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A Review of Measurements, Calculations and Specifications of Air Leakage Through Interior Door Assemblies

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ABSTRACT

A review was made of measurements and calculations of air leakage through door assemblies in order to evaluate their effectiveness as barriers to smoke flow. It was noted that typical "fire doors" are not capable of meeting proposed limitations of air leakage at ambient temperatures. It was also noted that significant air leakage may occur through interior walls which contain fire doors. It was concluded that first priority should be given to developing and validating a standardized test method for the accurate and consistent measurement of air leakage through door assemblies.

Key Words: Air leakage, building, door, fire door, fire test, infiltration, smoke control, smoke movement.

1. INTRODUCTION

For fire safety purposes, smoke is defined as the airborne solid and liquid particulates and gases evolved when a material undergoes pyrolysis or combustion. It is obvious that an open door will readily permit smoke to pass from its source in a building fire to other areas in the building. It is also generally accepted that a closed door will limit the passage of smoke, and, in controlled occupancies such as hospitals, schools, and certain office and apartment buildings, doors are required to be self-closing or to close automatically upon operation of an installed smoke detector device. However, the effectiveness of a door as a barrier to smoke is not well established, and it is the intent of this report to provide a review of the current status of our knowledge of air (and smoke) flow measurements through door assemblies in terms of occupant protection in the event of fire.

From the standpoint of fire, there are several different types of doors, each of which serves a specified purpose in current building codes[1]. A fire door is mandated as part of the building fire containment system primarily for property protection purposes. When installed in a fire separation wall of three or four hour rating, a fire door having a three hour rating is generally required. There is no expressed requirement for the prevention of smoke passage by a door in a fire separation wall. An exit stair door is expected to provide ready access to the stairshaft for fleeing occupants while maintaining its integrity and preventing passage of flames or heat for an extended period of exposure to a fire located in the corridor. In the usual case, where the stair enclosure walls are required to have a two hour fire resistance rating, the exit stair door assembly is required to have a 1-1/2 hour fire resistance rating. However, there is no mention of the ability of the door assembly to prevent the passage of smoke. A horizontal exit door is expected to provide a barrier to horizontal fire spread while permitting building occupants to pass through the horizontal exit to (a) seek refuge on the unexposed side of the exit, or (b) continue on to an exit leading directly to the outside. The exit door is also required to have a 1-1/2 hour fire resistance rating and also to serve as a "smoke barrier". However, there is no prescribed test method or meaningful performance criteria on which to assess the door's effectiveness as a smoke barrier. A corridor/room separation door is expected to have a dual function: (a) to keep a fire located in the corridor from entering a room (patient room, school room, apartment, etc.), and (b) to keep a

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1 In common practice, fire doors are classified by a letter designation according to the opening for which the door is suitable and an hourly rating designation [1]; the type description according to use is considered more appropriate here.

fire located in a room or apartment from entering the corridor. While it is not anticipated that these doors will resist a fire for long durations, codes currently anticipate that such doors will serve as both fire and smoke barriers for a period of 20 minutes [2] although 3/4 hour fire ratings were commonly required in the past. A smoke barrier door is one which is expressly intended to prevent smoke passage for occupant protection purposes. Such doors are required by code in building corridors where heavy fire exposure is not anticipated and may be specified as having a fire resistance rating of up to 20 minutes. However, as before, there is no prescribed test method to measure effectiveness as a smoke barrier.

It is clear that the roles played by doors in the event of fire are different. Certain doors are only intended to withstand severe fire exposure; others are intended only as barriers to relatively cool smoke; and some doors are intended to serve as both fire and smoke barriers. In addition, sophisticated building smoke control systems are now being used (primarily in tall buildings) that utilize zones of pressurized air to prevent smoke entry; in these cases, the air leakage characteristics of door assemblies (and other building elements) are important design features. It follows that standardized procedures are needed for measuring the leakage of air and of smoke laden air over the range of temperatures and pressures likely to be experienced in buildings.

2. GENERAL PRINCIPLES

The flow of air throughout a building depends upon existing or induced pressure differences. Typically, pressure differences arise as a result of (a) forced ventilation from mechanical (HVAC) systems, (b) differences between internal and external temperature (stack effects) and (c) wind effects. In a building fire of limited extent, it may be assumed that smoke particulates and combustion gases will be carried along with the air, provided their concentrations and densities do not result in an air and smoke mixture whose properties differ considerably from normal air. In addition to these three sources of pressure difference, there is also a pressure effect due to the expansion of hot gases in the vicinity of the fire. In a large building, this effect will be fairly localized.

The flow of air through a corridor, through an open doorway, or through small cracks in walls or small gaps around closed doors follows the same general relationship. Thus, the flow of air at constant temperature through an opening (or passageway) is expressed in terms of the area of the opening and the static pressure differential across the opening as follows:

$$Q = KA(\Delta p)^n \qquad [1]$$

where Q = volume flow rate of air

K = a flow factor incorporating the discharge coefficient (C_d) of the leakage openings, and the relationship between the units used

A = area of the opening or passage

Δp = pressure difference

n = exponent which can vary between 0.5 and 1.0

When Q is expressed in m^3/s, A in m^2, and Δp in Pa, K = 0.827

In considering flow through cracks around closed door assemblies, it has been common to assume that n = 0.5 and C_d = 0.6 to 0.7, which are typical values for flow through thin-walled, square-edged (or sharp-edged) orifice plates or other small openings. Then, A represents the "equivalent area of opening".

The exponent n should not automatically be assumed equal to 0.5. At fairly high Reynolds numbers, corresponding to sizable characteristic dimensions and velocities where the flow is turbulent and the flow resistance is due mainly to inertia forces, n approaches 0.5. However, in laminar flow, where the resistance is mainly due to viscous forces and the Reynolds number is low, n approaches 1. Table 1 lists examples of assumed or derived values of n.

In practice, the exponent and flow factor may be determined by measuring flow rate over the anticipated range of pressure differences, either in a laboratory or in an actual installation. It has been suggested that in-place wall leakage is significantly higher in actual houses than in wall sections measured in the laboratory [3].

Discharge coefficients for thick walled orifices have been tabulated as a function of the geometry of the orifice and the Reynolds number [4]. These are plotted in Fig. 1, using the Bernoulli relation ($n = 0.5$) for convenience. This shows the critical importance of both the Reynolds number and the geometry of the leakage path. For closed doors designed to be effective smoke barriers, the geometry of the leakage path will more closely approximate a thick-walled than a thin-walled orifice, and the Reynolds number will be quite low (less than 1000). Since the flow coefficient varies so greatly, particularly at the anticipated low values of Reynolds number, it becomes critically important to make direct and accurate measurements of the leakage around closed doors over the necessary pressure range.

Several additional factors should be considered in air leakage measurements. Although the fundamental relationship still applies, the flow of air through openings at elevated temperatures is more complicated due to effects of buoyancy, mixing, and heat exchange between hot air (gases) and cool surfaces. Except where wind and pressurization are dominant, the typical flow through a door opening in a compartment is bidirectional, with heated air flowing out at high levels and cool air flowing in at low levels. Furthermore, to prevent the convective flow of smoke-laden air resulting from an increase in temperature, one effective technique involves the use of pressurized air in shafts and corridors, and this introduces flow in the reverse direction.

The basic theory of volumetric air exchange due to natural convection through an opening in a vertical partition was clearly presented by Brown and Solvason [5]. The resultant equation for the convective flow through each half of an opening of width W and height H is given by:

$$Q = \frac{C_d W H^{3/2}}{3} \left[g \frac{\Delta\rho}{\bar{\rho}} \right]^{1/2} \qquad [2]$$

where g = gravitational constant

$\bar{\rho}$ = (avg) fluid density

$\Delta\rho$ = difference in fluid densities

This was extended by Shaw to take into account the combined effect of natural convection and forced air flow; subsequently Shaw and Whyte calculated the forced air supply required to counter the effects of small temperature differences (0 to 12 K) so as to prevent the exchange of contaminated air through open or partially open doors in hospitals [6]. The following equation represents the leakage flow of air through an opening against the forced air supply of velocity V_x:

$$Q = \frac{CW}{3} \frac{\bar{\rho}}{g\Delta\rho} \left[g \frac{\Delta\rho}{\bar{\rho}} H - V_x^2 \right]^{3/2} \qquad [3]$$

It may also be used to determine the value of V_x which will reduce Q to zero.

For the specific application involving a closed door, measurements are needed of the minimum flows of cool air and the corresponding pressure differences, to prevent any air from flowing from the heated area through the door assembly. There are no known measurements of this kind.

3. TEST METHODS

Standard test methods for measuring air leakage through exterior building elements have been used for at least 15 years. The current ASTM method for determining the air infiltration resistance of exterior windows, doors and walls [7] was originally published in 1965. The ASTM E 283 test method consists of sealing the test specimen into or against one face of an air chamber and supplying air to (or exhausting air from) the chamber at the rate required to maintain the specified test pressure difference across the specimen. Since this test is used for exterior building elements, air leakage measurements are commonly made at a pressure difference of 75 Pa (1.57 lbf/ft^2) corresponding to a wind velocity of 11.1 m/s (25 mph), although other pressure difference levels are possible.

A similar test method was adopted in 1968 as a British Standard [8] in which the pressure is applied in 50 Pa steps up to a maximum of 1000 Pa. In the test method adopted in 1975 as a European Standard [9] and in the version being balloted as an ISO standard by ISO Committee TC 162 on Windows [10], the pressure is also applied in stages (50, 100, 150, 200, 300, 400, 500, 600 Pa) up to the maximum pressure required for the test.

From the standpoint of pressure differences likely to exist under fire conditions, including winter stack effect in tall buildings and smoke control pressurization techniques, interior building pressures as high as 100 Pa are unlikely. ISO Committee TC 92 on Fire Tests is currently considering three separate test methods for measuring air flow through interior door assemblies. The test method proposed for use at ambient indoor temperature (25 °C) also measures air flow across a door assembly at several pressure difference levels (5, 10, 20, 30, 50, 70 and 100 Pa) [11]. It is intended that other test methods would be developed for measuring air leakage at elevated temperatures, (e.g., at temperatures which correspond to the standard fire exposure for fire doors [12]) and at moderate temperatures (e.g., 300-500 °C). None of these methods actually addresses the more direct but difficult question of measuring the quantity of smoke particulates which flow past the door assembly, the apparent assumption being that (a) the particulates will not be filtered or deposited out in passing through the door gaps or (b) the flow of smoke-laden air is essentially equivalent to the flow of air mixed with CO and other "smoke" gases.

In the usual case, these test methods do not prescribe the apparatus in detail, providing only the measurement principle and a stated measurement accuracy. Thus the apparatus may be small, large, or adjustable in size and temporary or permanent. There are approximately 20 laboratories in the U.S. equipped to perform the ASTM E 283 test, although it is likely that there are wide variations in the size of the test chamber, the method of sealing, the type of flow and pressure measuring devices, etc. No data on interlaboratory testing are known or provided. The situation is similar for the proposed international test methods[2].

4. SPECIFICATIONS

Air leakage rates are sometimes specified for selected types of exterior doors to limit energy losses due to air infiltration. Although the air leakage rate may be specified in terms of the door area, it seems more reasonable to express it in terms of the crack length (perimeter) through which the leakage occurs. For example, one standard [13] sets a limit of 1.25 cfm/ft^2 (equivalent to 7.62 m^3/h·m of crack length for a 1 by 2 m door) at a pressure difference of 0.3 in wg (75 Pa) for a residential-type swinging door. For a similar application, a specification for insulated steel door systems [14] specifies a value approximately 40 percent of this limit, whereas another specification [15] permits a leakage rate four times as large, i.e., equivalent to 30.5 m^3/h·m.

Whereas exterior doors are specifically designed with weather-stripping and seals to limit air leakage, interior doors are not so designed except for special applications. In the U.S., there are no known specifications limiting air leakage through interior door assemblies for smoke control purposes. The Uniform Building Code Standard No. 43-2 (1979 edition) defines a smoke and draft control door assembly in terms of performance in the standard fire endurance test for an exposure period of not less than 20 minutes. The acceptance conditions are based on limitations on (1) flaming on the unexposed surface, (2) excessive movements, and (3) emission of excessive smoke from the door. In addition,

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[2] One known commercial source for an apparatus for measuring air leakage of doors and windows is: ALCO - Fensterprüfstand Typ 3030 SP, manufactured by ALCO Bauzubehorgesellschaft MBH & Co., Goslar, W. Germany.

it is required that "smoke and draft control door assemblies shall be provided with a gasket so installed as to provide a seal where the door meets the stop on both sides and across the top. The gasketing need not be installed on the test assembly". It is clear that the effectiveness of sealing methods are not quantitatively prescribed. In 1977, the NFPA Committee on Fire Doors and Windows prepared a Recommended Practice for the Installation of Smoke and Draft Control Door Assemblies (NFPA No. 105-1977). This proposal was intended to assist public safety authorities in considering methods for restricting and minimizing the potential flow of smoke and gases through door opening assemblies. It contained recommendations on frames, doors, hanging means, closing, holding and releasing means, detection, latching and sealing. As part of the recommendation for sealing, gasketing was to be provided along the door perimeter, and clearances (e.g., for carpeting) were to be "kept to a minimum". While this Recommended Practice was never adopted, it seems obvious that a quantitative performance level based on a suitable standard test method would have made such a Recommended Practice and other general requirements more meaningful and practical.

It may be of interest to note that in Germany the following tentative requirements have been proposed to limit the flow of heated (200°C) air through interior door assemblies: (1) 60 m^3/h at Δp = 10 Pa for the complete door assembly as used, (2) 20 m^3/h at Δp = 10 Pa for the door assembly with the threshold taped. The second measurement using an impervious seal at the bottom ledge of the door takes into account the fact that doors are usually undercut and that leakage at the threshold (floor) level would be disproportionately high in the (uniform pressure) laboratory test compared to the actual situation in a building.

5. MEASUREMENTS

A summary of some published information on air leakage rates for doors is given in Table 2. Data for windows, walls, and complete buildings are given in Table 3.

It may be noted first that exterior wall leakage rates are listed per unit area and for a pressure difference of either 75 or 200 Pa whereas windows and doors are listed per unit crack length and for a pressure difference of 25, 75 or 100 Pa. The leakage (crack) length is taken to be equal to the perimeter for a single leaf door and to the perimeter plus height for a double leaf door. Where interior doors are of principal concern, the maximum pressure difference due to stack effect, due to expansion of gases, and due to building pressurization is not considered likely to exceed 50 Pa. In certain cases, higher pressure differences could conceivably be attained across an interior door, e.g., due to high wind pressure where the window is broken, but this would not be common.

Secondly, there is a wide range in the air leakage rates among different doors, even of similar construction, and among different types of walls. It is clearly necessary to make sure that air leakage measurements are accurate and consistent before performance criteria are selected.

The leakage rate through conventional walls without windows is not negligible. Whereas the leakage rate at a pressure difference of 200 Pa may range up to 30 $m^3/h \cdot m^2$, it is still substantial at 50 Pa and 25 Pa; e.g. using equation (1) with n = 1, the equivalent flows are computed to be 7.5 $m^3/h \cdot m^2$ at 50 Pa and 3.8 $m^3/h \cdot m^2$ at 25 Pa. It is well to keep in mind that walls cover larger areas than doors and that interior walls are probably at least as permeable as exterior walls.

It appears that interior doors which are not specifically designed with sealing devices will not be capable of meeting the leakage limit of 16 $m^3/h \cdot m$ at 100 Pa which is currently proposed in DIS 5925 Part 1 [11]. Even close-fitting doors such as fire-check doors complying with British Standard BS 459 would allow a flow rate many times this figure.

Finally, as an illustrative example, the estimated leakage through a 1 by 2 m "smoke control door assembly" designed to the suggested limit in DIS 5925 Part 1 would be 70 m^3/h at 50 Pa. At this pressure, the leakage through the walls of an interior (or "core") stair shaft measuring 3 by 6 m and constructed of concrete block may be about 120 m^3/h per story. Thus, the advantage of using an effective smoke control door assembly may be limited if the door is mounted in a wall of normal construction.

6. DISCUSSION

This report was prepared to provide a review of available measurements of air leakage through interior door assemblies and a discussion of future needs and approaches for defining the performance of "smoke control doors". It has been pointed out that currently used doors separating each room from the corridor (e.g., apartment entrance doors), smoke barrier doors used in corridors, and exit stair doors will not meet the arbitrary 16 $m^3/h \cdot m$ leakage limit proposed in DIS 5925 Part 1. Is there a more rational basis for this limit or other limit?

In 1970, McGuire et al [16] suggested that the control of smoke within a high building could, as a first approximation, be accomplished by limiting the density of smoke at any point to 1 percent of the smoke density at the source. This value was based on a review of data on smoke generation, and on visibility in smoke-filled rooms and occupant tenability. The concept of using a limiting value of 1 percent may also be extended to air flow through door openings. What would such an approach provide in terms of evaluating the performance of conventional apartment entrance doors and typical fire-rated stair shaft doors?

For example, what is the likely flow of air past a closed apartment entrance door if the air flow were limited to 1 percent of the flow through the open door? Assuming a temperature difference of 10 K, the convective air flow through an open apartment entrance door according to Equation 2 would be approximately 0.48 m^3/s (1730 m^3/h). Thus, 1 percent of this flow would be 17.3 m^3/h or approximately 2.9 $m^3/h{\cdot}m$ for a 1 by 2 m door. According to Table 1, which is admittedly incomplete and subject to verification, interior doors, including many provided with seals along the door frame edges, would be unable to meet this criterion.

In buildings designed with pressurized stairwells, corridors or other selected zones, it may also be of value to use Equation 3 to compute the air supply necessary to prevent flow of heated air through an open (or partially open) doorway. This flow amounts to 1.6 m^3/s (5760 m^3/h) for ΔT = 10 K and 4.8 m^3/s (17300 m^3/h) for ΔT = 100 K. The forced air supply necessary to prevent flow of heated air through a door or other wall opening is about 3 times the flow induced by natural convection.

7. CONCLUSIONS

Based on a review of the factors governing air flow through closed door assemblies and of available measurements of air leakage through interior door assemblies, the following conclusions appear justified:

1) The flow of air past closed door assemblies may be expressed in terms of a leakage coefficient and a power function of the pressure difference. The assumption of conventional values for these factors based on turbulent flow past sharp-edged orifices may introduce considerable error. The appropriate pressure difference should be based on the maximum anticipated value according to door location, building design and environmental factors.

2) There is a wide range in the reported measurements of air leakage rates among different doors, even of similar construction. As a first priority, accurate and consistent air leakage measurements on a wide variety of interior doors according to a standardized and validated test method are needed. To take account of differences in the design of

doors, door frames, and sealing devices, as well as the effects of the anticipated differences of pressure, many interior door assemblies will need to be tested with air pressure applied separately in each direction.

3) Interior doors which are not specifically designed with special sealing devices will not be capable of meeting the leakage limit of 16 $m^3/h \cdot m$ at 100 Pa which is currently proposed in DIS 5925 Part 1. Even many doors provided with seals along the door frame edges may be unable to meet a criterion based on limiting flow to 1 percent of the <u>open</u> door flow.

4) An appreciable fraction of air leakage may occur through interior walls, including stair shaft walls, according to published measurements of leakage rates. Thus, the advantage of using an effective smoke control door assembly may be limited if the door is mounted in a wall of normal construction.

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Table 1. Values of exponent in Equation 1

Building Component	Exponent n	Reference
Brick Walls	0.87, 1.0	17, 18
Leakage Openings	0.77	3
Exterior Walls	0.67	19
Window Gaps	0.62	17, 20
Door Gaps	0.5	17, 20
Air Supply and Return Openings	0.5	19
Shaft Walls; Floors	0.5	19

Table 2. Measured and estimated air leakage rates for doors

Type	Description	Leakage Rate [1] $m^3/h \cdot m$	Pressure Difference Pa	Reference
Interior stair door	Gap width 2.0 mm	38	25	21
Interior stair door	Gap width 4.6 mm	92	25	21
Elevator door	Gap width 4.8 mm	100	25	21
Elevator door	Gap width 6.8 mm	140	25	21
Installed office door with catch, single-leaf	Computed gap width 1.9 mm	29	25	17
Installed door without catch, single-leaf	Computed gap width 3.7 mm	55	25	17
Installed double leaf door	Computed gap width 3.2 mm	48	25	17
Installed elevator door	Computed gap width 5.9 mm	88	25	17
Interior wood door	30 min. fire rating; without seals; avg. rebated clearance 0.6 mm	8	25	22
Interior wood (acoustic door)	60 min. fire rating; double seals along four edges	0.5	25	22
Interior steel door	60 min. fire rating; single seal all edges except bottom	16	25	17
Exterior steel door	Weatherstripped on four edges and special bottom corner seal	0.2 to 0.8	75	23
Interior wood door	Threshold with 7 mm stop, no sealing strips	>15	25	24
Interior wood door	Same, with sealing strips in door frame	5	25	24
Interior wood door	Same, with sealing strips in door frame and threshold	0.3	25	24
Interior wood door	Hung as in use	>40	25	25
Interior wood door	Same, with 25 mm stop	>40	25	25
Interior wood door	Same, with 25 mm stop and smoke seal	20	25	25
Interior wood door	Same, with 25 mm stop, smoke seal and threshold taped	1.3	25	25
Interior door	90 min. fire rating; without seals	30	25	26
Interior door	Wired glass in aluminum frame; seals along four edges of door and frame	7	25	26
Interior door	Wired glass panels (2) in steel frame seal on all edges except bottom	24	25	26

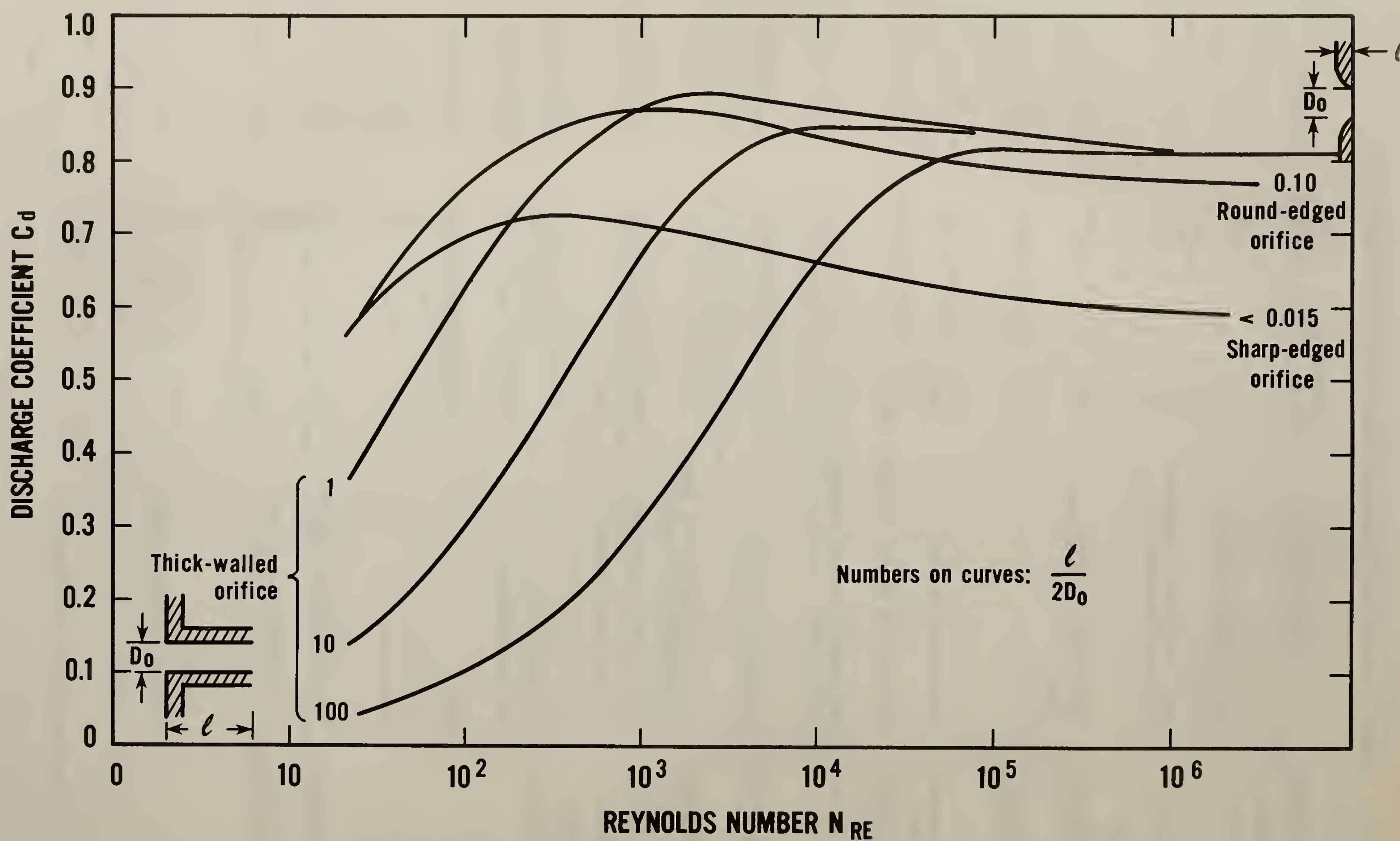
[1] Per unit crack length

Table 3. Measured and estimated air leakage rates for building components

Component	Description	Leakage Rate[1] $m^3/h\ m^2$	$m^3/h\ m$	Pressure Difference	Reference
Buildings					
School	Precast concrete panel walls; gasket joints; plasterboard lining.	5		200	27
House	Timber-frame panels; fiberboard sheathing; plasterboard lining.	10		200	27
Walls					
Factory (windowless)	Profiled steel cladding; quilt insulation; plasterboard lining.	30		200	27
Warehouse (windowless)	As above.	20		200	27
Elevator Shaft	Cast-in-place concrete	4-15		75	21
Elevator Shaft	Concrete block or clay tile block.	30-35		75	21
Stair Shaft	Cast-in-place concrete; concrete or tile block.	0.5-4		75	21
Wood Frame	Insulated 1 and 2 story	3-23		75	28
Wood Frame	Shingles; sheathing; bldg. paper; lath and plaster (3 coats)	0.1		75	3
Brick	8.5 in. thick, unplastered.	7		75	3
Brick	8.5 in. thick, plastered	0.06		75	3
Windows					
Household	Weatherstripped		2.2-13.8	100	29
	Non Weatherstripped		6-25	100	29
	Fixed		0.006-0.08	75	30
	Wooden Sash		5-25	75	30
	Metallic Sash		0.5-30	75	30
Household, wood double-hung	Nonweatherstripped, avg. fit		5	75	3
Household, wood double-hung	Weatherstripped, avg. fit		3	75	3
	Pivoted		5.8 (1-20)	25	31
	Pivoted and weatherstripped		0.8 (0.1-6)	25	31
	Sliding		2.2 (0.5-9)	25	31

[1] Per unit area; per unit crack length

Figure 1. Discharge coefficients for orifice flow



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15. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

A review was made of measurements and calculations of air leakage through door assemblies in order to evaluate their effectiveness as barriers to smoke flow. It was noted that typical "fire doors" are not capable of meeting proposed limitations of air leakage at ambient temperatures and that significant air leakage may also occur through interior walls. It was concluded that first priority should be given to developing and validating a standardized test method for air leakage measurements.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Air leakage, buildings, doors, fire doors, fire tests, infiltration, orifice flow, smoke control, smoke movement.

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