizing of smoke shafts. Smoke shafts used in conjunction with pressurization of nonsmoke zones can produce pressure differences to restrict smoke to the smoke zone.

Smoke shafts lend themselves to use in buildings with open floor plans. The air movement caused by smoke shafts operating during normal stack effect tends to pull smoke toward the smoke shaft inlet on the fire floor. It is recommended that smoke shafts be located as far as possible from exit stairwells, so that smoke in the vicinity of the shaft inlet does not pose an increased hazard during evacuation or fire fighting. Because hot smoke frequently stratifies near the ceiling, it is recommended that smoke shaft inlets be located in or near the ceiling.

9.5 MECHANICAL EXHAUST

Mechanical exhaust of the smoke zone can be accomplished by either a dedicated exhaust system or by the exhaust fans of the HVAC system. Generally, such exhaust is done in conjunction with pressurization of nonsmoke zones. These systems can also include stairwell pressurization.

Mechanical exhaust by itself can result in sufficient pressure differences to control smoke. However, in the event of window breakage or a other large opening to the outside form the smoke zone, the pressure differences can decrease significantly. For this reason, mechanical exhaust alone does not constitute an adequate smoke control system when there is a significant probability of window breakage or an opening from the smoke zone to the outside.

In the smoke zone, the location of the exhaust inlets is important. These inlets should be located away from exit stairs, so that smoke in the vicinity of the shaft inlet does not pose an increased hazard during evacuation or fire fighting. Because hot smoke frequently stratifies near the ceiling, it is recommended that smoke shaft inlets be located in or near the ceiling.

Exhausting air from the smoke zone results in air from the outside and from other zones being pulled into the smoke zone. This air flowing into the smoke zone can provide oxygen to the fire. Most commercial air-conditioning systems are capable of moving about four to six air changes per hour, which probably accounts for the popularity of six air changes in smoke control applications.

Current designs are based on the assumption that the adverse effect of supplying oxygen at six air changes per hour is insignificant in comparison with the benefit of maintaining tenable conditions in zones away from the fire. Thus, six air changes is recommended as the upper limit for exhaust air flow.

In any analysis of a smoke control system, the fire effects of buoyancy and expansion need to be addressed. This can be done directly as part of the analysis or indirectly. As discussed in Chapter 4, the indirect approach consists of establishing a minimum design pressure difference that will not be overcome by buoyancy pressures resulting from smoke at design temperatures. This indirect approach is much simpler, and so human errors in analysis, other aspects of design, construction and commissioning are less likely. The following sections present both methods.

When the temperatures on both sides of the boundary of the smoke zone are the same, the pressure difference across the boundary is the same over the height of the barrier. This is the condition under which smoke control systems are almost always tested. When the gases in the smoke zone are "hot," the buoyancy of the hot gases results in a non-uniform pressure difference. Figure 9.4(a) is a uniform pressure difference at the minimum design value. This minimum value is selected such that positive pressurization of the smoke zone continues, provided that the mass flow from nonsmoke zones to the smoke zone remains unchanged and that the smoke zone does not exceed its design temperature [figure 9.4(b)]. However, if this mass flow decreases, smoke may flow into the "protected" spaces as illustrated in figure 9.4(c). The method of analysis presented in the following section allows evaluation of this decreased mass flow rate.

9.5.1 Mass Flows and Pressure Differences

In this section, an analysis of pressure differences and mass flows during smoke exhaust operation with the exhaust fan serving only one zone is presented. The analysis of this section leads to insight regarding the extent to which the indirect approaches are appropriate. For this analysis, the exhaust fan serves only the smoke zone. This analysis is an abbreviated form of one developed for evaluation of the data from fire experiments at the Plaza Hotel (Klote 1990).

The smoke zone may be made up of a number of rooms, each of which has an average temperature. During a fire, mass is exhausted by the smoke control system, and mass enters form pressurized zones. The law of conservation of mass applied to the smoke zone is that the net mass flow into the smoke zone equals the rate of mass change within the smoke zone. Expressed mathematically, this is

$$\dot{m}_i - \dot{m}_e = \frac{dm}{dt} \tag{9.11}$$

where:
$\dot{m}_i$ = flow rate of mass into smoke zone, lb/s (kg/s)
$\dot{m}_e$ = flow rate of mass leaving smoke zone, lb/s (kg/s)
m = mass within smoke zone, lb (kg)

The mass, m, inside the smoke zone can be expressed as

$$m = \bar{\rho}_f \; V_f \tag{9.12}$$

where:
$\bar{\rho}_f$ = average density of the gases inside the smoke zone, lb/ft^3 (kg/m^3)
V_f = volume of the smoke zone, ft^3 (m^3)

During idealized smoke control operation, the only mass leaving the smoke zone is through the exhaust fan. Consideration of a fan as a constant volumetric flow device is a good first order assumption, so the mass flow rate from the smoke zone can be expressed as

$$\dot{m}_e = \rho_{fan} \; Q_{fan} \tag{9.13}$$

where:
ρ_{fan} = density of the gases going through the fan, lb/ft^3 (kg/m^3)
Q_{fan} = volumetric flow rate of the fan, ft^3/s (kg/s)

The mass flow rate into the smoke zone consists of flows through numerous paths into all of the rooms of that zone. If the average pressure difference is nearly the same for all the paths, the mass flow rate into the smoke zone can be expressed as

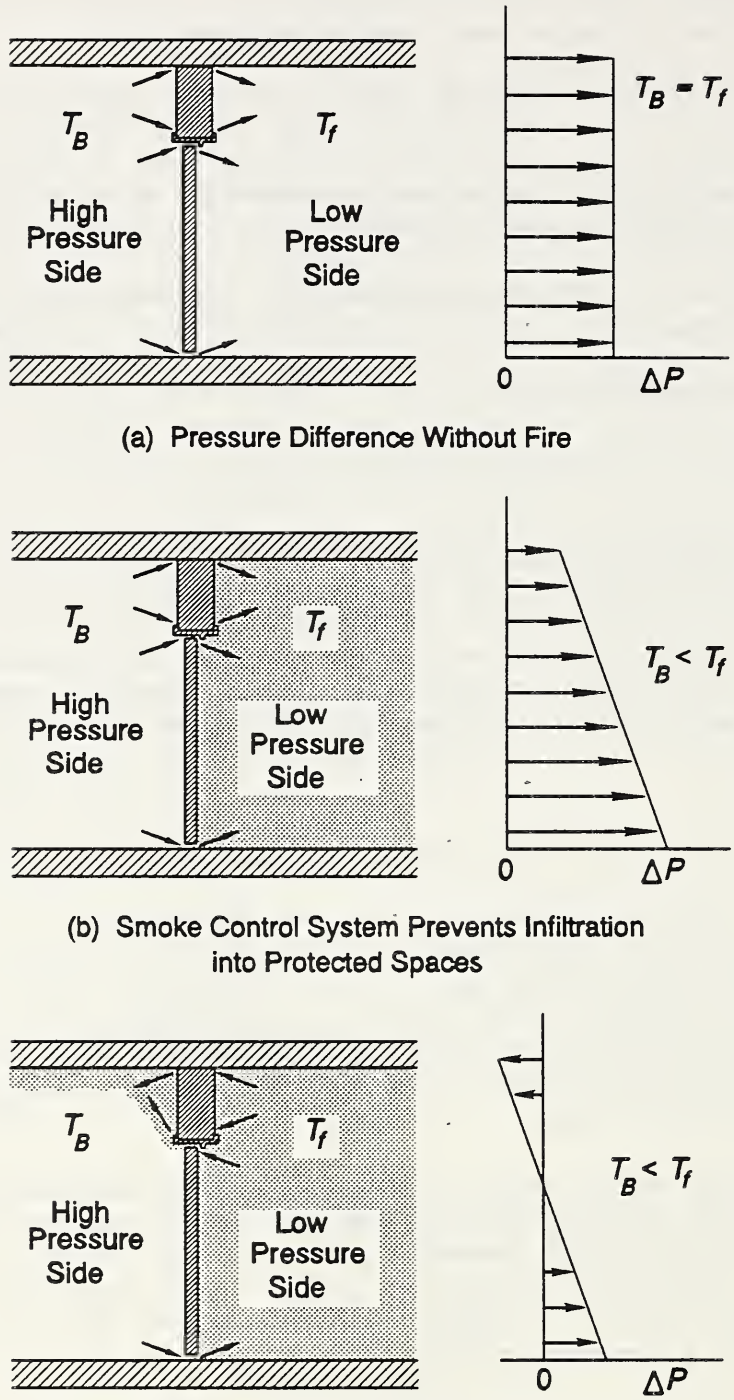
$$\dot{m}_i = K_m \; C \; A_e \sqrt{2 \; \rho_s \; \overline{\Delta P}} \tag{9.14}$$

where:
$\dot{m}_i$ = mass flow rate into smoke zone, lb/s (kg/s)
C = dimensionless flow coefficient
A_e = flow area in boundary of the smoke zone, ft^2 (m^2)
ρ_s = density of gas in flow path, in H_2O (Pa)
ΔP = average pressure difference across the flow paths, in H_2O (Pa)
K_m = coefficient, 12.9 (1.00)

The average pressure difference can be evaluated in a manner similar to the way the relation for the average pressure difference was developed between a stairwell and the outside in Chapter 7.

$$\overline{\Delta P} = \frac{4}{9}\left(\frac{\Delta P_h^{3/2} - [\Delta P_h + (\rho_B - \bar{\rho}_f)K_g h]^{3/2}}{2\Delta P_h + (\rho_B - \rho_f)K_g h}\right)^2 \tag{9.15}$$

where:



(a) Pressure Difference Without Fire

(b) Smoke Control System Prevents Infiltration into Protected Spaces

(c) Smoke Infiltration into "Protected Space" Due to Reduced Mass Flow of Smoke Zone Exhaust

Figure 9.4 Pressure difference at boundary of smoke zone

$\overline{\Delta P}$ = average pressure difference across the flow paths, in H_2O (Pa)
ΔP_h = pressure difference at ceiling elevation, in H_2O (Pa)
ρ_B = air density in nonsmoke zones, in H_2O (Pa)
ρ_f = average gas density in smoke zone in vicinity of path, lb/ft^3 (kg/m^3)
h = ceiling height above floor, ft (m)
K_g = coefficient, 0.192 (9.8)

The pressure difference, ΔP_o, across the boundary of the smoke zone near the floor is

$$\Delta P_o = \Delta P_h + (\rho_B - \overline{\rho}_f) K_g h \tag{9.20}$$

Analysis by Klote (1990) of the experiments of zoned smoke control at the Plaza Hotel using the above method resulted in good agreement with measured pressured differences as illustrated in figure 9.5. Figure 9.6 is a graphical representation of the law of conservation of mass for one of the fire experiments at the Plaza Hotel Building.

9.5.2 Expansion of Gases

As a fire develops, gases on the smoke zone are heated and expand. The increased volume of gases due to expansion flow out of the smoke zone with the rest of the gases exhausted by the fan. Accordingly, the mass flow rate into the smoke zone is decreased by the same amount. The decrease in flow into the smoke zone is accompanied by a decrease in pressure difference across the boundaries of the smoke zone. The effect of expansion on the flow rate through the boundary of the smoke zone is expressed as

$$Q_i = Q_{ir} + \frac{K_t}{\overline{\rho}_f} \left(\frac{dm}{dt} \right) \tag{9.21}$$

where:
Q_i = volumetric flow rate through the boundary of the smoke zone, cfm (m^3/s)
Q_{ir} = volumetric flow rate thorough the boundary of the smoke zone without a fire, cfm (m^3/s)
dm/dt = time rate of change of the mass of gases in the smoke zone, lb/s (kg/s)
$\overline{\rho}_f$ = average gas density in smoke zone in vicinity of path, lb/ft^3 (kg/m^3)
K_t = coefficient, 60 (1.00)

The expansion results in a decrease in the mass in the smoke zone and in a negative dm/dt. The value of dm/dt varies considerably from fire to fire and depends on fire growth and heat transfer. An evaluation of dm/dt is beyond the scope of this manual, but for the smoke control tests at the Plaza Hotel dm/dt was about -1.0 lb/s (-0.5 kg/s). The pressure difference is related to the volumetric flow rate as

$$\overline{\Delta P} = \overline{\Delta P}_r \, (Q_i/Q_{ir})^2 \tag{9.22}$$

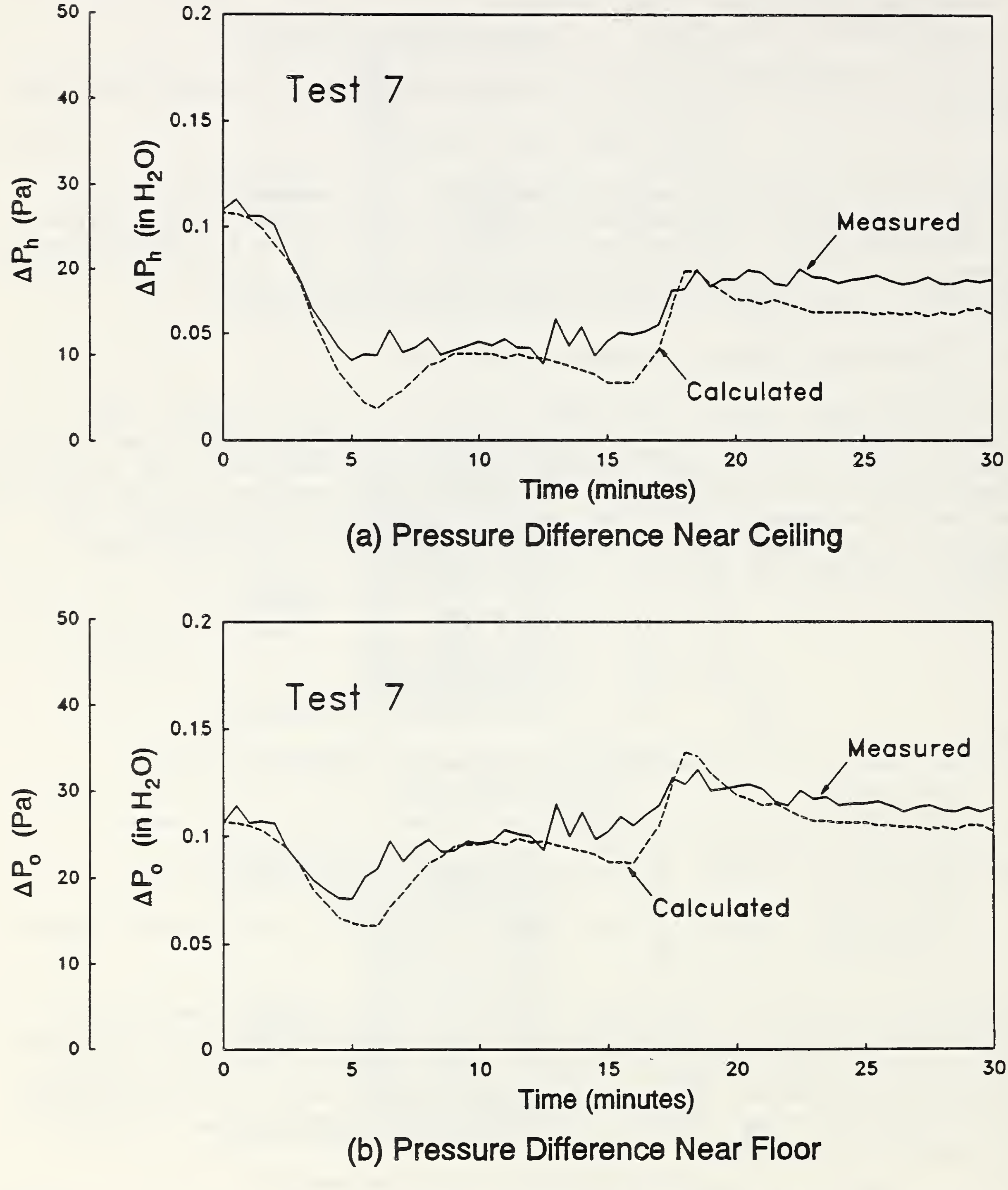


Figure 9.5 Comparison of pressure differences measured and calculated by equations (9.11) to (9.20) (Klote 1990)

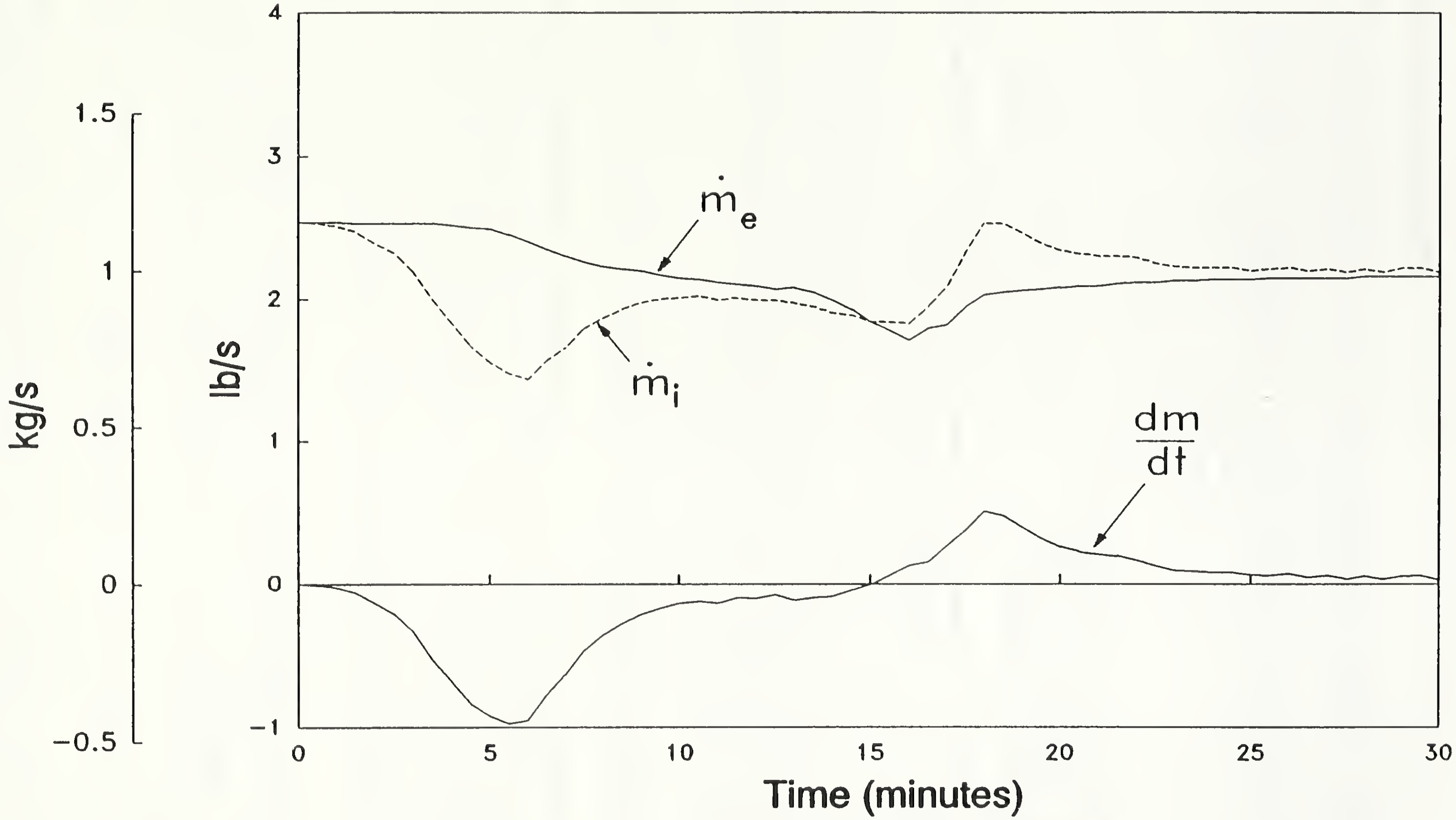


Figure 9.6 Graphical representation of the law of conservation of mass applied to the smoke zone

where:
$\overline{\Delta P}$ = average pressure difference across the boundary of the smoke zone, in H_2O (Pa)
$\overline{\Delta P_r}$ = average pressure difference across the boundary of the smoke zone without a fire, in H_2O (Pa)

The air change rate is related to the volumetric flow rate as

$$Q = \frac{\alpha V}{K_\alpha} \tag{9.23}$$

where:
Q = volumetric flow rate, cfm (m^3/s)
α = air change rate, hr^{-1} (hr^{-1})
V = volume of space, ft^3 (m^3)
K_α = coefficient, 60 (3600)

Example 9.3 Expansion and Smoke Zone Size

1. The average pressure difference across the barrier of smoke zone is 0.10 in H_2O (25 Pa). At the peak of expansion, a value of 0.08 in H_2O (20 Pa) is considered acceptable. Exhaust is not to exceed 6 air changes per hour. For dm/dt of -1.0 lb/s (0.5 kg/s) at peak expansion, will the pressure difference be acceptable for a smoke zone of 45,000 ft^3 (1270 m^3)?

The parameters are: $\overline{\Delta P_r}$ = 0.10 in H_2O (25 Pa), α = 6 hr^{-1}, dm/dt = -1.0 lb/s (0.5 kg/s), and V = 45,000 ft^3 (1270 m^3).

From equation (9.23), Q_{ir} = 6(45,000)/60 = 4500 cfm (1.23 m^3/s).
From equation (9.21), Q_i = 4500 + 60(-1)/0.07 = 3640 cfm (0.998 m^3/s).
From equation (9.22), $\overline{\Delta P}$ = 0.10 $(3640/4500)^2$ = 0.066 in H_2O (16.4 Pa).

This level of pressurization is not sufficient.

2. For the problem above, will the pressure difference be acceptable for a smoke zone of 90,000 ft^3 (2540 m^3)?

From equation (9.23), Q_{ir} = 6(90,000)/60 = 9000 cfm (4.25 m^3/s).
From equation (9.21), Q_i = 9000 + 60(-1)/0.07 = 8140 cfm (3.84 m^3/s).
From equation (9.22), $\overline{\Delta P}$ = 0.10 $(8140/9000)^2$ = 0.082 in H_2O (20.4 Pa).

This level of pressurization is acceptable. Thus, a 90,000 ft^3 (2540 m^3) smoke zone can handle the pressure that results from a fire producing a mass change of -1.0 lb/s (0.5 kg/s), but the same fire in a smaller smoke zone results in unacceptable pressurization.

9.5.3 Exhaust Fan Temperature

The effect of fan temperature on smoke control system performance is of concern. Fans are approximately constant volumetric flow rate devices. Thus the mass flow rate through the fan is a function of the absolute temperature of the gases in the fan. Increased fan temperature decreases the mass flow rate of the exhaust fan resulting in a reduction in smoke control system pressurization. The maximum allowable fan temperature can be calculated as

$$T_{fan} = T_r/(1 - \phi) \qquad (9.24)$$

where:
T_{fan} = maximum allowable absolute temperature of gases in fan, °R (K)
T_r = absolute temperature of gases in fan during normal operation, °R (K)
ϕ = allowable fraction reduction in mass flow rate through fan

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Example 9.4 Fan Temperature

If a reduction of 20% in the mass flow rate is acceptable, what is the maximum allowable fan temperature?

The parameters are: T_r = 70°F + 460 = 530°R, ϕ = 0.2.

From equation (9.24), T_{fan} = 530/(1 - .2) = 663°R or 203°F (95°C).

From example 9.4, a 20% reduction in mass flow through the fan occurs at 203°F (95°C). When many HVAC systems are used for smoke control, they exhaust air from all or most of the rooms on a floor. Thus, hot fire gases and lower temperature air from remote rooms are mixed, and the fan temperature is much lower than that of the fire gases. Also, heat transfer from the exhaust duct lowers the fan temperature.

The temperature of the gases in the fan can be conservatively estimated by considering dilution of hot gases with cooler gases and neglecting heat transfer. Considering constant specific heat, the fan temperature can be expressed as

$$T_{fan} = \frac{\sum_{j=1}^{n} \rho_j Q_j T_j}{\sum_{j=1}^{n} \rho_j Q_j} \qquad (9.25)$$

where:
T_{fan} = temperature of gases in fan, °F (°C)
ρ_j = density of gases in space j, lb/ft^3 (kg/m^3)

Q_j = volumetric flow rate of exhaust from space j, cfm (m^3/s)
T_j = temperature of space j, °F (°C)
n = number of spaces

Table 9.1 lists typical gas temperatures and densities for severe building fires which can be used in equation (9.25). The following idealized types of spaces are addressed in this table:

- Fire space
- Communicating space
- Removed space
- Separated space

Table 9.1 Typical gas temperatures and densities for severe building fires

	Temperature °F	(°C)	Density lb/ft^3	(kg/m^3)
Fire space is a room or corridor fully involved in fire.	1700	(927)	0.0184	(0.294)
Communicating space is a room or other space connected to the fire space by an open door or other large opening.	800	(427)	0.0315	(0.504)
Removed space is a room or other space connected to a communicating space by an open door or other large opening. The removed space is not connected to the fire space or is only connected to it by very small cracks or gaps.	400	(204)	0.0462	(0.739)
Separated space is a room or other space not connected to any of the three spaces above, or it is only connected to them by very small cracks or gaps.	80	(27)	0.0736	(1.18)

A fire space is a room or a corridor that is fully involved in fire. A communicating space is one that is connected to the fire space by an open door or other large opening. A removed space is a room or other space connected to a communicating space by an open door or other large opening. The removed space is not connected to the fire space or is only connected to it by very small cracks or gaps. A separated space is a space that is not connected to any of the three spaces above, or it is only connected to them by very small cracks or gaps.

To determine the extent of each type of space, a floor plan should be evaluated in light of likely locations of fires, doors likely to be opened, and doors likely to be closed. From example 9.5, it can be seen that cool air from the separated spaces mixes with the hot gases from other spaces and cools them. If the fan temperature is too high, the zone can be increased in size so that air from separated spaces will further dilute the hot gases.

Example 9.5 Fan Temperature and Smoke Control Zone Size

A smoke control system has exhaust rates from the following spaces:

Fire space:	400 cfm (0.189 m^3/s)
Communicating space:	800 cfm (0.378 m^3/s)
Removed space:	1800 cfm (0.850 m^3/s)
Separated space:	6000 cfm (2.83 m^3/s)

Table 9.1 provides descriptions of these spaces, gas temperatures, and densities. Will the fan temperature have a significant adverse effect of the performance of the system?

From example 9.4, the fan temperature can be 203°F (95°C) or less and the effect on system performance will be acceptable.

Using equation (9.25), T_{fan} =

$$\frac{.184(400)1700 + .0315(800)800 + .0462(1800)400 + .0736(6000)80}{.184(400) + .0315(800) + .0462(1800) + .0736(6000)}$$

$$= 182°F\ (83°C)$$

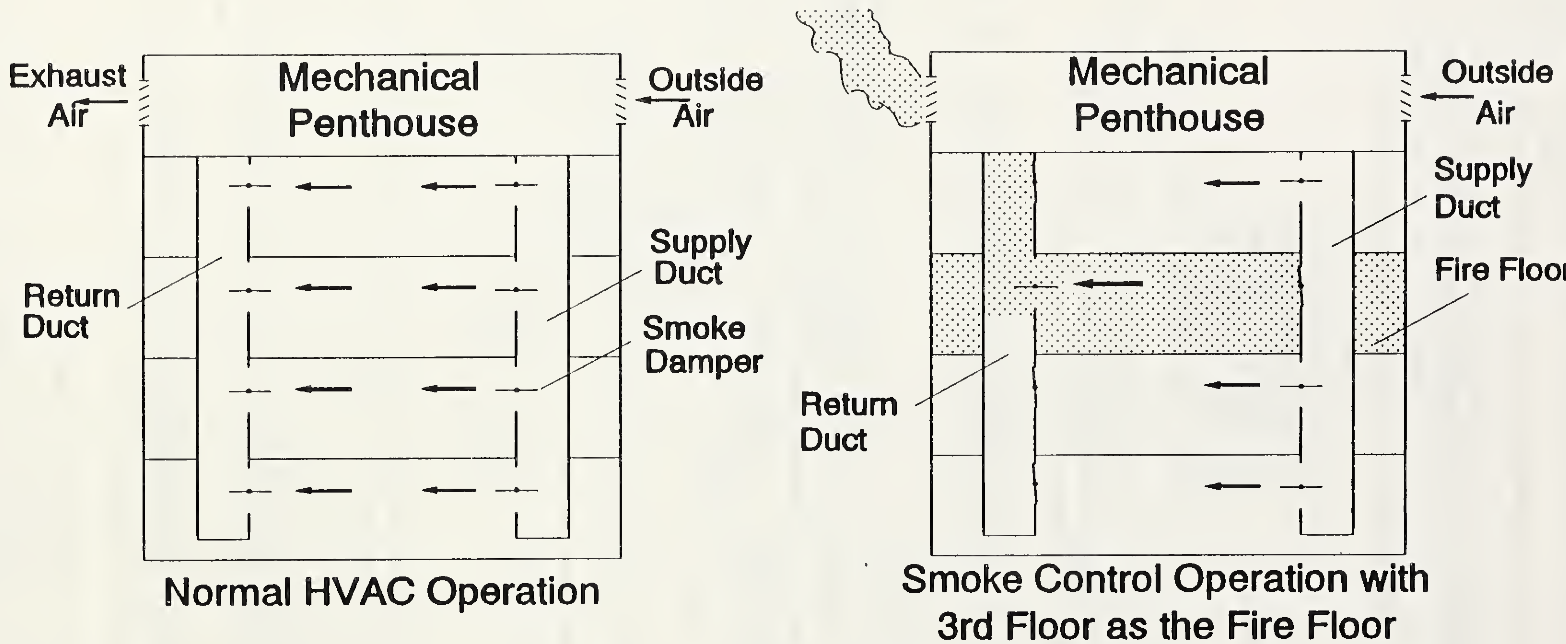
Fan temperature will not adversely effect system performance.

9.6 USE OF HVAC SYSTEM

In many buildings, the HVAC system serves many zones as illustrated in figure 9.7. 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 nonsmoke zones are closed.
- If the system has a return air damper, it is closed.

Precautions must be taken to minimize the probability of smoke feedback into the supply air system. Exhaust air outlets must be located away from outside air intakes. To conserve energy, most HVAC systems in modern commercial



Notes:
1. Smoke control is achieved by closing the smoke damper in the supply duct to the smoke zone and 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 the supply air.
2. For simplicity, distribution ducts on each floor and equipment in the penthouse are not shown.

Figure 9.7 Schematic of zoned smoke control system using an HVAC system that serves many smoke control zones 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 9.8. During smoke control operation the return damper must be tightly closed to prevent smoke feedback into the supply air as is illustrated in figure 9.9.

As discussed in Chapter 6, smoke dampers are supplied in several leakage classifications. 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 9.7 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 9.8 and 9.9).

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 the 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 (Klote 1986). 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 9.10 illustrates the failure of a supply-damper-only system to control smoke movement with resulting smoke flow to the floor above the fire floor due to buoyancy or stack effect.

For systems where the HVAC system serves only one smoke control zone, smoke control can be achieved by putting the HVAC systems in the modes below.

- <u>Smoke Zone:</u> return fan on, supply fan off, return damper closed, and exhaust damper open (optionally the outside air damper may be closed).

- <u>Nonsmoke Zone:</u> return fan off, supply fan on, return damper closed, and outside air damper open (optionally the exhaust air damper may be closed).

This kind of system was tested at two new Veterans Administration hospitals (Klote 1986), where each floor of each wing was a smoke control zone supplied by a separate HVAC system. This preformed well, was especially simple and required no expensive dedicated equipment.

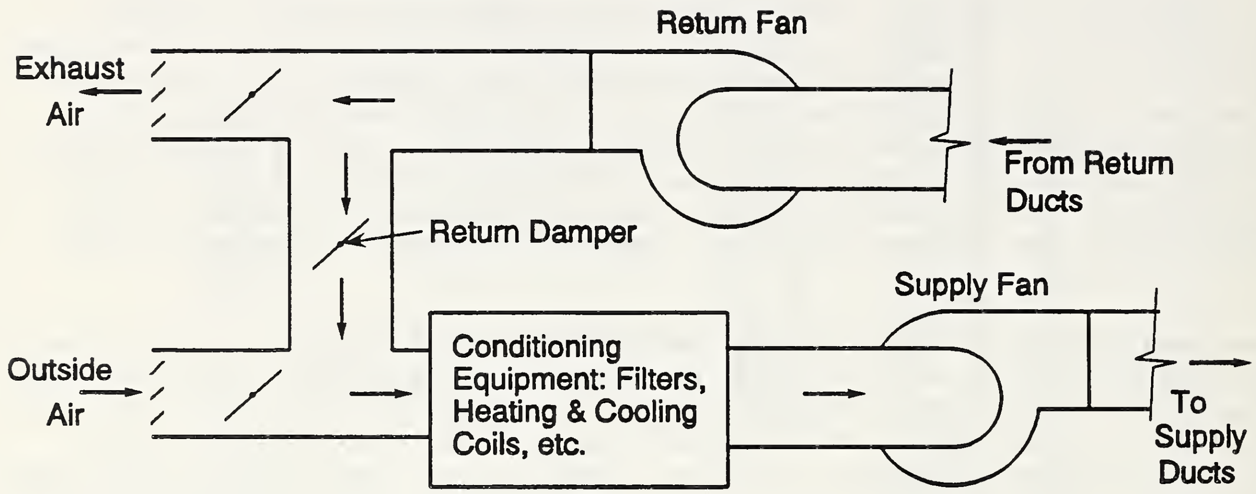


Figure 9.8 HVAC system with recirculation capability in the normal HVAC mode

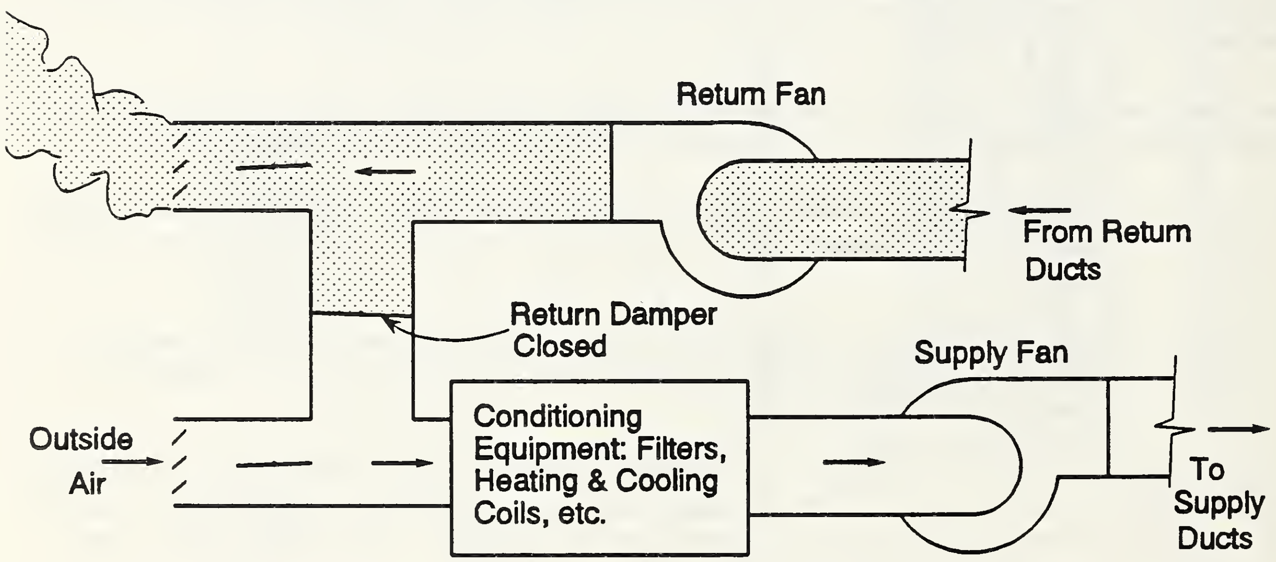


Figure 9.9 HVAC system with recirculation capability in the smoke control mode

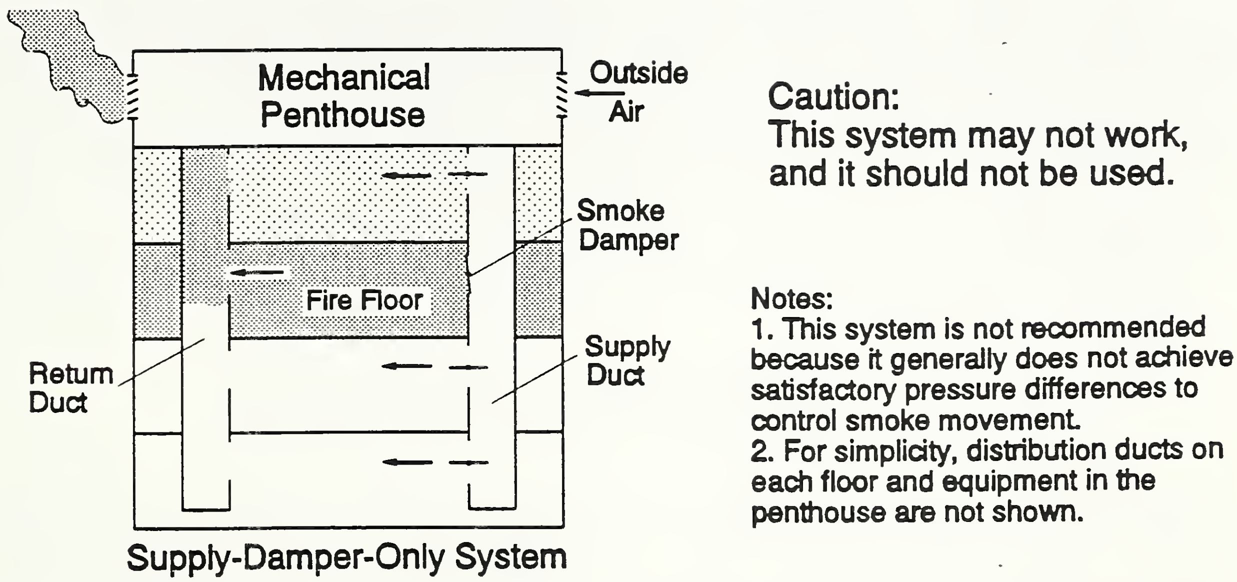


Figure 9.10 Schematic of failure to achieve smoke control by only shutting a smoke damper in the supply duct to the smoke zone

9.7 REFERENCES

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Chapter 10. COMMISSIONING AND ROUTINE TESTING

Commissioning and routine testing are needed to assure that smoke control systems will function as intended during fire situations. Many of the problems encountered during acceptance testing stem from misconceptions about the system's ability to control smoke and misunderstandings about the intended function of a particular system. This chapter deals with determination of what type of measurements should be made and how to make them. Further, most smoke control systems should require adjustments of supply air flow rates or pressure relief vent openings to accommodate the particular leakage characteristics of the buildings in which they are located. These adjustments can be made in conjunction with the acceptance test. Commissioning proceeders for new systems should include:

- inspection of the system components,
- testing of the system operation, and
- balancing of the system to assure performance.

Testing and balancing of the system can be conducted together. Frequently, local authorities want to be present at a formal acceptance test of a smoke control system. Such a formal acceptance test should be preceded by inspection, testing and balancing. Before acceptance testing, the owner, designer, builder and code officials should agree upon what constitutes acceptable performance. Acceptable performance should be based on measurements of appropriate design parameters, such as pressure differences, air velocities, and flow rates. If appropriate, the capabilities of the system to prevent smoke feedback into protected spaces should be tested.

Acceptable performance for a new system does not assure that, years later, the system will perform acceptably during a fire. Components deteriorate with age and can be inadvertently damaged during building modifications. For these reasons, annual testing of smoke control systems is recommended to provide a level of assurance that the system will function as desired in the event of a fire. The methods of routine testing should be the same as those of acceptance testing. Deficiencies encountered during routine testing should be corrected as soon as possible. These corrections may include balancing to correct for changes in building leakage and patching of gaps, holes and cracks in barriers of smoke control systems.

Inspection, testing and balancing of smoke control systems can be conducted by the building owner, the construction contractor, a testing and balancing contractor, a code official, or some other person. Regardless of who performs the work, all measurements made should be recorded for inspection. Typically, code officials check for compliance with local codes, whereas building owners and engineering and architectural firms also conduct inspections checking for compliance with the contract documents. Commissioning and routine testing are simplified when compliance is checked or measured against some standard. Contract documents can be prepared to reflect agreement between the owner, designer, builder and code official as to what constitutes acceptable performance. In the following discussion in this chapter and the referenced appendices, the phrase 'as specified' is used to mean as specified in accordance with a standard or standards which has been agreed upon by the parties involved.

General information about testing and balancing of HVAC systems is provided by SMACNA (1983) and ASHRAE (1987). ASHRAE is currently developing a standard for commissioning of smoke management systems.

10.1 INSPECTION

Inspection consists of checking smoke control system components which include barriers, air moving equipment, controls, and electric power supply. For pressurized stairwells, the barriers consist of the stairwell walls, ceiling and doors. For zoned smoke control, the barriers are the walls, floor and ceiling separating the zones. For elevator smoke control, the barriers would be of the elevator shaft and its lobbies. Walls, partitions, floors and ceilings should be checked for obvious and unusual openings that could adversely affect smoke control performance. Gaps around doors should be as specified. Automatic door closers that are part of the smoke control system should be of the type specified.

The air moving equipment to be checked includes ducts, access openings in ducts, fans, fire dampers, ceiling dampers, and smoke dampers. The materials and construction of ducts should be checked. Dampers should be the type specified and installed where and in the manner specified. Components of the control system should be checked to determine that they as specified. Any special electrical power requirements such as standby power or dual feeds should be checked. General inspection procedures are presented in appendix G, and these are only intended as a guide for the development of specific procedures for individual smoke control systems.

10.2 TESTING AND BALANCING

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 initiating device into alarm.

With all stairwell doors closed, pressure differences across each stairwell door should be measured. 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 opened equals the number of doors required by the code authority to be opened.

A caution needs to be given concerning the use of smoke bombs. The major problem with most smoke bomb tests of smoke control systems is that they are intended to test some improvement of 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 smoke. Because the smoke control system is exhausting air and 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 specific distance (such as 20 ft), the smoke control system is declared a success.

The problems with this type of smoke bomb test are numerous, and the unrealistic nature of these tests was illustrated by the experiments at the Plaza Hotel (Klote 1990). The criterion for successful operation is not objective. Further, the potential danger of exposing the observer or other people to toxic chemical smoke must dealt with. The obscuration of smoke from a building fire is much different from that of chemical smoke. Most flaming fires produce a hot, dense, black smoke; while most smoke bombs produce a cool, 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 the 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. Possibly the flow of unheated chemical smoke is 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 to 1000 °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. This is impractical because of the associated danger to life and property.

Chemical smoke or a tracer gas (such as sulfur hexaflouride) 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 metal container, and all bombs are simultaneously ignited. The container is located near an 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, the path should be blocked, and then the smoke feedback test should be conducted again.

Smoke bombs or other tracers 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. General testing procedures are presented in appendices H and I. As with Appendix G these are intended as a guide for the development of specific procedures for individual smoke control systems.

10.3 DIFFERENTIAL PRESSURE INSTRUMENTATION

The set-up for measuring pressure difference across a door is illustrated in figure 10.1. The convention of this set up is that the instrument is on the low pressure side of the door. Experience has shown that adherence to a particular convention reduces confusion and thus the potential for human error. A hose connected to the high pressure port of the instrument goes through a gap underneath and is terminated with a tee on the high pressure side of the door. The tee is used to minimize any pressure errors due to air velocity. Alternatively, the tube can end without a tee provided that it is located so that the dynamic pressure component is negligible. Rubber or flexible plastic tube of 0.25 in (6.4 mm) outside diameter works well for most cases. A narrow gap may result in a pinched tube invalidating any measurement. Small diameter metal tubing can sometimes be used in such cases particularly through the gaps of some gasketed doors.

The differential pressure instrument should have a sensitivity of at least 0.01 in H_2O (2.5 Pa), and generally a range from 0 to 0.25 in H_2O (0 to 62 Pa) is sufficient. Occasionally an instrument with a range of 0 to 0.50 in H_2O (0 to 124 Pa) is needed.

10.3.1 Inclined Liquid Manometer

An inclined manometer with a liquid reservoir is illustrated in figure 10.2. This device indicates pressure by the height of a column of liquid. Before any measurements, the instrument must be adjusted so that it is level. Generally, the scales of inclined manometers are compensated for the liquid rise in the reservoir so that the pressure difference can be read directly. The zero level of these instruments can be adjusted by adding or removing liquid from the reservoir or by changing the position of the scale. Because the measurement principle of these devices is so fundamental, it is believed that commercially available inclined manometers are of sufficient accuracy for smoke control testing without independent calibration.

10.3.2 Differential Pressure Gages

A gage without liquid has the advantage of convenience over the inclined manometer. Bourdon-tube gages are the most common type of pressure gages, but the friction of the mechanical linkages of these instruments limits sensitivity. No Bourdon-tube gage is known with sufficient sensitivity for smoke control application. However, a magnetically coupled gage as illustrated in

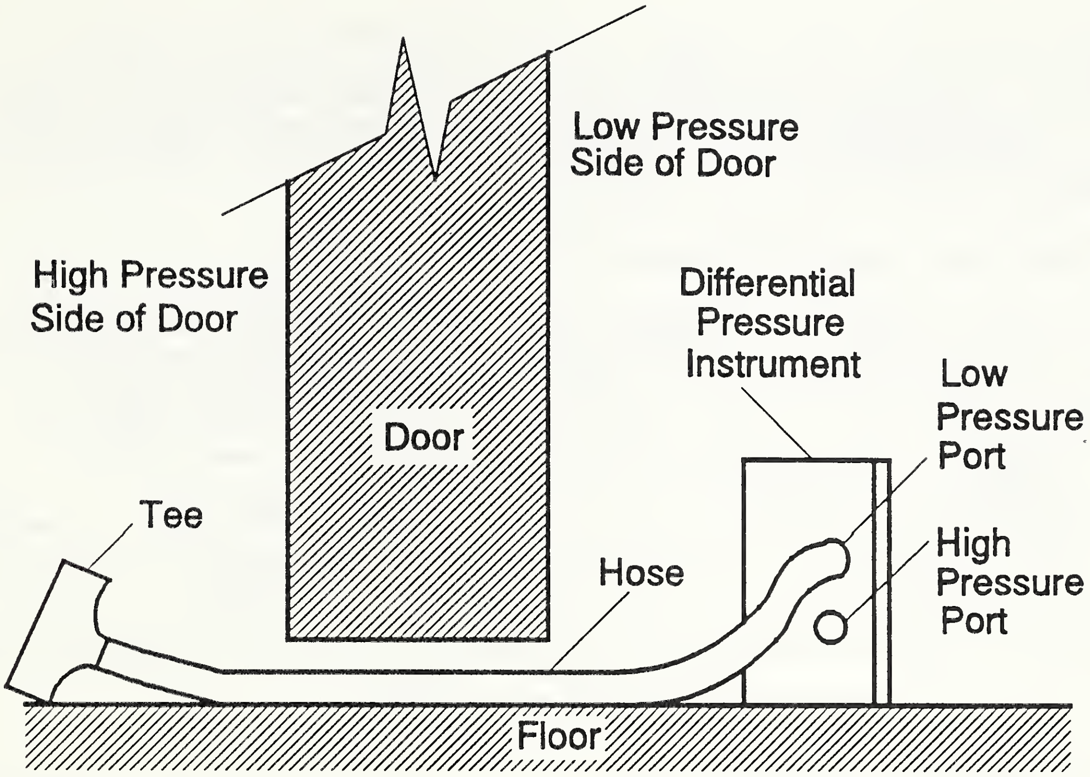

Figure 10.1 Set-up for measuring pressure difference across a door

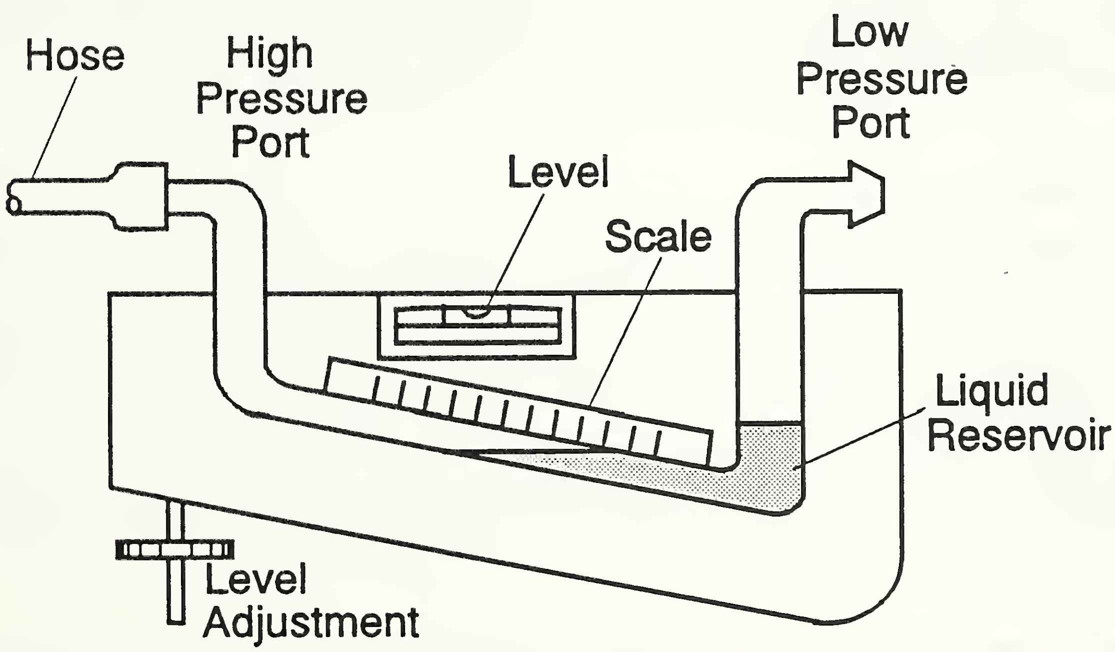

Figure 10.2 Inclined manometer with liquid reservoir

figure 10.3 is sufficiently sensitive, and these gages have been used extensively for field tests of smoke control systems. The gage should have a stand so that it can be set on the floor or other flat surface. The instrument has a zero adjustment that can correct for minor deviations in surface level. Thus an instrument level adjustment is unnecessary. A differential gage should be calibrated.

10.3.3 Electronic Pressure Transducers

Most electronic differential pressure transducers are of the diaphragm type. Changes in pressure across a diaphragm cause diaphragm displacement which can be measured by strain gages, piezoelectric elements, inductance pickups, capacitance pickups, etc. These transducers require electrical power and should be calibrated periodically. Many instruments are commercially available with the necessary sensitivity and in appropriate ranges. For many applications, a major advantage of these instruments is that they have analog voltage output suitable for monitoring by computer data acquisition systems. For field tests conducted with hand held instruments, analog output seems to have little advantage. For this reason and because of the expense of these instruments, they are not generally the instrument of choice for smoke control testing.

10.4 FLOW INDICATION AND MEASUREMENT

During acceptance and routine testing, there are many situations for which the knowledge of flow direction is desirable. Such cases abound during the initial checkout of a smoke control system. A piece of paper placed in front of an air grill provides an immediate and simple indication of flow and flow direction. Air flow will cause a hanging strip of tissue paper to noticeably deflect diagonally at flow velocities as low as 15 fpm (0.08 m/s). Smoke flow from a punk stick or a cigarette can also be used to detect such low air flows.

10.4.1 Volumetric Flow Rate

Air flow velocity through an open doorway or across a section of a corridor is generally far from uniform. Such flow is frequently characterized by the presence of large stationary vortices; especially flow through open stairwell doorways. This makes accurate determination of volumetric air flow difficult unless extreme care is taken. Fortunately, air flow through large openings is not the major principle of smoke control for most building systems. It follows that for the majority of smoke control systems for buildings, flow measurements in doorways and corridors are not necessary. However, flow measurements of the supply and exhaust of a smoke control system are often desired, and sometimes information about the flows through doorways is also needed.

Flow can be measured directly by using a flow hood or determined indirectly from a set of velocity measurements. Flow hoods are commercially available instruments which have a grid of static and dynamic pressure taps form which the volumetric flow through the hood is obtained and displayed directly on a

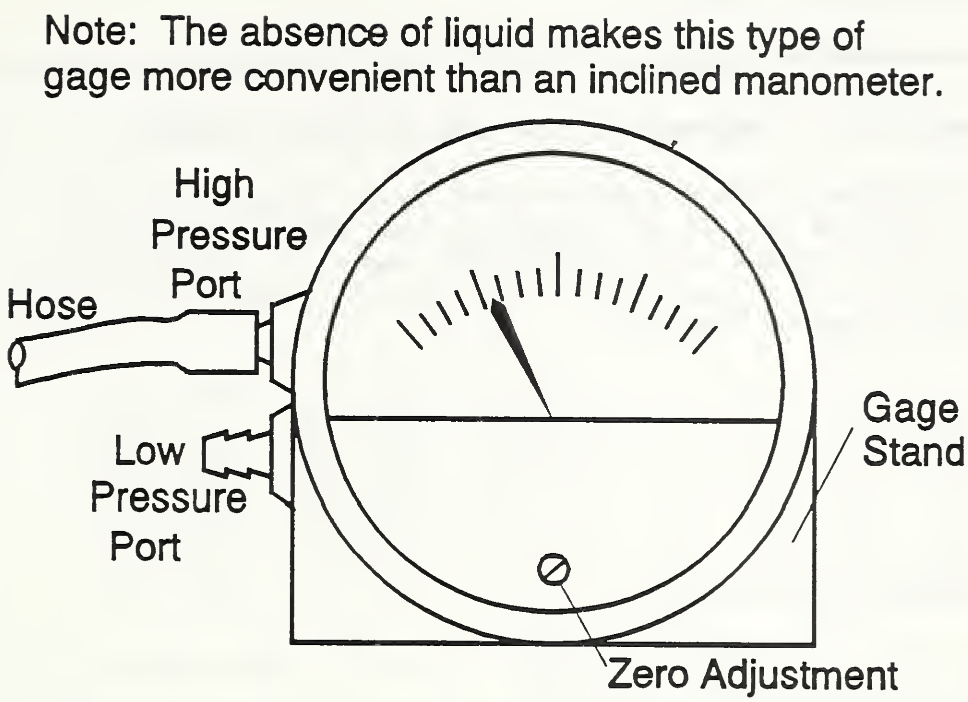

Figure 10.3 Magnetically coupled differential pressure gage

meter. Figure 10.4 illustrates a flow hood being used to measure flow from a ceiling supply. The device also can be used to measure exhaust flows, and it can be oriented for use with wall mounted inlets and outlets. Provided that the pressure loss through the hood is small compared to the duct losses, the accuracy of flow hoods is believed to be in the range of 10 to 15%.

When volumetric flow is obtained from velocity measurements, a traverse should be made. Traversing open doorways or sections of corridor can be done in a manner similar to that for rectangular ducts, as illustrated in figure 10.5. Velocity readings should be taken in the center of equal areas over the cross section. The ASHRAE Handbook of Fundamentals (1989) recommends 16 to 64 such readings for flow in ducts, however because of the likely variations of velocity in doorways and corridors at least 30 readings are recommended. Flows through doorways in particular should be checked for stationary vortices by use of smoke from a punk stick or cigarette. If stationary vortices exist, care should be taken that flows against the main flow direction should be assigned negative values when calculating the average velocity. The volumetric flow rate is calculated from the formula

$$Q = HWV \tag{10.1}$$

where:
Q = volumetric flow rate, cfm (m^3/s)
H = height of opening, ft (m)

W = width of opening, ft (m)
V = average velocity, fpm (m/s)

Example 10.1 Volumetric flow from velocity traverse

Calculation of the volumetric flow rate through a doorway 3 ft by 7 ft (0.91 m by 2.13 m) is desired, and the presence of a stationary vortex was observed with smoke. A traverse of 35 readings is like that shown in figure 10.5, and the velocities are listed below in fpm (m/s).

-80 (-.41)	20 (.1)	100 (.51)	530 (2.7)	480 (2.4)
-100 (-.51)	-20 (-.1)	130 (.66)	640 (3.3)	710 (3.6)
-140 (-.71)	10 (.05)	160 (.81)	630 (3.2)	640 (3.3)
-120 (-.61)	5 (.03)	180 (.91)	690 (3.5)	630 (3.2)
-110 (-.56)	-10 (-.05)	70 (.36)	750 (3.8)	640 (3.3)
-60 (.30)	-15 (-.08)	200 (1.0)	710 (3.6)	750 (3.8)
320 (1.6)	400 (2.0)	420 (2.1)	680 (3.5)	550 (2.8)

The average velocity is 300 fpm (1.5 m/s). Using equation (10.1) the flow is 6300 cfm (3.0 m^3/s).

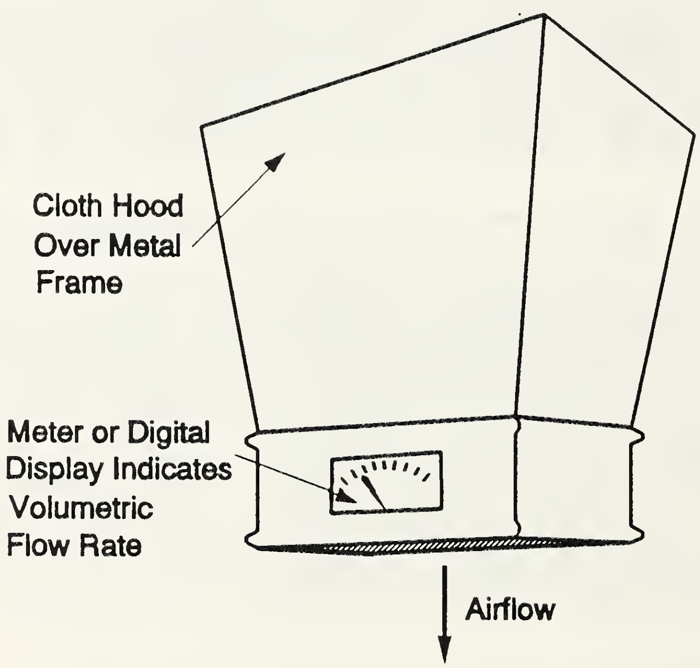

Figure 10.4 Flow hood being used to measure volumetric flow of ceiling mounted supply

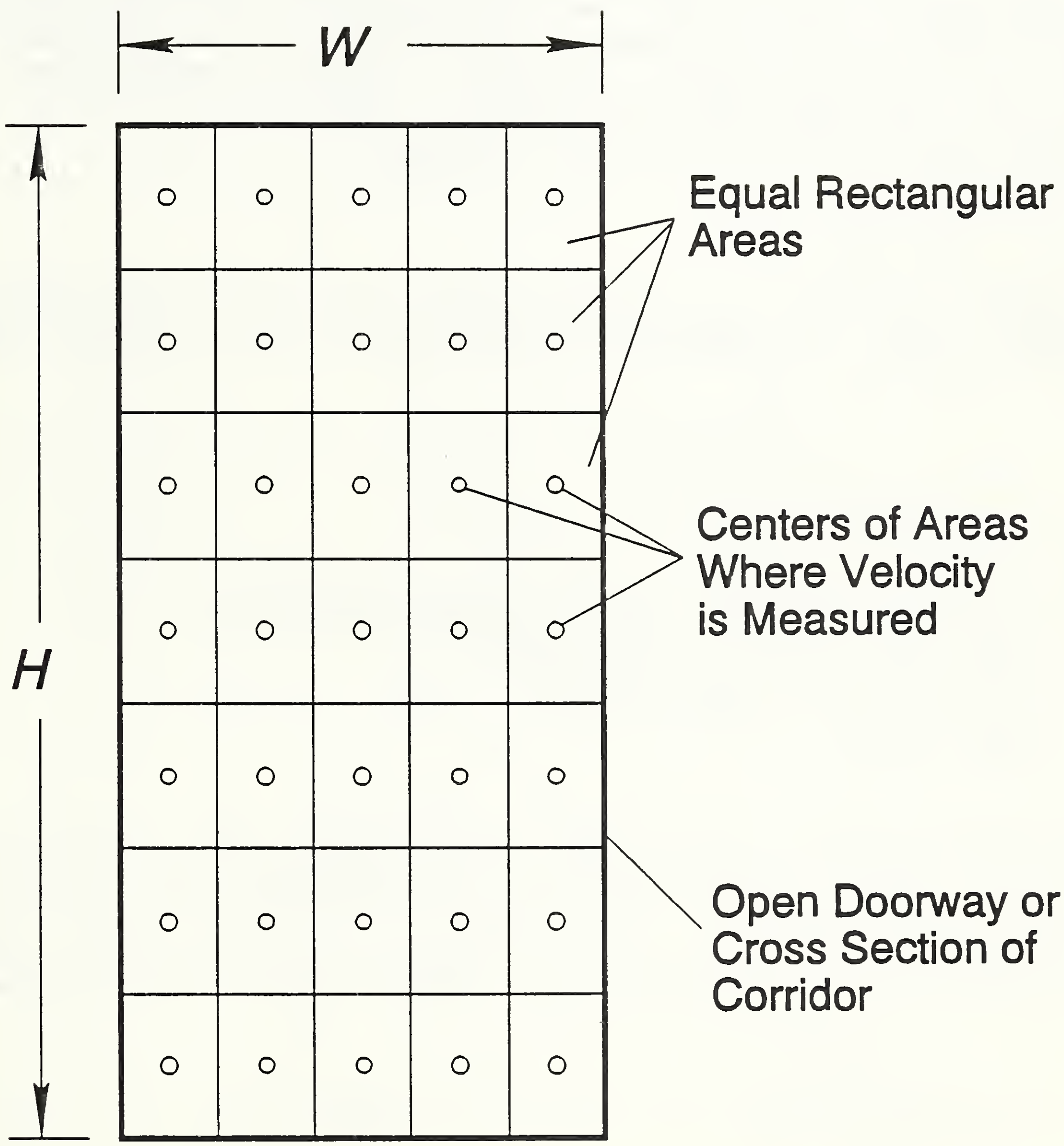

Figure 10.5 Flow measurement traverse for corridors and open doorways

10.4.2 Velocity Measurement Instruments

Pitot tubes, deflecting-vane anemometers, and thermal anemometers are commonly used to measure air flow in buildings. These instruments are discussed in the following sections.

10.4.2.1 Deflecting Vane Anemometer

The deflecting vane anemometer consists of a vane hung from a pin such that air velocity will cause a diagonal deflection of the vane as illustrated in figure 10.6. Manufacturers rate the accuracy of these instruments at 5% for flows less than 100 fpm (0.5 m/s) and 10% for greater flows. The ASHRAE handbook identifies the limitations of not being well suited for many air flow readings and of needing periodic calibration. Because of their low cost and compact size, these instruments are popular for making spot checks and obtaining rough estimates of velocity. However, it is not believed that they are appropriate for acceptance or routine testing.

10.4.2.2 Pitot Tube

The stagnation pressure, P_{stag}, is the pressure that results when moving gas is brought to rest. An expression for this pressure can be obtained from Bernoulli's equation

$$P_{stag} = P_{stat} + \frac{C \rho V^2}{K_{pt}^2} \qquad (10.2)$$

where:
P_{stag} = stagnation pressure of the gas, in H_2O (mm H_2O)
P_{stat} = static pressure of the moving gas, in H_2O (mm H_2O)
C = correction factor, (dimensionless)
ρ = density of gas, lb/ft^3 (kg/m^3)
V = gas velocity, fpm (m/s)
K_{pt} = 1097 (4.427)

For an idealized frictionless fluid, the coefficient, C, has a value of one, and the value differs for real fluids. Pitot tubes measure the stagnation pressure of a moving gas, and some pitot tube incorporate static pressure taps as illustrated in figure 10.7. Manufacturers of Pitot-static tubes frequently supply information about the correction factor as a function of flow velocity or of Reynolds number. The velocity from equation (10.2) can be expressed as

$$V = K_{pt} \sqrt{\frac{\Delta P}{C \; \rho}} \qquad (10.3)$$

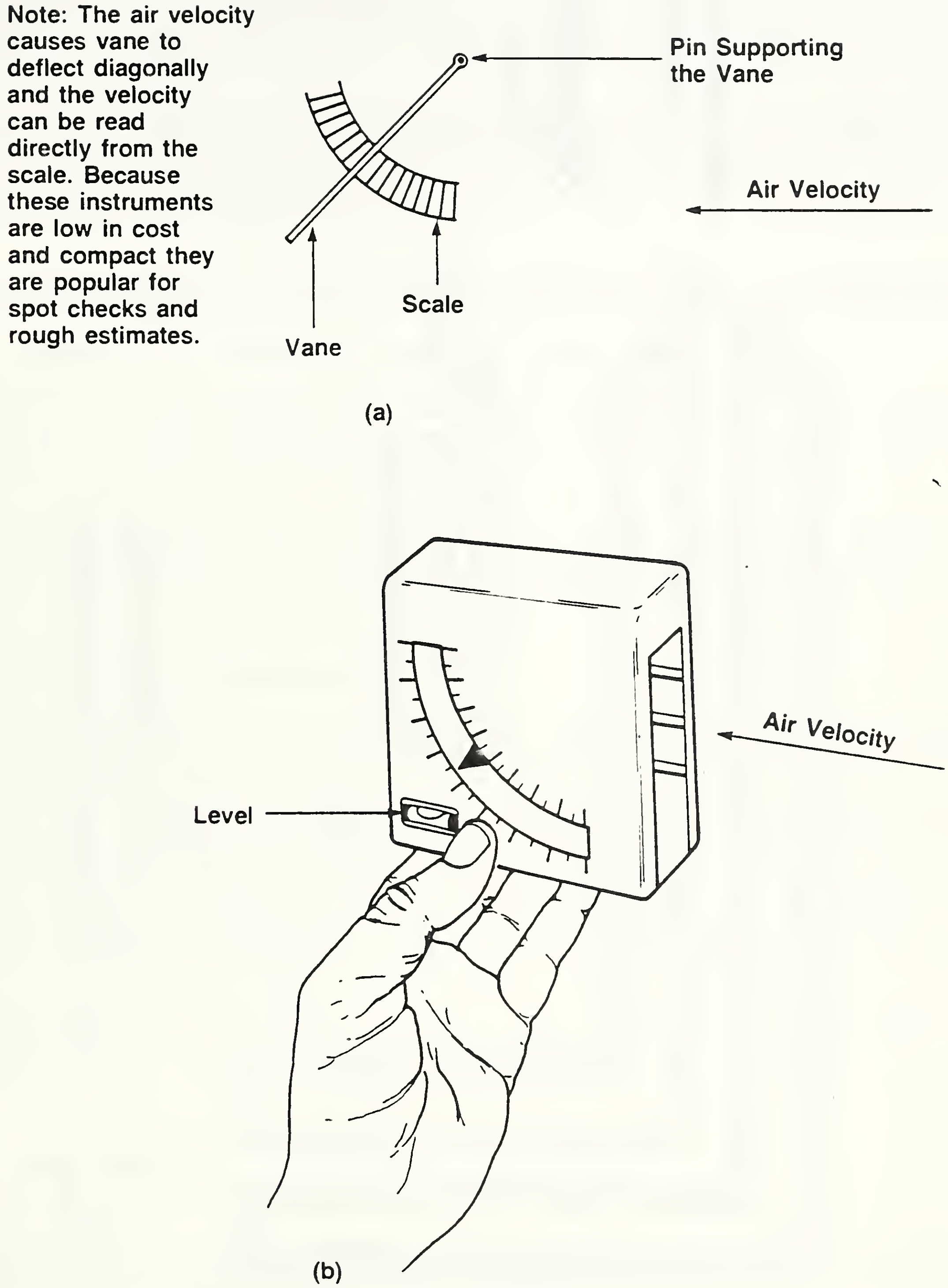

Figure 10.6 Deflecting vane anemometer: (a) principle of operation and (b) the instrument in use

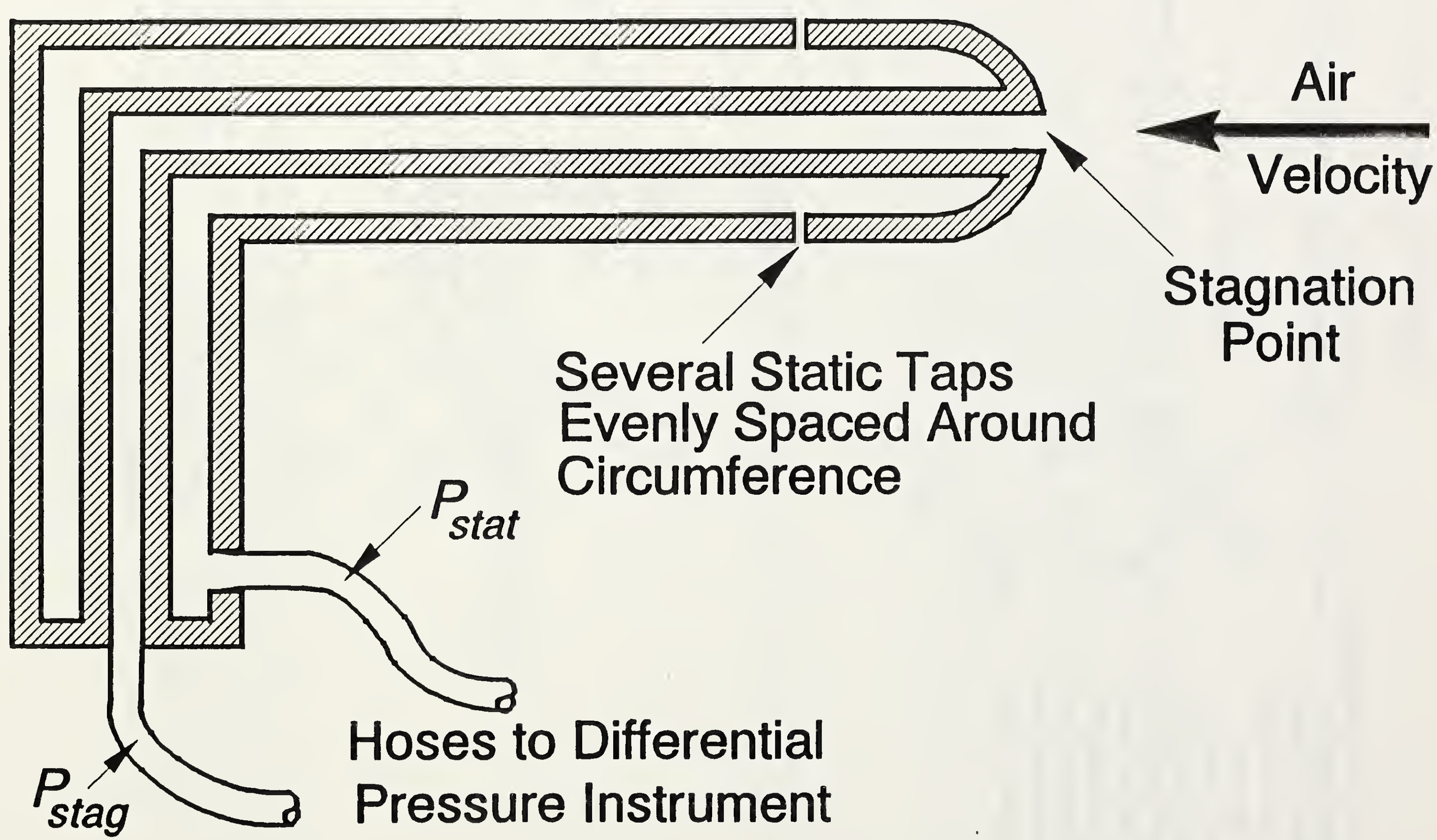

Figure 10.7 Pitot-static tube

where:
V = velocity, fpm (m/s)
ΔP = pressure difference from manometer, in H_2O (mm H_2O)
ρ = density of air, lb/ft^3 (kg/m^3)
C = pitot tube correction factor, (dimensionless)
K_{pt} = 1097 (4.427)

A pitot-static tube can be used to measure velocities in the range of 400 to 2000 fpm (2 to 10 m/s) when connected to an inclined manometer. With an electronic differential pressure transducer a pitot tube can be used in the range of 200 to 3000 fpm (1 to 15 m/s).

Example 10.2 Velocity from Pitot-static tube reading

The manometer connected to a pitot-static tube reads 0.08 in H_2O (2.03 mm H_2O), the air density is 0.075 lb/ft^3 (1.2 kg/m^3), and the pitot tube correction factor is 1.05.

The velocity calculated from equation (10.3) is 1110 fpm (5.62 m/s)

10.4.2.3 Thermal Anemometer

Thermal Anemometers (also called hot-wire anemometers and hot-film anemometers) are available in two types: constant-current and constant-temperature. Both types have a velocity probe with a filum (fine wire). For the constant-current type, a filum is subjected to a constant electrical current and the temperature of the filum depends upon the convective cooling of air flowing past it. Thus, temperature is a measure of velocity. The constant-temperature type uses the same principle in a different way. The electrical current through a filum is adjusted so that its temperature remains constant. For this instrument, current is a measurement of velocity. Hand held, battery powered, temperature compensated thermal anemometers are commercially available for air temperatures normally encountered in building heating and cooling systems. Such instruments have ranges of approximately 10 to 5000 fpm (0.05 to 25 m/s) with accuracies of about 5%.

10.5 REFERENCES

ASHRAE Handbook - 1989 Fundamentals, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA.

ASHRAE Handbook - 1987 HVAC System and Applications, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA.

Klote, J.H. 1990. Fire Experiments of Zoned Smoke Control at the Plaza Hotel in Washington DC, ASHRAE Transactions, Vol 96, Part 2.

SMACNA 1983. HVAC Systems Testing, Adjusting and Balancing, Sheet Metal and Air Conditioning Contractors' Association, Inc., Vienna, VA.

Appendix A UNITS OF MEASUREMENT AND PHYSICAL DATA

Physical quantities such as length, weight, and time are expressed in terms of standard units of measurement. In this book, both English units and international system (SI) units are used.

Newton's second law of motion states that the force, F, on a body of fixed mass, m, is proportional to the product of the mass and the acceleration, a.

$$F \approx m\, a$$

There are three common English unit systems with regard to mass and force: the pound mass and pound force system, the slug and pound system, and the pound mass and poundal system. Introduction of the proportionality constant $1/g_c$ into the above relation yields

$$F = \frac{m\, a}{g_c}$$

Table A.1 lists the units for these systems and the SI system along with the values of g_c for each. Generally, a pound is thought of as a unit of force. However, in some engineering applications, the pound also has been used as a unit of mass. One pound mass (lbm) is the mass of a body that weighs one pound (lb) at sea level. One slug equals 32.174 lbm, and one poundal is a force of 0.03108 pounds. For the systems listed in table A.1 for which the value of g_c is one, Newton' second law can be written as

$$F = m\, a$$

This formulation of Newton's law simplifies derived equations and calculations. It is accomplished by defining one of the four units (length, mass, time and force) in terms of the other three. Thus three of the units become base units and the other is a derived unit. Theoretically, any three can be selected as base units. However, the only two combinations to be used extensively are:

Base Units	Derived Unit
mass, length and time	force
force, length and time	mass

Because force is a derived unit in the SI system, that convention is used in the following discussion for the English system. For convenience, the unit of mass in the English system will be taken to be the slug. A slug can be thought of as a mass that has a weight of 32.174 pounds at sea level. In the English system, the unit of force is the pound, lb, which is the force required to accelerate a mass of one slug at a rate of one foot per second squared. In the SI system, the unit of force is the newton, N, which is the force required to accelerate a mass of one kilogram at a rate of one meter per second squared.

The base units and derived unit derived unit discussed above relate force and mass, but many more units are needed for engineering calculations. The base units and derived units needed for smoke control applications are listed in tables A.2 and A.3. In the SI system, prefixes are used to form decimal multiples and submultiples of the SI units. The SI prefixes are listed in table A.4. The conversion factors listed in Tables A.5 and A.6 have been rounded off to three or four significant figures, which is sufficient for most smoke control calculations.

Absolute temperature is measured in the Kelvin scale in the SI system and the Rankine scale in the English system. In addition, temperature is frequently measured in the Celsius or the Fahrenheit scale. Because Celcus and Fahrenheit scales are so commonly used by design engineers, these scales are used exclusively in the discussions in the text and in figures. However, caution should be exercised to assure that absolute temperatures are used in calculations where necessary. Tables A.7 and A.8 and the following equations can be used to convert between temperature scales:

$$T_F = 1.8\ T_K - 459.67$$
$$T_F = 1.8(T_C) + 32$$
$$T_F = T_R - 459.67$$

$$T_C = (T_F - 32)/1.8$$
$$T_C = T_K - 273.15$$
$$T_C = T_R/1.8 - 273.15$$

$$T_R = T_F + 459.67$$
$$T_R = 1.8\ (T_C + 273.15)$$
$$T_R = 1.8\ T_K$$

$$T_K = T_R/1.8$$
$$T_K = (T_F + 459.67)/1.8$$
$$T_K = T_C + 273.15$$

where:

T_F is temperature in degrees Fahrenheit
TC is temperature in degrees Celsius
T_R is temperature in degrees Rankine
T_K is temperature in the kelvin scale

Tables A10 and A11 list density, specific heat, viscosity, and thermal conductivity of air. For further information concerning the SI system, the reader is referred to the ASHRAE Metric Guide, 2nd ed., American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA, 1977; and to the American National Standard - Metric Practice, ANSI Z201.1-1976, Institute of Electrical and Electronics Engineers, Inc., New York, NY, 1976.

Table A.1 Units relating force and mass in various systems

Quantity	Pound Mass & Pound Force System	Slug & Pound System	Pound Mass & Poundal System	International System (SI)
length	foot (ft)	foot (ft)	foot (ft)	meter (m)
time	second (sec)	second (sec)	second (sec)	second (s)
mass	pound mass (lbm)	slug	pound mass (lbm)	kilogram (kg)
force	pound force (lbf)	pound (lb)	poundal	Newton (N)
g_c	$\frac{32.174 \text{ lbm ft}}{\text{lbf sec}^2}$	$\frac{1 \text{ slug ft}}{\text{lbf sec}^2}$	$\frac{1 \text{ lbm ft}}{\text{poundal sec}^2}$	$\frac{1 \text{ kg m}}{\text{N s}^2}$

Table A.2 Base units

	SI System		English System	
Quantity	Unit	Symbol	Unit	Symbol
length	meter	m	foot	ft
mass	kilogram	kg	slug	slug
time	second	s	second	sec
thermodynamic (absolute) temperature	kelvin	K	degree Rankine	°R

Table A.3 Derived units

Quantity	SI System Unit	SI System Symbol	SI System Formula	English System Unit	English System Symbol	English System Formula
force	newton	N	kg·m/s^2	pound	lb	slug·ft/sec^2
pressure	pascal	Pa	N/m^2	-	-	lb/ft^2
energy, work or heat	joule	J	N·m	-	-	lb·ft
power, energy release rate	watt	W	J/s	-	-	lb·ft/sec
mass flow rate	-	-	kg/s	-	-	slug/sec

Table A.4 SI prefixes

Prefix	Symbol	Multiplication Factor
giga	G	10^9 = 1 000 000 000
mega	M	10^6 = 1 000 000
kilo	k	10^3 = 1 000
centi[1]	c	10^{-2} = 0.01
millii	m	10^{-3} = 0.001
micro	μ	10^{-6} = 0.000 001
nano	n	10^{-9} = 0.000 000 001

[1]The prefix centi is to be avoided where possible.

Table A.5 Factors for conversion to SI units

Multiply	By	To Obtain
Btu	1055	J
Btu/hr	0.293	W
Btu/lb	2330.	J/kg
erg	$1x10^{-7}$	J
foot (ft)	0.3048	m
ft^2	0.0929	m^2
foot per minute (fpm)	0.00508	m/s
ft/sec	0.3048	m/s
ft of water	2990.	Pa
ft^3/min (cfm)	$4.72x10^{-4}$	m^3/s
ft^3/min (cfm)	0.472	L*/s
gallon (US)	3.79	L*
gallon (US)	$3.79x10^{-3}$	m^3
horsepower	745.6	W
hour	3600.	s
inch (in)	0.0254	m
inch of mercury (in Hg)	3380.	Pa
inch of water (in H_2O)	249.	Pa
kilogram force (kgf)	9.807	N
kilowatt-hour (kW h)	$3.6x10^6$	J
kilometer per hour (km/h)	0.2778	m/s
knot	0.5144	m/s
mile (mi)	1609.	m
mile per hour (mph)	0.447	m/s
millimeter of mercury (mm Hg)	133.3	Pa
millimeter of water (mm H_2O)	9.80	Pa
minute	60.	s
pound mass (lbm)	0.454	kg
pound force (lbf)	4.445	N
pound per square inch (psi)	6895.	Pa
pound per square foot	47.88	Pa
poundal	0.1383	N
pound per cubic foot (lbm/ft^3)	16.0	kg/m^3
slug	14.59	kg
standard cubic feet per minute (scfm)**	$4.72x10^{-4}$	sm^3/s
standard cubic feet per minute (scfm)**	0.472	sL*/s
standard cubic feet per minute (scfm)**	$5.68x10^{-4}$	kg/s
ton (long, 2240 lbm)	1016.	kg
ton (metric)	1000.	kg
ton (refrigeration)	3517.	W
ton (short, 2000 lbm)	907.2	kg
yard (yd)	0.9144	m

*L is the symbol for liter which is a cubic decimeter, i.e., 1000 L = 1 m^3.
** scfm is a form of mass flow rate used for air movement, and for this text it is at 70°F (21°C) and one atmosphere.

Table A.6 Factors for conversion to the English units

Multiply	By	To Obtain
Btu	778.2	ft lbf
Btu/hr	0.2162	ft lbf/sec
Btu/lbm	25040.	ft lbf/slug
foot per minute (fpm)	0.01667	ft/sec
feet of water (ft H_2O)	62.4	lbf/ft^2
cubic feet per minute (cfm)	0.01667	ft^3/sec
gallon (US)	0.1337	ft^3
horsepower	550	ft lbf/sec
hour (hr)	3600.	sec
inch (in)	0.08333	ft
inch of water (in H_2O)	5.20	lbf/ft^2
inch of mercury (in Hg)	70.7	lbf/ft^2
in^2	$6.944x10^{-3}$	ft^2
in^3	$5.79x10^{-4}$	ft^3
kilogram force (kgf)	2.205	lbf
kilogram (kg)	2.205	lbm
kilometer per hour (km/h)	0.9113	ft/sec
kilowatt hours (kW h)	$2.655x10^6$	ft lbf
kilowatt (kW)	737.6	ft lbf/sec
knot	1.688	ft/sec
liter per second (L/s)	2.119	ft^3/sec
meter (m)	3.281	ft
m^2	10.76	ft^2
meter per second (m/s)	3.281	ft/sec
m^3/s	2119	ft^2/sec
mile (mi)	5280	ft
mile per hour (mph)	1.467	ft/sec
millimeter of mercury (mm Hg)	2.785	lbf/ft^2
minute (min)	60.	sec
pascal (Pa)	0.0209	lbf/ft^2
pound per cubic foot (lbm/ft^3)	0.03108	$slug/ft^3$
pound per square inch (psi)	144	lbf/ft^2
pound mass (lbm)	0.03108	slug
poundal	0.03109	lbf
standard cubic feet per minute (scfm)*	$3.89x10^{-5}$	slug/s
standard cubic feet per minute (scfm)*	0.00125	lbm/s
ton (metric)	2205	lbm
ton (long)	2240	lbm
ton (short)	2000.	lbm
ton (refrigeration)	12000.	Btu/hr
ton (refrigeration)	2594.	ft lb/sec
yard (yd)	3.0	ft
watt (W)	0.7376	ft lbf/sec

* scfm is a form of mass flow rate used for air movement, and for this text it is at 70°F (21°C) and one atmosphere.

Table A.7 Constants

acceleration of gravity at sea level, g	9.80665 m/s^2 32.174 ft/sec^2
gas constant of air, R	287.0 J/kg K 53.34 ft lbf/lbm °R 1716. ft lbf/slug °R 0.06858 Btu/lbm °R
standard atmospheric pressure, P_{atm}	101325 Pa 14.696 psi 2116. lbf/ft^2 30.00 in Hg at 60 °F 407.3 in H_2O at 60 °F 33.94 ft H_2O at 60 °F

Table A.8 Temperature conversions for degrees Fahrenheit

°F	°C	°R	K	°F	°C	°R	K	°F	°C	°R	K
-25.	-31.7	435.	241.	41.	5.0	501.	278.	170.	76.7	630.	350.
-24.	-31.1	436.	242.	42.	5.6	502.	279.	180.	82.2	640.	355.
-23.	-30.6	437.	243.	43.	6.1	503.	279.	190.	87.8	650.	361.
-22.	-30.0	438.	243.	44.	6.7	504.	280.	200.	93.3	660.	366.
-21.	-29.4	439.	244.	45.	7.2	505.	280.	210.	98.9	670.	372.
-20.	-28.9	440.	244.	46.	7.8	506.	281.	220.	104.	680.	378.
-19.	-28.3	441.	245.	47.	8.3	507.	281.	230.	110.	690.	383.
-18.	-27.8	442.	245.	48.	8.9	508.	282.	240.	116.	700.	389.
-17.	-27.2	443.	246.	49.	9.4	509.	283.	250.	121.	710.	394.
-16.	-26.7	444.	246.	50.	10.0	510.	283.	260.	127.	720.	400.
-15.	-26.1	445.	247.	51.	10.6	511.	284.	270.	132.	730.	405.
-14.	-25.6	446.	248.	52.	11.1	512.	284.	280.	138.	740.	411.
-13.	-25.0	447.	248.	53.	11.7	513.	285.	290.	143.	750.	416.
-12.	-24.4	448.	249.	54.	12.2	514.	285.	300.	149.	760.	422.
-11.	-23.9	449.	249.	55.	12.8	515.	286.	310.	154.	770.	428.
-10.	-23.3	450.	250.	56.	13.3	516.	286.	320.	160.	780.	433.
-9.	-22.8	451.	250.	57.	13.9	517.	287.	330.	166.	790.	439.
-8.	-22.2	452.	251.	58.	14.4	518.	288.	340.	171.	800.	444.
-7.	-21.7	453.	251.	59.	15.0	519.	288.	350.	177.	810.	450.
-6.	-21.1	454.	252.	60.	15.6	520.	289.	360.	182.	820.	455.
-5.	-20.6	455.	253.	61.	16.1	521.	289.	370.	188.	830.	461.
-4.	-20.0	456.	253.	62.	16.7	522.	290.	380.	193.	840.	466.
-3.	-19.4	457.	254.	63.	17.2	523.	290.	390.	199.	850.	472.
-2.	-18.9	458.	254.	64.	17.8	524.	291.	400.	204.	860.	478.
-1.	-18.3	459.	255.	65.	18.3	525.	291.	410.	210.	870.	483.
0.	-17.8	460.	255.	66.	18.9	526.	292.	420.	216.	880.	489.
1.	-17.2	461.	256.	67.	19.4	527.	293.	430.	221.	890.	494.
2.	-16.7	462.	256.	68.	20.0	528.	293.	440.	227.	900.	500.
3.	-16.1	463.	257.	69.	20.6	529.	294.	450.	232.	910.	505.
4.	-15.6	464.	258.	70.	21.1	530.	294.	460.	238.	920.	511.
5.	-15.0	465.	258.	71.	21.7	531.	295.	470.	243.	930.	516.
6.	-14.4	466.	259.	72.	22.2	532.	295.	480.	249.	940.	522.
7.	-13.9	467.	259.	73.	22.8	533.	296.	490.	254.	950.	528.
8.	-13.3	468.	260.	74.	23.3	534.	296.	500.	260.	960.	533.
9.	-12.8	469.	260.	75.	23.9	535.	297.	510.	266.	970.	539.
10.	-12.2	470.	261.	76.	24.4	536.	298.	520.	271.	980.	544.
11.	-11.7	471.	261.	77.	25.0	537.	298.	530.	277.	990.	550.
12.	-11.1	472.	262.	78.	25.6	538.	299.	540.	282.	1000.	555.
13.	-10.6	473.	263.	79.	26.1	539.	299.	550.	288.	1010.	561.
14.	-10.0	474.	263.	80.	26.7	540.	300.	560.	293.	1020.	566.
15.	-9.4	475.	264.	81.	27.2	541.	300.	570.	299.	1030.	572.
16.	-8.9	476.	264.	82.	27.8	542.	301.	580.	304.	1040.	578.
17.	-8.3	477.	265.	83.	28.3	543.	301.	590.	310.	1050.	583.
18.	-7.8	478.	265.	84.	28.9	544.	302.	600.	316.	1060.	589.
19.	-7.2	479.	266.	85.	29.4	545.	303.	610.	321.	1070.	594.
20.	-6.7	480.	266.	86.	30.0	546.	303.	620.	327.	1080.	600.
21.	-6.1	481.	267.	87.	30.6	547.	304.	630.	332.	1090.	605.
22.	-5.6	482.	268.	88.	31.1	548.	304.	640.	338.	1100.	611.
23.	-5.0	483.	268.	89.	31.7	549.	305.	650.	343.	1110.	616.
24.	-4.4	484.	269.	90.	32.2	550.	305.	660.	349.	1120.	622.
25.	-3.9	485.	269.	91.	32.8	551.	306.	670.	354.	1130.	628.
26.	-3.3	486.	270.	92.	33.3	552.	306.	680.	360.	1140.	633.
27.	-2.8	487.	270.	93.	33.9	553.	307.	690.	366.	1150.	639.
28.	-2.2	488.	271.	94.	34.4	554.	308.	700.	371.	1160.	644.
29.	-1.7	489.	271.	95.	35.0	555.	308.	710.	377.	1170.	650.
30.	-1.1	490.	272.	96.	35.6	556.	309.	720.	382.	1180.	655.
31.	-0.6	491.	273.	97.	36.1	557.	309.	730.	388.	1190.	661.
32.	0.0	492.	273.	98.	36.7	558.	310.	740.	393.	1200.	666.
33.	0.6	493.	274.	99.	37.2	559.	310.	750.	399.	1210.	672.
34.	1.1	494.	274.	100.	37.8	560.	311.	760.	404.	1220.	678.
35.	1.7	495.	275.	110.	43.3	570.	316.	770.	410.	1230.	683.
36.	2.2	496.	275.	120.	48.9	580.	322.	780.	416.	1240.	689.
37.	2.8	497.	276.	130.	54.4	590.	328.	790.	421.	1250.	694.
38.	3.3	498.	276.	140.	60.0	600.	333.	800.	427.	1260.	700.
39.	3.9	499.	277.	150.	65.6	610.	339.	810.	432.	1270.	705.
40.	4.4	500.	278.	160.	71.1	620.	344.	820.	438.	1280.	711.

Table A.8 Temperature conversions for degrees Fahrenheit - Continued

°F	°C	°R	K	°F	°C	°R	K	°F	°C	°R	K
830.	443.	1290.	716.	1490.	810.	1950.	1083.	2150.	1177.	2610.	1450.
840.	449.	1300.	722.	1500.	816.	1960.	1089.	2160.	1182.	2620.	1455.
850.	454.	1310.	728.	1510.	821.	1970.	1094.	2170.	1188.	2630.	1461.
860.	460.	1320.	733.	1520.	827.	1980.	1100.	2180.	1193.	2640.	1466.
870.	466.	1330.	739.	1530.	832.	1990.	1105.	2190.	1199.	2650.	1472.
880.	471.	1340.	744.	1540.	838.	2000.	1111.	2200.	1204.	2660.	1478.
890.	477.	1350.	750.	1550.	843.	2010.	1116.	2210.	1210.	2670.	1483.
900.	482.	1360.	755.	1560.	849.	2020.	1122.	2220.	1216.	2680.	1489.
910.	488.	1370.	761.	1570.	854.	2030.	1128.	2230.	1221.	2690.	1494.
920.	493.	1380.	766.	1580.	860.	2040.	1133.	2240.	1227.	2700.	1500.
930.	499.	1390.	772.	1590.	866.	2050.	1139.	2250.	1232.	2710.	1505.
940.	504.	1400.	778.	1600.	871.	2060.	1144.	2260.	1238.	2720.	1511.
950.	510.	1410.	783.	1610.	877.	2070.	1150.	2270.	1243.	2730.	1516.
960.	516.	1420.	789.	1620.	882.	2080.	1155.	2280.	1249.	2740.	1522.
970.	521.	1430.	794.	1630.	888.	2090.	1161.	2290.	1254.	2750.	1528.
980.	527.	1440.	800.	1640.	893.	2100.	1166.	2300.	1260.	2760.	1533.
990.	532.	1450.	805.	1650.	899.	2110.	1172.	2310.	1266.	2770.	1539.
1000.	538.	1460.	811.	1660.	904.	2120.	1178.	2320.	1271.	2780.	1544.
1010.	543.	1470.	816.	1670.	910.	2130.	1183.	2330.	1277.	2790.	1550.
1020.	549.	1480.	822.	1680.	916.	2140.	1189.	2340.	1282.	2800.	1555.
1030.	554.	1490.	828.	1690.	921.	2150.	1194.	2350.	1288.	2810.	1561.
1040.	560.	1500.	833.	1700.	927.	2160.	1200.	2360.	1293.	2820.	1566.
1050.	566.	1510.	839.	1710.	932.	2170.	1205.	2370.	1299.	2830.	1572.
1060.	571.	1520.	844.	1720.	938.	2180.	1211.	2380.	1304.	2840.	1578.
1070.	577.	1530.	850.	1730.	943.	2190.	1216.	2390.	1310.	2850.	1583.
1080.	582.	1540.	855.	1740.	949.	2200.	1222.	2400.	1316.	2860.	1589.
1090.	588.	1550.	861.	1750.	954.	2210.	1228.	2410.	1321.	2870.	1594.
1100.	593.	1560.	866.	1760.	960.	2220.	1233.	2420.	1327.	2880.	1600.
1110.	599.	1570.	872.	1770.	966.	2230.	1239.	2430.	1332.	2890.	1605.
1120.	604.	1580.	878.	1780.	971.	2240.	1244.	2440.	1338.	2900.	1611.
1130.	610.	1590.	883.	1790.	977.	2250.	1250.	2450.	1343.	2910.	1616.
1140.	616.	1600.	889.	1800.	982.	2260.	1255.	2460.	1349.	2920.	1622.
1150.	621.	1610.	894.	1810.	988.	2270.	1261.	2470.	1354.	2930.	1628.
1160.	627.	1620.	900.	1820.	993.	2280.	1266.	2480.	1360.	2940.	1633.
1170.	632.	1630.	905.	1830.	999.	2290.	1272.	2490.	1366.	2950.	1639.
1180.	638.	1640.	911.	1840.	1004.	2300.	1278.	2500.	1371.	2960.	1644.
1190.	643.	1650.	916.	1850.	1010.	2310.	1283.	2510.	1377.	2970.	1650.
1200.	649.	1660.	922.	1860.	1016.	2320.	1289.	2520.	1382.	2980.	1655.
1210.	654.	1670.	928.	1870.	1021.	2330.	1294.	2530.	1388.	2990.	1661.
1220.	660.	1680.	933.	1880.	1027.	2340.	1300.	2540.	1393.	3000.	1666.
1230.	666.	1690.	939.	1890.	1032.	2350.	1305.	2550.	1399.	3010.	1672.
1240.	671.	1700.	944.	1900.	1038.	2360.	1311.	2560.	1404.	3020.	1678.
1250.	677.	1710.	950.	1910.	1043.	2370.	1316.	2570.	1410.	3030.	1683.
1260.	682.	1720.	955.	1920.	1049.	2380.	1322.	2580.	1416.	3040.	1689.
1270.	688.	1730.	961.	1930.	1054.	2390.	1328.	2590.	1421.	3050.	1694.
1280.	693.	1740.	966.	1940.	1060.	2400.	1333.	2600.	1427.	3060.	1700.
1290.	699.	1750.	972.	1950.	1066.	2410.	1339.	2610.	1432.	3070.	1705.
1300.	704.	1760.	978.	1960.	1071.	2420.	1344.	2620.	1438.	3080.	1711.
1310.	710.	1770.	983.	1970.	1077.	2430.	1350.	2630.	1443.	3090.	1716.
1320.	716.	1780.	989.	1980.	1082.	2440.	1355.	2640.	1449.	3100.	1722.
1330.	721.	1790.	994.	1990.	1088.	2450.	1361.	2650.	1454.	3110.	1728.
1340.	727.	1800.	1000.	2000.	1093.	2460.	1366.	2660.	1460.	3120.	1733.
1350.	732.	1810.	1005.	2010.	1099.	2470.	1372.	2670.	1466.	3130.	1739.
1360.	738.	1820.	1011.	2020.	1104.	2480.	1378.	2680.	1471.	3140.	1744.
1370.	743.	1830.	1016.	2030.	1110.	2490.	1383.	2690.	1477.	3150.	1750.
1380.	749.	1840.	1022.	2040.	1116.	2500.	1389.	2700.	1482.	3160.	1755.
1390.	754.	1850.	1028.	2050.	1121.	2510.	1394.	2710.	1488.	3170.	1761.
1400.	760.	1860.	1033.	2060.	1127.	2520.	1400.	2720.	1493.	3180.	1766.
1410.	766.	1870.	1039.	2070.	1132.	2530.	1405.	2730.	1499.	3190.	1772.
1420.	771.	1880.	1044.	2080.	1138.	2540.	1411.	2740.	1504.	3200.	1778.
1430.	777.	1890.	1050.	2090.	1143.	2550.	1416.	2750.	1510.	3210.	1783.
1440.	782.	1900.	1055.	2100.	1149.	2560.	1422.	2760.	1516.	3220.	1789.
1450.	788.	1910.	1061.	2110.	1154.	2570.	1428.	2770.	1521.	3230.	1794.
1460.	793.	1920.	1066.	2120.	1160.	2580.	1433.	2780.	1527.	3240.	1800.
1470.	799.	1930.	1072.	2130.	1166.	2590.	1439.	2790.	1532.	3250.	1805.
1480.	804.	1940.	1078.	2140.	1171.	2600.	1444.	2800.	1538.	3260.	1811.

Table A.9 Temperature conversions for degrees Celsius

°C	°F	°R	K	°C	°F	°R	K	°C	°F	°R	K
-30.	-22.0	438.	243.	36.	96.8	556.	309.	230.	446.	906.	503.
-29.	-20.2	439.	244.	37.	98.6	558.	310.	235.	455.	915.	508.
-28.	-18.4	441.	245.	38.	100.	560.	311.	240.	464.	924.	513.
-27.	-16.6	443.	246.	39.	102.	562.	312.	245.	473.	933.	518.
-26.	-14.8	445.	247.	40.	104.	564.	313.	250.	482.	942.	523.
-25.	-13.0	447.	248.	41.	106.	565.	314.	255.	491.	951.	528.
-24.	-11.2	448.	249.	42.	108.	567.	315.	260.	500.	960.	533.
-23.	-9.4	450.	250.	43.	109.	569.	316.	265.	509.	969.	538.
-22.	-7.6	452.	251.	44.	111.	571.	317.	270.	518.	978.	543.
-21.	-5.8	454.	252.	45.	113.	573.	318.	275.	527.	987.	548.
-20.	-4.0	456.	253.	46.	115.	574.	319.	280.	536.	996.	553.
-19.	-2.2	457.	254.	47.	117.	576.	320.	285.	545.	1005.	558.
-18.	-0.4	459.	255.	48.	118.	578.	321.	290.	554.	1014.	563.
-17.	1.4	461.	256.	49.	120.	580.	322.	295.	563.	1023.	568.
-16.	3.2	463.	257.	50.	122.	582.	323.	300.	572.	1032.	573.
-15.	5.0	465.	258.	51.	124.	583.	324.	305.	581.	1041.	578.
-14.	6.8	466.	259.	52.	126.	585.	325.	310.	590.	1050.	583.
-13.	8.6	468.	260.	53.	127.	587.	326.	315.	599.	1059.	588.
-12.	10.4	470.	261.	54.	129.	589.	327.	320.	608.	1068.	593.
-11.	12.2	472.	262.	55.	131.	591.	328.	325.	617.	1077.	598.
-10.	14.0	474.	263.	56.	133.	592.	329.	330.	626.	1086.	603.
-9.	15.8	475.	264.	57.	135.	594.	330.	335.	635.	1095.	608.
-8.	17.6	477.	265.	58.	136.	596.	331.	340.	644.	1104.	613.
-7.	19.4	479.	266.	59.	138.	598.	332.	345.	653.	1113.	618.
-6.	21.2	481.	267.	60.	140.	600.	333.	350.	662.	1122.	623.
-5.	23.0	483.	268.	61.	142.	601.	334.	355.	671.	1131.	628.
-4.	24.8	484.	269.	62.	144.	603.	335.	360.	680.	1140.	633.
-3.	26.6	486.	270.	63.	145.	605.	336.	365.	689.	1149.	638.
-2.	28.4	488.	271.	64.	147.	607.	337.	370.	698.	1158.	643.
-1.	30.2	490.	272.	65.	149.	609.	338.	375.	707.	1167.	648.
0.	32.0	492.	273.	66.	151.	610.	339.	380.	716.	1176.	653.
1.	33.8	493.	274.	67.	153.	612.	340.	385.	725.	1185.	658.
2.	35.6	495.	275.	68.	154.	614.	341.	390.	734.	1194.	663.
3.	37.4	497.	276.	69.	156.	616.	342.	395.	743.	1203.	668.
4.	39.2	499.	277.	70.	158.	618.	343.	400.	752.	1212.	673.
5.	41.0	501.	278.	75.	167.	627.	348.	405.	761.	1221.	678.
6.	42.8	502.	279.	80.	176.	636.	353.	410.	770.	1230.	683.
7.	44.6	504.	280.	85.	185.	645.	358.	415.	779.	1239.	688.
8.	46.4	506.	281.	90.	194.	654.	363.	420.	788.	1248.	693.
9.	48.2	508.	282.	95.	203.	663.	368.	425.	797.	1257.	698.
10.	50.0	510.	283.	100.	212.	672.	373.	430.	806.	1266.	703.
11.	51.8	511.	284.	105.	221.	681.	378.	435.	815.	1275.	708.
12.	53.6	513.	285.	110.	230.	690.	383.	440.	824.	1284.	713.
13.	55.4	515.	286.	115.	239.	699.	388.	445.	833.	1293.	718.
14.	57.2	517.	287.	120.	248.	708.	393.	450.	842.	1302.	723.
15.	59.0	519.	288.	125.	257.	717.	398.	455.	851.	1311.	728.
16.	60.8	520.	289.	130.	266.	726.	403.	460.	860.	1320.	733.
17.	62.6	522.	290.	135.	275.	735.	408.	465.	869.	1329.	738.
18.	64.4	524.	291.	140.	284.	744.	413.	470.	878.	1338.	743.
19.	66.2	526.	292.	145.	293.	753.	418.	475.	887.	1347.	748.
20.	68.0	528.	293.	150.	302.	762.	423.	480.	896.	1356.	753.
21.	69.8	529.	294.	155.	311.	771.	428.	485.	905.	1365.	758.
22.	71.6	531.	295.	160.	320.	780.	433.	490.	914.	1374.	763.
23.	73.4	533.	296.	165.	329.	789.	438.	495.	923.	1383.	768.
24.	75.2	535.	297.	170.	338.	798.	443.	500.	932.	1392.	773.
25.	77.0	537.	298.	175.	347.	807.	448.	505.	941.	1401.	778.
26.	78.8	538.	299.	180.	356.	816.	453.	510.	950.	1410.	783.
27.	80.6	540.	300.	185.	365.	825.	458.	515.	959.	1419.	788.
28.	82.4	542.	301.	190.	374.	834.	463.	520.	968.	1428.	793.
29.	84.2	544.	302.	195.	383.	843.	468.	525.	977.	1437.	798.
30.	86.0	546.	303.	200.	392.	852.	473.	530.	986.	1446.	803.
31.	87.8	547.	304.	205.	401.	861.	478.	535.	995.	1455.	808.
32.	89.6	549.	305.	210.	410.	870.	483.	540.	1004.	1464.	813.
33.	91.4	551.	306.	215.	419.	879.	488.	545.	1013.	1473.	818.
34.	93.2	553.	307.	220.	428.	888.	493.	550.	1022.	1482.	823.
35.	95.0	555.	308.	225.	437.	897.	498.	555.	1031.	1491.	828.

Table A.9 Temperature conversions for degrees Celsius - Continued

°C	°F	°R	K	°C	°F	°R	K	°C	°F	°R	K
560.	1040.	1500.	833.	890.	1634.	2094.	1163.	1220.	2228.	2688.	1493.
565.	1049.	1509.	838.	895.	1643.	2103.	1168.	1225.	2237.	2697.	1498.
570.	1058.	1518.	843.	900.	1652.	2112.	1173.	1230.	2246.	2706.	1503.
575.	1067.	1527.	848.	905.	1661.	2121.	1178.	1235.	2255.	2715.	1508.
580.	1076.	1536.	853.	910.	1670.	2130.	1183.	1240.	2264.	2724.	1513.
585.	1085.	1545.	858.	915.	1679.	2139.	1188.	1245.	2273.	2733.	1518.
590.	1094.	1554.	863.	920.	1688.	2148.	1193.	1250.	2282.	2742.	1523.
595.	1103.	1563.	868.	925.	1697.	2157.	1198.	1255.	2291.	2751.	1528.
600.	1112.	1572.	873.	930.	1706.	2166.	1203.	1260.	2300.	2760.	1533.
605.	1121.	1581.	878.	935.	1715.	2175.	1208.	1265.	2309.	2769.	1538.
610.	1130.	1590.	883.	940.	1724.	2184.	1213.	1270.	2318.	2778.	1543.
615.	1139.	1599.	888.	945.	1733.	2193.	1218.	1275.	2327.	2787.	1548.
620.	1148.	1608.	893.	950.	1742.	2202.	1223.	1280.	2336.	2796.	1553.
625.	1157.	1617.	898.	955.	1751.	2211.	1228.	1285.	2345.	2805.	1558.
630.	1166.	1626.	903.	960.	1760.	2220.	1233.	1290.	2354.	2814.	1563.
635.	1175.	1635.	908.	965.	1769.	2229.	1238.	1295.	2363.	2823.	1568.
640.	1184.	1644.	913.	970.	1778.	2238.	1243.	1300.	2372.	2832.	1573.
645.	1193.	1653.	918.	975.	1787.	2247.	1248.	1305.	2381.	2841.	1578.
650.	1202.	1662.	923.	980.	1796.	2256.	1253.	1310.	2390.	2850.	1583.
655.	1211.	1671.	928.	985.	1805.	2265.	1258.	1315.	2399.	2859.	1588.
660.	1220.	1680.	933.	990.	1814.	2274.	1263.	1320.	2408.	2868.	1593.
665.	1229.	1689.	938.	995.	1823.	2283.	1268.	1325.	2417.	2877.	1598.
670.	1238.	1698.	943.	1000.	1832.	2292.	1273.	1330.	2426.	2886.	1603.
675.	1247.	1707.	948.	1005.	1841.	2301.	1278.	1335.	2435.	2895.	1608.
680.	1256.	1716.	953.	1010.	1850.	2310.	1283.	1340.	2444.	2904.	1613.
685.	1265.	1725.	958.	1015.	1859.	2319.	1288.	1345.	2453.	2913.	1618.
690.	1274.	1734.	963.	1020.	1868.	2328.	1293.	1350.	2462.	2922.	1623.
695.	1283.	1743.	968.	1025.	1877.	2337.	1298.	1355.	2471.	2931.	1628.
700.	1292.	1752.	973.	1030.	1886.	2346.	1303.	1360.	2480.	2940.	1633.
705.	1301.	1761.	978.	1035.	1895.	2355.	1308.	1365.	2489.	2949.	1638.
710.	1310.	1770.	983.	1040.	1904.	2364.	1313.	1370.	2498.	2958.	1643.
715.	1319.	1779.	988.	1045.	1913.	2373.	1318.	1375.	2507.	2967.	1648.
720.	1328.	1788.	993.	1050.	1922.	2382.	1323.	1380.	2516.	2976.	1653.
725.	1337.	1797.	998.	1055.	1931.	2391.	1328.	1385.	2525.	2985.	1658.
730.	1346.	1806.	1003.	1060.	1940.	2400.	1333.	1390.	2534.	2994.	1663.
735.	1355.	1815.	1008.	1065.	1949.	2409.	1338.	1395.	2543.	3003.	1668.
740.	1364.	1824.	1013.	1070.	1958.	2418.	1343.	1400.	2552.	3012.	1673.
745.	1373.	1833.	1018.	1075.	1967.	2427.	1348.	1405.	2561.	3021.	1678.
750.	1382.	1842.	1023.	1080.	1976.	2436.	1353.	1410.	2570.	3030.	1683.
755.	1391.	1851.	1028.	1085.	1985.	2445.	1358.	1415.	2579.	3039.	1688.
760.	1400.	1860.	1033.	1090.	1994.	2454.	1363.	1420.	2588.	3048.	1693.
765.	1409.	1869.	1038.	1095.	2003.	2463.	1368.	1425.	2597.	3057.	1698.
770.	1418.	1878.	1043.	1100.	2012.	2472.	1373.	1430.	2606.	3066.	1703.
775.	1427.	1887.	1048.	1105.	2021.	2481.	1378.	1435.	2615.	3075.	1708.
780.	1436.	1896.	1053.	1110.	2030.	2490.	1383.	1440.	2624.	3084.	1713.
785.	1445.	1905.	1058.	1115.	2039.	2499.	1388.	1445.	2633.	3093.	1718.
790.	1454.	1914.	1063.	1120.	2048.	2508.	1393.	1450.	2642.	3102.	1723.
795.	1463.	1923.	1068.	1125.	2057.	2517.	1398.	1455.	2651.	3111.	1728.
800.	1472.	1932.	1073.	1130.	2066.	2526.	1403.	1460.	2660.	3120.	1733.
805.	1481.	1941.	1078.	1135.	2075.	2535.	1408.	1465.	2669.	3129.	1738.
810.	1490.	1950.	1083.	1140.	2084.	2544.	1413.	1470.	2678.	3138.	1743.
815.	1499.	1959.	1088.	1145.	2093.	2553.	1418.	1475.	2687.	3147.	1748.
820.	1508.	1968.	1093.	1150.	2102.	2562.	1423.	1480.	2696.	3156.	1753.
825.	1517.	1977.	1098.	1155.	2111.	2571.	1428.	1485.	2705.	3165.	1758.
830.	1526.	1986.	1103.	1160.	2120.	2580.	1433.	1490.	2714.	3174.	1763.
835.	1535.	1995.	1108.	1165.	2129.	2589.	1438.	1495.	2723.	3183.	1768.
840.	1544.	2004.	1113.	1170.	2138.	2598.	1443.	1500.	2732.	3192.	1773.
845.	1553.	2013.	1118.	1175.	2147.	2607.	1448.	1505.	2741.	3201.	1778.
850.	1562.	2022.	1123.	1180.	2156.	2616.	1453.	1510.	2750.	3210.	1783.
855.	1571.	2031.	1128.	1185.	2165.	2625.	1458.	1515.	2759.	3219.	1788.
860.	1580.	2040.	1133.	1190.	2174.	2634.	1463.	1520.	2768.	3228.	1793.
865.	1589.	2049.	1138.	1195.	2183.	2643.	1468.	1525.	2777.	3237.	1798.
870.	1598.	2058.	1143.	1200.	2192.	2652.	1473.	1530.	2786.	3246.	1803.
875.	1607.	2067.	1148.	1205.	2201.	2661.	1478.	1535.	2795.	3255.	1808.
880.	1616.	2076.	1153.	1210.	2210.	2670.	1483.	1540.	2804.	3264.	1813.
885.	1625.	2085.	1158.	1215.	2219.	2679.	1488.	1545.	2813.	3273.	1818.

Table A.10 Properties of air in English units

T (°F)	ρ (lbm/ft^3)	c_p (Btu/lbm °F)	μ (lbm/ft sec)	ν (ft^2/sec)	k (Btu/hr ft °F)
0	0.086	0.239	1.110×10^{-5}	0.130×10^{-3}	0.0133
32	0.081	0.240	1.165	0.145	0.0140
100	0.071	0.240	1.285	0.180	0.0154
200	0.060	0.241	1.440	0.239	0.0174
300	0.052	0.243	1.610	0.306	0.0193
400	0.046	0.245	1.750	0.378	0.0212
500	0.0412	0.247	1.890	0.455	0.0231
600	0.0373	0.250	2.000	0.540	0.0250
700	0.0341	0.253	2.14	0.625	0.0268
800	0.0314	0.256	2.25	0.717	0.0286
900	0.0291	0.259	2.36	0.815	0.0303
1000	0.0271	0.262	2.47	0.917	0.0319
1500	0.0202	0.276	3.00	1.47	0.0400
2000	0.0161	0.286	3.45	2.14	0.0471
2500	0.0133	0.292	3.69	2.80	0.051
3000	0.0114	0.297	3.86	3.39	0.054

Notation: T = temperature, ρ = density, c_p = constant pressure specific heat, μ = absolute viscosity, ν = kinematic viscosity ($\nu=\mu/\rho$), k = thermal conductivity

Table A.11 Properties of air in SI units

T (K)	ρ (kg/m^3)	c_p (J/kg °C)	μ (kg/m s)	ν (m^2/s)	k (W/m °C)
200	1.7684	1.0061×10^3	1.3289×10^{-5}	7.514×10^{-6}	0.01809
250	1.4128	1.0053	1.488	10.53	0.02227
300	1.1774	1.0057	1.983	16.84	0.02624
350	0.9980	1.0090	2.075	20.76	0.03003
400	0.8826	1.0140	2.286	25.90	0.03365
500	0.7048	1.0295	2.671	37.90	0.04038
600	0.5879	1.0551	3.018	51.34	0.04659
700	0.5030	1.0752	3.332	66.25	0.05230
800	0.4405	1.0978	3.625	82.29	0.05779
900	0.3925	1.1212	3.899	99.3	0.06279
1000	0.3524	1.1417	4.152	117.8	0.06752
1200	0.3204	1.160	4.44	138.6	0.0732
1400	0.2515	1.214	5.17	205.5	0.0891
1600	0.2211	1.248	5.63	254.5	0.100
1800	0.1970	1.287	6.07	308.1	0.111
2000	0.1762	1.338	6.50	369.0	0.124

Note: Notation listed at bottom of table A.10.

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Appendix C USER'S GUIDE FOR THE COMPUTER PROGRAM ASCOS

The ASCOS program is intended for analysis of smoke control systems, but it can be used for general analysis of air flow in buildings. The theory behind the program is discussed in chapter 5. This appendix provides information about using the program.

1. GENERAL INPUT DESCRIPTION

Data input consists of the following elements:

1. Initial data;
2. building heights;
3. temperature profiles;
4. outside pressure profiles;
5. building data;
6. shaft data.

In the following sections, the input required for each of the six data elements is described in detail in an input data file. Each block or line of blocks below represents a line of data in the input file. Unless otherwise stated, these lines are unformatted, that is, the numbers do not have to be placed in specific columns and integers can be written with or without decimal points. However, separate pieces of numerical data must be separated by one or more spaces. An example of input data is provided in this appendix, other examples are in later appendices.

1.1 Initial Data

project title (col. 1-72)

outside temperature (°F, °C)	unit indication (2 for Eng., 1 for SI)	summary output (0 for none, or file number)

1.2 Building Heights

Nh, no. of building levels	input parameter (either 0 or 1)

If input parameter = 0, then heights for each building level are to be individually entered as follows:

$h_{(1)}$	$h_{(2)}$	$h_{(3)}$	...	$h_{(i)}$	...	$h_{(Nh)}$
			...		...	

where $h_{(i)}$ is the elevation of the midheight of level i above the ground (ft, m). If input parameter = 1, then the following line must be entered.

$h_{(1)}$	distance between floors (ft, m)

where $h_{(1)}$ is the elevation of the midheight of level 1 above the ground (ft, m).

1.3 Temperature Profiles

no. of temperature profiles

For each temperature profile the following data must be supplied.

no. of temp. points	level no.	temperature (°F,°C)	...	level no.	temperature (°F,°C)
			...		

1.4 Outside Pressure Profiles

Npo no. of outside pressure profiles	input parameter (either 0 or 1)

If the input parameter = 0, each outside pressure profile is entered as follows:

$P_{o(1)}$	$P_{o(2)}$	$P_{o(3)}$	...	$P_{o(i)}$	...	$Po_{(Npo)}$
			...		...	

where $P_{o(i)}$ is the outside pressure at the center of level i.

If the input parameter = 1, the outside pressures are calculated and the following data are required.

V_o wind velocity (mph, m/s)	h_o, height at which velocity is measured (ft, m)	n wind exponent

Also, the pressure coefficients for each pressure profile are required.

$C_{W(1)}$	$C_{W(2)}$	...	$C_{W(Npo)}$
		...	

1.5 Building Data

N_f no. of levels (or floors)

All the following data in this input element are supplied for each level or consecutive groups of similar levels.

I_1 starting floor	I_2 ending floor	N_{com} no. of compartments per floor

(Floor data is entered in ascending order of levels or floors. When data are for only one level, then $I_1 = I_2$, and the same number is supplied for both.)

For each compartment on a level the following data are supplied.

N_{CS} no. of connections to other spaces on same floor	N_{CA} no. of connections to other spaces on floor above	N_{CO} no. of connections to the outside	F_f net flow* (scfm, sL/s)	temp. profile number

For each connection between this compartment and another on the same floor the following data are required.

other compartment number on the same level	C flow coefficient	A flow area (ft^2, m^2)

For each connection between this compartment and one on the level above the following data are required.

other compartment number on floor above	C flow coefficient	A floor area (ft^2, m^2)
	.	

For each connection to the outside the following data are required.

outside pressure profile number	C flow coefficient	A flow area (ft^2, m^2)

1.6 Shaft Data

no. of shafts

*All net flows are at standard conditions of 70°F (21°C) and one atmosphere.

All the following data in this input element are required for each shaft.

shaft title (col. 1-20)

C_s shaft flow coefficient	bottom level of shaft	top level of shaft	temperature profile number

Enter the following typical data, which applies to each level of the shaft. Exceptions can be entered later.

no. of connections between typical level of shaft and outside	F_f net flow into typical level of shaft (scfm, sL/s)

The connection data to the building for a typical level are required.

compartment no. to which shaft is connected	C flow coefficient	A flow area (ft^2, m^2)

For each connection to the outside, the connection data for a typical floor are required.

outside pressure profile number	C flow coefficient	A flow area (ft^2, m^2)

The number of exceptions to the typical data is required.

no. of exceptions

All the following data in this input element are required for each exception.

exception type (1, 2, or 3)	level of shaft

The next line depends on the exception type. For exception type = 1, an exception to the net flow into the floor or the shaft is defined.

F_f net flow (scfm, sL/s)

For excepting type = 2, and exception to an outside connection for this shaft is defined.

outside pressure profile number	C flow coefficient	A flow area (ft^2, m^2)

For exception type = 3, an exception to the connection between the shaft and the building is defined.

compartment no. to which shaft is connected	C flow coefficient	A flow area (ft^2, m^2)

2. EXAMPLE PROBLEM

The example for this user's guide is a twelve story building in summer when the outside temperature is 85°F (29°C). The data for this building was selected as an example of data illustrating the input form of ASCOS, and none of the data is intended to represent recommended values. The building has zoned smoke control and two pressurized stairwells. The sixth floor is the smoke zone and is exhausted at a rate of 2000 scfm (940 sL/s)**. All the other floors are pressurized at this same flow rate.

The stairwells are pressurized by 400 scfm (190 sL/s) per floor except for the second floor which is supplied 6000 scfm (2800 sL/s). The exterior doors of both stairs are open at ground level. One stairwell goes to the roof and has the fourth floor door open. The other stairwell has the sixth floor door open. All other stairwell doors are closed. The building has a top vented elevator shaft.

The building is at 72°F (22°C), and the stairwells are 76°F (24°C) at the ground level (first floor) and increase linearly to 90° F (32°C) at the twelfth floor. The wind is 10 mph (4.5 m/s) at 30

**scfm and sL/s are standard cubic feet per minute and standard liters per second. Both scfm and sL/s are a form of mass flow rate, and they are at 70°F (21°C) and one atmosphere.

ft (10 m) above ground level. There are two wind coefficients, 0.8 and -0.8, which are used to simulate the pressures on windward and leeward walls respectively. The input data for this example is listed in table C.1 in the form needed by the program. The following sections discuss the example data.

2.1 Initial Data

project title (col. 1-72)

Explanation: A "heading" that can range from 1-72 characters, is printed at the top of each page of output, and is used for quickly referencing a particular page of output.

Example:

SUMMER, FIRE ON THE 6TH FLOOR, NO DOORS OPEN

outside temperature (°F, °C)	unit indication (2 for Eng., 1 for SI)	summary output (0 for none, or file number)

Explanation: Outside temperature - Enter in °F or °C depending on specified units (see Unit Indication). It is used as constant around the entire exterior of the building.

Unit indication - Enter a "2" to use English units. Enter a "1" to use SI units. The unit system specified is used throughout all the input data. Unit indication also applies to the output.

Summary output - For general use enter "0", any other number requires program modification.

Example:

85	2	0

2.2 Building Heights

Nh, no. of building levels	input parameter (either 0 or 1)

Explanation: Nh - The number of levels in each building which may include the basement. If shafts extend to the roof, the roof is considered a level.

Input parameter - A "0" is used when distance between floors is not uniform. A "1" is used when distance between floors is uniform.

Example building is 12 stories tall, but a shaft goes to the roof. Thus, Nh is 13.

Example:

13	1

If input parameter = 0, then the heights for each building level is individually entered.

$h_{(1)}$	$h_{(2)}$	$h_{(3)}$	...	$h_{(i)}$	...	$h_{(Nh)}$
			...		...	

Explanation: $h_{(i)}$ is the height of the center of each level above the ground (m, ft).

Example: Not applicable to example problem, because the input parameter is 1.

If Input Parameter = 1, then the following line is entered.

$h_{(1)}$	distance between floors (ft, m)

Explanation: When Input Parameter = 1, h(1) is the height of the center of level 1, and the distance between floors is the same from floor to floor.

Example:

$h_{(1)}$	distance between floors (ft)
6	12

2.3 Temperature Profiles

no. of temperature profiles

Explanation: For each different temperature that exists within the building a temperature profile is entered. The temperature profile is simply an explanation to the computer of each different temperature in the building.

Example:

no. of temperature profiles
2

For each temperature profile, the following data is supplied.

no. of temp. points	level no.	temp. (°F,°C)	...	level no.	temp. (°F,°C)
			...		

Explanation: No. of temperature points - The number of temperature points that define the temperature profile. When more than one point is entered, the program will linearly interpolate the other temperatures.

Level no. - The level at which the temperature is defined.

Temp. - Temperature at level number.

Example: Temperature Profile One - (Building)

no. of temp. points	level no.	temp. (°F)	level no.	temp. (°F)
1	1	72		

Temperature Profile Two - (Stairwells)

2	1	76	12	90

2.4 Outside Pressure Profiles

Npo, no. of outside pressure profiles	input parameter (either 0 or 1)

Explanation: *Npo* - For each different outside pressure profile, pressure data is defined. A pressure profile is an explanation to the computer of the pressure on the building exterior.

Input parameter - "0" for individual pressures entered for each level, and "1" for pressures calculated by the computer using given wind data.

Example:

Npo, no. of outside pressure profiles	input parameter (either 0 or 1)
2	1

If input parameter = 0, then the outside pressures for each building level are individually entered.

$P_{o(1)}$	$P_{o(2)}$	$P_{o(3)}$	...	$P_{o(i)}$	...	$P_{o(Nh)}$
			...		...	

Explanation: $P_{o(i)}$ is the outside pressure at the center of level i. Extreme care is needed to assure that these outside pressures properly incorporate hydrostatic and wind effects. This individual input method is intended as a research option, and the next method is recommended whenever possible.

Example: Not applicable, because input parameter is 1.

If Input Parameter = 1, the following wind data is entered.

V_o wind velocity (mph, m/s)	h_o, height at which velocity is measured (ft, m)	n wind exponent

Explanation: V_o - the speed of the local wind as measured or as would be measured at elevation, ho, above the ground.

h_o - the height above the ground at which Vo is measured.

n - wind exponent that is used in the power law equation to calculate variation in wind velocity with elevation.

Example:

V_o wind velocity (mph)	h_o, height at which velocity is measured (ft)	n wind exponent
10	30	0.16

If Input Parameter = 1, the additional wind data is entered for all Npo wind directions.

$C_{W(1)}$	$C_{W(2)}$	...	$C_{W(Npo)}$
		...	

Explanation: $C_{W(i)}$ - the pressure coefficient in wind direction i.

Example: Two wind directions are defined below.

$C_{W(1)}$	$C_{W(2)}$
0.8	-0.8

2.5 Building Data

N_f no. of levels (or floors)

Explanation: Number of floors - This number may be less than N because shafts can be taller than the building, for example stairs opening onto a roof.

Example:

12

Building data describing all these floors including connections are required.

I_1 starting floor	I_2 ending floor	N_{com} no. of compartments per floor

Explanation: Data defining the building are entered in blocks of similar floors, from floor I_1 to floor I_2. If a floor is different from the ones above and below, the it is entered as a block of one floor, where $I_1 = I_2$. Floors are always entered in ascending order, from floor 1 to floor N_f. Floors can be made up of a number of compartments, N_{com}.

Example: The floors 1 through 5 are similar, and they each consist of one compartment.

1	5	1

For each compartment on a level the following data are supplied.

N_{CS}	N_{CA}	N_{CO}	F_f	temp. profile number

Explanation: N_{CS} - number of connections from this compartment to other spaces on same floor.

N_{CA} - number of connections to other spaces on floor above.

N_{CO} - number of connections from this compartment to the outside.

F_f - net flow of pressurization air in scfm (sL/s) to this compartment. A negative value of F_f indicates that the compartment is being exhausted. If air is both supplied and exhausted from a compartment, F_f is supply rate less the exhaust rate.

The temperature profile number was defined earlier.

Example: The one compartment on each of floors 1 through 5 is described by the data below.

N_{CS}	N_{CA}	N_{CO}	F_f	temp. profile number
0	1	2	2000	1

other compartment number on the same level	C flow coefficient	A flow area (ft^2, m^2)

Explanation: For each connection between this compartment and another on the same level, the above data is supplied.

Example: Not applicable to example problem, because $N_{CS} = 0$.

other compartment number on floor above	C flow coefficient	A flow area (ft^2, m^2)

Explanation: For each connection between this compartment and another on the level above, the above data is supplied.

Example: Because $N_{CA} = 1$, data for one connection to compartment 1 on the floor above is supplied.

1	.65	1.17

outside pressure profile number	C flow coefficient	A flow area (ft^2, m^2)

Explanation: For each connection between this compartment and the outside, the above data is supplied.

Example: Because $N_O = 2$, data for two connections to the outside is supplied. The data is for flow paths in two walls in different directions, corresponding to the pressure profiles.

1	.65	.75
2	.65	.75

Floor 6 is different in that it is exhausted not pressurized, and it must be entered separately.

I_1	I_2	N_{com}		
6	6	1		
N_{CS}	N_{CA}	N_{CO}	F_f	temp. profile number
0	1	2	-2000	1

Because N_{CS} = 0, no data are supplied for connections to compartments on the same level.

other compartment number on floor above	C flow coefficient	A floor area (ft^2)
1	.65	1.17

outside pressure profile number	C flow coefficient	A floor area (ft^2
1	.65	.75
2	.65	.75

The following are data for floors 7 through 12.

I_1	I_2	N_{com}
7	12	1

N_{CS}	N_{CA}	N_{CO}	F_f	temp. profile number
0	1	2	2000	1

Because $N_{CS} = 0$, no data are supplied for connections to compartments on the same level.

A connection to the floor above does not have meaning for the top floor of a building. Thus, when data are supplied for a block of more than one floor, the computer disregards this connection for the top floor. If data for the top floor is supplied as a block of only one floor, specification of a connection to the floor above results in an input error.

other compartment number on floor above	C flow coefficient	A floor area (ft^2)
1	.65	1.17

outside pressure profile number	C flow coefficient	A floor area (ft^2
1	.65	.75
2	.65	.75

2.6 Shaft Data

no. of shafts

Explanation: no. of shafts - The total number of shafts that are to be modeled in the building flow network. These can be stairwells, elevator shafts, smoke shafts, or any other shaft in a building.

Example:

3

shaft title (col. 1-20)

Explanation: The shaft title is 1 to 20 characters and used as a "heading" for shaft output.

Example:

STAIRWELL 1

C_s shaft flow coefficient	bottom level of shaft	top level of shaft	temperature profile number

Explanation: C_s is a coefficient that allows the computer to account for friction pressure losses in the shaft. Methods to calculate this coefficient are in Chapter 5.

Example: The bottom level of this shaft is at floor 1, and the top is at the roof level. Temperatures in the stairwell are given by temperature profile 2.

1.6E5	1	13	2

no. of connections between typical level of shaft and outside	F_f net flow into typical level of shaft (scfm, sL/s)

Explanation: F_f is the net flow into a typical level of the shaft. This data applies to every level of the shaft, unless there is a specific exception as discussed later.

Example: This an interior stairwell, and so the typical floor has no connection to the outside. At each floor of the stairwell, 400 scfm of pressurization air is supplied.

0	400

compartment no. to which shaft is connected	C flow coefficient	A flow area (ft^2, m^2)

Explanation: This data describes the connection between the shaft and the building at every level, unless there is a specific exception as discussed later.

Example: The shaft is connected to compartment 1 on each floor by a path with a flow area of 0.212 ft^2.

1	.65	.212

outside pressure profile number	C flow coefficient	A flow area (ft^2, m^2)

Explanation: This data describes the connection between the shaft and the outside at every level, unless there is a specific exception as discussed later.

Example: Not applicable to example problem, because the shaft is in the building interior and it does not have a connection to the outside at a typical floor.

no. of exceptions

[ ]

Explanation: The number of specific exceptions to the typical data are supplied.

Example: There are 4 exceptions to the typical data describing this stair shaft.

[4]

The exceptions to the typical shaft data are specified by the following data.

exception type (1, 2, or 3)	level of shaft

Explanation: The exception type applies only to the specific level of the shaft. The exception types are described below, and the above line must be directly followed by one of the three lines below.

Exception type 1 is an exception to the net flow:

F_f net flow (scfm, sL/s)

Exception type 2 is an exception to the connection to the outside:

outside pressure profile number	C flow coefficient	A flow area (ft^2, m^2)

Exception type 3 is an exception to the connection to the building:

compartment no. to which shaft is connected	C flow coefficient	A flow area (ft^2, m^2)

Data for the exception to net flow for Stairwell 1 of the example are below. This indicates that at level 2 of the stairwell, 6000 scfm of pressurization air is supplied.

exception type (1, 2, or 3)	level of shaft
1	2

F_f net flow (scfm)
6000

These two lines describe an open exterior door of 10.5 ft^2 at the first floor.

exception type (1, 2, or 3)	level of shaft
2	1

outside pressure profile number	C flow coefficient	A flow area (ft^2)
1	.65	10.5

These line describe the exception of an open stair door of 10.5 ft^2 on the fourth floor.

exception type (1, 2, or 3)	level of shaft
3	4

compartment no. to which shaft is connected	C flow coefficient	A flow area (ft^2)
1	.65	10.5

These lines describe an open door onto the roof of 10.5 ft^2.

exception type (1, 2, or 3)	level of shaft	
2	13	
outside pressure profile number	*C* flow coefficient	*A* flow area (ft^2)
1	.65	10.5

The example data for stairwell 2 and the elevator shaft are not presented, because the input of these data is similar to that of stairwell 1. All of this data is listed in table C.1.

3. INPUT DATA ECHO

To help in "trouble shooting" input data, an echo of the input data is produced while the program is reading the data. Because of the restrictions on variable names in FORTRAN, the variables used in the echo differ from those in the text discussion of the program. The variables used in the echo are listed in table C.2. Table C.3 is the echo for the example data listed in table C.1 Table C.4 is an example of a echo of an data file with an error, and examination of the echo can be of considerable help in locating the error.

4. FREQUENTLY ASKED QUESTIONS

Q How do I specify the pressurization for a single injection system?

A Use exception number 1, and set the net flow into a typical level of the shaft to zero.

Q How do I specify an open exterior door?

A Use exception number 2.

Q How do I specify an open stairwell door to the building interior?

A Use exception number 3.

Q The building I must analyze is too large for the dimension statements in ASCOS, what can I do?

A The program can be modified and complied with larger dimensions or symmetry can be applied to divide the building into equivalent segments.

Q Under what circumstances should I use connections on the same level?

A Connections on the same level can only be used when there are more than one compartment on the level. Using more than one compartment is appropriate for zoned smoke control systems having are more than one zone on a floor. Another application is elevator smoke control where the elevator lobby is one compartment and the rest of the building space is another. Generally, a building with pressurized stairwells and no other smoke control system would be modeled by only one compartment per floor.

Q Must I include all leakage paths that exist in a building?

A An analysis should include all significant leakage paths. In conventionally build structures, all floors and walls have leakage paths. Thus, a compartment with an exterior wall will have leakage to the outside. Unless on the top floor, compartments will have leakage to the floor above. Generally, connections should be included in an analysis to account for these leakages. Some relatively small leakage paths can be omitted without adversely affecting the analysis, but this is only recommended for the experienced user.

Q ASCOS printed out the following message: SHAFT CONNECTION ERROR
PROGRAM STOPPED

What has happened?

A This is probably the most common input error. The first thing to do is to check if you have specified a leakage from the top floor of the building to the floor above. When this happens, the program makes a connection from the top floor to the first level of first shaft specified. If this is not the problem, examine the list of connections printed after the message to find the error. A level of a shaft can only be connected to building compartments on the same level. For example the second floor of a shaft can be connected to the second floor of the building, but it cannot be connected to the third floor of the building.

Table C.1 Example Data

```
SUMMER, FIRE ON THE 6TH FLOOR, NO DOORS OPEN
85 2 0
13 1
6 12
2
1 1 72
2 1 76 12 90
2 1
10 30 .16
0.8 -.8
12
1 5 1
0 1 2 2000 1
1 .65 1.17
1 .65 .75
2 .65 .75
6 6 1
0 1 2 -2000 1
1 .65 1.51
1 .65 .75
2 .65 .75
7 12 1
0 1 2 2000 1
1 .65 1.17
1 .65 .75
2 .65 .75
3
STAIRWELL 1
1.6E5 1 13 2
0 400
1 .65 .212
4
1 2
6000
2 1
1 .65 10.5
3 4
1 .65 10.5
2 13
1 .65 .2
```

Table C.1 Continued

```
STAIRWELL 2
1.6E5 1 12 2
0 400
1 .65 .212
3
1 2
6000
2 1
1 .65 10.5
3 6
1 .65 10.5
ELEVATOR
3.E5 1 13 1
0 0
1 .65 1.4
1
2 13
2 .65 4.
```

Table C.2 Variables used in input data echo

Variable Symbols Echo	Text	Description	Variable Symbols Echo	Text	Description
A	A	Area	KE	-	Exception type
C	C	Flow coefficient	NA	N_{CA}	No. of connections on same level
CS	C_s	Shaft flow coefficient	NFLS	N_f	No. of floors in building
CW	$C_{W'}$	Pressure coefficient	NFS1	-	Bottom level of shaft
DH	-	Uniform distance between floors	NFS2	-	Top level of shaft
FF	F_f	Net flow to space	NH	Nh	No. of levels
FFF	F_f	Net flow to typical shaft level	NN	-	Indicator, 0 for input or 1 for calc.
H(1)	$h_{(1)}$	Elevation of midpoint of 1st floor	NNO	N_{CO}	No. of connections to outside
HW	h_o	Height of wind measurement	NOC	N_{com}	No. of compartment per floor
IF1	I_1	Lower floor in series	NPO	Npo	No. of pressure profiles
IF2	I_2	Upper floor in series	NTP	-	No. of temperature profiles
IOUT	-	Summary output indicator	NZ	N_{CS}	No. of compartments on same level
IT	-	Temperature profile	TOUT	T_{out}	Outside temperature
ITS	-	Temperature profile for shaft	VW	V_o	Velocity of wind
IUNIT	-	Indicator, 1 for SI or 2 for Eng.	XH	n	wind exponent
J	-	compartment number			

Table C.3 Input data echo for example data

```
 SUMMER, FIRE ON THE 6TH FLOOR, NO DOORS OPEN


 TOUT =  85., IUNIT =  2, IOUT =  0
 NH = 13, NN =  1
 H(1) =    6.00, DH =   12.00
  NTP =  2
 TEMPERATURE PROFILE
1  1   72.0
 TEMPERATURE PROFILE
2  1   76.0  12   90.0
 NPO =  2, NN =  1
 VW =  10.0, HW =  30.0, XW = .16, CW = .80-.80

 NFLS = 12
 IF1 =  1, IF2 =  5, NOC =  1
 NZ =  0 NA =   1, NNO =  2, FF =  2000.0,  IT =  1
 CONNECTION TO FLOOR ABOVE
 J =  1, C =      .650, A =   1.1700
 CONNECTION TO OUTSIDE
 J =  1, C =      .650, A =    .7500
 J =  2, C =      .650, A =    .7500
 IF1 =  6, IF2 =  6, NOC =  1
 NZ =  0 NA =   1, NNO =  2, FF = -2000.0,  IT =  1
 CONNECTION TO FLOOR ABOVE
 J =  1, C =      .650, A =   1.5100
 CONNECTION TO OUTSIDE
 J =  1, C =      .650, A =    .7500
 J =  2, C =      .650, A =    .7500
 IF1 =  7, IF2 = 12, NOC =  1
 NZ =  0 NA =   1, NNO =  2, FF =  2000.0,  IT =  1
 CONNECTION TO FLOOR ABOVE
 J =  1, C =      .650, A =   1.1700
 CONNECTION TO OUTSIDE
 J =  1, C =      .650, A =    .7500
 J =  2, C =      .650, A =    .7500
 STAIRWELL 1
 CS = 160000.0, NFS1 =  1, NFS2 = 13, ITS =  2
 NNO =  0, FFF =   400.0, J =  1, C =      .650, A =    .2120
 KE =  1, IFF =  2
 FF =  6000.0
 KE =  2, IFF =  1
```

CONNECTION TO OUTSIDE
J = 1, C = .650, A = 10.5000
KE = 3, IFF = 4
CONNECTION ON SAME FLOOR
J = 1, C = .650, A = 10.5000
KE = 2, IFF = 13
CONNECTION TO OUTSIDE
J = 1, C = .650, A = .2000
STAIRWELL 2
CS = 160000.0, NFS1 = 1, NFS2 = 12, ITS = 1
NNO = 0, FFF = 400.0, J = 1, C = .650, A = .2120
KE = 1, IFF = 2
FF = 6000.0
KE = 2, IFF = 1
CONNECTION TO OUTSIDE
J = 1, C = .650, A = 10.5000
KE = 3, IFF = 6
CONNECTION ON SAME FLOOR
J = 1, C = .650, A = 10.5000
ELEVATOR
CS = 300000.0, NFS1 = 1, NFS2 = 13, ITS = 1
NNO = 0, FFF = .0, J = 1, C = .650, A = 1.4000
KE = 2, IFF = 13
CONNECTION TO OUTSIDE
J = 2, C = .650, A = 4.0000

Table C.4 Input data echo for example data with error

SUMMER, FIRE ON THE 6TH FLOOR, NO DOORS OPEN

```
 TOUT =   85., IUNIT =  2, IOUT =  0
 NH = 13, NN =  1
 H(1) =    6.00, DH =   12.00
  NTP =  2
 TEMPERATURE PROFILE
1  1   72.0
 TEMPERATURE PROFILE
2  1   76.0  12   90.0
 NPO =  2, NN =  1
 VW =  10.0, HW =  30.0, XW = .16, CW = .80-.80

 NFLS = 12
 IF1 =  1, IF2 =  5, NOC =  1
 NZ =  0 NA =   1, NNO =  2, FF =  2000.0,  IT =  1
 CONNECTION TO FLOOR ABOVE
 J =  1, C =      .650, A =    .7500
 CONNECTION TO OUTSIDE
 J =  2, C =      .650, A =    .7500
 J =  6, C =     6.000, A =   1.0000
 IF1 =  0, IF2 =  1, NOC =  2
```

Note: Inspection shows that the computer read a value of C = 6 on the second to last line echoed. This is physically unrealistic, and a likely cause of such an error is missing data on a earlier line. Examination of the echo file shows that line 14 of the data was missing for this attempted run.

Appendix D DATA AND COMPUTER OUTPUT FOR EXAMPLE 7.6

Example 7.6 Run 1

```
15 STORY PRESSURIZED STAIRWELL IN SUMMER
93 2 0
16 1
6 12
2
1 1 70
1 1 82
1 1
0 1 1
1
15
1 14 1
0 1 1 0 1
1 .65 .85
1 .65 1.13
15 15 1
0 0 1 -1800 1
1 .65 1.13
2
STAIRWELL
7.0E4 1 15 2
0 0
1 .65 0.323
8
1 2
17000
2 1
1 .65 10.5
3 1
1 .65 10.5
3 2
1 .65 10.5
3 3
1 .65 10.5
3 4
1 .65 10.5
3 5
1 .65 10.5
3 6
1 .65 10.5
ELEVATOR
2.4E5 1 16 1
0 0
1 .65 .67
1
2 16
1 .65 1.5
```

15 STORY PRESSURIZED STAIRWELL IN SUMMER

FLOOR	COMPART-MENT	PRESSURE	FIXED FLOW	CONNECTION TO	DIFF PRESSURE	FLOW AREA	FLOW
1	1	2.976	0.	FLOOR 2 COMPARTMENT 1	.018	.850	296.8
				STAIRWELL	.001	10.500	684.4
				ELEVATOR	-.001	.670	-65.1
				OUTSIDE DIRECTION 1	-.097	1.130	-916.3
							NET -.2
2	1	2.821	0.	FLOOR 3 COMPARTMENT 1	-.002	.850	-106.7
				FLOOR 1 COMPARTMENT 1	-.018	.850	-296.8
				STAIRWELL	.004	10.500	1610.9
				ELEVATOR	-.019	.670	-242.8
				OUTSIDE DIRECTION 1	-.107	1.130	-965.1
							NET -.4
3	1	2.646	0.	FLOOR 4 COMPARTMENT 1	-.001	.850	-76.7
				FLOOR 2 COMPARTMENT 1	.002	.850	106.7
				STAIRWELL	.002	10.500	1117.8
				ELEVATOR	-.017	.670	-227.7
				OUTSIDE DIRECTION 1	-.098	1.130	-920.5
							NET -.4
4	1	2.471	0.	FLOOR 5 COMPARTMENT 1	.000	.850	29.3
				FLOOR 3 COMPARTMENT 1	.001	.850	76.7
				STAIRWELL	.001	10.500	992.3
				ELEVATOR	-.016	.670	-219.5
				OUTSIDE DIRECTION 1	-.089	1.130	-879.1
							NET -.4
5	1	2.299	0.	FLOOR 6 COMPARTMENT 1	.000	.850	49.0
				FLOOR 4 COMPARTMENT 1	.000	.850	-29.3
				STAIRWELL	.001	10.500	1044.2
				ELEVATOR	-.016	.670	-220.8
				OUTSIDE DIRECTION 1	-.082	1.130	-843.0
							NET .1
6	1	2.127	0.	FLOOR 7 COMPARTMENT 1	-.028	.850	-367.8
				FLOOR 5 COMPARTMENT 1	.000	.850	-49.0
				STAIRWELL	.003	10.500	1447.7
				ELEVATOR	-.016	.670	-224.2
				OUTSIDE DIRECTION 1	-.075	1.130	-806.9
							NET -.3
7	1	1.927	0.	FLOOR 8 COMPARTMENT 1	-.003	.850	-114.5
				FLOOR 6 COMPARTMENT 1	.028	.850	367.8
				STAIRWELL	.034	.323	152.8
				ELEVATOR	.011	.670	183.7
				OUTSIDE DIRECTION 1	-.040	1.130	-590.1
							NET -.3

15 STORY PRESSURIZED STAIRWELL IN SUMMER

FLOOR	COMPART- MENT	PRESSURE	FIXED FLOW	CONNECTION TO	DIFF PRESSURE	FLOW AREA	FLOW
8	1	1.751	0.	FLOOR 9 COMPARTMENT 1	.000	.850	26.4
				FLOOR 7 COMPARTMENT 1	.003	.850	114.5
				STAIRWELL	.040	.323	165.9
				ELEVATOR	.014	.670	204.5
				OUTSIDE DIRECTION 1	-.030	1.130	-511.6
							NET -.3
9	1	1.579	0.	FLOOR 10 COMPARTMENT 1	.002	.850	96.7
				FLOOR 8 COMPARTMENT 1	.000	.850	-26.4
				STAIRWELL	.043	.323	172.6
				ELEVATOR	.014	.670	203.3
				OUTSIDE DIRECTION 1	-.023	1.130	-446.6
							NET -.3
10	1	1.409	0.	FLOOR 11 COMPARTMENT 1	.003	.850	122.6
				FLOOR 9 COMPARTMENT 1	-.002	.850	-96.7
				STAIRWELL	.045	.323	175.9
				ELEVATOR	.012	.670	188.4
				OUTSIDE DIRECTION 1	-.018	1.130	-390.2
							NET .0
11	1	1.239	0.	FLOOR 12 COMPARTMENT 1	.003	.850	123.6
				FLOOR 10 COMPARTMENT 1	-.003	.850	-122.6
				STAIRWELL	.045	.323	176.9
				ELEVATOR	.009	.670	161.7
				OUTSIDE DIRECTION 1	-.013	1.130	-339.8
							NET -.1
12	1	1.070	0.	FLOOR 13 COMPARTMENT 1	.002	.850	97.8
				FLOOR 11 COMPARTMENT 1	-.003	.850	-123.6
				STAIRWELL	.046	.323	178.0
				ELEVATOR	.005	.670	129.0
				OUTSIDE DIRECTION 1	-.009	1.130	-281.4
							NET -.2
13	1	.900	0.	FLOOR 14 COMPARTMENT 1	.000	.850	-6.3
				FLOOR 12 COMPARTMENT 1	-.002	.850	-97.8
				STAIRWELL	.047	.323	181.4
				ELEVATOR	.004	.670	103.4
				OUTSIDE DIRECTION 1	-.004	1.130	-180.7
							NET -.1

15 STORY PRESSURIZED STAIRWELL IN SUMMER

FLOOR	COMPART- MENT	PRESSURE	FIXED FLOW	CONNECTION	TO	DIFF PRESSURE	FLOW AREA	FLOW
14	1	.728	0.	FLOOR 15 COMPARTMENT	1	-.045	.850	-470.3
				FLOOR 13 COMPARTMENT	1	.000	.850	6.3
				STAIRWELL		.051	.323	188.5
				ELEVATOR		.004	.670	103.5
				OUTSIDE DIRECTION	1	.004	1.130	171.7
								NET -.4
15	1	.511	-1800.	FLOOR 14 COMPARTMENT	1	.045	.850	470.3
				STAIRWELL		.100	.323	263.4
				ELEVATOR		.049	.670	384.8
				OUTSIDE DIRECTION	1	.056	1.130	681.5
								NET .0

STAIRWELL

TEMPERATURE PROFILE 2
SHAFT FLOW COEFFICIENT 70000.

FLOOR	PRESSURE	FIXED FLOW	CONNECTION	TO	DIFF PRESSURE	FLOW AREA	FLOW
1	2.976	0.	FLOOR 1 COMPARTMENT	1	-.001	10.500	-684.4
			OUTSIDE DIRECTION	1	-.097	10.500	-8447.6
2	2.824	17000.	FLOOR 2 COMPARTMENT	1	-.004	10.500	-1610.9
3	2.647	0.	FLOOR 3 COMPARTMENT	1	-.002	10.500	-1117.8
4	2.473	0.	FLOOR 4 COMPARTMENT	1	-.001	10.500	-992.3
5	2.300	0.	FLOOR 5 COMPARTMENT	1	-.001	10.500	-1044.2
6	2.130	0.	FLOOR 6 COMPARTMENT	1	-.003	10.500	-1447.7
7	1.960	0.	FLOOR 7 COMPARTMENT	1	-.034	.323	-152.8
8	1.791	0.	FLOOR 8 COMPARTMENT	1	-.040	.323	-165.9
9	1.622	0.	FLOOR 9 COMPARTMENT	1	-.043	.323	-172.6
10	1.453	0.	FLOOR 10 COMPARTMENT	1	-.045	.323	-175.9
11	1.284	0.	FLOOR 11 COMPARTMENT	1	-.045	.323	-176.9
12	1.116	0.	FLOOR 12 COMPARTMENT	1	-.046	.323	-178.0
13	.947	0.	FLOOR 13 COMPARTMENT	1	-.047	.323	-181.4
14	.779	0.	FLOOR 14 COMPARTMENT	1	-.051	.323	-188.5
15	.611	0.	FLOOR 15 COMPARTMENT	1	-.100	.323	-263.4
							-.3 NET

15 STORY PRESSURIZED STAIRWELL IN SUMMER

ELEVATOR

TEMPERATURE PROFILE 1
SHAFT FLOW COEFFICIENT 240000.

FLOOR	PRESSURE	FIXED FLOW	CONNECTION	TO	DIFF PRESSURE	FLOW AREA	FLOW
1	2.974	0.	FLOOR 1	COMPARTMENT 1	.001	.670	65.1
2	2.801	0.	FLOOR 2	COMPARTMENT 1	.019	.670	242.8
3	2.629	0.	FLOOR 3	COMPARTMENT 1	.017	.670	227.7
4	2.456	0.	FLOOR 4	COMPARTMENT 1	.016	.670	219.5
5	2.283	0.	FLOOR 5	COMPARTMENT 1	.016	.670	220.8
6	2.110	0.	FLOOR 6	COMPARTMENT 1	.016	.670	224.2
7	1.938	0.	FLOOR 7	COMPARTMENT 1	-.011	.670	-183.7
8	1.765	0.	FLOOR 8	COMPARTMENT 1	-.014	.670	-204.5
9	1.593	0.	FLOOR 9	COMPARTMENT 1	-.014	.670	-203.3
10	1.420	0.	FLOOR 10	COMPARTMENT 1	-.012	.670	-188.4
11	1.248	0.	FLOOR 11	COMPARTMENT 1	-.009	.670	-161.7
12	1.076	0.	FLOOR 12	COMPARTMENT 1	-.005	.670	-129.0
13	.903	0.	FLOOR 13	COMPARTMENT 1	-.004	.670	-103.4
14	.731	0.	FLOOR 14	COMPARTMENT 1	-.004	.670	-103.5
15	.559	0.	FLOOR 15	COMPARTMENT 1	-.049	.670	-384.8
16	.387	0.					
			OUTSIDE DIRECTION 1		.015	1.500	462.1
							-.3 NET

THE FOLLOWING UNITS ARE USED FOR OUTPUT

FLOW IN CFM AT 70 DEG F AND 1 ATM
PRESSURE IN INCHES H2O
AREA IN FEET SQUARED

Example 7.6 Run 2

```
15 STORY PRESSURIZED STAIRWELL IN WINTER
14 2 0
16 1
6 12
2
1 1 70
1 1 45
1 1
0 1 1
1
15
1 1 1
0 1 1 -1800 1
1 .65 .85
1 .65 1.13
2 15 1
0 1 1 0 1
1 .65 .85
1 .65 1.13
2
STAIRWELL
7.0E4 1 15 2
0 0
1 .65 0.323
8
1 2
17000
2 1
1 .65 10.5
3 10
1 .65 10.5
3 11
1 .65 10.5
3 12
1 .65 10.5
3 13
1 .65 10.5
3 14
1 .65 10.5
3 15
1 .65 10.5
ELEVATOR
2.4E5 1 16 1
0 0
1 .65 .67
1
2 16
1 .65 1.5
```

15 STORY PRESSURIZED STAIRWELL IN WINTER

FLOOR	COMPART- MENT	PRESSURE	FIXED FLOW	CONNECTION TO	DIFF PRESSURE	FLOW AREA	FLOW
1	1	3.183	-1800.	FLOOR 2 COMPARTMENT 1	.053	.850	508.0
				STAIRWELL	.185	.323	371.1
				ELEVATOR	-.003	.670	-97.9
				OUTSIDE DIRECTION 1	.107	1.130	1018.4
							NET -.4
2	1	3.063	0.	FLOOR 3 COMPARTMENT 1	.000	.850	25.3
				FLOOR 1 COMPARTMENT 1	-.053	.850	-508.0
				STAIRWELL	.138	.323	320.0
				ELEVATOR	-.056	.670	-412.2
				OUTSIDE DIRECTION 1	.034	1.130	574.8
							NET -.1
3	1	2.890	0.	FLOOR 4 COMPARTMENT 1	-.010	.850	-217.8
				FLOOR 2 COMPARTMENT 1	.000	.850	-25.3
				STAIRWELL	.114	.323	291.5
				ELEVATOR	-.056	.670	-412.6
				OUTSIDE DIRECTION 1	.014	1.130	363.9
							NET -.3
4	1	2.708	0.	FLOOR 5 COMPARTMENT 1	-.017	.850	-291.0
				FLOOR 3 COMPARTMENT 1	.010	.850	217.8
				STAIRWELL	.102	.323	275.0
				ELEVATOR	-.046	.670	-375.2
				OUTSIDE DIRECTION 1	.003	1.130	173.1
							NET -.2
5	1	2.518	0.	FLOOR 6 COMPARTMENT 1	-.018	.850	-295.0
				FLOOR 4 COMPARTMENT 1	.017	.850	291.0
				STAIRWELL	.098	.323	269.4
				ELEVATOR	-.029	.670	-296.9
				OUTSIDE DIRECTION 1	.000	1.130	31.2
							NET -.4
6	1	2.328	0.	FLOOR 7 COMPARTMENT 1	-.011	.850	-231.6
				FLOOR 5 COMPARTMENT 1	.018	.850	295.0
				STAIRWELL	.095	.323	265.6
				ELEVATOR	-.011	.670	-185.0
				OUTSIDE DIRECTION 1	-.002	1.130	-144.3
							NET -.3
7	1	2.144	0.	FLOOR 8 COMPARTMENT 1	-.004	.850	-134.2
				FLOOR 6 COMPARTMENT 1	.011	.850	231.6
				STAIRWELL	.086	.323	253.0
				ELEVATOR	.000	.670	-32.5
				OUTSIDE DIRECTION 1	-.012	1.130	-318.4
							NET -.4

15 STORY PRESSURIZED STAIRWELL IN WINTER

FLOOR	COMPART-MENT	PRESSURE	FIXED FLOW	CONNECTION TO	DIFF PRESSURE	FLOW AREA	FLOW
8	1	1.968	0.	FLOOR 9 COMPARTMENT 1	.000	.850	31.1
				FLOOR 7 COMPARTMENT 1	.004	.850	134.2
				STAIRWELL	.071	.323	229.6
				ELEVATOR	.003	.670	99.8
				OUTSIDE DIRECTION 1	-.028	1.130	-494.7
							NET .0
9	1	1.796	0.	FLOOR 10 COMPARTMENT 1	.030	.850	386.6
				FLOOR 8 COMPARTMENT 1	.000	.850	-31.1
				STAIRWELL	.052	.323	197.4
				ELEVATOR	.003	.670	95.9
				OUTSIDE DIRECTION 1	-.049	1.130	-649.2
							NET -.4
10	1	1.654	0.	FLOOR 11 COMPARTMENT 1	-.011	.850	-231.1
				FLOOR 9 COMPARTMENT 1	-.030	.850	-386.6
				STAIRWELL	.004	10.500	1834.2
				ELEVATOR	-.027	.670	-289.4
				OUTSIDE DIRECTION 1	-.099	1.130	-927.5
							NET -.4
11	1	1.471	0.	FLOOR 12 COMPARTMENT 1	-.011	.850	-232.8
				FLOOR 10 COMPARTMENT 1	.011	.850	231.1
				STAIRWELL	.002	10.500	1196.5
				ELEVATOR	-.017	.670	-225.2
				OUTSIDE DIRECTION 1	-.108	1.130	-969.8
							NET -.2
12	1	1.288	0.	FLOOR 13 COMPARTMENT 1	-.009	.850	-214.5
				FLOOR 11 COMPARTMENT 1	.011	.850	232.8
				STAIRWELL	.002	10.500	1122.7
				ELEVATOR	-.006	.670	-131.5
				OUTSIDE DIRECTION 1	-.118	1.130	-1009.8
							NET -.1
13	1	1.106	0.	FLOOR 14 COMPARTMENT 1	-.009	.850	-209.3
				FLOOR 12 COMPARTMENT 1	.009	.850	214.5
				STAIRWELL	.001	10.500	944.7
				ELEVATOR	.004	.670	105.0
				OUTSIDE DIRECTION 1	-.128	1.130	-1054.8
							NET .1

15 STORY PRESSURIZED STAIRWELL IN WINTER

FLOOR	COMPART-MENT	PRESSURE	FIXED FLOW	CONNECTION TO	DIFF PRESSURE	FLOW AREA	FLOW
14	1	.925	0.	FLOOR 15 COMPARTMENT 1	-.008	.850	-200.7
				FLOOR 13 COMPARTMENT 1	.009	.850	209.3
				STAIRWELL	.001	10.500	895.9
				ELEVATOR	.012	.670	194.9
				OUTSIDE DIRECTION 1	-.139	1.130	-1099.8
							NET -.4
15	1	.745	0.	FLOOR 14 COMPARTMENT 1	.008	.850	200.7
				STAIRWELL	.001	10.500	693.8
				ELEVATOR	.021	.670	250.6
				OUTSIDE DIRECTION 1	-.151	1.130	-1145.6
							NET -.4

STAIRWELL

TEMPERATURE PROFILE 2
SHAFT FLOW COEFFICIENT 70000.

FLOOR	PRESSURE	FIXED FLOW	CONNECTION TO	DIFF PRESSURE	FLOW AREA	FLOW
1	3.368	0.	FLOOR 1 COMPARTMENT 1	-.185	.323	-371.1
			OUTSIDE DIRECTION 1	-.078	10.500	-7839.6
2	3.201	17000.	FLOOR 2 COMPARTMENT 1	-.138	.323	-320.0
3	3.005	0.	FLOOR 3 COMPARTMENT 1	-.114	.323	-291.5
4	2.810	0.	FLOOR 4 COMPARTMENT 1	-.102	.323	-275.0
5	2.616	0.	FLOOR 5 COMPARTMENT 1	-.098	.323	-269.4
6	2.422	0.	FLOOR 6 COMPARTMENT 1	-.095	.323	-265.6
7	2.230	0.	FLOOR 7 COMPARTMENT 1	-.086	.323	-253.0
8	2.039	0.	FLOOR 8 COMPARTMENT 1	-.071	.323	-229.6
9	1.848	0.	FLOOR 9 COMPARTMENT 1	-.052	.323	-197.4
10	1.658	0.	FLOOR 10 COMPARTMENT 1	-.004	10.500	-1834.2
11	1.473	0.	FLOOR 11 COMPARTMENT 1	-.002	10.500	-1196.5
12	1.289	0.	FLOOR 12 COMPARTMENT 1	-.002	10.500	-1122.7
13	1.107	0.	FLOOR 13 COMPARTMENT 1	-.001	10.500	-944.7
14	.926	0.	FLOOR 14 COMPARTMENT 1	-.001	10.500	-895.9
15	.746	0.	FLOOR 15 COMPARTMENT 1	-.001	10.500	-693.8
						.0 NET

15 STORY PRESSURIZED STAIRWELL IN WINTER

ELEVATOR

TEMPERATURE PROFILE 1
SHAFT FLOW COEFFICIENT 240000.

FLOOR	PRESSURE	FIXED FLOW	CONNECTION	TO		DIFF PRESSURE	FLOW AREA	FLOW
1	3.180	0.	FLOOR 1	COMPARTMENT	1	.003	.670	97.9
2	3.007	0.	FLOOR 2	COMPARTMENT	1	.056	.670	412.2
3	2.834	0.	FLOOR 3	COMPARTMENT	1	.056	.670	412.6
4	2.662	0.	FLOOR 4	COMPARTMENT	1	.046	.670	375.2
5	2.489	0.	FLOOR 5	COMPARTMENT	1	.029	.670	296.9
6	2.316	0.	FLOOR 6	COMPARTMENT	1	.011	.670	185.0
7	2.144	0.	FLOOR 7	COMPARTMENT	1	.000	.670	32.5
8	1.971	0.	FLOOR 8	COMPARTMENT	1	-.003	.670	-99.8
9	1.799	0.	FLOOR 9	COMPARTMENT	1	-.003	.670	-95.9
10	1.627	0.	FLOOR 10	COMPARTMENT	1	.027	.670	289.4
11	1.454	0.	FLOOR 11	COMPARTMENT	1	.017	.670	225.2
12	1.282	0.	FLOOR 12	COMPARTMENT	1	.006	.670	131.5
13	1.110	0.	FLOOR 13	COMPARTMENT	1	-.004	.670	-105.0
14	.938	0.	FLOOR 14	COMPARTMENT	1	-.012	.670	-194.9
15	.766	0.	FLOOR 15	COMPARTMENT	1	-.021	.670	-250.6
16	.594	0.						
			OUTSIDE	DIRECTION	1	-.192	1.500	-1712.6
								-.3 NET

THE FOLLOWING UNITS ARE USED FOR OUTPUT

FLOW IN CFM AT 70 DEG F AND 1 ATM
PRESSURE IN INCHES H2O
AREA IN FEET SQUARED

Appendix E DATA AND COMPUTER OUTPUT FOR EXAMPLE 8.3

Example 8.3 Run 1

```
14 STORY PRESSURIZED ELEVATOR IN WINTER
14 2 0
14 1
6 12
2
1 1 70
1 1 45
1 1
0 1 1
1
14
1 1 1
0 1 1 0 1
1 .65 .85
1 .65 20.
2 14 1
0 1 1 0 1
1 .65 .85
1 .65 1.13
2
STAIRWELL
7.0E4 1 14 2
0 0
1 .65 0.323
0
ELEVATOR
2.4E5 1 14 1
0 0
1 .65 .67
1
1 2
8550
```

14 STORY PRESSURIZED ELEVATOR IN WINTER

FLOOR	COMPART-MENT	PRESSURE	FIXED FLOW	CONNECTION TO	DIFF PRESSURE	FLOW AREA	FLOW
1	1	2.906	0.	FLOOR 2 COMPARTMENT 1	-.011	.850	-235.4
				STAIRWELL	-.026	.323	-135.3
				ELEVATOR	.050	.670	391.6
				OUTSIDE DIRECTION 1	.000	20.000	-21.2
							NET -.3
2	1	2.722	0.	FLOOR 3 COMPARTMENT 1	-.014	.850	-262.1
				FLOOR 1 COMPARTMENT 1	.011	.850	235.4
				STAIRWELL	-.023	.323	-128.0
				ELEVATOR	.062	.670	433.2
				OUTSIDE DIRECTION 1	-.009	1.130	-278.8
							NET -.3
3	1	2.535	0.	FLOOR 4 COMPARTMENT 1	-.014	.850	-263.7
				FLOOR 2 COMPARTMENT 1	.014	.850	262.1
				STAIRWELL	-.018	.323	-112.0
				ELEVATOR	.074	.670	476.6
				OUTSIDE DIRECTION 1	-.015	1.130	-363.3
							NET -.2
4	1	2.348	0.	FLOOR 5 COMPARTMENT 1	-.014	.850	-258.7
				FLOOR 3 COMPARTMENT 1	.014	.850	263.7
				STAIRWELL	-.012	.323	-92.6
				ELEVATOR	.088	.670	517.1
				OUTSIDE DIRECTION 1	-.021	1.130	-429.5
							NET -.1
5	1	2.162	0.	FLOOR 6 COMPARTMENT 1	-.013	.850	-250.3
				FLOOR 4 COMPARTMENT 1	.014	.850	258.7
				STAIRWELL	-.007	.323	-70.8
				ELEVATOR	.101	.670	553.6
				OUTSIDE DIRECTION 1	-.028	1.130	-491.6
							NET -.3
6	1	1.977	0.	FLOOR 7 COMPARTMENT 1	-.012	.850	-237.9
				FLOOR 5 COMPARTMENT 1	.013	.850	250.3
				STAIRWELL	-.003	.323	-45.4
				ELEVATOR	.113	.670	585.9
				OUTSIDE DIRECTION 1	-.035	1.130	-553.4
							NET -.4
7	1	1.793	0.	FLOOR 8 COMPARTMENT 1	-.011	.850	-234.3
				FLOOR 6 COMPARTMENT 1	.012	.850	237.9
				STAIRWELL	.000	.323	.2
				ELEVATOR	.124	.670	613.7
				OUTSIDE DIRECTION 1	-.044	1.130	-617.7
							NET -.2

14 STORY PRESSURIZED ELEVATOR IN WINTER

FLOOR	COMPART-MENT	PRESSURE	FIXED FLOW	CONNECTION TO	DIFF PRESSURE	FLOW AREA	FLOW
8	1	1.609	0.	FLOOR 9 COMPARTMENT 1	-.012	.850	-240.2
				FLOOR 7 COMPARTMENT 1	.011	.850	234.3
				STAIRWELL	.003	.323	43.7
				ELEVATOR	.134	.670	639.7
				OUTSIDE DIRECTION 1	-.053	1.130	-677.9
							NET -.3
9	1	1.425	0.	FLOOR 10 COMPARTMENT 1	-.012	.850	-242.3
				FLOOR 8 COMPARTMENT 1	.012	.850	240.2
				STAIRWELL	.006	.323	65.2
				ELEVATOR	.146	.670	666.3
				OUTSIDE DIRECTION 1	-.061	1.130	-729.8
							NET -.4
10	1	1.240	0.	FLOOR 11 COMPARTMENT 1	-.012	.850	-240.4
				FLOOR 9 COMPARTMENT 1	.012	.850	242.3
				STAIRWELL	.009	.323	82.3
				ELEVATOR	.157	.670	692.5
				OUTSIDE DIRECTION 1	-.070	1.130	-776.9
							NET -.2
11	1	1.057	0.	FLOOR 12 COMPARTMENT 1	-.011	.850	-231.4
				FLOOR 10 COMPARTMENT 1	.012	.850	240.4
				STAIRWELL	.012	.323	95.6
				ELEVATOR	.169	.670	717.4
				OUTSIDE DIRECTION 1	-.078	1.130	-822.3
							NET -.2
12	1	.873	0.	FLOOR 13 COMPARTMENT 1	-.009	.850	-206.0
				FLOOR 11 COMPARTMENT 1	.011	.850	231.4
				STAIRWELL	.015	.323	104.4
				ELEVATOR	.180	.670	739.9
				OUTSIDE DIRECTION 1	-.087	1.130	-869.8
							NET -.1
13	1	.693	0.	FLOOR 14 COMPARTMENT 1	-.004	.850	-143.3
				FLOOR 12 COMPARTMENT 1	.009	.850	206.0
				STAIRWELL	.015	.323	104.8
				ELEVATOR	.188	.670	757.3
				OUTSIDE DIRECTION 1	-.099	1.130	-925.2
							NET -.4
14	1	.517	0.	FLOOR 13 COMPARTMENT 1	.004	.850	143.3
				STAIRWELL	.010	.323	88.0
				ELEVATOR	.192	.670	765.5
				OUTSIDE DIRECTION 1	-.115	1.130	-997.1
							NET -.3

14 STORY PRESSURIZED ELEVATOR IN WINTER

STAIRWELL

TEMPERATURE PROFILE 2
SHAFT FLOW COEFFICIENT 70000.

FLOOR	PRESSURE	FIXED FLOW	CONNECTION	TO		DIFF PRESSURE	FLOW AREA	FLOW
1	2.880	0.	FLOOR 1	COMPARTMENT	1	.026	.323	135.3
2	2.699	0.	FLOOR 2	COMPARTMENT	1	.023	.323	128.0
3	2.518	0.	FLOOR 3	COMPARTMENT	1	.018	.323	112.0
4	2.336	0.	FLOOR 4	COMPARTMENT	1	.012	.323	92.6
5	2.155	0.	FLOOR 5	COMPARTMENT	1	.007	.323	70.8
6	1.974	0.	FLOOR 6	COMPARTMENT	1	.003	.323	45.4
7	1.793	0.	FLOOR 7	COMPARTMENT	1	.000	.323	-.2
8	1.611	0.	FLOOR 8	COMPARTMENT	1	-.003	.323	-43.7
9	1.430	0.	FLOOR 9	COMPARTMENT	1	-.006	.323	-65.2
10	1.250	0.	FLOOR 10	COMPARTMENT	1	-.009	.323	-82.3
11	1.069	0.	FLOOR 11	COMPARTMENT	1	-.012	.323	-95.6
12	.888	0.	FLOOR 12	COMPARTMENT	1	-.015	.323	-104.4
13	.707	0.	FLOOR 13	COMPARTMENT	1	-.015	.323	-104.8
14	.527	0.	FLOOR 14	COMPARTMENT	1	-.010	.323	-88.0
								-.1 NET

THE FOLLOWING UNITS ARE USED FOR OUTPUT

FLOW IN CFM AT 70 DEG F AND 1 ATM
PRESSURE IN INCHES H2O
AREA IN FEET SQUARED

14 STORY PRESSURIZED ELEVATOR IN WINTER

ELEVATOR

TEMPERATURE PROFILE 1
SHAFT FLOW COEFFICIENT 240000.

FLOOR	PRESSURE	FIXED FLOW	CONNECTION	TO	DIFF PRESSURE	FLOW AREA	FLOW
1	2.957	0.	FLOOR 1	COMPARTMENT 1	-.050	.670	-391.6
2	2.784	8550.	FLOOR 2	COMPARTMENT 1	-.062	.670	-433.2
3	2.610	0.	FLOOR 3	COMPARTMENT 1	-.074	.670	-476.6
4	2.436	0.	FLOOR 4	COMPARTMENT 1	-.088	.670	-517.1
5	2.263	0.	FLOOR 5	COMPARTMENT 1	-.101	.670	-553.6
6	2.089	0.	FLOOR 6	COMPARTMENT 1	-.113	.670	-585.9
7	1.916	0.	FLOOR 7	COMPARTMENT 1	-.124	.670	-613.7
8	1.743	0.	FLOOR 8	COMPARTMENT 1	-.134	.670	-639.7
9	1.570	0.	FLOOR 9	COMPARTMENT 1	-.146	.670	-666.3
10	1.398	0.	FLOOR 10	COMPARTMENT 1	-.157	.670	-692.5
11	1.225	0.	FLOOR 11	COMPARTMENT 1	-.169	.670	-717.4
12	1.053	0.	FLOOR 12	COMPARTMENT 1	-.180	.670	-739.9
13	.881	0.	FLOOR 13	COMPARTMENT 1	-.188	.670	-757.3
14	.709	0.	FLOOR 14	COMPARTMENT 1	-.192	.670	-765.5
							-.4 NET

THE FOLLOWING UNITS ARE USED FOR OUTPUT

FLOW IN CFM AT 70 DEG F AND 1 ATM
PRESSURE IN INCHES H2O
AREA IN FEET SQUARED

Example 8.3 Run 2

```
14 STORY PRESSURIZED ELEVATOR IN SUMMER
93 2 0
14 1
6 12
2
1 1 70
1 1 82
1 1
0 1 1
1
14
1 1 1
0 1 1 0 1
1 .65 .85
1 .65 20.
2 14 1
0 1 1 0 1
1 .65 .85
1 .65 1.13
2
STAIRWELL
7.0E4 1 14 2
0 0
1 .65 0.323
0
ELEVATOR
2.4E5 1 14 1
0 0
1 .65 .67
1
1 2
8550
```

14 STORY PRESSURIZED ELEVATOR IN SUMMER

FLOOR	COMPART-MENT	PRESSURE	FIXED FLOW	CONNECTION TO	DIFF PRESSURE	FLOW AREA	FLOW
1	1	2.550	0.	FLOOR 2 COMPARTMENT 1	.047	.850	478.4
				STAIRWELL	.058	.323	200.7
				ELEVATOR	.206	.670	792.9
				OUTSIDE DIRECTION 1	-.001	20.000	-1472.0
							NET -.1
2	1	2.424	0.	FLOOR 3 COMPARTMENT 1	.015	.850	267.5
				FLOOR 1 COMPARTMENT 1	-.047	.850	-478.4
				STAIRWELL	.015	.323	103.1
				ELEVATOR	.159	.670	697.3
				OUTSIDE DIRECTION 1	-.040	1.130	-589.7
							NET -.2
3	1	2.266	0.	FLOOR 4 COMPARTMENT 1	.007	.850	189.0
				FLOOR 2 COMPARTMENT 1	-.015	.850	-267.5
				STAIRWELL	.005	.323	56.4
				ELEVATOR	.144	.670	662.5
				OUTSIDE DIRECTION 1	-.047	1.130	-640.7
							NET -.2
4	1	2.100	0.	FLOOR 5 COMPARTMENT 1	.005	.850	156.7
				FLOOR 3 COMPARTMENT 1	-.007	.850	-189.0
				STAIRWELL	.001	.323	28.5
				ELEVATOR	.136	.670	643.8
				OUTSIDE DIRECTION 1	-.047	1.130	-640.1
							NET -.1
5	1	1.932	0.	FLOOR 6 COMPARTMENT 1	.004	.850	145.8
				FLOOR 4 COMPARTMENT 1	-.005	.850	-156.7
				STAIRWELL	.000	.323	4.4
				ELEVATOR	.130	.670	630.3
				OUTSIDE DIRECTION 1	-.045	1.130	-624.1
							NET -.4
6	1	1.764	0.	FLOOR 7 COMPARTMENT 1	.004	.850	147.7
				FLOOR 5 COMPARTMENT 1	-.004	.850	-145.8
				STAIRWELL	.000	.323	-17.8
				ELEVATOR	.125	.670	618.5
				OUTSIDE DIRECTION 1	-.042	1.130	-602.8
							NET -.2
7	1	1.596	0.	FLOOR 8 COMPARTMENT 1	.005	.850	149.6
				FLOOR 6 COMPARTMENT 1	-.004	.850	-147.7
				STAIRWELL	-.001	.323	-27.1
				ELEVATOR	.121	.670	606.4
				OUTSIDE DIRECTION 1	-.039	1.130	-581.6
							NET -.2

14 STORY PRESSURIZED ELEVATOR IN SUMMER

FLOOR	COMPART-MENT	PRESSURE	FIXED FLOW	CONNECTION TO	DIFF PRESSURE	FLOW AREA	FLOW
8	1	1.428	0.	FLOOR 9 COMPARTMENT 1	.005	.850	151.4
				FLOOR 7 COMPARTMENT 1	-.005	.850	-149.6
				STAIRWELL	-.002	.323	-35.2
				ELEVATOR	.116	.670	594.0
				OUTSIDE DIRECTION 1	-.036	1.130	-560.8
							NET -.2
9	1	1.260	0.	FLOOR 10 COMPARTMENT 1	.005	.850	152.5
				FLOOR 8 COMPARTMENT 1	-.005	.850	-151.4
				STAIRWELL	-.003	.323	-42.7
				ELEVATOR	.111	.670	581.3
				OUTSIDE DIRECTION 1	-.034	1.130	-539.8
							NET -.1
10	1	1.093	0.	FLOOR 11 COMPARTMENT 1	.005	.850	151.9
				FLOOR 9 COMPARTMENT 1	-.005	.850	-152.5
				STAIRWELL	-.003	.323	-49.6
				ELEVATOR	.106	.670	568.2
				OUTSIDE DIRECTION 1	-.031	1.130	-518.4
							NET -.4
11	1	.925	0.	FLOOR 12 COMPARTMENT 1	.004	.850	148.1
				FLOOR 10 COMPARTMENT 1	-.005	.850	-151.9
				STAIRWELL	-.004	.323	-55.5
				ELEVATOR	.101	.670	555.1
				OUTSIDE DIRECTION 1	-.028	1.130	-496.1
							NET -.2
12	1	.757	0.	FLOOR 13 COMPARTMENT 1	.004	.850	135.6
				FLOOR 11 COMPARTMENT 1	-.004	.850	-148.1
				STAIRWELL	-.005	.323	-59.4
				ELEVATOR	.097	.670	542.5
				OUTSIDE DIRECTION 1	-.026	1.130	-470.7
							NET -.2
13	1	.589	0.	FLOOR 14 COMPARTMENT 1	.002	.850	99.1
				FLOOR 12 COMPARTMENT 1	-.004	.850	-135.6
				STAIRWELL	-.005	.323	-59.0
				ELEVATOR	.093	.670	531.7
				OUTSIDE DIRECTION 1	-.022	1.130	-436.5
							NET -.3
14	1	.419	0.	FLOOR 13 COMPARTMENT 1	-.002	.850	-99.1
				STAIRWELL	-.003	.323	-46.8
				ELEVATOR	.091	.670	525.8
				OUTSIDE DIRECTION 1	-.017	1.130	-380.1
							NET -.2

14 STORY PRESSURIZED ELEVATOR IN SUMMER

STAIRWELL

TEMPERATURE PROFILE 2
SHAFT FLOW COEFFICIENT 70000.

FLOOR	PRESSURE	FIXED FLOW	CONNECTION	TO	DIFF PRESSURE	FLOW AREA	FLOW
1	2.608	0.	FLOOR 1	COMPARTMENT 1	-.058	.323	-200.7
2	2.439	0.	FLOOR 2	COMPARTMENT 1	-.015	.323	-103.1
3	2.270	0.	FLOOR 3	COMPARTMENT 1	-.005	.323	-56.4
4	2.101	0.	FLOOR 4	COMPARTMENT 1	-.001	.323	-28.5
5	1.932	0.	FLOOR 5	COMPARTMENT 1	.000	.323	-4.4
6	1.764	0.	FLOOR 6	COMPARTMENT 1	.000	.323	17.8
7	1.595	0.	FLOOR 7	COMPARTMENT 1	.001	.323	27.1
8	1.426	0.	FLOOR 8	COMPARTMENT 1	.002	.323	35.2
9	1.258	0.	FLOOR 9	COMPARTMENT 1	.003	.323	42.7
10	1.089	0.	FLOOR 10	COMPARTMENT 1	.003	.323	49.6
11	.921	0.	FLOOR 11	COMPARTMENT 1	.004	.323	55.5
12	.752	0.	FLOOR 12	COMPARTMENT 1	.005	.323	59.4
13	.584	0.	FLOOR 13	COMPARTMENT 1	.005	.323	59.0
14	.415	0.	FLOOR 14	COMPARTMENT 1	.003	.323	46.8
							-.1 NET

THE FOLLOWING UNITS ARE USED FOR OUTPUT

FLOW IN CFM AT 70 DEG F AND 1 ATM
PRESSURE IN INCHES H2O
AREA IN FEET SQUARED

14 STORY PRESSURIZED ELEVATOR IN SUMMER

ELEVATOR

TEMPERATURE PROFILE 1
SHAFT FLOW COEFFICIENT 240000.

FLOOR	PRESSURE	FIXED FLOW	CONNECTION	TO	DIFF PRESSURE	FLOW AREA	FLOW
1	2.757	0.	FLOOR 1	COMPARTMENT 1	-.206	.670	-792.9
2	2.584	8550.	FLOOR 2	COMPARTMENT 1	-.159	.670	-697.3
3	2.410	0.	FLOOR 3	COMPARTMENT 1	-.144	.670	-662.5
4	2.236	0.	FLOOR 4	COMPARTMENT 1	-.136	.670	-643.8
5	2.063	0.	FLOOR 5	COMPARTMENT 1	-.130	.670	-630.3
6	1.890	0.	FLOOR 6	COMPARTMENT 1	-.125	.670	-618.5
7	1.717	0.	FLOOR 7	COMPARTMENT 1	-.121	.670	-606.4
8	1.544	0.	FLOOR 8	COMPARTMENT 1	-.116	.670	-594.0
9	1.371	0.	FLOOR 9	COMPARTMENT 1	-.111	.670	-581.3
10	1.198	0.	FLOOR 10	COMPARTMENT 1	-.106	.670	-568.2
11	1.026	0.	FLOOR 11	COMPARTMENT 1	-.101	.670	-555.2
12	.854	0.	FLOOR 12	COMPARTMENT 1	-.097	.670	-542.5
13	.681	0.	FLOOR 13	COMPARTMENT 1	-.093	.670	-531.7
14	.509	0.	FLOOR 14	COMPARTMENT 1	-.091	.670	-525.8
							-.3 NET

THE FOLLOWING UNITS ARE USED FOR OUTPUT

FLOW IN CFM AT 70 DEG F AND 1 ATM
PRESSURE IN INCHES H2O
AREA IN FEET SQUARED

Appendix F LISTING OF COMPUTER PROGRAM ASCOS

MAIN PROGRAM

```
C
C     ASCOS VERSION 1.12  FOR PERSONAL COMPUTERS
C     WRITTEN BY JOHN H. KLOTE
C     ADAPTED FOR PERSONAL COMPUTERS BY WILLIAM D. WALTON
C
C     A COMPUTER PROGRAM FOR AIR FLOW ANALYSIS IN BUILDINGS,
C     SPECIFICALLY FOR ANALYSIS OF SMOKE CONTROL SYSTEMS
C
C     CONTRIBUTION OF THE NATIONAL BUREAU OF STANDARDS (U.S.)
C     NOT SUBJECT TO COPYRIGHT
C
C     DOCUMENTATION: ASHRAE "DESIGN OF SMOKE CONTROL SYSTEMS
C                    FOR BUILDINGS" AND FILE ASCOSDOC.DOC
C
C***********************************************************************
C
C     PROGRAM VARIABLES
C     AI     LEAKAGE AREA OF INTERNAL CONNECTION
C     AO     LEAKAGE AERA OF CONNECTION TO OUTSIDE
C     C      FLOW COEFFICIENT BETWEEN BUILDING POINTS
C     CO     FLOW COEFFICIENT TO OUTSIDE
C     CS     FLOW COEFFICIENT OF SHAFT
C     E      LIMIT WITHIN WHICH CONVERGENCE IS ACCEPTABLE
C     F      NET FLOW INTO POINT I
C     FC     FLOW BETWEEN INTERNAL POINTS
C     FF     FIXED FLOW INTO POINT I
C     FO     FLOW TO OUTSIDE
C     FSS    NET FLOW INTO SHAFT IS
C     H      HEIGHT FROM GROUND TO MIDPOINT OF FLOOR
C     IBUG   OUTPUT VARIABLE
C     ICONV  INTEGER USED IN SUBROUTINES BLDGP AND SHAFTP
C            IF ICONV = 0 THEN  THE PRESSURES WERE UNCHANGED
C     IFLOOR FLOOR LEVEL WHERE POINT IS LOCATED
C     IT     POINTER TO TEMP PROFILE FOR POINT I
C     ITS    POINTER TO TEMPERATURE PROFILE OF SHAFT
C     JC     POINT NO. CONNECTED TO POINT I
C     JOC    DIRECTION OF OUTSIDE CONNECTION
C     N      NO. OF BUILDING COMPARTMENTS
C     NC     NO. OF INTERNAL POINTS CONNECTED TO POINT I
C     NCO    NO. OF OUTSIDE CONNECTIONS
C     NFS1   BOTTOM FLOOR OF SHAFT
C     NFS2   TOP FLOOR OF SHAFT
C     NH     NO. OF FLOORS
C     NPO    NO. OF OUTSIDE PRESSURE PROFILES
C     NS     NO. OF SHAFTS
C     NS1    I VALUE FOR START OF SHAFT
C     NS2    I VALUE FOR END OF SHAFT
C     NT     TOTAL NO. OF POINTS (BLDG AND SHAFT)
C     NTP    NO. OF TEMPERATURE PROFILES
C     P      PRESSURE AT POINT I
C     PFO    OUTSIDE PRESSURE PROFILES
C     PO     OUTSIDE PRESSURE
C     PS     PRESSURE PROFILE OF SHAFT - WORKSPACE
C     PZ     PRESSURE DUE TO ELEVATION DIFFERENCE
C     T      TEMPERATURE PROFILE ARRAY
C     TITLE  PROJECT TITLE
C     TITSH  SHAFT TITLE
C
C
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C     PROGRAM PARAMETERS
C     MM     MAX NO. OF POINTS
C     MS     MAX NO. OF SHAFTS
C     MC     MAX NO. OF CONNECTIONS FOR ANY POINT
C     MPO    MAX NO. OF OUTSIDE PRESSURE PROFILES
C     MTP    MAX NO. OF TEMPERATURE PROFILES
C     MFL    MAX NO. OF FLOORS
C     MB     MAX NO. OF BUILDING COMPARTMENTS
C
C
      PARAMETER  (MM=150,MS=12,MC=9,MPO=4,MTP=4,MFL=40,MB=40)
      PARAMETER  (MBP=MB+1)
      COMMON NT,P(MM),C(MM,MC),NC(MM),JC(MM,MC),ITS(MS),
     1 FC(MM,MC),PZ(MM,MC),PO(MM,MPO),CO(MM,MPO),F(MM),PFO(MFL,MPO),
     2 FF(MM),FO(MM,MPO),CS(MS),PS(MFL),NS1(MS),NS2(MS),
     3 FSS(MS),N,NS,NPO,ICONV,E,IBUG,AI(MM,MC),AO(MM,MPO),TITSH(MS,5),
     4 NH,H(MFL),IFLOOR(MM),T(MTP,MFL),NFS1(MS),NFS2(MS),IT(MB),NTP
     5 ,NCO(MM),JOC(MM,MPO),TOUT,PGZ
      DOUBLE PRECISION P,PO,PS
      COMMON /CORRR/C1(MM,MC),C2(MM,MC),CO1(MM,MPO),CO2(MM,MPO)
      COMMON /MAT/A(MB,MBP),XX(MB),NNN
      DOUBLE PRECISION A,XX
      COMMON /RUN/IRUN
      COMMON /IO/TITLE(18),IOUT,IUNIT,NCOMP(MFL),SNCOMP(MFL),IOWIDE,
     1NFLS
      COMMON /LVAR/B1(MM,MC),B2(MM,MPO),II(MFL),TT(MFL),CW(MPO),
     1PH(MFL),NZZ(MM),SC(MS),SCO(MS)
      NITER=5000
      IRUN=1
C
C       CALL ZERO TO ZERO ARRAYS
C
      CALL ZERO
C
C       CALL INPUT TO READ DATA
C
      CALL INPUT
C
      E=0.2
      ICS=1
C
C         SAVE AI(I,J) IN B1(I,J) AND FIND
C           MAX VALUE OF AI(I,J)
C
      AZZ=0
      AMAX=0
      DO 10 I=1,NT
      NNC=NC(I)
      DO 8 J=1,NNC
      B1(I,J)=AI(I,J)
      IF(AI(I,J) .GT. AMAX)AMAX=AI(I,J)
8     CONTINUE
      DO 9 J=1,NPO
      B2(I,J)=AO(I,J)
      IF(AO(I,J) .GT. AMAX)AMAX=AO(I,J)
9     CONTINUE
10    CONTINUE
C
C         ADJUST FOR LARGE VALUES OF FLOW AREA
C
      IF(AMAX .LT. 0.3)GO TO 25
      AZZ=1
      AM=0.2/(AMAX-0.1)
      BB=0.1*(1.0-AM)
      DO 15 I=1,NT
      NNC=NC(I)
```

```
      DO 12 J=1,NNC
      IF(AI(I,J) .LT. 0.1)GO TO 12
      AI(I,J)=AM*AI(I,J)+BB
12    CONTINUE
      DO 14 J=1,NPO
      IF(AO(I,J) .LT. 0.1)GO TO 14
      AO(I,J)=AM*AO(I,J)+BB
14    CONTINUE
15    CONTINUE
C
C       TEMPERATURE CORRECTION
C
25    CALL CORR
C
C       CALL INIT TO INITIALIZE PRESSURE ARRAY , P
C
      CALL INIT
C
C
C       DO LOOP TO 30 IS ITERATIVE SOLUTION TO PRESSURE ARRAY
C
24    DO 30 ITER=1,NITER
C
C       CALL BLDGP TO SOLVE FOR BUILDING PRESSURES
C
      CALL BLDGP
      ICB=ICONV
      IF(ICB .EQ. 0 .AND. ICS .EQ. 0)GO TO 40
C
C       CALL SHAFTP TO SOLVE FOR SHAFT PRESSURES
C
      CALL SHAFTP
      ICS=ICONV
      IF(ICB .EQ. 0 .AND. ICS .EQ. 0)GO TO 40
C
C       CALL PZAD TO CALCULATE PZ TERMS
C
      CALL PZAD
30    CONTINUE
C
C       IF ROUTINE FAILS TO CONVERGE IN NITER
C       ITERATIONS PRINT ERROR MESSAGE
C
      WRITE(6,800)
40    CONTINUE
      WRITE(6,801)ITER
      IF(AZZ .EQ. 0.)GO TO 42
      AZZ = 0.
      DO 60 I=1,NT
      NNC=NC(I)
      DO 50 J=1,NNC
50    AI(I,J)=B1(I,J)
      DO 55 J=1,NPO
55    AO(I,J)=B2(I,J)
60    CONTINUE
      CALL CORR
      GO TO 24
C
C
C
C       CALL OUT132 OR OUT80 TO OUTPUT SOLUTION
C
42    IF(IOWIDE.EQ.132) THEN
      CALL OUT132
      ELSE
      CALL OUT80
```

```
      ENDIF
C
      WRITE(6,805)
       STOP
C
C
C      FORMAT STATEMENTS
C
800   FORMAT(/////5X,35(1H1)//5X,
     +35HFAILURE OF MAIN PROGRAM TO CONVERGE   //5X,35(1H1)//)
801   FORMAT(   10X,I5,5X,11HITERATIONS    )
805   FORMAT(1H1)
      END
```

SUBROUTINE INPUT

```
      SUBROUTINE INPUT
C
C      THIS ROUTINE READS AND PRINTS DATA
C       AND INITIALIZES PZ ARRAY
C
      PARAMETER  (MM=150,MS=12,MC=9,MPO=4,MTP=4,MFL=40,MB=40)
      COMMON /IO/TITLE(18),IOUT,IUNIT,NCOMP(MFL),SNCOMP(MFL),IOWIDE,
     1NFLS
      COMMON NT,P(MM),C(MM,MC),NC(MM),JC(MM,MC),ITS(MS),
     1 FC(MM,MC),PZ(MM,MC),PO(MM,MPO),CO(MM,MPO),F(MM),PFO(MFL,MPO),
     2 FF(MM),FO(MM,MPO),CS(MS),PS(MFL),NS1(MS),NS2(MS),
     3 FSS(MS),N,NS,NPO,ICONV,E,IBUG,AI(MM,MC),AO(MM,MPO),TITSH(MS,5),
     4 NH,H(MFL),IFLOOR(MM),T(MTP,MFL),NFS1(MS),NFS2(MS),IT(MB),NTP
     5 ,NCO(MM),JOC(MM,MPO),TOUT,PGZ
      DOUBLE PRECISION P,PO,PS
      COMMON /LVAR/B1(MM,MC),B2(MM,MPO),II(MFL),TT(MFL),CW(MPO),
     1PH(MFL),NZZ(MM),SC(MS),SCO(MS)
      CHARACTER PAR*6,INFILE*12,IOFILE*12
      DIMENSION PAR(7)
      DATA  PAR/' MM',' MS',' MC','MPO','MTP','MFL',' MB'/
      IBUG=0
C
C       READ INPUT AND OUTPUT FILE NAMES
C
      WRITE(*,700)
750    WRITE(*,701)
      READ(*,702) INFILE
      IF (INFILE.EQ.' ') GO TO 750
      OPEN(5,FILE=INFILE)
751   WRITE(*,703)
      READ(*,702) IOFILE
      IF (IOFILE.EQ.' ') GO TO 751
      OPEN(6,FILE=IOFILE,STATUS='NEW')
      WRITE(*,704)
      READ(*,*) IOWIDE
      IF(IOWIDE.LE.100) IOWIDE=80
      IF(IOWIDE.GT.100) IOWIDE=132
C
C       READ AND WRITE PROJECT TITLE
C
      READ(5,600)(TITLE(I),I=1,18)
      WRITE(6,601)(TITLE(I),I=1,18)
C
```

```
C
C       READ GENERAL DATA
C
C
C       TOUT = OUTSIDE TEMPERATURE
C       IUNIT = 1 FOR SI UNITS
C             = 2 FOR ENG UNITS
C       IOUT = 0 FOR NO SUMMARY OUTPUT
C       OTHERWISE IOUT IS FILE NO. TO
C       WHICH SUMMARY OUTPUT IS WRITTEN
C
      READ(5,*)TOUT,IUNIT,IOUT
      WRITE(6,411)TOUT,IUNIT,IOUT
      IF(IUNIT .GT. 2 .OR. IUNIT .LT. 1)GO TO 105
C
C       READ HEIGHTS
C       NN=0 FOR INPUT OF ALL HEIGHTS
C       NN=1 FOR CALCULATION OF HEIGHTS
C
      READ(5,*)NH,NN
      WRITE(6,412)NH,NN
      IF(NH .LE. MFL)GO TO 89
      IPAR=6
      GO TO 110
89    IF(NN .EQ. 1)GO TO 97
      READ(5,*)(H(I),I=1,NH)
      WRITE(6,413)(H(I),I=1,NH)
      GO TO 99
97    READ(5,*)H(1),DH
      WRITE(6,414)H(1),DH
      DO 98 I=2,NH
      IM=I-1
98    H(I)=H(IM)+DH
C
C       READ TEMPERATURE PROFILES
C
99    READ(5,*)NTP
      WRITE(6,415)NTP
      IF(NTP .LE. MTP)GO TO 90
      IPAR=5
      GO TO 110
90    DO 3 IP=1,NTP
      READ(5,*)NNN,(II(J),TT(J),J=1,NNN)
      WRITE(6,416)NNN,(II(J),TT(J),J=1,NNN)
      IF(NNN .GT. 1)GO TO 2
      DO 1 IFF=1,NH
1     T(IP,IFF)=TT(1)
      GO TO 3
2     J=1
      JP1=2
      DO 4 IFF=1,NH
      T(IP,IFF)=TT(J)+(TT(JP1)-TT(J))*(IFF-II(J))/(II(JP1)-II(J))
      IF(IFF .NE. II(JP1))GO TO 4
      IF(JP1 .EQ. NNN)GO TO 4
      J=JP1
      JP1=J+1
4     CONTINUE
3     CONTINUE
C
C
C       READ OUTSIDE PRESSURE PROFILES
C       NN=0 FOR INPUT OF ALL PRESSURES
C       NN=1 FOR CALCULATION BY POWER LAW
C
```

```
      READ(5,*)NPO,NN
      WRITE(6,417)NPO,NN
      IF(NPO .LE. MPO)GO TO 91
      IPAR=4
      GO TO 110
91    IF(NN .EQ. 1)GO TO 81
C
C       READ ALL OUTSIDE PRESSURES
C
      DO 6 I=1,NPO
6     READ(5,*) PGZ,(PFO(J,I),J=1,NH)
      WRITE(6,418)PGZ,(PFO(J,I),J=1,NH)
      GO TO 85
C
C       CALCULATE OUTSIDE PRESSURES
C       PATMOS IS ATMOSPHERIC PRESSURE (PA)
C
81    READ(5,*)VW,HW,XW,(CW(I),I=1,NPO)
      WRITE(6,419)VW,HW,XW,(CW(I),I=1,NPO)
      IF(IUNIT .EQ. 1)VW=VW*0.2778
      IF(IUNIT .EQ. 2)VW=VW*0.4470
      PATMOS=101325.
      TOO=TOUT+273.
      IF(IUNIT .EQ. 2)TOO=(TOUT+460.)/1.8
      PVA=176.4*VW*VW/TOO
      Z=-0.03417/TOO
      IF(IUNIT .EQ. 2)Z=0.3048*Z
      CWM=CW(1)
      IF(NPO .EQ. 1)GO TO 212
      DO 211 I=1,NPO
      IF(CW(I) .LT. CWM)CWM=CW(I)
211   CONTINUE
212   PGZ=PATMOS*EXP(H(NH)*Z)+CWM*PVA*((H(NH)/HW)**(2.*XW))-100.
      DO 210 I=1,NH
      PH(I)=PATMOS*EXP(H(I)*Z)
210   CONTINUE
      DO 82 I=1,NPO
      DO 82 J=1,NH
      PFO(J,I)=PH(J)+CW(I)*PVA*((H(J)/HW)**(2.*XW))-PGZ
82    CONTINUE
C
C
C        BUILDING DATA INPUT
C       NFLS = NO. OF FLOORS IN BUILDING
C       IF1 = LOWER FLOOR IN SERIES OF SIMILAR FLOORS
C       IF2 = UPPER FLOOR IN SERIES OF SIMILAR FLOORS
C       NOC = NO. OF COMPARTMENTS PER FLOOR
C       NZ = NO. OF CONNECTIONS TO COMPARTMENTS ON SAME FLOOR
C       NA = NO. OF CONNECTIONS TO COMPARTMENTS ON FLOOR ABOVE
C
85    I=0
      SNCOMP(1)=0.
      READ(5,*)NFLS
      WRITE(6,420)NFLS
      IF(NFLS .GT. NH)GO TO 106
7     READ(5,*)IF1,IF2,NOC
      WRITE(6,400)IF1,IF2,NOC
      IF(IF1 .GT. IF2)GO TO 107
      NCOMP(IF1)=NOC
      IFP=IF1+1
      SNCOMP(IFP)=SNCOMP(IF1)+NOC
      DO 10 IZ=1,NOC
      I=I+1
      READ(5,*)NZ,NA,NNO,FF(I),IT(I)
      WRITE(6,401)NZ,NA,NNO,FF(I),IT(I)
```

```
      NZZ(I)=NZ
      NN=NZ+NA
      IFLOOR(I)=IF1
      IF(NN .LE. MC)GO TO 111
      IPAR=3
      GO TO 110
111   IF(NNO .LE. MPO)GO TO 112
      IPAR=4
      GO TO 110
112   IF(IT(I) .GT. NTP .OR. IT(I) .LT. 1)GO TO 102
      NC(I)=NN
      IF(NZ .EQ. 0)GO TO 63
C
C       INPUT CONNECTIONS TO COMPARTMENTS ON SAME FLOOR
C
      READ(5,*)(JC(I,J),C(I,J),AI(I,J),J=1,NZ)
      WRITE(6,402)
      WRITE(6,403)(JC(I,J),C(I,J),AI(I,J),J=1,NZ)
      DO 62 J=1,NZ
62    JC(I,J)=JC(I,J)+SNCOMP(IF1)
63    IF(NA .EQ. 0)GO TO 8
C
C       INPUT CONNECTIONS TO COMPARTMENTS ON FLOOR ABOVE
C
      NP=NZ+1
      READ(5,*)(JC(I,J),C(I,J),AI(I,J),J=NP,NN)
      WRITE(6,404)
      WRITE(6,403)(JC(I,J),C(I,J),AI(I,J),J=NP,NN)
      DO 66 J=NP,NN
66    JC(I,J)=JC(I,J)+NCOMP(IF1)+SNCOMP(IF1)
8     NCO(I)=NNO
      IF(NNO .EQ. 0)GO TO 10
C
C       INPUT CONNECTION TO OUTSIDE
C
      READ(5,*)(JOC(I,JJ),CO(I,JJ),AO(I,JJ),JJ=1,NNO)
      WRITE(6,405)
      WRITE(6,403)(JOC(I,JJ),CO(I,JJ),AO(I,JJ),JJ=1,NNO)
      DO 9 JJ=1,NNO
      J=JOC(I,JJ)
9     PO(I,JJ)=PFO(IF1,J)
10    CONTINUE
      IF(IF1 .NE. IF2)GO TO 11
      IF(IF1 .EQ. NFLS)GO TO 20
      GO TO 19
C
C       ASIGN DATA FOR FLOORS SIMILAR TO FLOOR IF1
C
11    IFP=IF1+1
      DO 17 IFF=IFP,IF2
      NCOMP(IFF)=NOC
      IFFP=IFF+1
      SNCOMP(IFFP)=SNCOMP(IFF)+NOC
      DO 16 IZ=1,NOC
      I=I+1
      I1=IZ+SNCOMP(IF1)
      IFLOOR(I)=IFF
      FF(I)=FF(I1)
      IT(I)=IT(I1)
      NN=NC(I1)
      NNO=NCO(I1)
      NC(I)=NN
      NCO(I)=NNO
      IF(IFF .NE. NFLS)GO TO 23
      NN=NZZ(I1)
```

```
      NC(I)=NN
23    IF(NN .EQ. 0)GO TO 14
      DO 12 J=1,NN
      C(I,J)=C(I1,J)
      AI(I,J)=AI(I1,J)
      JC(I,J)=JC(I1,J)+SNCOMP(IFF)-SNCOMP(IF1)
12    CONTINUE
14    IF(NNO .EQ. 0)GO TO 16
      DO 15 JJ=1,NNO
      JOC(I,JJ)=JOC(I1,JJ)
      J=JOC(I,JJ)
      CO(I,JJ)=CO(I1,JJ)
      AO(I,JJ)=AO(I1,JJ)
15    PO(I,JJ)=PFO(IFF,J)
16    CONTINUE
17    CONTINUE
      IF(IF2 .EQ. NFLS)GO TO 20
19    CONTINUE
      GO TO 7
20    N=I
      N2=N
      IF(N .LE. MB)GO TO 114
      IPAR=7
      GO TO 110
C
C       SHAFT DATA INPUT
C
114   READ(5,*)NS
      IF(NS .LE. MS)GO TO 113
      IPAR=2
      GO TO 110
113   DO 100 IS=1,NS
      READ(5,603)(TITSH(IS,I),I=1,5)
      WRITE(6,406)(TITSH(IS,I),I=1,5)
      READ(5,*)CS(IS),NFS1(IS),NFS2(IS),ITS(IS)
      WRITE(6,407)CS(IS),NFS1(IS),NFS2(IS),ITS(IS)
      N1=N2+1
      N2=N1+NFS2(IS)-NFS1(IS)
      NS1(IS)=N1
      NS2(IS)=N2
      IFF=NFS1(IS)-1
      READ(5,*)NNO,FFF,JCP,CC,AA
      WRITE(6,408)NNO,FFF,JCP,CC,AA
      IF(NNO .EQ. 0)GO TO 21
      READ(5,*)(JOC(N1,J),CO(N1,J),AO(N1,J),J=1,NNO)
      WRITE(6,403)(JOC(N1,J),CO(N1,J),AO(N1,J),J=1,NNO)
21    DO 24 I=N1,N2
      NC(I)=1
      NCO(I)=NNO
      IFF=IFF+1
      IFLOOR(I)=IFF
      IF(IFF .GT. NFLS)GO TO 25
      FF(I)=FFF
      IF(JCP .GT. NCOMP(IFF))GO TO 25
      JC(I,1)=JCP+SNCOMP(IFF)
      C(I,1)=CC
      AI(I,1)=AA
26    IF(NNO .EQ. 0)GO TO 24
      DO 22 J=1,NNO
      JJ=JOC(N1,J)
      PO(I,J)=PFO(IFF,JJ)
      JOC(I,J)=JJ
      CO(I,J)=CO(N1,J)
22    AO(I,J)=AO(N1,J)
      GO TO 24
```

```
25    NC(I)=0
      GO TO 26
24    CONTINUE
C
C        EXCEPTIONS TO GENERAL SHAFT INPUT
C        NNN = NO. OF EXCEPTIONS
C        KE = 1 FOR FF EXCEPTION
C        KE = 2 FOR OUTSIDE CONNECTION
C        KE = 3 FOR INTERNAL CONNECTION
C
      READ(5,*)NNN
      IF(NNN .EQ. 0)GO TO 100
      DO 69 IK=1,NNN
      READ(5,*)KE,IFF
      WRITE(6,409)KE,IFF
      I=NS1(IS)+IFF-NFS1(IS)
      IF(KE .EQ. 1)GO TO 41
      IF(KE .EQ. 2)GO TO 42
      IF(KE .EQ. 3)GO TO 51
      GO TO 104
41    READ(5,*)FF(I)
      WRITE(6,410)FF(I)
      GO TO 69
42    READ(5,*)J,CCO,AAO
      WRITE(6,405)
      WRITE(6,403)J,CCO,AAO
      NNC=NCO(I)
      IF(NNC .EQ. 0)GO TO 44
      DO 43 K=1,NNC
      IF(JOC(I,K) .EQ. J)GO TO 46
43    CONTINUE
44    NJO=NNC+1
      NCO(I)=NJO
47    PO(I,NJO)=PFO(IFF,J)
      JOC(I,NJO)=J
      CO(I,NJO)=CCO
      AO(I,NJO)=AAO
      GO TO 69
46    NJO =K
      KK=K+1
      IF(CCO .NE. 0)GO TO 47
      NJO=NNC-1
      NCO(I)=NJO
      IF(NJO .EQ. 0)GO TO 69
      DO 49 K=KK,NNC
      KM=K-1
      PO(I,KM)=PO(I,K)
      JOC(I,KM)=JOC(I,K)
      CO(I,KM)=CO(I,K)
49    AO(I,KM)=AO(I,K)
      GO TO 69
51    READ(5,*)JCP,CC,AA
      WRITE(6,402)
      WRITE(6,403)JCP,CC,AA
      J=JCP+SNCOMP(IFF)
      NN=NC(I)
      IF(NN .EQ. 0)GO TO 53
      DO 52 K=1,NN
      IF(JC(I,K) .EQ. J)GO TO 55
52    CONTINUE
      IF(CC .NE. 0.)GO TO 53
      WRITE(6,520)IS,KE,IFF
      GO TO 69
53    NJ=NN+1
      NC(I)=NJ
```

```
54    JC(I,NJ)=J
      C(I,NJ)=CC
      AI(I,NJ)=AA
      GO TO 69
55    NJ=K
      KK=K+1
      IF(AA .NE. 0.)GO TO 54
      NJ=NN-1
      NC(I)=NJ
      IF(NJ .EQ. 0)GO TO 69
      DO 61 K=KK,NN
      KM=K-1
      JC(I,KM)=JC(I,K)
      C(I,KM)=C(I,K)
61    AI(I,KM)=AI(I,K)
69    CONTINUE
100   CONTINUE
      NT=N2
      IF(NT .LE. MM)GO TO 160
      IPAR=1
      GO TO 110
C
C       PRINT OUTSIDE TEMPERATURE
C
160   WRITE(6,601)(TITLE(I),I=1,12)
      IF(IUNIT .EQ. 1)WRITE(6,800)TOUT
      IF(IUNIT .EQ. 2)WRITE(6,500)TOUT
      IF(IUNIT .EQ. 2)TOUT=(TOUT-32.)/1.8
      TOUT=TOUT+273.
C
C       PRINT HEIGHT AND TEMPERATURE PROFILES
C
      IF(IUNIT .EQ. 1)WRITE(6,811)(IP,IP=1,NTP)
      IF(IUNIT .EQ. 2)WRITE(6,511)(IP,IP=1,NTP)
      WRITE(6,813)
      DO 30 IFF=1,NH
30    WRITE(6,812)H(IFF),(T(IP,IFF),IP=1,NTP)
C
C       CONVERT TEMPERATURES TO DEG K
C
      DO 33 IFF=1,NH
      DO 33 IP=1,NTP
      IF(IUNIT .EQ. 2)T(IP,IFF)=(T(IP,IFF)-32.)/1.8
33    T(IP,IFF)=T(IP,IFF)+273.
C
C       PRINT OUTSIDE PRESSURE PROFILES
C
      IF(IUNIT .EQ. 1)GO TO 79
      WRITE(6,514)(IP,IP=1,NPO)
      WRITE(6,813)
      DO 76 IFF=1,NH
      DO 77 J=1,NPO
77    PFO(IFF,J)=PFO(IFF,J)/248.8
      WRITE(6,515)H(IFF),(PFO(IFF,J),J=1,NPO)
      DO 78 J=1,NPO
78    PFO(IFF,J)=PFO(IFF,J)*248.8
76    CONTINUE
      GO TO 83
79    WRITE(6,814)(IP,IP=1,NPO)
      WRITE(6,813)
      DO 31 IFF=1,NH
      WRITE(6,815)H(IFF),(PFO(IFF,J),J=1,NPO)
31    CONTINUE
C
C       CORRECT FOR CONNECTIONS ONLY INPUTED ONCE
C
```

```
83    DO 60 I=1,NT
      NN=NC(I)
      IF(NN .EQ. 0)GO TO 60
      DO 58 JJ=1,NN
      J=JC(I,JJ)
      IF(J .EQ. 0)GO TO 58
      NNJ=NC(J)
      IF(NNJ .EQ. 0)GO TO 57
      DO 56 IA=1,NNJ
      IF(JC(J,IA) .EQ. I)GO TO 58
56    CONTINUE
57    NNJ=NNJ+1
      IF(NNJ .LE. MC)GO TO 59
      IPAR=3
      GO TO 110
59    NC(J)=NNJ
      JC(J,NNJ)=I
      C(J,NNJ)=C(I,JJ)
      AI(J,NNJ)=AI(I,JJ)
      IF(J .GT. N .OR. I .GT. N)GO TO 58
      PZ(J,NNJ)=-PZ(I,JJ)
58    CONTINUE
60    CONTINUE
C
C       CORRECT UNITS
C
      IF(IUNIT .EQ. 2)CALL UNITS
C
C       INITIALIZE PZ FOR BUILD COMPARTMENTS
C
      DO 40 I=1,N
      NN=NC(I)
      IF(NN .EQ. 0)GO TO 40
      IA=IT(I)
      IFI=IFLOOR(I)
      DO 38 JJ=1,NN
      J=JC(I,JJ)
      IFJ=IFLOOR(J)
      IF(IFI .EQ. IFJ)GO TO 38
      IB=IT(J)
      TEMPA=0.5*(T(IA,IFI)+T(IB,IFJ))
      PZ(I,JJ)=3462.*(H(IFJ)-H(IFI))/TEMPA
38    CONTINUE
40    CONTINUE
C
C       INITIALIZE PZ FOR SHAFTS
C
      DO 50 IS=1,NS
      N1=NS1(IS)
      N2=NS2(IS)-1
      ITT=ITS(IS)
      DO 45 I=N1,N2
      IFI=IFLOOR(I)
      IFJ=IFI+1
      TEMPA=0.5*(T(ITT,IFI)+T(ITT,IFJ))
      PZ(I,1)=3462.*(H(IFJ)-H(IFI))/TEMPA
45    CONTINUE
50    CONTINUE
C
C       CHECK SHAFT CONNECTIONS
C
      DO 240 IS=1,NS
      N1=NS1(IS)
      N2=NS2(IS)
      DO 239 I=N1,N2
```

```
      NN=NC(I)
      IF(NN .EQ. 0)GO TO 239
      DO 236 J=1,NN
      JJ=JC(I,J)
      IF(IFLOOR(I) .NE. IFLOOR(JJ))GO TO 103
236   CONTINUE
239   CONTINUE
240   CONTINUE
      RETURN
C
C
C       DIAGNOSTIC OUTPUT
C
102   WRITE(6,902)I,IT(I)
      GO TO 109
103   WRITE(6,903)
      GO TO 109
104   WRITE(6,904)
      GO TO 109
105   WRITE(6,905)
      GO TO 109
106   WRITE(6,906)
      GO TO 109
107   WRITE(6,907)
      GO TO 109
110   WRITE(6,910)PAR(IPAR)
C
C       PRINT CORRECTED BUILDING DATA
C
109   WRITE(6,940)
      DO 70 I=1,N
      NN=NC(I)
      IF(NN .GT. 0)GO TO 180
      WRITE(6,941)I,IFLOOR(I),IT(I),FF(I)
      GO TO 182
180   WRITE(6,942)I,IFLOOR(I),IT(I),FF(I),JC(I,1),C(I,1),AI(I,1)
      IF(NN .EQ. 1)GO TO 182
      WRITE(6,943)(JC(I,J),C(I,J),AI(I,J),J=2,NN)
182   NNO=NCO(I)
      IF(NNO .EQ. 0)GO TO 70
      WRITE(6,944)(JOC(I;J),CO(I,J),AO(I,J),J=1,NNO)
70    CONTINUE
C
C       PRINT CORRECTED SHAFT INPUT DATA
C
      DO 80 IS=1,NS
      WRITE(6,816)(TITSH(IS,I),I=1,5)
      WRITE(6,806)IS,CS(IS),ITS(IS)
      N1=NS1(IS)
      N2=NS2(IS)
      WRITE(6,807)
      DO 75 I=N1,N2
      NN=NC(I)
      IF(NN .GT. 0)GO TO 72
      WRITE(6,801)IFLOOR(I),FF(I)
      GO TO 74
72    WRITE(6,808)IFLOOR(I),FF(I),JC(I,1),C(I,1),AI(I,1)
      IF(NN .EQ. 1)GO TO 74
      WRITE(6,809)(JC(I,J),C(I,J),AI(I,J),J=2,NN)
74    NNO=NCO(I)
      IF(NNO .EQ. 0)GO TO 75
      WRITE(6,810)(JOC(I,J),CO(I,J),AO(I,J),J=1,NNO)
75    CONTINUE
80    CONTINUE
      STOP
```

```
C
C       FORMAT STATEMENTS
C
400   FORMAT(5X,5HIF1 =,I3,7H, IF2 =,I3,7H, NOC =,I3)
401   FORMAT(5X,4HNZ =,I3,6H NA = ,I3,7H, NNO = ,I3,6H, FF =,F8.1,
     + 7H,  IT =,I3)
402   FORMAT(5X,25HCONNECTION ON SAME FLOOR    )
403   FORMAT(5X,3HJ =,I3,5H, C =,F10.3,5H, A =,F9.4)
404   FORMAT(5X,26HCONNECTION TO FLOOR ABOVE    )
405   FORMAT(5X,22HCONNECTION TO OUTSIDE     )
406   FORMAT(5X,5A4)
407   FORMAT(5X,4HCS =,F9.1,8H, NFS1 =,I3,8H, NFS2 =,I3,7H, ITS =,I3)
408   FORMAT(5X,5HNNO =,I3,7H, FFF =,F8.1,5H, J =,I3,5H, C =, F10.3,
     + 5H, A = ,F9.4)
409   FORMAT(5X,4HKE =,I3, 7H, IFF =,I3)
410   FORMAT(5X,4HFF =,F8.1)
411   FORMAT(5X,6HTOUT =,F6.0,9H, IUNIT =,I3,8H, IOUT =,I3)
412   FORMAT(5X,4HNH =,I3,6H, NN =,I3)
413   FORMAT(5X,7HHEIGHTS /(10F8.2))
414   FORMAT(5X,6HH(1) =,F8.2,6H, DH =,F8.2)
415   FORMAT(6X,5HNTP =,I3)
416   FORMAT(5X,20HTEMPERATURE PROFILE  /I5,(10(I4,F7.1)))
417   FORMAT(5X,5HNPO =,I3,6H, NN =,I3)
418   FORMAT(5X,5HPGZ =,F12.1/17HPRESSURE PROFILE  /(10F12.1))
419   FORMAT(5X,4HVW =,F6.1,6H, HW =,F6.1,6H, XW =,F4.2,6H, CW =,
     + (10F4.2))
420   FORMAT(/5X,6HNFLS =,I3)
500   FORMAT(//10X,20HOUTSIDE TEMPERATURE    ,F6.1,2H F)
511   FORMAT(    ///5X,6HHEIGHT,5X,29HTEMPERATURE PROFILES (DEG F)    /
     + 7X,2HFT,3X,19I6)
514   FORMAT(////5X,6HHEIGHT ,5X,26HOUTSIDE PRESSURE PROFILES
     1 11H (IN H2O)    /7X,2HFT,3X,8I10)
515   FORMAT(F11.2,3X,8F10.3)
520   FORMAT(///5X,15HERROR IN SHAFT   ,I2,15HEXCEPTION KE =   ,I2,
     + 2X,5HFLOOR ,I3//)
600   FORMAT(18A4)
601   FORMAT(1H1///10X,18A4///)
603   FORMAT(5A4)
700   FORMAT(
     1' ************************************************************'/
     2' ASCOS VERSION 1.12'/
     3' WRITTEN BY JOHN H. KLOTE'/
     4' ADAPTED FOR PERSONAL COMPUTERS BY WILLIAM D. WALTON'//
     5' CONTRIBUTION OF THE NATIONAL BUREAU OF STANDARDS (U.S.)'/
     6' NOT SUBJECT TO COPYRIGHT'//
     7' DOCUMENTATION: ASHRAE  "DESIGN OF SMOKE CONTROL SYSTEMS'/
     8'                FOR BULIDINGS" AND FILE IDSKA03.TXT'/
     9' ************************************************************'//)
701   FORMAT(/' ENTER INPUT FILE NAME')
702   FORMAT(A12)
703   FORMAT(/' ENTER OUTPUT FILE NAME OR USE'/' CON FOR SCREEN   ',
     1'PRN FOR PRINTER')
704   FORMAT(/' ENTER OUTPUT WIDTH (80 OR 132)')
800   FORMAT(//10X,20HOUTSIDE TEMPERATURE    ,F6.1,2H C)
801   FORMAT(I13,F11.1)
806   FORMAT(    10X,12HSHAFT NUMBER ,I4/10X,17HSHAFT COEFFICIENT ,F10.1/
     1 10X,20HTEMPERATURE PROFILE   ,I4)
807   FORMAT(/21X,5HFIXED,25X,4HFLOW,12X,4HFLOW/10X,5HFLOOR,6X,
     1 4HFLOW,5X,12HCONNECTED TO   ,6X,11HCOEFFICIENT ,6X,8H   AREA
     2  /)
808   FORMAT(I13,F11.1,6X,5HPOINT,I5,F16.1,F15.4)
809   FORMAT(30X,5HPOINT,I5,F16.1,F15.4)
810   FORMAT(30X,7HOUTSIDE ,I3,F16.1,F15.4)
811   FORMAT(    ///5X,6HHEIGHT,5X,29HTEMPERATURE PROFILES (DEG C)    /
     + 7X,2HM ,3X,19I6)
```

```
812   FORMAT(F11.2,3X,19F6.1)
813   FORMAT(/)
814   FORMAT(////5X,6HHEIGHT ,5X,26HOUTSIDE PRESSURE PROFILES
     1 11H (PASCALS)   /7X,2HM ,3X,8I10)
815   FORMAT(F11.2,3X,8F10.1)
816   FORMAT(///10X,5A4)
902   FORMAT(10(/),10X,11HCOMPARTMENT  ,I4/
     1 10X,20HTEMPERATURE PROFILE  ,I4,17H  DOES NOT EXIST  /
     + 10X,16HPROGRAM STOPPED  ,10(/))
903   FORMAT(10(/),5X,23HSHAFT CONNECTION ERROR     ,
     1 /10X,16HPROGRAM STOPPED  ,10(/))
904   FORMAT(10(/),10X,40HINPUT ERROR IN EXCEPTIONS TO SHAFT DATA
     1 /10X,16HPROGRAM STOPPED  ,10(/))
905   FORMAT(10(/),10X,37HINPUT ERROR IN UNIT TYPE DESIGNATION    /
     1  10X,16HPROGRAM STOPPED    ,10(/))
906   FORMAT(10(/),10X,37HINPUT ERROR NO. OF FLOORS EXCEEDS NH   /
     1 10X,16HPROGRAM STOPPED  ,10(/))
907    FORMAT(10(/),10X,25HINPUT ERROR IF1 .GT. IF2    /
     1 10X,16HPROGRAM STOPPED  ,10(/))
910   FORMAT(10(/),10X,36HINPUT EXCEEDS DIMENSION PARAMETER  ,A3/
     + 10X,16HPROGRAM STOPPED  ,10(/))
940   FORMAT(10X,15HBUILDING  DATA  //34X,11HTEMPERATURE  ,4X,5HFIXED,
     1 12X,2(11X,4HFLOW)/10X,11HCOMPARTMENT ,4X,5HFLOOR,6X,7HPROFILE,
     2 6X,4HFLOW,5X,13HCONNECTION TO ,4X,11HCOEFFICIENT ,4X,
     3 8H  AREA   )
941   FORMAT(/4X,3I12,F14.1)
942   FORMAT(/4X,3I12,F14.1,4X,5HPOINT,I7,F11.2,F15.4)
943   FORMAT(58X,5HPOINT,I7,F11.2,F15.4)
944   FORMAT(58X,9HOUTSIDE   ,I3,F11.2,F15.4)
      END
```

SUBROUTINE CORR

```
      SUBROUTINE CORR
C
C       THIS ROUTINE CALCULATES ADJUSTED FLOW COEFFICIENTS
C                       (C1,C2,CO1,CO2)
C
      PARAMETER  (MM=150,MS=12,MC=9,MPO=4,MTP=4,MFL=40,MB=40)
      COMMON /CORRR/C1(MM,MC),C2(MM,MC),CO1(MM,MPO),CO2(MM,MPO)
      COMMON NT,P(MM),C(MM,MC),NC(MM),JC(MM,MC),ITS(MS),
     1 FC(MM,MC),PZ(MM,MC),PO(MM,MPO),CO(MM,MPO),F(MM),PFO(MFL,MPO),
     2 FF(MM),FO(MM,MPO),CS(MS),PS(MFL),NS1(MS),NS2(MS),
     3 FSS(MS),N,NS,NPO,ICONV,E,IBUG,AI(MM,MC),AO(MM,MPO),TITSH(MS,5),
     4 NH,H(MFL),IFLOOR(MM),T(MTP,MFL),NFS1(MS),NFS2(MS),IT(MB),NTP
     5 ,NCO(MM),JOC(MM,MPO),TOUT,PGZ
      DOUBLE PRECISION P,PO,PS
C
C       CORRECT C
C
      DO 12 I=1,NT
      PATMOS=101325.
      BB=1000.*SQRT(2.*PATMOS/287.)/1.2
      NN=NC(I)
      IF(I .GT. N)GO TO 1
      IP=IT(I)
      GO TO 4
1     DO 2 IS=1,NS
      IF(I .LE. NS2(IS) .AND. I .GE. NS1(IS))GO TO 3
2     CONTINUE
      WRITE(6,700)
```

```
      STOP
3     IP=ITS(IS)
4     IFF=IFLOOR(I)
      T1=T(IP,IFF)
      IF(NN .EQ. 0)GO TO 10
      DO 9 J=1,NN
      JJ=JC(I,J)
      C1(I,J)=BB*C(I,J)*AI(I,J)/SQRT(T1)
      IF(JJ .GT. N)GO TO 5
      IP=IT(JJ)
      GO TO 8
5     DO 6 IS=1,NS
      IF(JJ .LE. NS2(IS) .AND. JJ .GE. NS1(IS))GO TO 7
6     CONTINUE
      WRITE(6,700)
      STOP
7     IP=ITS(IS)
8     IFF=IFLOOR(JJ)
      T2=T(IP,IFF)
      C2(I,J)=BB*C(I,J)*AI(I,J)/SQRT(T2)
9     CONTINUE
C
C       CORRECT CO
C
10    NNC=NCO(I)
      IF(NNC .EQ. 0)GO TO 12
      DO 11 J=1,NNC
      CO1(I,J)=BB*CO(I,J)*AO(I,J)/SQRT(T1)
      CO2(I,J)=BB*CO(I,J)*AO(I,J)/SQRT(TOUT)
11    CONTINUE
12    CONTINUE
      RETURN
700   FORMAT(///10X,36HPROGRAM STOPPED IN SUBROUTINE CORR    //)
      END
```

SUBROUTINE INIT

```
      SUBROUTINE INIT
C
C
C      THIS ROUTINE INITIALIZES THE PRESSURE ARRAY
C
      PARAMETER  (MM=150,MS=12,MC=9,MPO=4,MTP=4,MFL=40,MB=40)
      PARAMETER  (MBP=MB+1)
      COMMON /CORRR/C1(MM,MC),C2(MM,MC),CO1(MM,MPO),CO2(MM,MPO)
      COMMON NT,P(MM),C(MM,MC),NC(MM),JC(MM,MC),ITS(MS),
     1 FC(MM,MC),PZ(MM,MC),PO(MM,MPO),CO(MM,MPO),F(MM),PFO(MFL,MPO),
     2 FF(MM),FO(MM,MPO),CS(MS),PS(MFL),NS1(MS),NS2(MS),
     3 FSS(MS),N,NS,NPO,ICONV,E,IBUG,AI(MM,MC),AO(MM,MPO),TITSH(MS,5),
     4 NH,H(MFL),IFLOOR(MM),T(MTP,MFL),NFS1(MS),NFS2(MS),IT(MB),NTP
     5 ,NCO(MM),JOC(MM,MPO),TOUT,PGZ
      DOUBLE PRECISION P,PO,PS
      COMMON /LVAR/B1(MM,MC),B2(MM,MPO),II(MFL),TT(MFL),CW(MPO),
     1PH(MFL),NZZ(MM),SC(MS),SCO(MS)
      COMMON /MAT/A(MB,MBP),XX(MB),NNN
      DOUBLE PRECISION A,XX
      NNN=N
C
C       CALCULATE AVERAGE OUTSIDE PRESSURE
C
```

```
      SUM=0.
      DO 10 J=1,NPO
      DO 10 I=1,NH
10    SUM=SUM+PFO(I,J)
      PA=SUM/(NPO*NH)
C
C
C
C       THE DO LOOP TO STATEMENT 30 ESTIMATES
C         SHAFT PRESSURES
C
      DO 30 IS=1,NS
C
C       CALCULATE SHAFT PRESSURE DIFFERENCE , DP
C
      SUM=0.
      SUMN=0.
      N1=NS1(IS)
      N2=NS2(IS)
      DO 18 I=N1,N2
      SUM=SUM+FF(I)
      NN=NC(I)
      IF(NN .EQ. 0.)GO TO 16
      DO 15 J=1,NN
      SUMN=SUMN+C1(I,J)
15    CONTINUE
      SC(IS)=SUMN
16    NNO=NCO(I)
      IF(NNO .EQ. 0)GO TO 18
      DO 17 J=1,NNO
      SUMN=SUMN+CO1(I,J)
17    CONTINUE
      SCO(IS)=SUMN-SC(IS)
18    CONTINUE
      DP2=SUM/SUMN
      SIGN=1.
      IF(DP2 .LT. 0.)SIGN=-1.
      DP=SIGN*(SIGN*DP2)**2
C
C       CALCULATE AVERAGE TEMP OF SHAFT
C
      SUM=0.
      IP=ITS(IS)
      DO 20 I=N1,N2
      IFF=IFLOOR(I)
20    SUM=SUM+T(IP,IFF)
      TA=SUM/(N2-N1+1)
C
C       ESTIMATE PRESSURE AT BOTTOM OF SHAFT , PBOT
C
      HH=0.5*(H(NH)-H(1))+H(1)
      NF1=NFS1(IS)
      PBOT=PA+DP+3462.*(HH-H(NF1))/TA
C
C       ESTIMATE OTHER SHAFT PRESSURES
C
      P(N1)=PBOT
      NM=N2-1
      DO 24 I=N1,NM
      IP1=I+1
24    P(IP1)=P(I)-PZ(I,1)
30    CONTINUE
C
C       END OF SHAFT PRESSURE ESTIMATES
C
```

```
C       SET UP MATRIX FOR BUILDING COMPARTMENTS
C
      NP1=N+1
      DO 50 I=1,N
      NN=NC(I)
      SUMII=0.
      SUMNP=0.
      IF(NN .EQ. 0.)GO TO 42
      DO 40 JJ=1,NN
      J=JC(I,JJ)
      IF(J .GT. N)GO TO 34
      A(I,J)=C1(I,JJ)
      SUMII=SUMII-C1(I,JJ)
      SUMNP=SUMNP-C1(I,JJ)*PZ(I,JJ)
      GO TO 40
34    SUMII=SUMII-C1(I,JJ)
      SUMNP=SUMNP-C1(I,JJ)*P(J)
40    CONTINUE
42    NNO=NCO(I)
      IF(NNO .EQ. 0)GO TO 46
      DO 45 K=1,NNO
      SUMII=SUMII-CO1(I,K)
45    SUMNP=SUMNP-CO1(I,K)*PO(I,K)
46    A(I,I)=SUMII
      A(I,NP1)=SUMNP-FF(I)
50    CONTINUE
C
C       WRITE MATRIX
C
      IF(IBUG .EQ. 0)GO TO 84
      WRITE(6,802)
      DO 52 I=1,N
52    WRITE(6,803)(A(I,J),J=1,NP1)
C
C
C       CALL ROUTINE TO SOLVE FOR INITIAL BUILDING PRESSURES
C
84    CALL SIMEQ
C
C       OUTPUT INITIAL PRESSURES
C
      IF(IBUG .EQ. 0)GO TO 89
      WRITE(6,800)
      WRITE(6,801)(I,XX(I),I=1,N)
      NN=NS1(1)
      WRITE(6,801)(I,P(I),I=NN,NT)
C
C
C      ASSIGN BUILDING PRESSURES
C
89    DO 90 I=1,N
90    P(I)=XX(I)
      RETURN
800   FORMAT(///8(6X,1HI,4X,3HP  )/)
801   FORMAT(8(I7,F7.1))
802    FORMAT(///10X,20HMATRIX COEFFICIENTS   /)
803   FORMAT(10X,11F11.1)
      END
```

```
      SUBROUTINE BLDGP
C
C
C      THIS ROUTINE CALCULATES STEADY STATE PRESSURES
C          FOR BUILDING COMPARTMENTS
C
C
C
      PARAMETER  (MM=150,MS=12,MC=9,MPO=4,MTP=4,MFL=40,MB=40)
      COMMON NT,P(MM),C(MM,MC),NC(MM),JC(MM,MC),ITS(MS),
     1 FC(MM,MC),PZ(MM,MC),PO(MM,MPO),CO(MM,MPO),F(MM),PFO(MFL,MPO),
     2 FF(MM),FO(MM,MPO),CS(MS),PS(MFL),NS1(MS),NS2(MS),
     3 FSS(MS),N,NS,NPO,ICONV,E,IBUG,AI(MM,MC),AO(MM,MPO),TITSH(MS,5),
     4 NH,H(MFL),IFLOOR(MM),T(MTP,MFL),NFS1(MS),NFS2(MS),IT(MB),NTP
     5 ,NCO(MM),JOC(MM,MPO),TOUT,PGZ
      DOUBLE PRECISION P,PO,PS,PI
      IF(IBUG .GT. 0)WRITE(6,806)
      ITM=100
      ICONV=0
      DO 15 I=1,N
C
C     CALCULATE NET FLOW ,FI, INTO POINT I
      FI=PFLOW(I,P(I))
C
C     CHECK MAGNITUDE OF FI
      IF(ABS(FI) .LT. E)GO TO 15
      ICONV=ICONV+1
C
C     SET UP PARAMETERS FOR ITERATION
      DP=1.0
      IPHASE=1
      DPI=0.
      EE=0.2*ABS(FI)
      IF(EE .LT. E)EE=E
      SIGN=1
      IF(FI .LT. 0.)SIGN=-1
      IK=0
      IF(IBUG .GT. 0)WRITE(6,802)
C
C     ITERATION TO REDUICE MAGNITUDE OF FN
2     IK=IK+1
C
C     NEW ESTIMATE OF PRESSURE ,PI, AT POINT I
      PI=P(I)+SIGN*DP
C
C     CALCULATE NET FLOW ,FN, INTO POINT I USING PI
      FN=PFLOW(I,PI)
      IF(IBUG.GT.0)WRITE(6,804)I,IK,FI,FN,FP,DPI,DP,DPP,PI,IPHASE
C
C     CHECK MAGNITUDE OF FN
      IF(ABS(FN) .LT. EE)GO TO 10
C
C     CHECK NUMBER OF ITERATIONS
      IF(IK .GT. ITM)GO TO 25
C
C     CHECK PHASE
      IF(IPHASE .EQ. 2)GO TO 6
C
C     CHECK FOR TRANSITION FROM PHASE 1 TO PHASE 2
      IF(FI*FN .LT. 0.)GO TO 4
C
C     PHASE 1
      DPI=DP
      DP=5.0*DP
      FI=FN
```

```
      GO TO 2
C
C     PHASE 2
4     IPHASE=2
      GO TO 9
6     IF(FI*FN .GT. 0.)GO TO 8
C
C     NEW DP BETWEEN DPI AND DP
9     DPP=DP
      FP=FN
      DP=DPI+(DPP-DPI)*FI/(FI-FN)
      GO TO 2
C
C     NEW DP BETWEEN DP AND DPP
8     FI=FN
      DPI=DP
      DP=DPI+(DPP-DPI)*FN/(FN-FP)
      GO TO 2
10    P(I)=PI
15    CONTINUE
C
      RETURN
25    WRITE(6,800)
      STOP
C
C      FORMAT STATEMENTS
C
800   FORMAT(///10X,20(1H*)///10X,22HEXCESSIVE ITERATIONS   /
     + 10X,8HIN BLDGP ///10X,20(1H*)//////)
802   FORMAT(//11X,1HI,2X,2HIT,12X,2HFI,13X,2HFN,13X,2HFP,12X,3HDPI,
     +13X,2HDP,12X,3HDPP,13X,2HPI,3X,5HPHASE /)
804   FORMAT(8X,2I4,3E15.4,4F15.6,I5)
806   FORMAT(   ///10X,6HBLDGP  )
      END
```

SUBROUTINE SHAFTP

```
      SUBROUTINE SHAFTP
C
C
C      THIS ROUTINE CALCULATES STEADY STATE PRESSURES
C          FOR SHAFTS
C
C
      PARAMETER  (MM=150,MS=12,MC=9,MPO=4,MTP=4,MFL=40,MB=40)
      COMMON NT,P(MM),C(MM,MC),NC(MM),JC(MM,MC),ITS(MS),
     1 FC(MM,MC),PZ(MM,MC),PO(MM,MPO),CO(MM,MPO),F(MM),PFO(MFL,MPO),
     2 FF(MM),FO(MM,MPO),CS(MS),PS(MFL),NS1(MS),NS2(MS),
     3 FSS(MS),N,NS,NPO,ICONV,E,IBUG,AI(MM,MC),AO(MM,MPO),TITSH(MS,5),
     4 NH,H(MFL),IFLOOR(MM),T(MTP,MFL),NFS1(MS),NFS2(MS),IT(MB),NTP
     5 ,NCO(MM),JOC(MM,MPO),TOUT,PGZ
      DOUBLE PRECISION P,PO,PS,PI
      IF(IBUG .GT. 0)WRITE(6,806)
      ITM=100
      ICONV=0
      DO 15 I=1,NS
C
C     CALCULATE NET FLOW ,FI, INTO POINT I
      N1=NS1(I)
      FI=SFLOW(I,P(N1))
C
```

```
C     CHECK MAGNITUDE OF FI
      IF(ABS(FI) .LT. E)GO TO 15
      ICONV=ICONV+1
C
C     SET UP PARAMETERS FOR ITERATION
      DP=1.0
      IPHASE=1
      DPI=0.
      EE=0.2*ABS(FI)
      IF(EE .LT. E)EE=E
      SIGN=1
      IF(FI .LT. 0.)SIGN=-1
      IK=0
      IF(IBUG .GT. 0)WRITE(6,802)
C
C     ITERATION TO REDUICE MAGNITUDE OF FN
2     IK=IK+1
C
C     NEW ESTIMATE OF PRESSURE ,PI, AT BOTTOM OF SHAFT I
      PI=P(N1)+SIGN*DP
C
C      CALCULATE NET FLOW ,FN, INTO SHAFT I USING PI
      FN=SFLOW(I,PI)
      IF(IBUG.GT.0)WRITE(6,804)I,IK,FI,FN,FP,DPI,DP,DPP,PI,IPHASE
C
C     CHECK MAGNITUDE OF FN
      IF(ABS(FN) .LT. EE)GO TO 10
C
C     CHECK NUMBER OF ITERATIONS
      IF(IK .GT. ITM)GO TO 25
C
C     CHECK PHASE
      IF(IPHASE .EQ. 2)GO TO 6
C
C     CHECK FOR TRANSITION FROM PHASE 1 TO PHASE 2
      IF(FI*FN .LT. 0.)GO TO 4
C
C     PHASE 1
      DPI=DP
      DP=5.0*DP
      FI=FN
      GO TO 2
C
C     PHASE 2
4     IPHASE=2
      GO TO 9
6     IF(FI*FN .GT. 0.)GO TO 8
C
C     NEW DP BETWEEN DPI AND DP
9     DPP=DP
      FP=FN
      DP=DPI+(DPP-DPI)*FI/(FI-FN)
      GO TO 2
C
C     NEW DP BETWEEN DP AND DPP
8     FI=FN
      DPI=DP
      DP=DPI+(DPP-DPI)*FN/(FN-FP)
      GO TO 2
10    N2=NS2(I)
      DO 11 IF=N1,N2
      II=IF+1-N1
11    P(IF)=PS(II)
15    CONTINUE
C
```

```
      RETURN
25    WRITE(6,800)
      STOP
C
C      FORMAT STATEMENTS
C
800   FORMAT(///10X,20(1H*)///10X,22HEXCESSIVE ITERATIONS   /
     + 10X,9HIN SHAFTP  ///10X,20(1H*)//////)
802   FORMAT(//11X,1HI,2X,2HIT,12X,2HFI,13X,2HFN,13X,2HFP,12X,3HDPI,
     +13X,2HDP,12X,3HDPP,13X,2HPI,3X,5HPHASE /)
804   FORMAT(8X,2I4,3E15.4,4F15.6,I5)
806   FORMAT(   ///10X,6HSHAFTP)
      END
```

SUBROUTINE PZAD

```
      SUBROUTINE PZAD
C
C       THIS ROUTINE CORRECTS PZ TERMS FOR PRESSURE
C
      PARAMETER  (MM=150,MS=12,MC=9,MPO=4,MTP=4,MFL=40,MB=40)
      COMMON NT,P(MM),C(MM,MC),NC(MM),JC(MM,MC),ITS(MS),
     1 FC(MM,MC),PZ(MM,MC),PO(MM,MPO),CO(MM,MPO),F(MM),PFO(MFL,MPO),
     2 FF(MM),FO(MM,MPO),CS(MS),PS(MFL),NS1(MS),NS2(MS),
     3 FSS(MS),N,NS,NPO,ICONV,E,IBUG,AI(MM,MC),AO(MM,MPO),TITSH(MS,5),
     4 NH,H(MFL),IFLOOR(MM),T(MTP,MFL),NFS1(MS),NFS2(MS),IT(MB),NTP
     5 ,NCO(MM),JOC(MM,MPO),TOUT,PGZ
      DOUBLE PRECISION P,PO,PS
      IF(IBUG .GT. -2)GO TO 1
      WRITE(6,800)
      DO 2 I=1,N
      NN=NC(I)
      IF(NN .EQ. 0)GO TO 2
      WRITE(6,801)(I,J,PZ(I,J),J=1,NN)
2     CONTINUE
      NP1=N+1
      WRITE(6,802)(IL,PZ(IL,1),IL=NP1,NT)
1     DO 10 I=1,N
      NN=NC(I)
      IF(NN .EQ. 0)GO TO 10
      IA=IT(I)
      IFI=IFLOOR(I)
      DO 8 JJ=1,NN
      J=JC(I,JJ)
      IFJ=IFLOOR(J)
      IF(IFI .EQ. IFJ)GO TO 8
      IB=IT(J)
      TEMPA=0.5*(T(IA,IFI)+T(IB,IFJ))
      PAVE=0.5*(P(I)+P(J))+PGZ
      PZ(I,JJ)=(0.03416*PAVE/TEMPA)*(H(IFJ)-H(IFI))
8     CONTINUE
10    CONTINUE
      DO 20 IS=1,NS
      N1=NS1(IS)
      N2=NS2(IS)-1
      ITT=ITS(IS)
      DO 15 I=N1,N2
      IFI=IFLOOR(I)
      IFJ=IFI+1
      TEMPA=0.5*(T(ITT,IFI)+T(ITT,IFJ))
```

```
      J=I+1
      PA=0.5*(P(I)+P(J))+PGZ
15    PZ(I,1)=(0.03416*PA/TEMPA)*(H(IFJ)-H(IFI))
20    CONTINUE
      RETURN
800   FORMAT(/10X,10HINITIAL PZ /)
801   FORMAT(10X,3HPZ(,I2,1H,I2,4H) =  ,F12.4)
802   FORMAT(10X,3HPZ(,I2,6H,1) '  ,F12.4)
      END
```

SUBROUTINE OUT132

```
      SUBROUTINE OUT132
C
C
C       THIS ROUTINE OUTPUTS FLOWS AND DIFFERENTIAL PRESSURES
C       FOR ALL SHAFTS AND BUILDING COMPARTMENTS IN 132 COLUMNS
C
C
      PARAMETER  (MM=150,MS=12,MC=9,MPO=4,MTP=4,MFL=40,MB=40)
      COMMON /CORRR/C1(MM,MC),C2(MM,MC),CO1(MM,MPO),CO2(MM,MPO)
      COMMON /IO/TITLE(18),IOUT,IUNIT,NCOMP(MFL),SNCOMP(MFL),IOWIDE,
     1NFLS
      COMMON NT,P(MM),C(MM,MC),NC(MM),JC(MM,MC),ITS(MS),
     1 FC(MM,MC),PZ(MM,MC),PO(MM,MPO),CO(MM,MPO),F(MM),PFO(MFL,MPO),
     2 FF(MM),FO(MM,MPO),CS(MS),PS(MFL),NS1(MS),NS2(MS),
     3 FSS(MS),N,NS,NPO,ICONV,E,IBUG,AI(MM,MC),AO(MM,MPO),TITSH(MS,5),
     4 NH,H(MFL),IFLOOR(MM),T(MTP,MFL),NFS1(MS),NFS2(MS),IT(MB),NTP
     5 ,NCO(MM),JOC(MM,MPO),TOUT,PGZ
      DOUBLE PRECISION P,PO,PS
      INTEGER  COM
C
C       IUNIT = 1 FOR SI UNITS
C       IUNIT = 2 FOR ENG UNITS
C       WHEN IUNIT = 2 GO TO 100
      IF(IUNIT .EQ. 2)GO TO 100
C
C       BUILDING COMPARTMENT OUTPUT
C
      I=0
      IL=0
      WRITE(6,800)TITLE
      DO 30 IFF=1,NFLS
      NNN=NCOMP(IFF)
      IF(NNN .EQ. 0)GO TO 30
      DO 29 IC=1,NNN
      I=I+1
      NN=NC(I)
      NNO=NCO(I)
      IL=IL+NN+NNO+2
      IF(IL .LT. 51)GO TO 2
      WRITE(6,800)TITLE
      IL=NN+NNO+2
 2    IF(NN .GT. 0)GO TO 3
      WRITE(6,801)IFF,IC,P(I),IT(I),FF(I)
      GO TO 21
 3    DO 20 J=1,NN
      JJ=JC(I,J)
      DP=P(JJ)-P(I)+PZ(I,J)
      CC=C2(I,J)
      IF(DP .LT. 0.)CC=C1(I,J)
```

```
      IF(JJ .LE. N)GO TO 10
      DO 5 IS=1,NS
      IF(JJ .GE. NS1(IS) .AND. JJ .LE. NS2(IS))GO TO 6
5     CONTINUE
6     IF(J .GT. 1)GO TO 7
      WRITE(6,802)IFF,IC,P(I),IT(I),FF(I),(TITSH(IS,K),K=1,5)
     + ,DP,CC,AI(I,1),FC(I,1)
      GO TO 20
7     WRITE(6,803)(TITSH(IS,K),K=1,5),DP,CC,AI(I,J),FC(I,J)
      GO TO 20
10    IFJ=IFLOOR(JJ)
      COM=JJ-SNCOMP(IFJ)
      IF(J .GT. 1)GO TO 12
      WRITE(6,804)IFF,IC,P(I),IT(I),FF(I),IFJ,COM,DP,CC,AI(I,1),FC(I,1)
      GO TO 20
12    WRITE(6,805)IFJ,COM,DP,CC,AI(I,J),FC(I,J)
20    CONTINUE
21    IF(NNO .EQ. 0)GO TO 29
      DO 23 J=1,NNO
      JJ=JOC(I,J)
      DP=PO(I,J)-P(I)
      CC=CO2(I,J)
      IF(DP .LT. 0.)CC=CO1(I,J)
23    WRITE(6,806)JJ,DP,CC,AO(I,J),FO(I,J)
29    WRITE(6,807)F(I)
30    CONTINUE
      WRITE(6,900)
C
C       SHAFT OUTPUT
C
      DO 60 IS=1,NS
      N1=NS1(IS)
      N2=NS2(IS)
      WRITE(6,814)TITLE
      WRITE(6,808)(TITSH(IS,K),K=1,5),ITS(IS),CS(IS)
      DO 50 I=N1,N2
      NN=NC(I)
      IF(NN .GT. 0)GO TO 35
      WRITE(6,809)IFLOOR(I),P(I),FF(I)
      GO TO 41
35    DO 40 J=1,NN
      JJ=JC(I,J)
      DP=P(JJ)-P(I)
      CC=C2(I,J)
      IF(DP .LT. 0.)CC=C1(I,J)
      IFJ=IFLOOR(JJ)
      COM=JJ-SNCOMP(IFJ)
      IF(J .GT. 1)GO TO 36
      WRITE(6,810)IFLOOR(I),P(I),FF(I),IFJ,COM,DP,CC, AI(I,1),FC(I,1)
      GO TO 40
36    WRITE(6,811)IFJ,COM,DP,CC, AI(I,J),FC(I,J)
40    CONTINUE
41    NNO=NCO(I)
      IF(NNO .EQ. 0)GO TO 50
      DO 46 J=1,NNO
      JJ=JOC(I,J)
      DP=PO(I,J)-P(I)
      CC=CO2(I,J)
      IF(DP .LT. 0.)CC=CO1(I,J)
46    WRITE(6,812)JJ,DP,CC,AO(I,J),FO(I,J)
50    CONTINUE
      WRITE(6,813)FSS(IS)
      WRITE(6,900)
60    CONTINUE
      GO TO 165
```

```
C
C       BUILDING DATA OUTPUT  FOR IUNIT = 2
C
100   I=0
      IL=0
      WRITE(6,800)TITLE
      DO 130 IFF=1,NFLS
      NNN=NCOMP(IFF)
      IF(NNN .EQ. 0)GO TO 130
      DO 129 IC=1,NNN
      I=I+1
      FFI=F(I)/0.4719
      PIII=P(I)/248.8
      FFF=FF(I)/0.4719
      NN=NC(I)
      NNO=NCO(I)
      IL=IL+NN+NNO+2
      IF(IL .LT. 51)GO TO 102
      WRITE(6,800)TITLE
      IL=NN+NNO+2
102   IF(NN .GT. 0)GO TO 103
      WRITE(6,601)IFF,IC,PIII,IT(I),FFF
      GO TO 121
103   DO 120 J=1,NN
      FCCC=FC(I,J)/0.4719
      JJ=JC(I,J)
      DP=(P(JJ)-P(I)+PZ(I,J))/248.8
      AAI=AI(I,J)/0.0929
      CC=C2(I,J)
      IF(DP .LT. 0.)CC=C1(I,J)
      CC=CC*33.43
      IF(JJ .LE. N)GO TO 110
      DO 105 IS=1,NS
      IF(JJ .GE. NS1(IS) .AND. JJ .LE. NS2(IS))GO TO 106
105   CONTINUE
106   IF(J .GT. 1)GO TO 107
      WRITE(6,602)IFF,IC,PIII,IT(I),FFF  ,(TITSH(IS,K),K=1,5)
     + ,DP,CC,AAI,FCCC
      GO TO 120
107   WRITE(6,603)(TITSH(IS,K),K=1,5),DP,CC,AAI,FCCC
      GO TO 120
110   IFJ=IFLOOR(JJ)
      COM=JJ-SNCOMP(IFJ)
      IF(J .GT. 1)GO TO 112
      WRITE(6,604)IFF,IC,PIII,IT(I),FFF  ,IFJ,COM,DP,CC,AAI,FCCC
      GO TO 120
112   WRITE(6,605)IFJ,COM,DP,CC,AAI,FCCC
120   CONTINUE
121   IF(NNO .EQ. 0)GO TO 129
      DO 123 J=1,NNO
      FOO=FO(I,J)/0.4719
      JJ=JOC(I,J)
      DP=(PO(I,J)-P(I))/248.8
      AAO=AO(I,J)/0.0929
      CC=CO2(I,J)
      IF(DP .LT. 0.)CC=CO1(I,J)
      CC=CC*33.43
123   WRITE(6,606)JJ,DP,CC,AAO,FOO
129   WRITE(6,807)FFI
130   CONTINUE
      WRITE(6,901)
C
C       SHAFT OUTPUT FOR IUNIT = 2
C
      DO 160 IS=1,NS
```

```
      CSS=CS(IS)/0.02992
      FFI=FSS(IS)/0.4719
      N1=NS1(IS)
      N2=NS2(IS)
      WRITE(6,814)TITLE
      WRITE(6,808)(TITSH(IS,K),K=1,5),ITS(IS),CSS
      DO 150 I=N1,N2
      FFF=FF(I)/0.4719
      PIII=P(I)/248.8
      NN=NC(I)
      IF(NN .GT. 0)GO TO 135
      WRITE(6,609)IFLOOR(I),PIII,FFF
      GO TO 141
135   DO 140 J=1,NN
      FCCC=FC(I,J)/0.4719
      JJ=JC(I,J)
      DP=(P(JJ)-P(I))/248.8
      AAI=AI(I,J)/0.0929
      CC=C2(I,J)
      IF(DP .LT. 0.)CC=C1(I,J)
      CC=CC*33.43
      IFJ=IFLOOR(JJ)
      COM=JJ-SNCOMP(IFJ)
      IF(J .GT. 1)GO TO 136
      WRITE(6,610)IFLOOR(I),PIII,FFF   ,IFJ,COM,DP,CC, AAI,FCCC
      GO TO 140
136   WRITE(6,611)IFJ,COM,DP,CC, AAI,FCCC
140   CONTINUE
141   NNO=NCO(I)
      IF(NNO .EQ. 0)GO TO 150
      DO 146 J=1,NNO
      FOO=FO(I,J)/0.4719
      JJ=JOC(I,J)
      DP=(PO(I,J)-P(I))/248.8
      AAO=AO(I,J)/0.0929
      CC=CO2(I,J)
      IF(DP .LT. 0.)CC=CO1(I,J)
      CC=CC*33.43
146   WRITE(6,612)JJ,DP,CC,AAO,FOO
150   CONTINUE
      WRITE(6,813)FFI
      WRITE(6,901)
160   CONTINUE
C
C       SUMMARY OUTPUT
C       USER INSERTS WRITE STATEMENTS TO FILE IOUT
C
165   CONTINUE
      RETURN
C
C
C       FORMAT STATEMENTS
C
601    FORMAT(/4X,I3,I10,F13.3,I8,F12.0)
602    FORMAT(/4X,I3,I10,F13.3,I8,F12.0,3X,5A4,F14.3,F15.0,F10.3,F11.1)
603    FORMAT(53X,5A4,F14.3,F15.0,F10.3,F11.1)
604    FORMAT(/4X,I3,I10,F13.3,I8,F12.0,3X,5HFLOOR,I3,12H COMPARTMENT,I3,
     1 F11.3,F15.0,F10.3,F11.1)
605    FORMAT(53X,5HFLOOR,I3,12H COMPARTMENT, I3,F11.3,F15.0,F10.3,F11.1)
606    FORMAT(53X,17HOUTSIDE DIRECTION,I3,F14.3,F15.0,F10.3,F11.1)
609    FORMAT(4X,I3,F10.3,F11.0)
610    FORMAT(4X,I3,F10.3,F11.0,3X,5HFLOOR,I3,12H COMPARTMENT,I3,F11.3,
     1 F15.0,F10.3,F11.1)
611    FORMAT(31X,5HFLOOR,I3,12H COMPARTMENT,I3,F11.3,F15.0,F10.3,F11.1)
612    FORMAT(31X,17HOUTSIDE DIRECTION ,I3,F14.3,F15.0,F10.3,F11.1)
```

```
800   FORMAT(1H1,20X,18A4,/94X,8HADJUSTED/35X,4HTEMP,7X,5HFIXED,28X,
     1 12HDIFFERENTIAL,5X,4HFLOW,8X,4HFLOW/4X,5HFLOOR,2X,11HCOMPARTMENT
     2 ,2X,8HPRESSURE,2X,7HPROFILE,5X,4HFLOW,3X,16HCONNECTION    TO ,
     312X,8HPRESSURE,4X,11HCOEFFICIENT,2X,8H  AREA   ,5X,4HFLOW /)
801   FORMAT(/4X,I3,I10,F13.1,I8,F12.0)
802   FORMAT(/4X,I3,I10,F13.1,I8,F12.0,3X,5A4,F14.1,F15.1,F10.4,F11.1)
803   FORMAT(53X,5A4,F14.1,F15.1,F10.4,F11.1)
804   FORMAT(/4X,I3,I10,F13.1,I8,F12.0,3X,5HFLOOR,I3,12H COMPARTMENT,I3,
     1 F11.1,F15.1,F10.4,F11.1)
805   FORMAT(53X,5HFLOOR,I3,12H COMPARTMENT, I3,F11.1,F15.1,F10.4,F11.1)
806   FORMAT(53X,17HOUTSIDE DIRECTION,I3,F14.1,F15.1,F10.4,F11.1)
807   FORMAT(115X,F8.1,4H NET)
808   FORMAT(////20X,5A4//20X,20HTEMPERATURE PROFILE  ,I3/ 20X,
     1 23HSHAFT FLOW COEFFICIENT  ,F10.0//72X,8HADJUSTED/24X,5HFIXED,
     2 28X,12HDIFFERENTIAL,5X,4HFLOW,8X,4HFLOW/4X,5HFLOOR,2X,8HPRESSURE,
     3 5X,4HFLOW,3X,16HCONNECTION    TO,12X,8HPRESSURE,4X,11HCOEFFICIENT
     4,2X,8H  AREA   ,5X,4HFLOW /)
809   FORMAT(4X,I3,F10.1,F11.0)
810   FORMAT(4X,I3,F10.1,F11.0,3X,5HFLOOR,I3,12H COMPARTMENT,I3,F11.1,
     1 F15.1,F10.4,F11.1)
811   FORMAT(31X,5HFLOOR,I3,12H COMPARTMENT,I3,F11.1,F15.1,F10.4,F11.1)
812   FORMAT(31X,17HOUTSIDE DIRECTION ,I3,F14.1,F15.1,F10.4,F11.1)
813   FORMAT(93X,F8.1,4H NET)
814   FORMAT(1H1,20X,18A4)
900   FORMAT(//15X,'THE FOLLOWING UNITS ARE USED FOR OUTPUT'
     1//5X,'FLOW IN  LITERS PER SECOND AT 21 DEG C AND 1 ATM'
     2/5X,'PRESSURE IN  PASCALS'/5X,'AREA IN  METERS SQUARED')
901   FORMAT(///,5X,'THE FOLLOWING UNITS ARE USED FOR OUTPUT'
     1 //5X,'FLOW IN  CFM AT 70 DEG F AND 1 ATM'
     2 /5X,'PRESSURE IN  INCHS H2O'/5X,'AREA IN  FEET SQUARED')
      END
```

SUBROUTINE OUT80

```
      SUBROUTINE OUT80
C
C
C       THIS ROUTINE OUTPUTS FLOWS AND DIFFERENTIAL PRESSURES
C       FOR ALL SHAFTS AND BUILDING COMPARTMENTS IN 80 COLUMNS
C
C
      PARAMETER  (MM=150,MS=12,MC=9,MPO=4,MTP=4,MFL=40,MB=40)
      COMMON /CORRR/C1(MM,MC),C2(MM,MC),CO1(MM,MPO),CO2(MM,MPO)
      COMMON /IO/TITLE(18),IOUT,IUNIT,NCOMP(MFL),SNCOMP(MFL),IOWIDE,
     1NFLS
      COMMON NT,P(MM),C(MM,MC),NC(MM),JC(MM,MC),ITS(MS),
     1 FC(MM,MC),PZ(MM,MC),PO(MM,MPO),CO(MM,MPO),F(MM),PFO(MFL,MPO),
     2 FF(MM),FO(MM,MPO),CS(MS),PS(MFL),NS1(MS),NS2(MS),
     3 FSS(MS),N,NS,NPO,ICONV,E,IBUG,AI(MM,MC),AO(MM,MPO),TITSH(MS,5),
     4 NH,H(MFL),IFLOOR(MM),T(MTP,MFL),NFS1(MS),NFS2(MS),IT(MB),NTP
     5 ,NCO(MM),JOC(MM,MPO),TOUT,PGZ
      DOUBLE PRECISION P,PO,PS
      INTEGER  COM
C
C       IUNIT = 1 FOR SI UNITS
C       IUNIT = 2 FOR ENG UNITS
C       WHEN IUNIT = 2 GO TO 100
      IF(IUNIT .EQ. 2)GO TO 100
C
C       BUILDING COMPARTMENT OUTPUT
```

```
C
      I=0
      IL=0
      WRITE(6,800)TITLE
      DO 30 IFF=1,NFLS
      NNN=NCOMP(IFF)
      IF(NNN .EQ. 0)GO TO 30
      DO 29 IC=1,NNN
      I=I+1
      NN=NC(I)
      NNO=NCO(I)
      IL=IL+NN+NNO+2
      IF(IL .LT. 51)GO TO 2
      WRITE(6,800)TITLE
      IL=NN+NNO+2
2     IF(NN .GT. 0)GO TO 3
      WRITE(6,801)IFF,IC,P(I),FF(I)
      GO TO 21
3     DO 20 J=1,NN
      JJ=JC(I,J)
      DP=P(JJ)-P(I)+PZ(I,J)
      CC=C2(I,J)
      IF(DP .LT. 0.)CC=C1(I,J)
      IF(JJ .LE. N)GO TO 10
      DO 5 IS=1,NS
      IF(JJ .GE. NS1(IS) .AND. JJ .LE. NS2(IS))GO TO 6
5     CONTINUE
6     IF(J .GT. 1)GO TO 7
      WRITE(6,802)IFF,IC,P(I),FF(I),(TITSH(IS,K),K=1,5)
     + ,DP,AI(I,1),FC(I,1)
      GO TO 20
7     WRITE(6,803)(TITSH(IS,K),K=1,5),DP,AI(I,J),FC(I,J)
      GO TO 20
10    IFJ=IFLOOR(JJ)
      COM=JJ-SNCOMP(IFJ)
      IF(J .GT. 1)GO TO 12
      WRITE(6,804)IFF,IC,P(I),FF(I),IFJ,COM,DP,AI(I,1),FC(I,1)
      GO TO 20
12    WRITE(6,805)IFJ,COM,DP,AI(I,J),FC(I,J)
20    CONTINUE
21    IF(NNO .EQ. 0)GO TO 29
      DO 23 J=1,NNO
      JJ=JOC(I,J)
      DP=PO(I,J)-P(I)
      CC=CO2(I,J)
      IF(DP .LT. 0.)CC=CO1(I,J)
23    WRITE(6,806)JJ,DP,AO(I,J),FO(I,J)
29    WRITE(6,807)F(I)
30    CONTINUE
      WRITE(6,900)
C
C       SHAFT OUTPUT
C
      DO 60 IS=1,NS
      N1=NS1(IS)
      N2=NS2(IS)
      WRITE(6,814)TITLE
      WRITE(6,808)(TITSH(IS,K),K=1,5),ITS(IS),CS(IS)
      DO 50 I=N1,N2
      NN=NC(I)
      IF(NN .GT. 0)GO TO 35
      WRITE(6,809)IFLOOR(I),P(I),FF(I)
      GO TO 41
35    DO 40 J=1,NN
      JJ=JC(I,J)
```

```
      DP=P(JJ)-P(I)
      CC=C2(I,J)
      IF(DP .LT. 0.)CC=C1(I,J)
      IFJ=IFLOOR(JJ)
      COM=JJ-SNCOMP(IFJ)
      IF(J .GT. 1)GO TO 36
      WRITE(6,810)IFLOOR(I),P(I),FF(I),IFJ,COM,DP,AI(I,1),FC(I,1)
      GO TO 40
36    WRITE(6,811)IFJ,COM,DP,AI(I,J),FC(I,J)
40    CONTINUE
41    NNO=NCO(I)
      IF(NNO .EQ. 0)GO TO 50
      DO 46 J=1,NNO
      JJ=JOC(I,J)
      DP=PO(I,J)-P(I)
      CC=CO2(I,J)
      IF(DP .LT. 0.)CC=CO1(I,J)
46    WRITE(6,812)JJ,DP,AO(I,J),FO(I,J)
50    CONTINUE
      WRITE(6,813)FSS(IS)
      WRITE(6,900)
60    CONTINUE
      GO TO 165
C
C        BUILDING DATA OUTPUT  FOR IUNIT = 2
C
100   I=0
      IL=0
      WRITE(6,800)TITLE
      DO 130 IFF=1,NFLS
      NNN=NCOMP(IFF)
      IF(NNN .EQ. 0)GO TO 130
      DO 129 IC=1,NNN
      I=I+1
      FFI=F(I)/0.4719
      PIII=P(I)/248.8
      FFF=FF(I)/0.4719
      NN=NC(I)
      NNO=NCO(I)
      IL=IL+NN+NNO+2
      IF(IL .LT. 51)GO TO 102
      WRITE(6,800)TITLE
      IL=NN+NNO+2
102   IF(NN .GT. 0)GO TO 103
      WRITE(6,601)IFF,IC,PIII,FFF
      GO TO 121
103   DO 120 J=1,NN
      FCCC=FC(I,J)/0.4719
      JJ=JC(I,J)
      DP=(P(JJ)-P(I)+PZ(I,J))/248.8
      AAI=AI(I,J)/0.0929
      CC=C2(I,J)
      IF(DP .LT. 0.)CC=C1(I,J)
      CC=CC*33.43
      IF(JJ .LE. N)GO TO 110
      DO 105 IS=1,NS
      IF(JJ .GE. NS1(IS) .AND. JJ .LE. NS2(IS))GO TO 106
105   CONTINUE
106   IF(J .GT. 1)GO TO 107
      WRITE(6,602)IFF,IC,PIII,FFF   ,(TITSH(IS,K),K=1,5)
     + ,DP,AAI,FCCC
      GO TO 120
107   WRITE(6,603)(TITSH(IS,K),K=1,5),DP,AAI,FCCC
      GO TO 120
110   IFJ=IFLOOR(JJ)
```

```
      COM=JJ-SNCOMP(IFJ)
      IF(J .GT. 1)GO TO 112
      WRITE(6,604)IFF,IC,PIII,FFF   ,IFJ,COM,DP,AAI,FCCC
      GO TO 120
112   WRITE(6,605)IFJ,COM,DP,AAI,FCCC
120   CONTINUE
121   IF(NNO .EQ. 0)GO TO 129
      DO 123 J=1,NNO
      FOO=FO(I,J)/0.4719
      JJ=JOC(I,J)
      DP=(PO(I,J)-P(I))/248.8
      AAO=AO(I,J)/0.0929
      CC=CO2(I,J)
      IF(DP .LT. 0.)CC=CO1(I,J)
      CC=CC*33.43
123   WRITE(6,606)JJ,DP,AAO,FOO
129   WRITE(6,807)FFI
130   CONTINUE
      WRITE(6,901)
C
C       SHAFT OUTPUT FOR IUNIT = 2
C
      DO 160 IS=1,NS
      CSS=CS(IS)/0.02992
      FFI=FSS(IS)/0.4719
      N1=NS1(IS)
      N2=NS2(IS)
      WRITE(6,814)TITLE
      WRITE(6,808)(TITSH(IS,K),K=1,5),ITS(IS),CSS
      DO 150 I=N1,N2
      FFF=FF(I)/0.4719
      PIII=P(I)/248.8
      NN=NC(I)
      IF(NN .GT. 0)GO TO 135
      WRITE(6,609)IFLOOR(I),PIII,FFF
      GO TO 141
135   DO 140 J=1,NN
      FCCC=FC(I,J)/0.4719
      JJ=JC(I,J)
      DP=(P(JJ)-P(I))/248.8
      AAI=AI(I,J)/0.0929
      CC=C2(I,J)
      IF(DP .LT. 0.)CC=C1(I,J)
      CC=CC*33.43
      IFJ=IFLOOR(JJ)
      COM=JJ-SNCOMP(IFJ)
      IF(J .GT. 1)GO TO 136
      WRITE(6,610)IFLOOR(I),PIII,FFF   ,IFJ,COM,DP,AAI,FCCC
      GO TO 140
136   WRITE(6,611)IFJ,COM,DP,AAI,FCCC
140   CONTINUE
141   NNO=NCO(I)
      IF(NNO .EQ. 0)GO TO 150
      DO 146 J=1,NNO
      FOO=FO(I,J)/0.4719
      JJ=JOC(I,J)
      DP=(PO(I,J)-P(I))/248.8
      AAO=AO(I,J)/0.0929
      CC=CO2(I,J)
      IF(DP .LT. 0.)CC=CO1(I,J)
      CC=CC*33.43
146   WRITE(6,612)JJ,DP,AAO,FOO
150   CONTINUE
      WRITE(6,813)FFI
      WRITE(6,901)
160   CONTINUE
```

```
C
C       SUMMARY OUTPUT
C       USER INSERTS WRITE STATEMENTS TO FILE IOUT
C
165   CONTINUE
      RETURN
C
C
C       FORMAT STATEMENTS
C
601   FORMAT(/1X,I3,I8,F10.3,F8.0)
602   FORMAT(/1X,I3,I8,F10.3,F8.0,2X,5A4,F12.3,F7.3,F8.1)
603   FORMAT(32X,5A4,F12.3,F7.3,F8.1)
604   FORMAT(/1X,I3,I8,F10.3,F8.0,2X,5HFLOOR,I3,12H COMPARTMENT,I3,
     1 F9.3,F7.3,F8.1)
605   FORMAT(32X,5HFLOOR,I3,12H COMPARTMENT, I3,F9.3,F7.3,F8.1)
606   FORMAT(32X,17HOUTSIDE DIRECTION,I3,F12.3,F7.3,F8.1)
609   FORMAT(1X,I3,F9.3,F8.0)
610   FORMAT(1X,I3,F9.3,F8.0,2X,5HFLOOR,I3,12H COMPARTMENT,I3,F9.3,
     1 F7.3,F8.1)
611   FORMAT(23X,5HFLOOR,I3,12H COMPARTMENT,I3,F9.3,F7.3,F8.1)
612   FORMAT(23X,17HOUTSIDE DIRECTION ,I3,F12.3,F7.3,F8.1)
800   FORMAT(1H1,20X,18A4,//7X,'COMPART-',11X,'FIXED',28X,'DIFF',4X,
     1 'FLOW'/' FLOOR   MENT   PRESSURE   FLOW   CONNECTION     TO',9X,
     2 'PRESSURE   AREA    FLOW'/)
801   FORMAT(/1X,I3,I8,F10.1,F8.0)
802   FORMAT(/1X,I3,I8,F10.1,F8.0,1X,5A4,F12.1,F7.4,F8.1)
803   FORMAT(32X,5A4,F12.1,F7.4,F8.1)
804   FORMAT(/1X,I3,I8,F10.1,F8.0,2X,5HFLOOR,I3,12H COMPARTMENT,I3,
     1 F9.1,F7.4,F8.1)
805   FORMAT(32X,5HFLOOR,I3,12H COMPARTMENT, I3,F9.1,F7.4,F8.1)
806   FORMAT(32X,17HOUTSIDE DIRECTION,I3,F12.1,F7.4,F8.1)
807   FORMAT(72X,'NET',F4.1)
808   FORMAT(////20X,5A4//20X,20HTEMPERATURE PROFILE  ,I3/ 20X,
     1 23HSHAFT FLOW COEFFICIENT  ,F10.0//17X,'FIXED',28X,'DIFF',4X,
     2 'FLOW'/' FLOOR PRESSURE   FLOW CONNECTION     TO',9X,
     3 'PRESSURE  AREA   FLOW'/)
809   FORMAT(1X,I3,F9.1,F8.0)
810   FORMAT(1X,I3,F9.1,F8.0,2X,5HFLOOR,I3,12H COMPARTMENT,I3,F9.1,
     1 F7.4,F8.1)
811   FORMAT(23X,5HFLOOR,I3,12H COMPARTMENT,I3,F9.1,F7.4,F8.1)
812   FORMAT(23X,17HOUTSIDE DIRECTION ,I3,F12.1,F7.4,F8.1)
813   FORMAT(62X,F8.1,4H NET)
814   FORMAT(1H1,20X,18A4)
900   FORMAT(//5X,'THE FOLLOWING UNITS ARE USED FOR OUTPUT'
     1//5X,'FLOW IN  LITERS PER SECOND AT 21 DEG C AND 1 ATM'
     2/5X,'PRESSURE IN  PASCALS'/5X,'AREA IN  METERS SQUARED')
901   FORMAT(///,5X,'THE FOLLOWING UNITS ARE USED FOR OUTPUT'
     1 //5X,'FLOW IN  CFM AT 70 DEG F AND 1 ATM'
     2 /5X,'PRESSURE IN  INCHS H2O'/5X,'AREA IN  FEET SQUARED')
      END
```

SUBROUTINE SIMEQ

```
      SUBROUTINE SIMEQ
C
C        CHOLESKY'S METHOD OF SOLUTION OF
C       SIMULTANEOUS LINEAR ALGEBRIC EQUATIONS
C
      PARAMETER  (MM=150,MS=12,MC=9,MPO=4,MTP=4,MFL=40,MB=40)
      PARAMETER  (MBP=MB+1)
```

```
      DOUBLE PRECISION A,X
      COMMON /MAT/ A(MB,MBP),X(MB),N
      NP1=N+1
      ZERO=1.0E-35
      K=0
C
C
C       SEE IF A(1,1) IS ZERO
C     IF SO ADD ANOTHER ROW TO ROW 1
      IF(ABS(A(1,1)) .GT. ZERO)GO TO 40
      DO 31 I=1,N
      IF(A(I,1) .NE. 0.)GO TO 32
   31 CONTINUE
   12 WRITE(6,804)K
      STOP
   32 DO 33 J=1,NP1
   33 A(1,J)=A(1,J)+A(I,J)
C
C     CALCULATE UPPER AND LOWER
C     TRIANGULAR MATRICES OVER ORIG
C     MATRIX A
   40 AA=A(1,1)
      DO 2 J=2,NP1
    2 A(1,J)=A(1,J)/AA
      DO 10 I=2,N
      K=0
C
C     STORE A(I,1) ... A(I,I) IN X ARRAY
C     IN CASE NEW A(I,I) IS ZERO
C     ROW I CAN BE RECALCULATED
    4 DO 5 J=1,I
    5 X(J)=A(I,J)
      K=K+1
      DO 10 J=2,NP1
      IF(J .GT. I)GO TO 8
      JM1=J-1
      AA=0.
      DO 3 IR=1,JM1
    3 AA=AA+A(I,IR)*A(IR,J)
      A(I,J)=A(I,J)-AA
C
C     CHECK IF A(I,I) IS ZERO
C     IF SO MULTIPLY OLD ROW I BY 2.
C
      IF(I .NE. J)GO TO 10
      IF(ABS(A(I,I)) .GT. ZERO)GO TO 10
      DO 6 JJ=1,I
    6 A(I,JJ)=X(JJ)
      DO 7 JJ=1,NP1
    7 A(I,J)=2.*A(I,J)
      IF(K .GT. 3)GO TO 12
      GO TO 4
    8 IM1=I-1
      AA=0.
      DO 9 IR=1,IM1
    9 AA=AA+A(I,IR)*A(IR,J)
      A(I,J)=(A(I,J)-AA)/A(I,I)
   10 CONTINUE
C     END OF CALCULATION OF TRIANGULAR MATRICES
C
C
C     BACKWARD SUBSTITUTION
C
      X(N)=A(N,NP1)
      DO 20 II=2,N
      AA=0.
```

```
      I=NP1-II
      IP1=I+1
      DO 15 J=IP1,N
   15 AA=AA+A(I,J)*X(J)
   20 X(I)=A(I,NP1)-AA
C
  804 FORMAT(//////10X,16HPROGRAM FAILURE   ,I3/////)
      END
```

SUBROUTINE UNITS

```
      SUBROUTINE UNITS
C
C       THIS ROUTINE CONVERTS VARIABLES H,FF,AI,AO,CS TO SI UNITS
C
C
      PARAMETER  (MM=150,MS=12,MC=9,MPO=4,MTP=4,MFL=40,MB=40)
      COMMON NT,P(MM),C(MM,MC),NC(MM),JC(MM,MC),ITS(MS),
     1 FC(MM,MC),PZ(MM,MC),PO(MM,MPO),CO(MM,MPO),F(MM),PFO(MFL,MPO),
     2 FF(MM),FO(MM,MPO),CS(MS),PS(MFL),NS1(MS),NS2(MS),
     3 FSS(MS),N,NS,NPO,ICONV,E,IBUG,AI(MM,MC),AO(MM,MPO),TITSH(MS,5),
     4 NH,H(MFL),IFLOOR(MM),T(MTP,MFL),NFS1(MS),NFS2(MS),IT(MB),NTP
     5 ,NCO(MM),JOC(MM,MPO),TOUT,PGZ
      DOUBLE PRECISION P,PO,PS
      DIMENSION B(5)
      DATA B/0.3048,248.8,0.4719,0.02992,0.0929/
      DO 10 I=1,NH
10    H(I)=H(I)*B(1)
      DO 20 I=1,NT
      FF(I)=FF(I)*B(3)
      NNC=NC(I)
      DO 16 J=1,NNC
      AI(I,J)=AI(I,J)*B(5)
16    CONTINUE
      DO 18 J=1,NPO
      AO(I,J)=AO(I,J)*B(5)
18    CONTINUE
20    CONTINUE
      DO 22 IS=1,NS
22    CS(IS)=CS(IS)*B(4)
      RETURN
      END
```

SUBROUTINE ZERO

```
      SUBROUTINE ZERO
C
C     THIS ROUTINE ZEROS THE ARRAYS
C
      PARAMETER  (MM=150,MS=12,MC=9,MPO=4,MTP=4,MFL=40,MB=40)
      PARAMETER  (MBP=MB+1)
      COMMON /CORRR/C1(MM,MC),C2(MM,MC),CO1(MM,MPO),CO2(MM,MPO)
      COMMON NT,P(MM),C(MM,MC),NC(MM),JC(MM,MC),ITS(MS),
     1 FC(MM,MC),PZ(MM,MC),PO(MM,MPO),CO(MM,MPO),F(MM),PFO(MFL,MPO),
     2 FF(MM),FO(MM,MPO),CS(MS),PS(MFL),NS1(MS),NS2(MS),
```

```
     3 FSS(MS),N,NS,NPO,ICONV,E,IBUG,AI(MM,MC),AO(MM,MPO),TITSH(MS,5),
     4 NH,H(MFL),IFLOOR(MM),T(MTP,MFL),NFS1(MS),NFS2(MS),IT(MB),NTP
     5 ,NCO(MM),JOC(MM,MPO),TOUT,PGZ
      DOUBLE PRECISION P,PO,PS
      COMMON /MAT/A(MB,MBP),XX(MB),NNN
      DOUBLE PRECISION A,XX
      COMMON /LVAR/B1(MM,MC),B2(MM,MPO),II(MFL),TT(MFL),CW(MPO),
     1PH(MFL),NZZ(MM),SC(MS),SCO(MS)
      COMMON /IO/TITLE(18),IOUT,IUNIT,NCOMP(MFL),SNCOMP(MFL),IOWIDE,
     1NFLS
C
      DO 10 I=1,MM
      P(I)=0.
      NC(I)=0
      F(I)=0.
      FF(I)=0.
      IFLOOR(I)=0
      NCO(I)=0
      NZZ(I)=0
      DO 20 J=1,MC
      C1(I,J)=0.
      C2(I,J)=0.
      C(I,J)=0.
      JC(I,J)=0
      FC(I,J)=0.
      PZ(I,J)=0.
      AI(I,J)=0.
      B1(I,J)=0.
20    CONTINUE
      DO 30 J=1,MPO
      CO1(I,J)=0.
      CO2(I,J)=0.
      PO(I,J)=0.
      CO(I,J)=0.
      FO(I,J)=0.
      AO(I,J)=0.
      JOC(I,J)=0
      B2(I,J)=0.
30    CONTINUE
10    CONTINUE
C
      DO 40 I=1,MS
      ITS(I)=0
      CS(I)=0.
      NS1(I)=0
      NS2(I)=0
      FSS(I)=0.
      NFS1(I)=0
      NFS2(I)=0
      SC(I)=0.
      SCO(I)=0.
40    CONTINUE
C
      DO 50 I=1,MFL
      PS(I)=0.
      H(I)=0.
      II(I)=0
      TT(I)=0.
      PH(I)=0.
      NCOMP(I)=0
      SNCOMP(I)=0.
      DO 60 K=1,MTP
      T(K,I)=0.
60    CONTINUE
      DO 70 J=1,MPO
      PFO(I,J)=0.
```

```
70    CONTINUE
50    CONTINUE
C
      DO 80 I=1,MB
      IT(I)=0
      XX(I)=0.
      DO 90 J=1,MBP
      A(I,J)=0.
90    CONTINUE
80    CONTINUE
      DO 100 I=1,MPO
      CW(I)=0.
100   CONTINUE
C
      RETURN
      END
```

FUNCTION FLOW

```
      FUNCTION FLOW(PI,PJ,PZ,C)
      DOUBLE PRECISION PI,PJ
C
C     THIS FUNCTION CALCULATES FLOWS BETWEEN TWO POINTS
C
      IF(C .LT. 0.001)GO TO 10
      DP=PJ-PI+PZ
      SIGN=1.0
      IF(DP .LT. .0)SIGN=-1.
      FLOW=SIGN*C*SQRT(SIGN*DP)
      RETURN
10    FLOW=0.0
      RETURN
      END
```

FUNCTION PFLOW

```
      FUNCTION PFLOW(I,PI)
C
C
C     THIS FUNCTION CALCULATES NET FLOWS INTO POINT I
C
      PARAMETER  (MM=150,MS=12,MC=9,MPO=4,MTP=4,MFL=40,MB=40)
      COMMON /CORRR/C1(MM,MC),C2(MM,MC),CO1(MM,MPO),CO2(MM,MPO)
      COMMON NT,P(MM),C(MM,MC),NC(MM),JC(MM,MC),ITS(MS),
     1 FC(MM,MC),PZ(MM,MC),PO(MM,MPO),CO(MM,MPO),F(MM),PFO(MFL,MPO),
     2 FF(MM),FO(MM,MPO),CS(MS),PS(MFL),NS1(MS),NS2(MS),
     3 FSS(MS),N,NS,NPO,ICONV,E,IBUG,AI(MM,MC),AO(MM,MPO),TITSH(MS,5),
     4 NH,H(MFL),IFLOOR(MM),T(MTP,MFL),NFS1(MS),NFS2(MS),IT(MB),NTP
     5 ,NCO(MM),JOC(MM,MPO),TOUT,PGZ
      DOUBLE PRECISION P,PO,PS,PI
      NN=NC(I)
      SUM=0.
      IF(NN .EQ. 0)GO TO 3
      DO 1 JJ=1,NN
      J=JC(I,JJ)
      CC=C1(I,JJ)
      IF(PI .LT. P(J))CC=C2(I,JJ)
```

```
      PZZ=PZ(I,JJ)
      IF(I .GT. N)PZZ=0.
      FC(I,JJ)=FLOW(PI,P(J),PZZ,CC)
1     SUM=SUM+FC(I,JJ)
3     NNO=NCO(I)
      IF(NNO .EQ. 0)GO TO 4
      DO 2 K=1,NNO
      CC=CO1(I,K)
      IF(PI .LT. PO(I,K))CC=CO2(I,K)
      FO(I,K)=FLOW(PI,PO(I,K),0.,CC)
2     SUM=SUM+FO(I,K)
4     PFLOW=SUM+FF(I)
      IF(I .LE. N)F(I)=SUM+FF(I)
      RETURN
      END
```

FUNCTION SFLOW

```
      FUNCTION SFLOW(IS,PI)
C
C
C     THIS ROUTINE CALCULATES NET FLOW INTO A SHAFT AND
C        SHAFT PRESSURE PROFILE
C
C
      PARAMETER  (MM=150,MS=12,MC=9,MPO=4,MTP=4,MFL=40,MB=40)
      COMMON NT,P(MM),C(MM,MC),NC(MM),JC(MM,MC),ITS(MS),
     1 FC(MM,MC),PZ(MM,MC),PO(MM,MPO),CO(MM,MPO),F(MM),PFO(MFL,MPO),
     2 FF(MM),FO(MM,MPO),CS(MS),PS(MFL),NS1(MS),NS2(MS),
     3 FSS(MS),N,NS,NPO,ICONV,E,IBUG,AI(MM,MC),AO(MM,MPO),TITSH(MS,5),
     4 NH,H(MFL),IFLOOR(MM),T(MTP,MFL),NFS1(MS),NFS2(MS),IT(MB),NTP
     5 ,NCO(MM),JOC(MM,MPO),TOUT,PGZ
      DOUBLE PRECISION P,PO,PS,PI
      IF(IBUG .GT.1)WRITE(6,800)IS
      SUM=0.
      N1=NS1(IS)
      N2=NS2(IS)
      PS(1)=PI
      FUP=0.
      CSS=CS(IS)
      DO 10 I=N1,N2
      II=I+1-N1
      FLO=PFLOW(I,PS(II))
      FUP=FLO+FUP
      SUM=SUM+FLO
      IF(I .EQ. N2)GO TO 5
      IIP1=II+1
      SIGN=1
      IF(FUP .GT. 0.)SIGN=-1.
      PS(IIP1)=PS(II)-PZ(I,1)+SIGN*FUP*FUP/(CSS*CSS)
5     IF(IBUG .GT. 1)WRITE(6,801)I,II,PS(II),FLO,FUP,SUM
10    CONTINUE
      FSS(IS)=SUM
      SFLOW=SUM
      RETURN
C
C      FORMAT STATEMENTS
C
800   FORMAT(///5X,17HFLOW - SHAFT NO  ,I5/)
801   FORMAT(5X,3HI =,I3,5X,4HII =,I3,5X,4HPS =,
     + E15.7,5X,5HFLO =,E10.4,5X,5HFUP =,E10.4,5X,5HSUM =,E10.4/)
      END
```

Appendix G INSPECTION PROCEDURES FOR SMOKE CONTROL SYSTEMS

1. Scope. The inspection procedures described in this appendix apply to smoke control systems which are dedicated only to controlling smoke in building fires or which make use of air moving equipment with another function such as heating and air conditioning. These procedures are of a general nature intended as a guide for the development of specific procedures for individual smoke control systems. These procedures address the major components of smoke control systems, but by their general nature can not address all possible components. In this appendix, the phrase 'as specified' is used to mean as specified in accordance with a contract documents, a code or some other standard or standards which has been agreed upon by the owner, designer, builder, code official, and other involved parties.

2. Barriers

a. Check walls, partitions, floors and ceilings of barriers of smoke control systems for obvious and unusual openings that could adversely affect smoke control performance.

b. Check that gaps around doors do not exceed the limits specified. If gasketing is required, check that it is as specified.

c. Check that automatic door closers in barriers of smoke control systems are as specified.

3. Air Moving Equipment

a. Check ducts to verify that materials of duct material and construction are as specified.

b. Check duct installation. Duct installation including the hangers must not reduce the fire resistance rating of structural members and of assemblies. Frequently, structural members and assemblies have fire protective coverings, such as drywall construction or a sprayed-on layer. Check that ducts are installed in such a manner that these protective coverings are not damaged. Check that clearance from ducts to combustible construction is as specified. In addition, check that where ducts pass through walls, floors, or partitions the openings in construction around the ducts are as specified.

c. Check that installation and materials of duct connectors and flexible duct connectors are as specified. <u>CAUTION: Because the characteristics of duct connectors and flexible duct connectors are different, one should not be substituted for the other.</u>

d. Check duct coverings and linings to verify that their fire safety requirements are as specified. Check that duct coverings do not conceal any service opening.

e. Check direct access and inspection provisions. Service openings and telescoping or removable duct sections are used for direct access and inspection. Check that a service opening or a telescoping or removable duct section is provided in ducts as specified adjacent to fire dampers, smoke dampers and smoke detectors. Check that these access openings are identified with letters as specified. Check that service openings are provided in horizontal ducts and plenums where specified.

f. Check air filters to verify that they have the classification specified.

g. Check that the location, fire protection rating and installation of fire, ceiling and smoke dampers are as specified. Generally, fire, ceiling and smoke dampers should be installed in accordance with the conditions of their listing and the manufacturer's installation instructions which are supplied with the damper. Further check installation by removing fusible link (where applicable) and operate damper to verify that it fully closes. It is desirable to operate dampers with normal air flow to assure that they are not held open by the air stream. Remember to reinstall all fusible links that have been removed during inspection.

4 Controls

a. Check manual controls. Check that devices for manual activation and deactivation of the smoke control system is of materials and installation as specified (a detailed check of the functioning of manual control is included in appendix H).

b. Check automatic controls. Check that devices for automatic activation and deactivation and control of the smoke control system is of materials and installation as specified (a detailed check of the functioning of automatic control is included in appendix H).

Table G.1 Inspection check list - barriers of pressurized stairwells

Date___________

Inspection agent_____________

NO.	DESCRIPTION	YES	NO	REMARKS
General:				
1	All materials in plenums appropriate			
2	Air filters appropriate			
3	Fan inlets protected by screens			
4	Heating equipment installation appropriate			
5	Cooling equipment installation appropriate			
6	Manual controls installed			
7	Automatic controls installed			
Ductwork:				
1	Duct material appropriate			
2	Duct installation appropriate			
3	Duct connectors appropriate			
4	Duct coverings appropriate			
5	Duct linings appropriate			
Duct access and inspection provisions:				
1	Access at all required locations			
2	Access properly identified			
Dampers:				
1	Fire dampers located where required			
2	Fire dampers of appropriate rating			
3	Fire dampers installed appropriately			
4	Ceiling dampers located where required			
5	Ceiling dampers of appropriate rating			
6	Ceiling dampers installed appropriately			
7	Smoke dampers located where required			
8	Smoke dampers of appropriate rating			
9	Smoke dampers installed appropriately			
10	Combination fire and smoke dampers located where required			
11	Combination fire and smoke dampers of appropriate rating			
12	Combination fire and smoke dampers installed appropriately			

COMMENTS:____

____

____

Table G.2 Inspection check list - barriers of elevator smoke control systems

Date____________

Inspection agent____________

NO.	DESCRIPTION	YES	NO	REMARKS
General:				
1	All materials in plenums appropriate			
2	Air filters appropriate			
3	Fan inlets protected by screens			
4	Heating equipment installation appropriate			
5	Cooling equipment installation appropriate			
6	Manual controls installed			
7	Automatic controls installed			
Ductwork:				
1	Duct material appropriate			
2	Duct installation appropriate			
3	Duct connectors appropriate			
4	Duct coverings appropriate			
5	Duct linings appropriate			
Duct access and inspection provisions:				
1	Access at all required locations			
2	Access properly identified			
Dampers:				
1	Fire dampers located where required			
2	Fire dampers of appropriate rating			
3	Fire dampers installed appropriately			
4	Ceiling dampers located where required			
5	Ceiling dampers of appropriate rating			
6	Ceiling dampers installed appropriately			
7	Smoke dampers located where required			
8	Smoke dampers of appropriate rating			
9	Smoke dampers installed appropriately			
10	Combination fire and smoke dampers located where required			
11	Combination fire and smoke dampers of appropriate rating			
12	Combination fire and smoke dampers installed appropriately			

COMMENTS:____

Table G.3 Inspection check list - barriers of zoned smoke control systems

Date___________

Inspection agent_____________

NO.	DESCRIPTION	YES	NO	REMARKS
General:				
1	All materials in plenums appropriate			
2	Air filters appropriate			
3	Fan inlets protected by screens			
4	Heating equipment installation appropriate			
5	Cooling equipment installation appropriate			
6	Manual controls installed			
7	Automatic controls installed			
Ductwork:				
1	Duct material appropriate			
2	Duct installation appropriate			
3	Duct connectors appropriate			
4	Duct coverings appropriate			
5	Duct linings appropriate			
Duct access and inspection provisions:				
1	Access at all required locations			
2	Access properly identified			
Dampers:				
1	Fire dampers located where required			
2	Fire dampers of appropriate rating			
3	Fire dampers installed appropriately			
4	Ceiling dampers located where required			
5	Ceiling dampers of appropriate rating			
6	Ceiling dampers installed appropriately			
7	Smoke dampers located where required			
8	Smoke dampers of appropriate rating			
9	Smoke dampers installed appropriately			
10	Combination fire and smoke dampers located where required			
11	Combination fire and smoke dampers of appropriate rating			
12	Combination fire and smoke dampers installed appropriately			

COMMENTS:____

Table G.4 Inspection check list - fire safety controls in HVAC systems

Date___________
Inspection agent____________

NO.	DESCRIPTION	YES	NO	REMARKS
Manual shutdown:				
1	Appropriate fans stopped			
2	Appropriate smoke dampers fully and tightly closed			
Automatic shutdown by return detector:				
1	Appropriate fans stopped			
2	Appropriate smoke dampers fully and tightly closed			
Automatic shutdown by supply detector:				
1	Appropriate fans stopped			
2	Appropriate smoke dampers fully and tightly closed			
Automatic shutdown by detector system:				
1	Appropriate fans stopped			
2	Appropriate smoke dampers fully and tightly closed			

COMMENTS:____

Appendix H TEST PROCEDURES FOR ZONED SMOKE CONTROL SYSTEMS

1. Scope. The test procedures described in this appendix apply to zoned smoke control systems that are either dedicated systems or part of systems for heating, ventilating, and air conditioning (HVAC).

2. Emergency power:

If standby power or other emergency power has been provided for the operation of the zoned smoke control system, acceptance testing shall be conducted with emergency power and normal power.

3. Smoke control diagram:

Identify the exact location of each smoke control zone. If it is not part of the building plans, make a smoke control zone diagram of the building. This diagram should include the locations of all zone boundaries and of all doors in those boundaries.

4. Normal operation test:

With all building HVAC systems in normal operation, the zoned smoke control system shut off, and the smoke barrier doors closed; measure and record the pressure differences across each smoke barrier door. Evaluate these pressure differences to determine that they are appropriate for the balanced HVAC system. Generally, this would be about 0.01 inches of water gage, but pressure differences as large as 0.03 inches water gage are not a cause for concern. However, higher pressure differences may occur for special systems such as those intended to control airborne pollutants. Additionally, greater pressure differences can be caused by stack effect (as explained in the ASHRAE Smoke Control Manual).

5. Smoke mode test:

Each smoke zone is to be individually tested by performing the following sequence.

a. Activate smoke control system operation in the zone. This should be accomplished by putting one of the detectors into alarm that are intended to activate the smoke control system in that zone.

b. Check that the operation of fans is as required by the contract documents.

c. Check that the position of smoke dampers is as required by the contract documents. Also, check that any smoke dampers required to be closed are fully and tightly closed.

d. Check to verify that all doors required by the contract documents to be closed during smoke control system operation are fully closed and that they operate freely allowing use during evacuation without becoming jammed in their door frames. This should include doors in the boundary of the smoke zone being tested.

e. Measure and record pressure differences across the all closed doors in the boundary of the smoke zone being tested. Pressure differences resulting from air flowing to the smoke zone being tested are to be recorded as positive values, and pressure differences resulting from air flowing from the smoke zone being tested are to be recorded as negative values.

f. Check that the measured pressure difference is within the acceptable range as defined in the contract documents. If the pressure difference is not in the acceptable range, double check that the states of fans, dampers and doors is as required. If any of these were not as required, they should be fixed and the zone retested. After this, if the pressure difference is not acceptable, the flow rates of air to and from the smoke zones in question should be measured and adjusted as appropriate. If the pressure differences are too low after these actions, excessive air leakage paths in the construction should be filled, caulked or sealed as appropriate. (Often it is very difficult to locate leakage paths in buildings. Chemical smoke from smoke bombs can be used to find these leakage paths. The high pressure sides of smoke barriers are exposed to heavy concentrations of chemical smoke, while the low pressure side of the barrier is examined for smoke leakage that indicates the location of a leakage path. Exterior walls, interior partitions, floors and ceilings including areas above suspended ceilings must not be overlooked when hunting for excessive leakage areas.) Then the zone should be retested.

g. Test for smoke feedback into supply air. Place six smoke bombs (3 minute duration size) in a metal container, simultaneously ignite all bombs, and locate container near exhaust inlet in smoke zone being tested so that all of the chemical smoke produced by the bombs is drawn directly into the exhaust air stream. Check that air supplied to other zones of the building has no trace of chemical smoke. If chemical smoke is detected in this supply air, its path should be determined, the path should be blocked, and then the smoke feedback test should be conducted again. (The two most likely causes of smoke feedback are a leaky or party opened return air damper and an outside air inlet located in the vicinity of the exhaust air outlet.)

h. Make sure that this zone has been returned to its normal setting before continuing to test other zones.

Table H.1 Test work sheet - zoned smoke control system

Date___________
Test agent_____________

NORMAL OPERATION TEST

Doors in barriers of smoke control zone	Pressure Difference (inches water gage)	Flow Direction: From Zone	To Zone

Table H.1 Continued

Smoke Control Zone No.__________
Date____________
Test agent______________

SMOKE MODE TEST

NO.	YES	NO	REMARKS
1. Fans operating appropriately			
2. Smoke dampers in required position			
3. Pass feedback test			

Doors in Boundary of Smoke Control Zone	Pressure Difference (inches of water gage)

COMMENTS:____

Appendix I TEST PROCEDURES FOR STAIRWELL PRESSURIZATION SYSTEMS

1. Scope. The test procedures described in this appendix apply to systems for stairwell pressurization.

2. Emergency power:

If standby power or other emergency power has been provided for the operation of the stairwell pressurization control system, acceptance testing shall be conducted with emergency power and normal power.

3. Normal operation test:

With all building HVAC systems in normal operation, any zoned smoke control systems shut off, and the stairwell doors closed; measure and record the pressure differences across each stairwell door. The sign convention for all pressure difference readings in the stairwell tests is: a pressure difference resulting from a flow from the stairwell is positive, and a pressure difference resulting from a flow to the stairwell is negative.

Evaluate these pressure differences to determine that they are appropriate for the balanced HVAC system. Generally, this would be about 0.01 inches of water gage, but pressure differences as large as 0.03 inches water gage are not a cause for concern. However, higher pressure differences may occur for special systems such as those intended to control airborne pollutants. Additionally, greater pressure differences can be caused by stack effect (as explained in the ASHRAE Smoke Control Manual).

4. Stairwell pressurization test:

Activate the stairwell pressurization systems by a putting a detector in alarm as required by the contract documents. Test each pressurized stairwell by conducting the following steps.

a. With all stairwell doors closed (except for the exterior ground floor door if it is required to be opened upon system activation), measure and record pressure differences across each closed stairwell door.

b. Open the exterior ground floor stairwell door (except if the exterior ground floor door is required to be opened upon system activation), and measure and record pressure differences across each closed stairwell door. For stairwells without a ground floor exterior door, another highly severe open door condition must be tested. This can be an exterior door not at the ground floor or a large flow path to the outside created by opening the stairwell door and other doors including an exterior building door.

c. Open an additional stairwell door, and measure and record pressure differences across each closed stairwell door. Repeat this step opening another door each time until the required number of doors is opened. The required number of doors is that number that must be opened during testing as stipulated in the applicable codes or contract documents.

d. With the required number of doors opened, check flow direction through open doorways using a 6 ft strip of tissue paper secured at the top of the door frame.

e. Check that the measured pressure difference is within the acceptable range as defined in the contract documents. If the pressure difference is not in the acceptable range, double check that the states of fans, dampers and doors is as required. If any of these were not as required, they should be fixed and the zone retested. After this, if the pressure difference is not acceptable, the flow rate of air to the stairwell in question should be measured and adjusted as appropriate. If the pressure differences are too low after these actions, excessive air leakage paths in the construction should be filled, caulked or sealed as appropriate. (Often it is very difficult to locate leakage paths in buildings. Chemical smoke from smoke bombs can be used to find these leakage paths. The stairwell is filled with chemical smoke and pressurized, while the low pressure side of the stairwell barriers are examined for smoke leakage that indicates the location of a leakage path.) Then the zone should be retested.

Table I.1 Test work sheet - pressurized stairwell system

Doors Open__________________

Date____________

Test agent______________

Stairwell No.________________

PRESSURE DIFFERENCE MEASUREMENTS

Doors in Pressurized Stairwell	Pressure Difference (inches water gage)

Table I.1 Continued

Date__________

Test agent____________

Stairwell No.__________

FLOW DIRECTION INDICATION

Doors Open in Pressurized Stairwell	Flow Direction: From Stair	To Stair

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11. ABSTRACT (A 200-WORD OR LESS FACTUAL SUMMARY OF MOST SIGNIFICANT INFORMATION. IF DOCUMENT INCLUDES A SIGNIFICANT BIBLIOGRAPHY OR LITERATURE SURVEY, MENTION IT HERE.)

This manual consolidates and systematically presents data and calculational procedures for use by smoke control system designers, and design criteria is discussed. Fundamental issues of smoke control include reliability, activation, smoke obscuration, toxicity, and the driving forces of smoke movement. The mechanisms of compartmentation, dilution, air flow, pressurization, and buoyancy are used by themselves or in combination to manage smoke conditions in fire situations. A computer program for analysis of smoke control systems is presented. Systems for stairwell pressurization, elevator smoke control, and zoned smoke control are presented. Numerous example calculations are included.

12. KEY WORDS (6 TO 12 ENTRIES; ALPHABETICAL ORDER; CAPITALIZE ONLY PROPER NAMES; AND SEPARATE KEY WORDS BY SEMICOLONS)

air flow; bibliographies; computer programs; fire protection; fire safety; smoke control; smoke movement; stairwells

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