LEAKAGE CHARACTERISTICS OF OPENINGS
FOR REACTOR HOUSING COMPONENTS

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ABSTRACT

Measurements have been made of the air leakage rates through structural components which penetrate semicontainment reactor housing installations.

Full-size test specimens were sealed inside a 10 ft diameter test sphere, and the leakage rate was measured as a function of pressure for pressure differentials of up to 25 in. of water. The data were fitted to empirical equations which describe the leak rate at any pressure differential within the range of the experimental tests. The forms of the equations are such that the total leak rate of a building can be obtained by summing the empirical constants and multiplying by a probable pressure differential.

I. INTRODUCTION

The study of reactor housing installations is a program conducted at Atomic International with a twofold objective: (1) to eliminate the potential hazard to the public of reactor accidents; and (2) to reduce the cost of power supplied by reactors.

Both of these goals can be achieved by making improvements in the design of reactor buildings. Such a building is more than a convenient shelter for reactor, associated equipment, and operating crew. The building must confine any radioactive material generated or released as a result of accident to the reactor. It is therefore necessary to design the building with care to prevent the escape of such material. The intent of this program is to provide information by which buildings can be designed to provide effective containment of radioactivity. Such buildings may also be cheaper to build than existing reactor-housing installations.

The experimental approach is used in conducting this program. Special equipment and special techniques are essential to the measurement of building and building component leakage.

Tests on complete buildings are necessary to verify that leakage of a building can be predicted from component leakage. For example, leakage around a door seal may be negligible when compared to leakage between the door frame and the wall itself. Component test installations must be typical of actual building installations, if the results are used to compute the building leakage rates.

Methods of improving components to reduce leakage must be developed. Standard building components can be modified to reduce leakage. It is economically important to find inexpensive ways of reducing leakage of these components to satisfactory levels.

Building fabrication techniques must also be analyzed to find suitable methods of reducing building leakage. The techniques employed must be designed for routine use by construction workers.

It is important to measure not only air leakage rates but also radioactivity leakage rates. In general, these rates will not be the same.

The problem of assessing the hazard to the public arising from the radioactivity liberated in a reactor accident is extremely difficult. To carry out a suitable analysis, one must consider the following questions:

- 1) How much radioactivity is generated and released from the primary containment shell?
- 2) Of this, how much escapes from the building?
- 3) How is the radioactive material then dispersed or distributed? What meteorological mechanisms promote exposure to the public?
- 4) What constitutes a hazardous radiation dose?

The reactor designer provides the answer to the first question by analysis and by such experiments as are feasible.

The present program is intended to provide an experimental answer to the second question. At the same time, some attention is given to the third question. The fourth question is clearly the most difficult to answer.

The purpose of this memo is to present information and data currently available in studies of building components. Though such information provides only fragmentary knowledge in this important field, it may yet serve as a guide in areas now lacking one. This memo is one of a series designed to describe leak rates through conventional construction materials.

II. STATEMENT OF THE PROBLEM

The leakage of contamination from a secondary reactor housing may occur through such openings in the structure as the exhaust system; components like doors, valves, and hatches necessary for entrance to the reactor building; the wall structure itself; joints between components and walls; and wall penetrations such as those provided for electrical conduits. All these types of openings can become leak paths which must be controlled in order to maintain the desired integrity. Knowledge of the leak rates of all leak paths for building structures using conventional housing materials would allow one to compute the total leak rate for a given pressure. Using this information, one could estimate the cost necessary to meet a certain containment integrity.

The leak-rate characteristics of several types of doors and similar penetrants have been determined. Hence, using future studies of walls and joints, the leak rate of a building may be forecast before construction.

III. ANALYTICAL TREATMENT

The leak from a building may occur through a crack, hole, or porous wall. The model in Figure 1 depicts both crack and hole leakage. For the crack, the laminar flow equation is:

$$V = \frac{g_c}{12\mu} \frac{b^3 L}{X} (P_i - P_o)^* \quad \dots (1)$$

where

V = volume flow rate
 g_c = gravitational constant
 μ = viscosity
 b = crack width

L = crack length
 X = wall thickness
 P_i = upstream pressure
 P_o = downstream pressure

*J. C. Knudsen and D. L. Katz, "Fluid Dynamics and Heat Transfer," Engineering Research Institute, Univ. of Mich. (1954)

Figure 1. Theoretical Model of Crack and Orifice Leak Conditions

For the hole, the flow can be described by the standard orifice equation:

$$V = Cb'L\sqrt{\frac{2g_c}{\rho}(P_i - P_1)} \quad * \quad \dots(2)$$

where

- V = volume flow rate
- C = orifice coefficient
- b' = orifice width
- L = orifice length
- g_c = gravitational constant
- ρ = density
- P_i = upstream pressure
- P_1 = downstream pressure for orifice

*G. G. Brown, "Unit Operations," John Wiley and Sons (1950)

These equations can be represented by

$$V_c = \frac{C_c}{\mu} (P_1 - P_o) \quad \dots (3)$$

and

$$V_o = \frac{C_o}{\sqrt{\rho}} (P_i - P_1)^{1/2} \quad \dots (4)$$

where

$$C_c = L \frac{g_c}{12} \frac{b^3}{X},$$

and

V_c = flow rate through crack,

and

$$C_o = LCb^1 \sqrt{2g_c},$$

and

V_o = flow rate through orifice.

Flow through a porous wall is similar to flow through a crack

$$V = A \frac{B}{X} \Delta P \quad \dots (5)$$

where

B = experimentally determined leakage coefficient for the wall

A = area

X = thickness of wall

ΔP = pressure differential

Since leak paths in a building are not due to simple cracks or holes, it is desirable to combine all leakages to obtain a general equation of total leakage. The resultant equation for a series crack-hole system is:

$$V = \frac{1}{\rho} \frac{C_o}{2} \sqrt{\left(\frac{C_o}{C_c}\right)^2 \mu^2 + 4\rho \Delta P} - \frac{C_o^2}{2C_c} \frac{\mu}{\rho} \quad \dots (6)$$

If this series equation is combined in parallel with a crack and orifice, the resulting equation is:

$$V_T = \frac{C_1}{\mu} \Delta P + \frac{C_2}{\sqrt{\rho}} \sqrt{\Delta P} + \frac{1}{\rho} \sqrt{C_3^2 \mu^2 + 4\rho \Delta P} - \frac{\mu}{\rho} C_3 \quad \dots (7)$$

In practice, this equation can be approximated by

$$V_T = C_4 (\Delta P)^n \quad \dots (8)$$

where C_4 contains viscosity and density terms.

The approximate equation

$$V_T = C' \Delta P + C'' (\Delta P)^{1/2}, \quad \dots (9)$$

where C' and C'' also contain viscosity and density factors, is a more suitable equation to use, as it is convenient when individual component leaks are summed. Since Equation 9 is representative of the individual leaks, the total leak from a building can be represented by

$$V_T = (\sum C_i') \Delta P + (\sum C_i'') (\Delta P)^{1/2} \quad \dots (10)$$

IV. METHODS AND INSTRUMENTS

In order to measure pressures and pressure changes, a test cell large enough to contain specimens 6 x 6 ft was designed. This unit consists of two 10-ft dia hemispheres with a plate to support test specimens between the two halves (Figures 2 and 3). A complete description of this cell is to be found in publication in NAA-SR-5138.

The test specimen is mounted on the support plate with "Apiezon" wax as a gasket. This joint is tested for leaks with Freon and a halogen leak detector. If the joint is satisfactory, the support plate is mounted on the diaphragm plate and the test cell is assembled. (Mounting details are described in NAA-SR-5138.) The pressure is increased in one hemisphere to as much as 25 in. of water above atmospheric pressure. The pressure difference between the two halves is monitored by means of a strain gage differential pressure transducer which is connected to a recorder. The gain in pressure with respect to a reference system in the low pressure half is also monitored by the same type of pressure-recording system.

This test system is installed in a room which is not temperature controlled. The temperature fluctuations which occur are reflected in temperature variations in the cell. The effect of these fluctuations on the pressure difference between the two hemispheres is small, as the two halves are equal in size and shape. Since the driving force is measured between two closed systems, the effect of barometric pressure changes is negated.

The effect of temperature and barometric changes is more pronounced when small rates of change in pressure are used to measure leak rates. These effects are minimized by using a 50-ft length of 3/8-in. copper tubing as an internal reference system in each half of the test cell. The reference system was grossly located by placing the tubing so that the average internal air temperature in the coil was the same as the average air temperature in the cell. The reference was finally located by moving the tubing until a zero pressure difference was developed between the reference system and the cell during a period of varying air temperatures (Figure 4).

Figure 2. Test Cell Showing Specimen Mounting Arrangement and Test Instrumentation

Figure 3. Assembled Test Cell

Figure 4. Test Hemisphere with Reference Coil Mounted in Final Position

Temperature measurements of the air in either hemisphere can be made with resistance thermometers which feed to an external selector and recorder.

If a pressure differential is developed across a specimen, the pressure change as a function of time should be proportional to the leakage through this component. This pressure rate of change can be measured and the leak rate calculated as a function of driving pressure, the differential pressure across the specimen. The procedure for computing the leak rate as a function of the driving force is shown in Appendix A.

The equation for a perfect gas, $PV = nRT$, can be used to calculate the STSP volume of gas in the test cell. This volume is:

$$V_1 = V_o \times \frac{BP_1 + \Delta P_1}{407.09} \times \frac{529.6}{T_1} \quad \dots(11)$$

where

V_o = the volume of a test cell at 70°F and one atmosphere.

$BP_1 + \Delta P_1$ = absolute pressure in inches of water

BP_1 = barometric pressure

ΔP_1 = gage pressure

T_1 = absolute temperature in degrees Rankine

The change in volume due to leakage is

$$\Delta V = V_o \times \frac{529.6}{407.09} \left(\frac{BP_1 + \Delta P_1}{T_1} - \frac{BP_2 + \Delta P_2}{T_2} \right) \quad \dots(12)$$

During short runs, the barometric pressure and temperature can be assumed constant, and Equation 12 becomes

$$\Delta V = V_o \times \frac{529.6}{407.09} \times \frac{1}{T} (+ \Delta P_1 - \Delta P_2) \quad \dots(13)$$

Equations 12 and 13 may be used to calculate volume changes at standard temperature and pressure as a function of pressure change between a reference system and one of the test cell hemispheres.

V. TESTS AND RESULTS

All specimens except the Keystone gasketed butterfly valves were mounted on the support plates by means of welded angle frames to which the test specimen could be clamped. The joints between the component and the welded frame were filled with Apiezon wax and tested for leakage with Freon-12 and a halogen detector.

A. BUTTERFLY VALVES

Flanges were welded to a mounting plate so that two Keystone hydraulic-actuated gasketed butterfly valves could be mounted in series and tested either singly or in combination (Figure 5). Pressures as high as 13.8 lb/in.^2 were applied across individual and series valves. The high pressure runs were done outside the cell by using the welded flanges as a small high-pressure test cell.

These valves showed no air leakage at pressures up to 25 in. of water; and the special test at 13.8 psi for 65 hr showed a leak rate of less than $0.018 \text{ ft}^3/\text{day}$.

B. ROOF ACCESS HATCH

A standard 30×36 in. gasketed roof access hatch was mounted on an angle frame and installed in the cell (Figures 6 and 7). Bidirectional measurements were made: one, in which the pressure tended to close the hatch against the gasket; the other, in which the hatch was pushed away from the gasket. These runs were made with differential pressures of 25 in. of water. It was noted that the leaks occurred through the joint between the cover and rubber seal.

The leak rate for the case in which the pressure tended to open the hatch is given by $\text{ft}^3/\text{min} = 9.34 \Delta P + 130 (\Delta P)^{1/2}$, while the leak rate when the pressure caused the hatch to seal was approximately one-sixth of this rate, or $\text{ft}^3/\text{min} = 21.5 (\Delta P)^{1/2}$.

In this and other expressions for the leak rate, the pressure (ΔP) is expressed in inches of water and the leak rate (CFM) in ft^3/min at STSP.

C. DOGGING BULKHEAD DOOR

A bulkhead door with individual dogs was mounted on its frame and installed (Figures 8 and 9). Bidirectional measurements of the leakage, starting at 25 in.

Figure 5. Keystone Valve Mounted on Support Plate
(Other Valve Mounted Directly Behind)

Figure 6. Access Hatch Mounted on Support Plate Showing Assembly Details

Figure 7. Opened Access Hatch Showing Structural Details

Figure 8. Individual Dogging Type Marine Door - Open, to Show Detail

Figure 9. Individual Dogging Type Marine Door - Closed

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of water differential pressure, were made on the unit with the dogs hand-tight. Another set of runs was made with the dogs hammered tight. It was found that the leaks in this unit occurred around the shafts going through the door as well as around the door edge.

There appears to be slight difference in the leak rates through this unit regardless of direction and degrees of tightness; if any, the pressure direction tending to close the door appears to yield a higher leak rate. The average leak rate relationship determined for this component was $\text{ft}^3/\text{min} = 0.0208 (\Delta P) + 0.207 (\Delta P)^{1/2}$.

D. QUICK-ACTING BULKHEAD DOOR

A quick-acting bulkhead door in which the closure dogs were operated by a central wheel was tested next. (Figure 10) Bidirectional runs starting at 25 in. were made on the unit as received. It was noted that paint had been left on the rubber door-seal, and the dogs had not been adjusted for maximum closure. After these defects had been corrected, bidirectional tests were again made. After these runs, it was found that the edge against which the door sealed was very irregular (Figure 11); therefore, the joint between the frame and door was packed with Apiezon wax in an attempt to reduce the leakage due to these defects. A run was made with a starting differential pressure of 25 in. of water, with the pressure applied to force the door away from its seal.

The test run on the door, as received, indicated the presence of very poor seals as seen in the equation for the leak rate when the door was being forced away from its seal: $\text{ft}^3/\text{min} = 0.258 (\Delta P) + 0.188 (\Delta P)^{1/2}$. Cleaning the rubber seal and making closure adjustments reduced the leak rate to 10% of this value: $\text{ft}^3/\text{min} = 0.00176 (\Delta P) + 0.0406 (\Delta P)^{1/2}$. Packing the seal groove to reduce the effect of irregularities in the frame reduced the leak rate to about 3% of the original value: $\text{ft}^3/\text{min} = 0.00234 (\Delta P) + 0.0110 (\Delta P)^{1/2}$.

The previous runs were primarily concerned with low pressure differentials (<25 in. of water). A test was made to determine if the equations relating leak rate and pressure could be extrapolated to higher pressures. A starting pressure of 5.7 in. of mercury or 2.8 psi was applied to the quick-acting bulkhead door in order to compare the leak-rate equations for high and low pressures.

Figure 10. Quick-Acting Marine Door

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Figure 11. Enlarged Detail of Quick-Acting Marine Door Lip Showing Irregularities Causing Leak

The results of comparing leak-rate characteristics of the quick-acting door from -25 to 0 in. of water pressure and from -6 to 0 in. of mercury are presented in the table below. These results indicate that higher pressures cause

TABLE I
COMPARISON OF HIGH AND LOW PRESSURE LEAK CHARACTERISTICS

Test	Leak Rate (ft ³ /min)	Leak Rate at ΔP (In. Water)		
		25	50	100
25 in. water	$0.00176\Delta P + 0.0406(\Delta P)^{1/2}$	0.247	0.376	0.582
5.7 in. Hg	$0.0113 \Delta P + 0.0170(\Delta P)^{1/2}$	0.368	0.686	1.300

larger openings to appear at the door seal with the corresponding increase in leak rate. Therefore, if a component is to be used at high pressures it should be tested at these pressures.

E. LOUVERS

The interiors of reactor buildings are connected to the outside through gasketed louvers which are closed by mechanical activators at the time of an accident. In order to determine the force which would be required to make the louver most resistant to air leakage, the unit was mounted upside down, and various weights (10, 20, and 30 lb) were attached to the closure lever (Figure 12). The pressure differential across this unit was never larger than 8 in. of water, due to structural problems. The minimum leakage occurred when the closure weight was at least 20 lb: $\text{ft}^3/\text{min} = 6.89 (\Delta P) + 25.9 (\Delta P)^{1/2}$.

F. HOLLOW METAL DOOR - SOUND INSULATION AND WEATHER STRIPPING

A hollow metal door with sound insulation-weather stripping and closure-actuated sill seal was mounted and installed (Figure 13). It was necessary to adjust the rubber stripping so that this was tight against the door when it was closed (Figure 14). The bidirectional leakage tests were made starting at a differential pressure of no more than 7 in. of water, since the unit could not stand higher pressures structurally. Tests thus revealed major leakages through the weather stripping at the corners of the door.

Figure 12. Gasketed Louver

Figure 13. Hollow Metal Door with Sound Insulation

Figure 14. Detail of Sound Insulation

The leakage through this type of door is much greater than through bulkhead doors. The equation during tests where the pressure tends to open the door was found to be: $\text{ft}^3/\text{min} = 23.5 (\Delta P) + 41.2 (\Delta P)^{1/2}$, while the equation for leakage in the reverse direction was approximately one-half this rate: $\text{ft}^3/\text{min} = 35.0 (\Delta P)^{1/2}$.

G. HOLLOW METAL DOOR - INTERLOCKING WEATHER STRIPPING

A hollow metal door was fitted with standard metal-interlocking weather stripping and a rubber flap-type floor seal, and then installed in the unit (Figures 15 and 16). This unit was tested at pressures no greater than 7.5 in. of water. The weather stripping had openings at the corners of the door.

The door was forced against the weather stripping by the pressure applied during this run, in which the leak rate was found to be: $\text{ft}^3/\text{min} = 12.0 (\Delta P) + 34.6 (\Delta P)^{1/2}$. The same door was then fitted with a rubber gasketed-interlocking weather stripping and the same floor seal (Figures 17 and 18) for tests at pressures no greater than 8 in. The leakage occurred at door corners where the weather stripping was not continuous.

The leakage when the door was forced from its seal was: $\text{ft}^3/\text{min} = 4.93(\Delta P) + 27.4 (\Delta P)^{1/2}$, while, in the reverse direction, the leak rate was 20% less: $\text{ft}^3/\text{min} = 4.37 (\Delta P) + 22.1 (\Delta P)^{1/2}$.

With the component correctly installed, the leak rate, when the pressure tends to close the pivoted section against its seal, should be less than when the pressure tends to force it away from the seal. This fact is demonstrated by the results of tests on the roof access hatch, on the quick-acting door after it had been cleaned and adjusted, on the hollow door with sound insulation door seals, and on the door with gasketed-interlocking weather stripping. The results on the individual dogging door indicate that the leak is not at the joint between the door and its seal, but is rather at some other location. This view accords with the Freon leak test, where it was noted that the leak was around the shafts of the closure dogs. The quick-acting door is less expensive, is a stock item, and appears to be satisfactory as a replacement for inflatable seal doors if the sealing edge is machined to yield a smooth surface against which the door can be seated.

Figure 15. Hollow Metal Door with Metal Interlocking Weather Stripping

Figure 16. Detail of Metal Interlocking Weather Stripping

An evaluation of leak rate relationships as functions of pressure (as exemplified in Appendix A) for the various test configurations is presented in Table II, which also lists the leakage rates for pressures of 0.25, 0.50, and 1.00 in. of water.

Figure 17. Detail of Gasketed Interlocking Weather Stripping

Figure 18. Detail of Door-Mounted Part of Gasketed Interlocking Weather Stripping

TABLE II
LEAK RATE CHARACTERISTICS OF STANDARD COMPONENTS

Component	Unit tends to:	Valid Range (in. Water)	Leak Rate Relation (ft ³ /min)	Leak Rate at ΔP (in. Water)		
				0.25	0.50	1.00
				(ft ³ /min)		
Roof Access Hatch (30 by 36 in.)	Open	0 - 25	$9.34\Delta P + 130(\Delta P)^{1/2}$	67.3	97.0	139.
	Close	0 - 25	$21.5(\Delta P)^{1/2}$	10.8	15.2	21.5
Individual Dogging Door, Hand-Tight (25 by 60 in.)	Open	0 - 25	$0.0192\Delta P + 0.170(\Delta P)^{1/2}$	0.090	0.130	0.189
	Close	0 - 25	$0.0234\Delta P + 0.242(\Delta P)^{1/2}$	0.126	0.184	0.265
Individual Dogging Door, Hammered Tight	Open	0 - 25	$0.0263\Delta P + 0.190(\Delta P)^{1/2}$	0.102	0.148	0.216
	Close	0 - 25	$0.0142\Delta P + 0.226(\Delta P)^{1/2}$	0.116	0.168	0.240
Quick-Acting Door, as Received (25 by 60 in.)	Open	0 - 25	$0.258\Delta P + 0.188(\Delta P)^{1/2}$	0.158	0.262	0.446
	Close	0 - 25	$0.0714\Delta P + 0.426(\Delta P)^{1/2}$	0.230	0.338	0.497
Quick-Acting Door, Cleaned and Adjusted	Open	0 - 25	$0.00176\Delta P + 0.0406(\Delta P)^{1/2}$	0.0207	0.0297	0.0424
	Close	0 - 25	$0.000116\Delta P + 0.0263(\Delta P)^{1/2}$	0.0131	0.0187	0.0264
Quick-Acting Door, Packed Seal	Open	0 - 25	$0.00234\Delta P + 0.0110(\Delta P)^{1/2}$	0.0060	0.0090	0.0134
	Close	0 - 25	$0.00086\Delta P + 0.00106(\Delta P)^{1/2}$	0.00074	0.00118	0.00192
Gasketed Louver (20 by 21 in.)						
10-lb Closure Force		0 - 7	$7.87\Delta P + 33.2(\Delta P)^{1/2}$	18.6	27.5	41.1
20-lb Closure Force		0 - 7	$6.89\Delta P + 25.9(\Delta P)^{1/2}$	14.6	21.8	32.8
30-lb Closure Force		0 - 7	$6.70\Delta P + 27.8(\Delta P)^{1/2}$	15.6	23.0	34.5
Hollow Door with Sound Insulation (30 by 60 in.)	Open	0 - 7	$23.5\Delta P + 41.2(\Delta P)^{1/2}$	26.4	41.0	64.7
	Close	0 - 7	$35.0(\Delta P)^{1/2}$	17.50	24.8	35.0
Hollow Door with Metal Interlocking - Weather Strip	— Close	0 - 7	$12.0\Delta P + 34.6(\Delta P)^{1/2}$	20.3	30.6	46.6
Hollow Door with Metal Interlocking and Gasket- Seal Weather Strip	Open	0 - 7	$4.93\Delta P + 27.4(\Delta P)^{1/2}$	14.9	21.9	32.3
	Close	0 - 7	$4.37\Delta P + 22.1(\Delta P)^{1/2}$	12.1	17.8	26.4

VI. LEAK MEASUREMENT TECHNIQUES

The leakage of a building is normally effected by pressurizing the structure to some known pressure and recording the change as a function of time. This requires a long period of time and is affected by ambient conditions. So that such external changes do not affect the results, it would be desirable to determine the leak rate rapidly. In an attempt to do this, the individual dogging door was installed in the cell. One hemisphere was opened to the atmosphere and the other evacuated at a constant known rate. The decrease in pressure was recorded as a function of time. The equilibrium pressure which resulted was the pressure at which the component was leaking at the rate of the constant pumping speed. A number of tests made at different pumping speeds yielded different equilibrium pressures (Table III). This method yielded results comparable to the pressure decay method. However, the pressures required a long time to reach equilibrium. By using data of pressure vs time for only a portion of the test, it was possible to extrapolate the equilibrium pressure without making long runs.

TABLE III
EQUILIBRIUM PRESSURES FOR CONSTANT PUMPING SPEEDS

Pumping Speed (ft ³ /min)	Extrapolated ΔP (in. Water)	Equilibrium ΔP (in. Water)
0.60	5.70	5.50
0.75	9.00	8.75
1.00	21.30	20.65

An example of the data treatment and computations is presented in Appendix B. In order to develop a more rapid method of measuring the leak rate of a building, the individual dogging door was tested by exhausting one side of the test cell at 0.6, 0.75, and 1.0 cfm; then observing the pressure as a function of time until equilibrium was reached (see Figure 21, Appendix B). Since this operation required long pumping periods, the data for the first ten minutes were recalculated as $\Delta P/\Delta t$ vs ΔP , and the plotted data extrapolated to $\Delta P/\Delta t = 0$ (see Figure 22, Appendix B). These values compare favorably with the experimental values in Table IV below.

Extrapolated pressures at the three pumping speeds were used to develop the leak rate equation for this component. The results obtained were compared with those equations computed by the pressure decay method. The comparisons are shown below, and computation techniques are in Appendix B.

TABLE IV
COMPARISON OF METHODS FOR DETERMINING LEAK EQUATION

Method	Leak Rate (ft ³ /min)	Leak Rate at ΔP (in. Water)			
		0.25	0.50	1.00	2.00
Pressure Decay	$0.0192 \Delta P + 0.170(\Delta P)^{1/2}$	0.090	0.130	0.189	0.278
Constant Pumping Speed	$0.235(\Delta P)^{1/2}$	0.117	0.166	0.235	0.331

The two methods yield leak rates which lie within 20% of the average at a constant ΔP . Since the constant pumping speed method is based on only three pumping speeds and equilibrium pressures, while the pressure decay method is based on many more points, it is planned to repeat this comparative study and obtain more points so as to verify the technique.

VII. CONCLUSIONS

A number of standard components have been tested, and the data fitted to an equation of the form

$$V = C_1 \Delta P + C_2 (\Delta P)^{1/2} = \text{ft}^3/\text{min} \quad .$$

In most cases the leakage occurred through gasketed joints in the specimens. The partial seals in these components are pressure-dependent. Therefore, at higher pressures the leak rate would not be forecast from low-pressure tests.

The leak rate through gasketed butterfly valves is so small that one valve should be sufficient to seal any ducts which might require closure. It would appear economically feasible to replace special access doors by standard bulkhead doors which have been adjusted correctly. A rapid means of determining a building leak rate can be developed from the method of constant pumping speed, to determine the equilibrium pressure. It might be possible to make these determinations fast enough to reduce the effect of ambient changes on leakage results.

APPENDIX A

DETERMINATION OF LEAK RATE EQUATION

The data from the testing of the components are shown graphically in Figure 19, which depicts the gain in pressure of the low-pressure half of the test cell with respect to the reference system. For this example, the starting pressure was -13.38 in. of water. The information required for calculation of the leak rate is recorded in the table below.

TABLE V
DIFFERENTIAL PRESSURE AND PRESSURE CHANGES VS TIME

Time (min)	Differential Pressure (in. Water)	Gain in Pressure Above Reference System Pressure
0	13.38	0.00
1	12.00	1.38
2	10.75	2.63
3	9.60	3.78
4	8.55	4.83
5	7.58	5.80
6	6.65	6.73
7	5.80	7.58
8	5.00	8.38
9	4.25	9.13
10	3.60	9.78
11	3.00	10.38
12	2.44	10.94
13	1.98	11.40
14	1.55	11.83
15	1.18	12.20
16	0.85	12.53
17	0.60	12.78
18	0.38	13.00
19	0.22	13.16
20	0.10	13.28
21	0.05	13.33

The volume of the west or low-pressure hemisphere was 258 cu ft. During this run, the air temperature in the hemisphere averaged 70°F. The leak rate is then calculated by

$$\frac{\Delta V}{\Delta t} = 258 \times \frac{529.6^\circ}{459.6^\circ + 70^\circ} \times \frac{\text{incremental gain in pressure per min}}{407.09 \text{ in. water}}$$

Figure 19. Record of Pressure Gain vs Time for Individual Dogging Type Marine Door

as in Equation 12. The calculations using the data in Table V are presented in Table VI, where the incremental gain in pressure is the gain from -13.38 in. of water.

TABLE VI
CALCULATIONS OF LEAK RATE VS DIFFERENTIAL PRESSURE

Time (min)	Differential Pressure (in. Water)	Incremental Gain in Pressure per Minute	$\frac{\Delta V}{\Delta t}$ (ft ³ /min)	$\Delta P = \frac{\text{Diff. Press.}_1 + \text{Diff. Press.}_2}{2}$
0	13.38	-	-	-
1	12.00	1.38	0.87	12.69
2	10.75	1.25	0.79	11.38
3	9.60	1.15	0.73	10.18
4	8.55	1.05	0.67	9.08
5	7.58	0.97	0.61	8.06
6	6.65	0.93	0.59	7.12
7	5.80	0.85	0.54	6.22
8	5.00	0.80	0.51	5.40
9	4.25	0.75	0.48	4.62
10	3.60	0.65	0.41	3.92
11	3.00	0.60	0.38	3.30
12	2.44	0.56	0.35	2.72
13	1.98	0.46	0.29	2.21
14	1.55	0.43	0.27	1.76
15	1.18	0.37	0.23	1.36
16	0.85	0.33	0.21	1.02
17	0.60	0.25	0.16	0.72
18	0.38	0.22	0.14	0.49
19	0.22	0.16	0.10	0.30
20	0.10	0.12	0.08	0.16
21	0.05	0.05	0.03	0.08

The constants of the equation relating $\Delta V/\Delta t$ and ΔP are calculated from the data by a least squares method. The equation with these constants is

$$V = 0.0192\Delta P + 0.170(\Delta P)^{1/2} .$$

The curve of V vs ΔP calculated from this equation is compared to the data in Figure 20. The leak rate equation constants for all the components are determined in this manner.

This form of the equation relating leak rate and pressure can be compared with another method of characterizing building leak rates which relates the change of excess pressure and time by an equation of the form

$$P_{(t)} = P_o e^{-Rt}$$

where

$P_{(t)}$ = excess pressure at time t ,

P_o = initial overpressure,

R = pressure decay constant of building, and

t = time.

The factor $R = KC_1$ is constant only when the leakage equation of the building can be expressed as

$$V = C_1 \Delta P$$

This relation is valid when the building is constructed of concrete, or if all the leaks occur through cracks in the building.

Verification of the relationship between R and C_1 can be obtained by summing all of the building component leakage constants, or through measurements of the pressure decay of a complex structure.

Figure 20. Leak Rate vs Pressure Relationship for Individual Dogging Type Marine Door

APPENDIX B

CONSTANT PUMPING SPEED METHOD FOR EVALUATION OF LEAK RATE

The evacuation rate was kept constant by means of a meter. The pressure change with time was recorded on a graph (Figure 21). Since the time required to reach the equilibrium pressure is long, the incremental change in ΔP (Table VII) is plotted against ΔP , and the extrapolated value of ΔP is read at $\Delta P/\Delta t = 0$ (Figure 22).

Figure 21. Pressure vs Time Relationship as a Function of Pumping Speed

TABLE VII
INCREMENTAL PRESSURE CHANGE AT CONSTANT PUMPING SPEEDS

Time (min)	0.60 (ft ³ /min)			0.75 (ft ³ /min)			1.00 (ft ³ /min)		
	ΔP	$\Delta P/\Delta t$	Average ΔP	ΔP	$\Delta P/\Delta t$	Average ΔP	ΔP	$\Delta P/\Delta t$	Average ΔP
0	0.00	—	—	0.00	—	—	0.00	—	—
1	1.03	1.03	0.51	1.48	1.48	0.74	1.78	1.78	0.89
2	1.75	0.72	1.40	2.35	0.87	1.92	3.20	1.42	2.49
3	2.25	0.50	2.00	3.02	0.67	2.68	4.38	1.18	3.79
4	2.70	0.45	2.48	3.60	0.58	3.31	5.42	1.04	4.90
5	3.02	0.32	2.86	4.10	0.50	3.85	6.38	0.96	5.90
6	3.32	0.30	3.17	4.50	0.40	4.30	7.28	0.90	6.83
7	3.58	0.26	3.45	4.88	0.38	4.69	8.15	0.87	7.72
8	3.81	0.23	3.70	5.20	0.32	5.04	8.95	0.80	8.55
9	4.03	0.22	3.92	5.50	0.30	5.35	9.72	0.77	9.34
10	4.22	0.19	4.12	5.78	0.28	5.64	10.48	0.76	10.10

The measured pumping speeds and extrapolated equilibrium pressures can then be used to determine the leak-rate equation for this door.

TABLE VIII
COMPARISON OF PRESSURE DECAY AND CONSTANT PUMPING SPEED METHODS

Method	Leak Rate Equation (ft ³ /min)	Leak Rate at ΔP , in. Water		
		0.25	0.50	1.00
Pressure Decay	$V = 0.0192\Delta P + 0.170(\Delta P)^{1/2}$	0.090	0.130	0.189
Constant Pumping Speed	$V = 0.229(\Delta P)^{1/2}$	0.114	0.162	0.229

If more pumping speeds are evaluated, the agreement between the two methods should become closer; but it appears that comparable results are obtained by the two methods.

Figure 22. Extrapolation Curves of $\Delta P/\Delta t$ vs ΔP for Various Pumping Speeds