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SPACE STATION *FREEDOM* SEAL LEAKAGE RATE ANALYSIS AND TESTING SUMMARY: AIR LEAKS IN AMBIENT VERSUS VACUUM EXIT CONDITIONS

By P.I. Rodriguez and R. Markovitch

Structures and Dynamics Laboratory
Science and Engineering Directorate

August 1992

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13. ABSTRACT *(Maximum 200 words)*

This report is intended to reveal the apparent relationship of air seal leakage rates between 2 atmospheres (atm) to 1 atm and 1 atm to vacuum conditions. Gas dynamic analysis is provided as well as data summarizing MSFC test report, "Space Station *Freedom* (S.S. *Freedom*) Seal Flaw Study With Delta Pressure Leak Rate Comparison Test Report," SSF/DEV/ED91-008.

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SPACE STATION *FREEDOM* SEAL LEAKAGE RATE ANALYSIS AND TESTING SUMMARY: AIR LEAKS IN AMBIENT VERSUS VACUUM EXIT CONDITIONS

I. INTRODUCTION

During the development phase of the Space Station *Freedom* (S.S. *Freedom*) work package 01 (WP 01) pressurized modules, the subject of atmosphere leakage qualification testing in standard atmosphere facilities had been proposed. These qualification tests would not verify the seal leakage rates in the normal on-orbit operating conditions, i.e., the external vacuum environment of space. The required pressure differential for leak testing would be obtained by pressurizing the modules to 14.7 gauge pressure (lb/in^2 gauge) and measuring the leak rate to the standard atmospheric pressure (14.7 lb/in^2 absolute).

Concern with validating the air seal's performance by a comparison between ground leak testing 2 atmospheres (atm) to 1 atm versus 1 atm to vacuum was initiated by W.K. Dahm,[1] Aerophysics Division Chief, Marshall Space Flight Center (MSFC). His concern was that the effects of compressible gas dynamics of air under these two conditions might lead to erroneous test data concerning actual on-orbit leak rates.

II. METHODOLOGY

A. Initial Discussion

Seal air leaks are attributed to various sources, such as permeation of air through the material, exudation of the seal material, offgassing of seal material constituents, and virtual or actual seal leak paths. In this report, the leak rate analysis addresses those leak paths that under idealized conditions could contribute to excessive atmospheric leakage of the modules.

The prediction of the actual behavior of air leaking past an elastomeric seal is extremely difficult. However, by using uniform flow paths and assuming idealized flow conditions, the compressible gas laws can be applied to estimate the air flow rates. This document will concentrate on two distinct methods of analysis, adiabatic pipe flow theory and compressible gas flow through an orifice.

B. Adiabatic Pipe Flow Analysis

This analysis considers the seal leak path as air flowing through a long slender pipe with a relatively high length-to-diameter (L/D) ratio, discharging air from a pressure chamber to a very large area. Since the gas in the flow area and the surrounding air are considered to be at the same temperature, this is an adiabatic flow problem, i.e., no heat transfer. Also, since the initial flow velocity of the gas is zero, the flow may be considered to be laminar.

Flow of fluid in a pipe is always accompanied by friction, therefore, there must be a pressure drop in the direction of flow. Since pressure decreases and velocity increases as the fluid proceeds downstream in the pipe, the maximum velocity occurs in the downstream end of the pipe. If the velocity is sufficiently high, the exit velocity will reach its maximum value, the velocity of sound or sonic velocity. Any further reduction in pressure will not increase the fluid flow. This "surplus" pressure drop caused by a decrease in exit pressure will take place beyond the end of the pipe, and it results in shock waves or turbulent jetting of the fluid. If the pipe length is extended, there is a reduction in the flow rate, and the flow is considered to be "choked."

The equation for sonic velocity in the pipe is expressed as:

$$v_s = \sqrt{kgRT} = \sqrt{kg\,144\,P'\,\overline{V}} \ , \tag{1}$$

where k is the ratio of specific heat at constant pressure to constant volume = 1.4, for air, g is the acceleration of gravity in ft/s^2, P' is the absolute pressure of the gas in lb/in^2, and $\overline{V}$ is the specific volume of the gas in ft^3/lb.

Maximum velocity, v_s, occurs at the downstream end of the flow path, when the pressure drop is sufficient. The pressure, temperature, and specific volume are those occurring at that point. Considering the restricted flow due to the velocity limitations, correction factors have been established, which can be applied to the flow equations to yield the correct flow rates for these "limiting" conditions. Since these correction factors compensate for the changes in fluid properties due to the expansion of the fluid, they are known as net expansion factors, Y. The limiting values for adiabatic pipe flow, choked versus unchoked conditions, for ΔP of 1 atm, are shown on the curve in figure 1.

The pressure drop along the length of the pipe, or head loss, is generally given as the term resistance coefficient, K, and, for this problem, is defined as;

$$K = 4f\frac{L}{D} \ , \tag{2}$$

where f is the friction factor (dimensionless), L is the pipe length (in inches), and D is the pipe equivalent diameter (in inches).

If the flow is laminar, i.e., the Reynolds number, $R_e < 2{,}000$, the friction factor may be determined from the equation:

$$f = \frac{64}{R_e} \ . \tag{3}$$

In this analysis, the cross-sectional areas of the leak flow paths have been determined by researching test reports on seal data from previous programs and selecting various credible seal flaws (fig. 3). These flaws are noncircular cross-sections, however, by using the hydraulic radius, R_H, the equivalent diameter, D, of the pipe can be found.

$$R_H = \frac{\text{cross–sectional flow area}}{\text{wetted perimeter}} \ , \tag{4}$$

$$D = 4R_H \ . \tag{5}$$

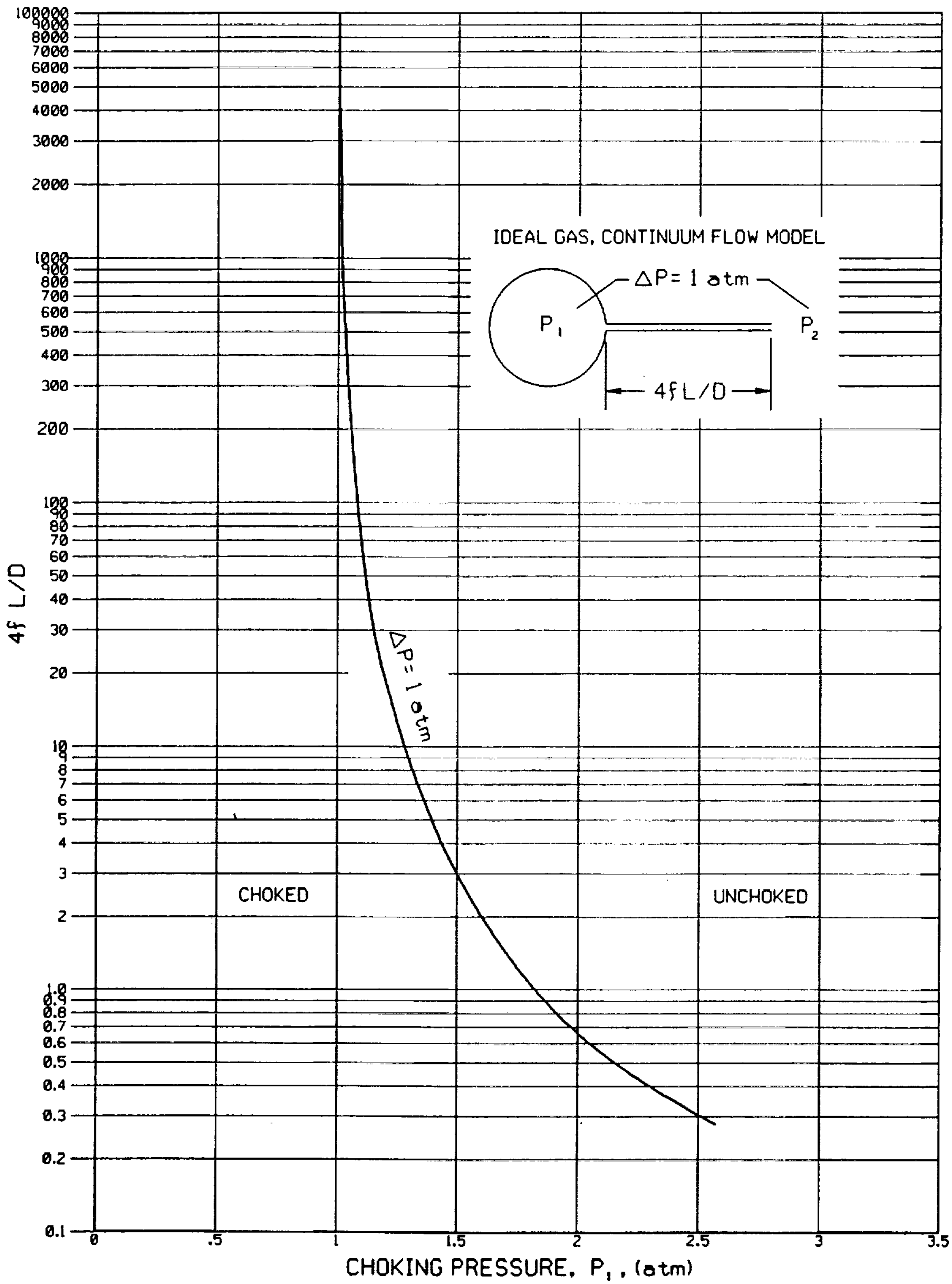


Figure 1. Choking of a viscous, adiabatic pipe flow.[1]

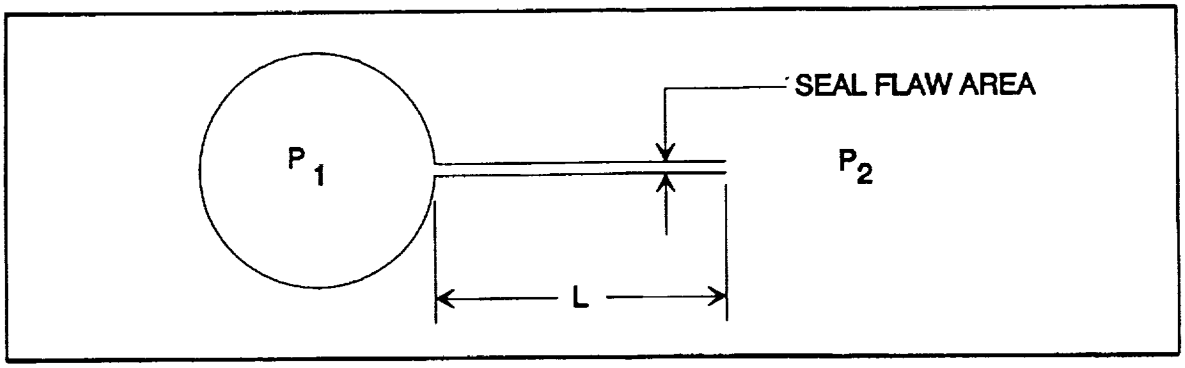
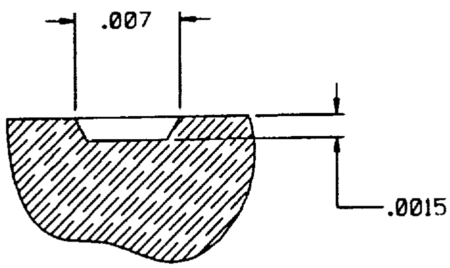
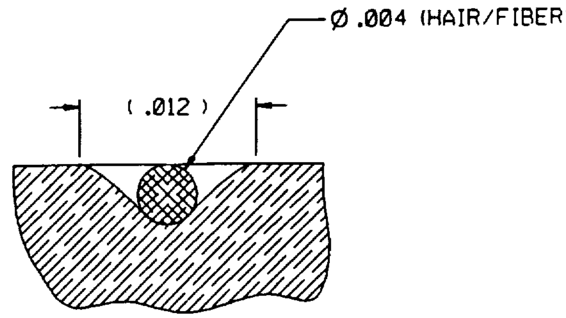


Figure 2. Pipe flow diagram for seal leak rate analysis.

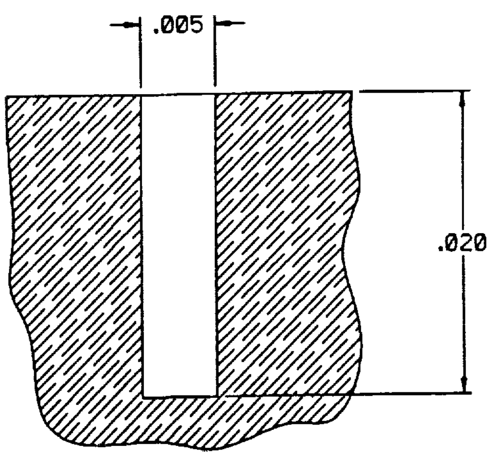
Typical seal flaw geometry used in this analysis is depicted in figure 3. These flaws are used to determine the flow area and to simulate the pipe cross section for this analysis.



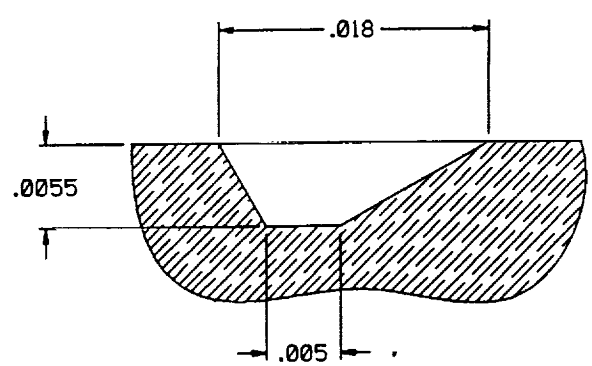
Seal Flaw No. 1
Ref: Atomic Energy of Canada, Ltd., Seal Testing Program
Area: 9.2×10^{-6} in^2
Wetted P: .0157 in
Hyd. Rad: 5.86×10^{-4} in



Seal Flaw No. 2
Ref: RSRM O-Ring Characteristics During Testing, TWR-16994
Area: 1.1×10^{-5} in^2
Wetted P: .0329 in
Hyd. Rad: 3.3×10^{-4} in



Seal Flaw No. 3
Ref: RSRM Defect Detection & Rejection Requirements, TWR-17750, Rev A
Area: 1.0×10^{-4} in^2
Wetted P: .050 in
Hyd. Rad: 2.0×10^{-3} in



Seal Flaw No. 4
Ref: Atomic Energy of Canada, Ltd., Seal Testing Program
Area: 6.3×10^{-5} in^2
Wetted P: .0406 in
Hyd. Rad: 1.55×10^{-3} in

Figure 3. Credible seal flaw geometry.

An idealized flow problem can now be defined, and pipe flow theory can be used to determine the air flow rates.

Given: Air flows from P_1 to P_2, adiabatically at standard room temperature, 70 °F. Assume laminar flow condition for each case. The leak path length is the distance across the seal footprint (for 0.275 O-ring, approximately 0.255 in). Two cases will be studied for each seal flaw.

Case 1: $P_1 = 2$ atm absolute (14.7 lb/in^2 gauge) $P_2 = 1$ atm
Case 2: $P_1 = 1$ atm, (14.7 lb/in^2 absolute) $P_2 = 0$ (vacuum)

Using the Darcy[2] pipe flow equation for compressible fluid flow through a pipe and discharging to a larger area,

$$q_m = 678\, Y D^2 \sqrt{\frac{\Delta P\, P'}{K T_1 S_g}} \quad . \tag{6}$$

Equation (6) will yield the flow rate in standard cubic feet per minute (ft^3/min). ΔP is the pressure differential between P_1 and P_2, P' is the chamber pressure, T_1 is the absolute temperature in °R, and S_g is the ratio of specific gravity to air, which would be 1, since the gas is air for this problem.

Refer to seal flaw geometry in figure 3 for hydraulic radius and equivalent diameter information.

Seal Flaw No. 1: Case 1

$$R_H = 5.86\times10^{-4} \text{ in}$$

$$D = 4(5.86\times10^{-4} \text{ in}) = 2.34\times10^{-3} \text{ in}$$

$$\text{At } R_e = 1{,}500\,, \quad \therefore f = 64/1{,}500 = 0.043$$

$$K = 4 f L/D = 4\,(0.043)\,(0.255/2.34\times10^{-3}) = 18.7$$

Find expansion factor, Y, in figure A-1, at $k = 1.4$

$$\text{At } K = 18.7 \text{ and } \Delta P/P' = 0.5, \quad \therefore Y = 0.82$$

$$q_m = 678\,(0.82)(2.34\times10^{-3})^2 \sqrt{\frac{(14.7)(29.4)}{(18.7)(530)(1)}} \;,$$

$$q_m = 6.36\times10^{-4}\, \frac{\text{ft}^3}{\text{min}} \text{ (convert to standard cc per second)}$$

$$q_s = 6.36\times10^{-4}\, \frac{\text{ft}^3}{\text{min}} \left[\frac{1 \text{ min}}{60 \text{ s}}\right]\left[(30.48)^3\, \frac{\text{cc}}{\text{ft}^3}\right] ,$$

$$q_s = 0.300 \text{ sccs} \;.$$

Seal Flaw No. 1: Case 2

At $K = 18.7$ and $\Delta P/P' = 1$ $\quad \therefore \; Y =$ "limiting factor"

Interpolate for expansion factor, Y:

From figure A-1, limiting factors for sonic velocity

K	$\Delta P/P'$	Y
15	0.818	0.702
18.7	a	b
20	0.839	0.710

$$a = 0.839 - \frac{(1.3)(0.021)}{5} \qquad b = 0.710 - \frac{(1.3)(0.008)}{5} \; ,$$

$$a = \Delta P/P' = 0.834 \qquad b = Y = 0.708$$

$$\therefore \; \Delta P = (14.7)(0.834) = 12.26 \text{ lb/in}^2$$

$$q_m = 678\,(0.708)(2.34\times10^{-3})^2 \sqrt{\frac{(12.26)(14.7)}{(18.7)(530)(1)}} \; ,$$

$$q_m = 3.54\times10^{-4} \, \frac{\text{ft}^3}{\text{min}} \text{ (convert to standard cc per second)}$$

$$q_s = 3.54\times10^{-4} \, \frac{\text{ft}^3}{\text{min}} \left[\frac{1 \text{ min}}{60 \text{ s}}\right] \left[(30.48)^3 \, \frac{\text{cc}}{\text{ft}^3}\right] ,$$

$$q_s = 0.167 \text{ sccs} \; .$$

The flow rates for the remaining seal flaw cases for pipe flow analysis are summarized in table 1.

Table 1. Seal flaw leak rate analysis summary.

Seal Flaw No.	Case No.	Hydraulic Radius (R_H) (in)	Equivalent Diameter (D) (in)	Resistance Coefficient (K)	Flow Rate (sccs)	
					Pipe	Orifice
1	1	5.86×10^{-4}	2.34×10^{-3}	18.7	0.300	0.661
	2				0.167	0.463
2	1	3.30×10^{-4}	1.32×10^{-3}	33.2	0.073	0.211
	2				0.041	0.150
3	1	2.00×10^{-3}	8.00×10^{-3}	5.5	6.072	7.787
	2				3.457	5.470
4	1	1.55×10^{-3}	6.20×10^{-3}	7.1	3.251	4.665
	2				1.734	3.298

C. Compressible Fluid Flow Through an Orifice Analysis

This analysis considers the seal leak path as an orifice discharging air to the atmosphere from a pressure chamber (fig. 4). The flow of compressible fluids through nozzles and orifices can be expressed by the following equation, which includes the net expansion factor, Y:

$$q_m = 678\, Y\, d_0^2\, C \sqrt{\frac{\Delta P\, P'}{T\, S_g}} \quad . \tag{7}$$

The net expansion factor, Y, is a function of:

1. The specific heat ratio, k.

2. The ratio of orifice or throat diameter to inlet diameter.

3. The ratio of downstream to upstream absolute pressure.

To use equation (7) for a compressible fluid discharge to the atmosphere, the flow coefficient, C, must be used in a Reynolds number regime where C is a constant for a given diameter ratio.

Given: Room temperature air discharges from a large diameter inlet, at pressure P_1, through an orifice to an open area, at pressure P_2. The ratios of the inlet diameter to the orifice diameter are very small, so that $d_0/d_1 \approx 0$.

Case 1: $P_1 = 2$ atm absolute (14.7 lb/in^2 gauge) $P_2 = 1$ atm
Case 2: $P_1 = 1$ atm, (14.7 lb/in^2 absolute) $P_2 = 0$ (vacuum)

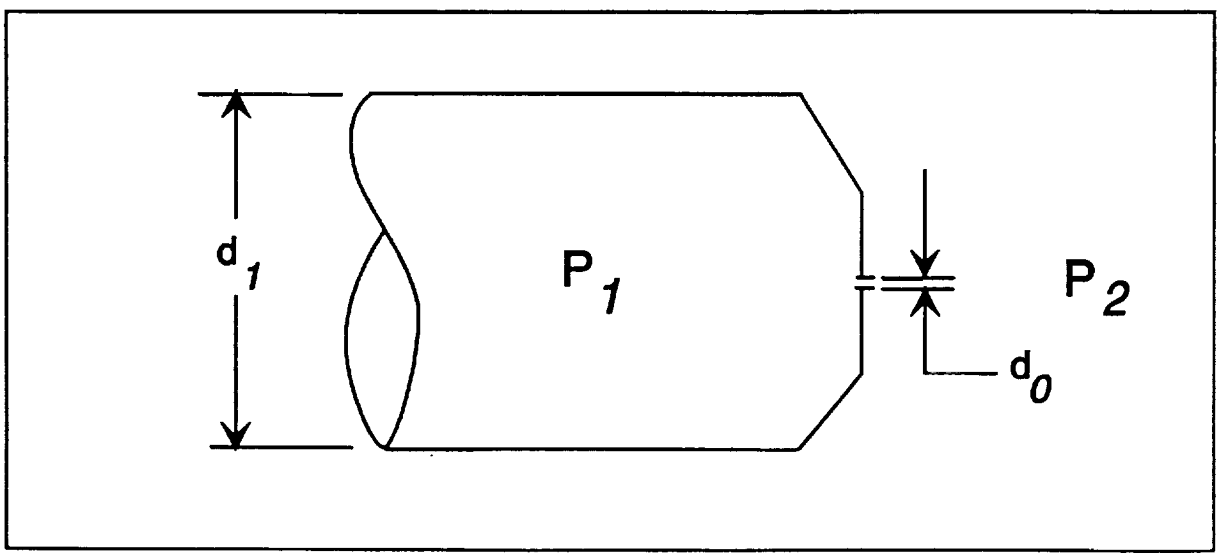


Figure 4. Compressible fluid orifice discharge for seal leak rate analysis.

Seal Flaw No. 1: Case 1

$$q_m = 678\, Y\, d_0^2\, C \sqrt{\frac{\Delta P\, P'}{T\, S_g}} \;.$$

Equation (7) will yield the flow rate in standard ft³/min.

d_0 = use the equivalent diameter of the seal flaw

d_1 = use the module internal diameter, 166 in

$$\Delta P = 14.7 \text{ lb/in}^2 \quad P' = 29.4 \text{ lb/in}^2 \text{ absolute} \;.$$

Find expansion factor, Y, in figure A-2

$$\text{At } \Delta P/P' = 0.5 \text{ and } d_0/d_1 = 0 \text{ to } 0.2 \;, \quad \therefore\; Y = 0.70 \;.$$

Find flow coefficient, C, in figure A-3.

$$\text{At } R_e \approx 2{,}000 \text{ and } d_0/d_1 = 0 \text{ to } 0.2, \quad \therefore\; C = 0.60 \;.$$

S_g = 1, for gas air, and T = 530 °R, for room temperature air.

$$q_m = 678(0.70)(2.34\times10^{-3})^2\,(0.60)\sqrt{\frac{(14.7)(29.4)}{(530)(1)}} \;,$$

$$q_m = 1.40\times10^{-3}\,\frac{\text{ft}^3}{\text{min}} \text{ (convert to standard cc per second)}$$

$$q_s = 1.40\times10^{-3}\,\frac{\text{ft}^3}{\text{min}}\left[\frac{1 \text{ min}}{60 \text{ s}}\right]\left[(30.48)^3\,\frac{\text{cc}}{\text{ft}^3}\right] ,$$

$$q_s = 0.661 \text{ sccs} \;.$$

Seal Flaw No. 1: Case 2

$$q_m = 678\, Y\, d_0^2\, C \sqrt{\frac{\Delta P\, P'}{T\, S_g}} \;.$$

d_0 = use the equivalent diameter of the seal flaw

d_1 = use the module internal diameter, 166 in

$$\Delta P = 14.7 \text{ lb/in}^2 \quad P' = 14.7 \text{ lb/in}^2 \text{ absolute} \;.$$

Find expansion factor, Y, in figure A-2

$$\text{At } \Delta P/P' = 1.0 \text{ and } d_0/d_1 = 0 \text{ to } 0.2 \;, \quad \therefore\; Y = 0.69 \;.$$

Find flow coefficient, C, in figure A-3.

$$\text{At } R_e \approx 2{,}000 \text{ and } d_0/d_1 = 0 \text{ to } 0.2, \quad \therefore\ C = 0.60\ .$$

$S_g = 1$, for gas air, and $T = 530$ °R, for room temperature air.

$$q_m = 678\ (0.69)(2.34\times10^{-3})^2\ (0.60)\sqrt{\frac{(14.7)(14.7)}{(530)(1)}}\ ,$$

$$q_m = 9.8\times10^{-4}\ \frac{\text{ft}^3}{\text{min}}\ \text{(convert to standard cc per second)}$$

$$q_s = 9.8\times10^{-4}\ \frac{\text{ft}^3}{\text{min}}\left[\frac{1\ \text{min}}{60\ \text{s}}\right]\left[(30.48)^3\ \frac{\text{cc}}{\text{ft}^3}\right]\ ,$$

$$q_s = 0.463\ \text{sccs}\ .$$

The flow rates for the remaining seal flaw cases for orifice analysis are summarized in table 1.

III. TESTING VERIFICATION

A. Test Objective

Subscale development testing was performed in order to validate the perceived relationship in leak rate ratios described in the foregoing analysis. The testing was accomplished by introducing a single flaw to an O-ring seal by placing a very small fiber material across the sealing footprint of the test fixture. The pressure differential across the seal was produced by a gas nitrogen source on the high-pressure side and a vacuum pump on the low-pressure side of the seal.

B. Test Description

The general test configuration is shown in figure 5. The equipment used to conduct the test included a vacuum pump (0.5 torr range), a glass bell jar with a sealed flange, pressure transducers (0 to 50 lb/in^2 absolute range), regulated dry gas nitrogen, a temperature sensor, a vacuum gauge, pneumatic lines, connections, and isolation and venting valves. The data acquisition system consisted of a personal computer that recorded the pressure transducer readings at intervals of 1 second.

The O-ring test fixture was made from a circular stainless steel plate. One half of the fixture housed two O-ring glands, and the other half had a small internal cavity to create a pressure chamber. The fixture halves were bolted together in eight places. Pressure was introduced to the internal cavity of the fixture through the pneumatic connections.

The test specimen used was a fluorocarbon (Viton V747-75[3]) elastomer material O-ring. The O-ring used had a 5.19-inch outer diameter dimension. The nominal cross section was 0.281 inches in diameter. The fixture's gland size was based on industry standard dimensions for this size seal (fig. 6). The seal was placed in the outer gland of the fixture, and a seal squeeze of 17 percent was created and controlled by placing shims between the fixture halves. Normally, vacuum seals are lightly lubricated which improves their sealing ability; however, the seal was used in a dry, or nonlubricated, condition for

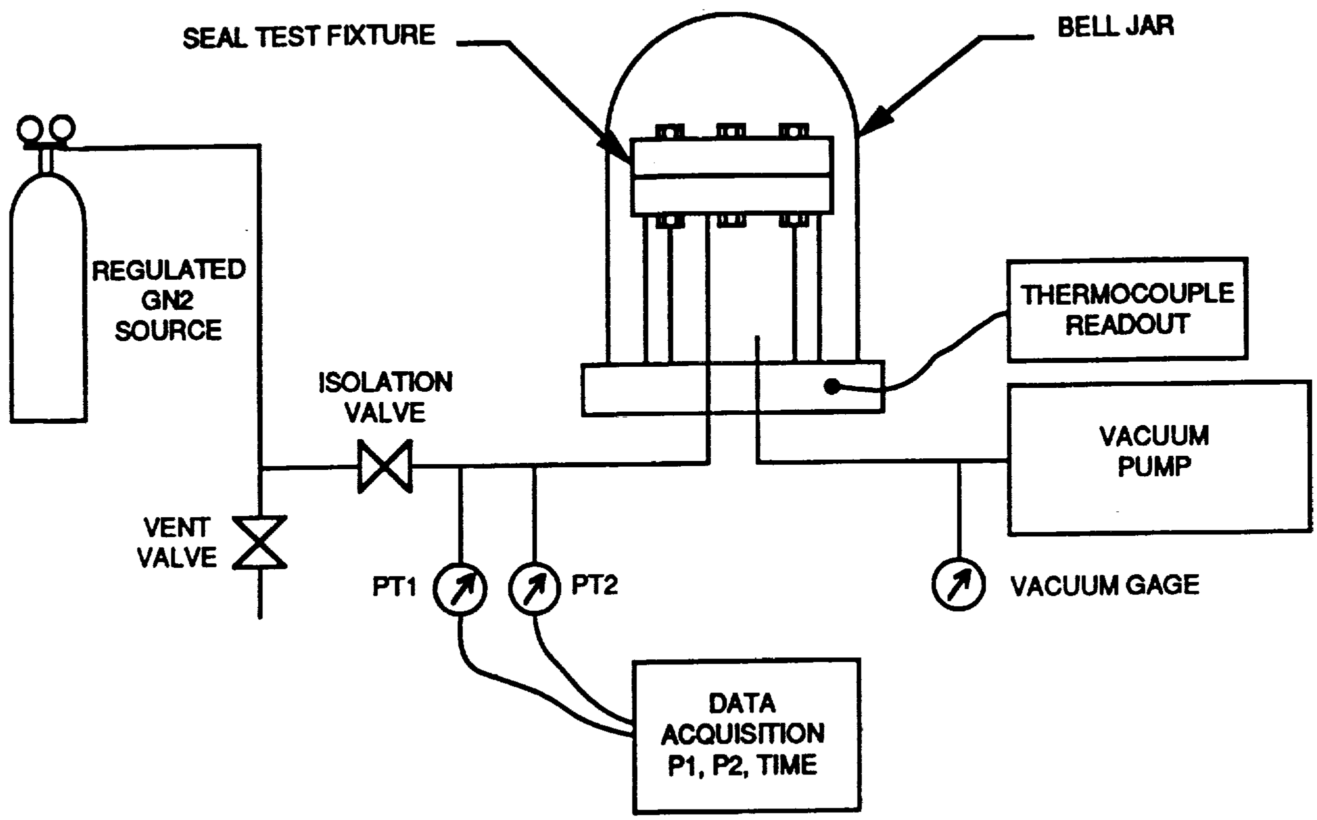


Figure 5. General leak rate test configuration.

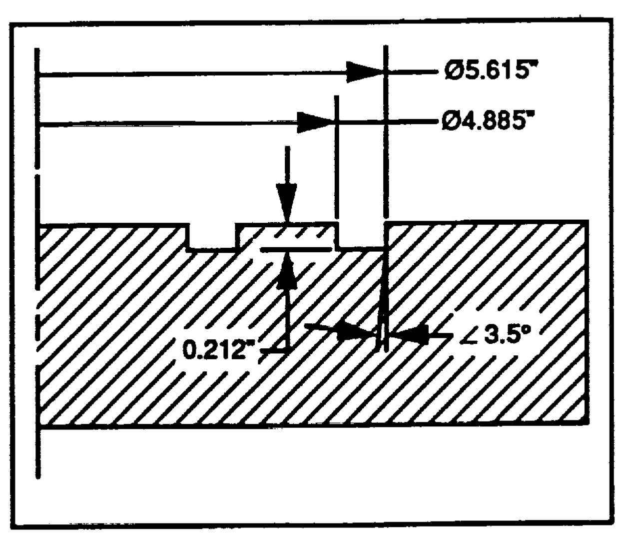


Figure 6. Test fixture gland dimensions.

this test. Pressure was recorded for each second of the test from transducers PT1 and PT2. The seal test was conducted three times for each leak type, and the leak rates were averaged over the duration of the test. The test was terminated after an appreciable amount of pressure drop was achieved.

C. Test Data

A total of seven tests were conducted. The first test was to validate the test setup itself in order to assure a "leak-tight" system and to establish the baseline test. Subsequent testing simulated five different flaws using various fiber/wire sizes. In addition, an O-ring with a poor splice was also tested. The results of all testing are summarized in table 2.

Table 2 summarizes the subscale testing leak rate results. These leak rate values are average leak rates for the specific test. The leak rate ratios are determined by dividing the average leak rate values of the 2 atm to 1 atm leak rate values to the 1 atm to vacuum leak rate values.

Table 2. Leak rate test results summary[5]

Flaw Type/ Fiber Size	Average Leak Rates (sccs)		Leak Rate Ratio 2/1 : 1/0
	2 atm/1 atm	1 atm/0 atm	
Baseline	4.74×10^{-4}	5.20×10^{-5}	9.12 : 1
1.8 mil	4.28×10^{-4}	7.20×10^{-5}	5.94 : 1
2.4 mil	4.89×10^{-2}	1.41×10^{-2}	3.47 : 1
3.0 mil	1.85×10^{-1}	7.53×10^{-2}	2.46 : 1
4.0 mil	2.18×10^{-1}	7.77×10^{-2}	2.81 : 1
5.0 mil	6.81×10^{-1}	2.35×10^{-1}	2.90 : 1
Splice	4.44×10^{-3}	1.84×10^{-3}	2.41 : 1

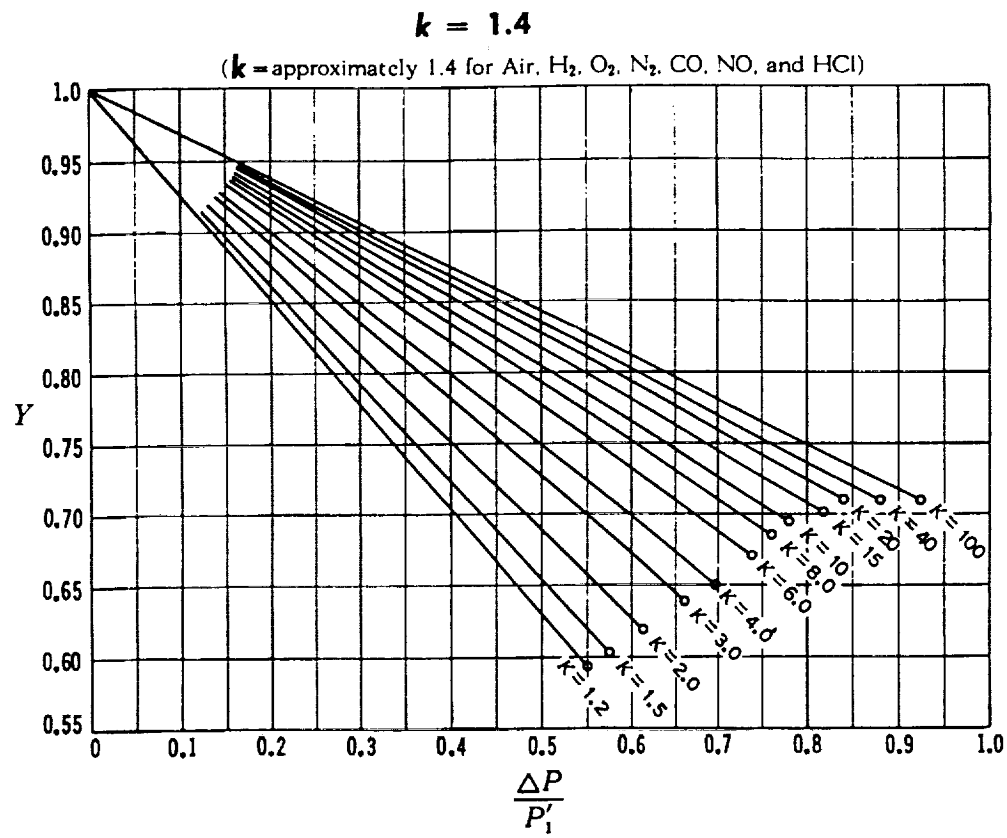
IV. CONCLUSION

Based on the leak rate analysis and the development testing performed over the course of this investigation, it is concluded that there exists a difference in the relationship of air leakage rates between pressure differentials of 2 atm to 1 atm and from 1 atm to vacuum.

Seal air leaks in a vacuum environment tend to leak at a slower rate than those in a standard atmosphere. The limited degree of testing performed makes it difficult to predict if this relationship would hold true for all types of leaks, and does not address permeation leak rates. However, within the scope of this investigation, the proposed method for qualifying the atmospheric leakage rate requirements by testing the pressurized elements in standard atmosphere facilities should be considered acceptable. Assuming that the leak rate requirements can be satisfied under this condition, the actual leak rates should be less in the space environment. This conservative approach would thereby provide an additional margin of safety for atmosphere leakage rate testing for the S.S. *Freedom* elements.

APPENDIX A

Physical Properties of Fluids and Flow Characteristics of Orifices and Pipes



Limiting Factors For Sonic Velocity

***k* = 1.4**

K	$\frac{\Delta P}{P'_1}$	Y
1.2	.552	.588
1.5	.576	.606
2.0	.612	.622
3	.662	.639
4	.697	.649
6	.737	.671
8	.762	.685
10	.784	.695
15	.818	.702
20	.839	.710
40	.883	.710
100	.926	.710

Figure A-1. Net expansion factor Y for compressible flow through pipe to a larger area.[2]

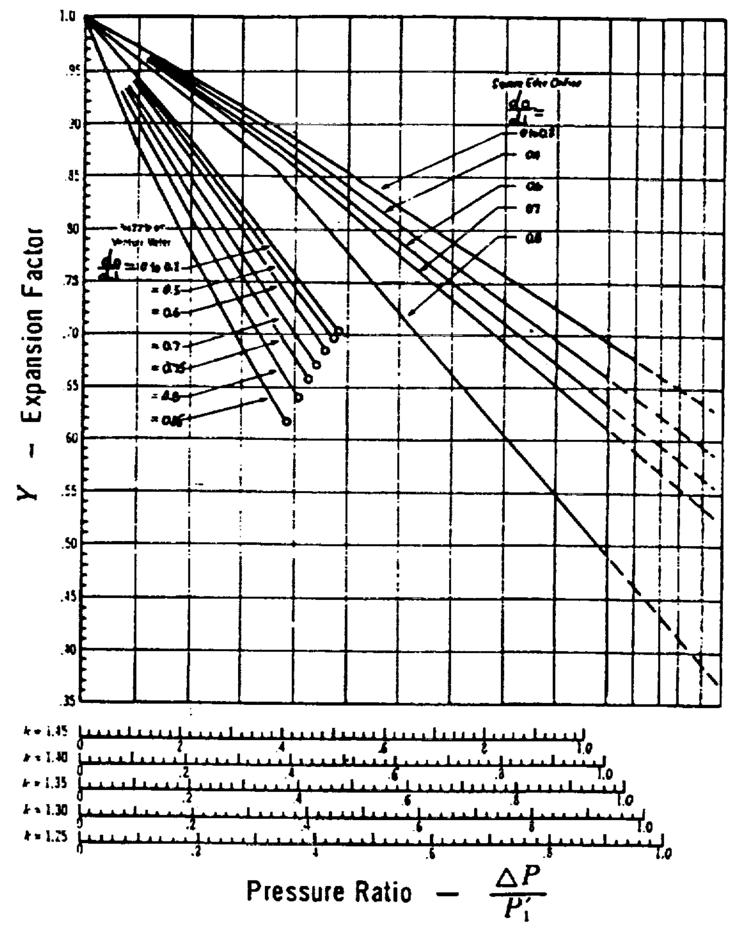


Figure A-2. Net expansion factor *Y* for compressible flow through nozzles and orifices.[2]

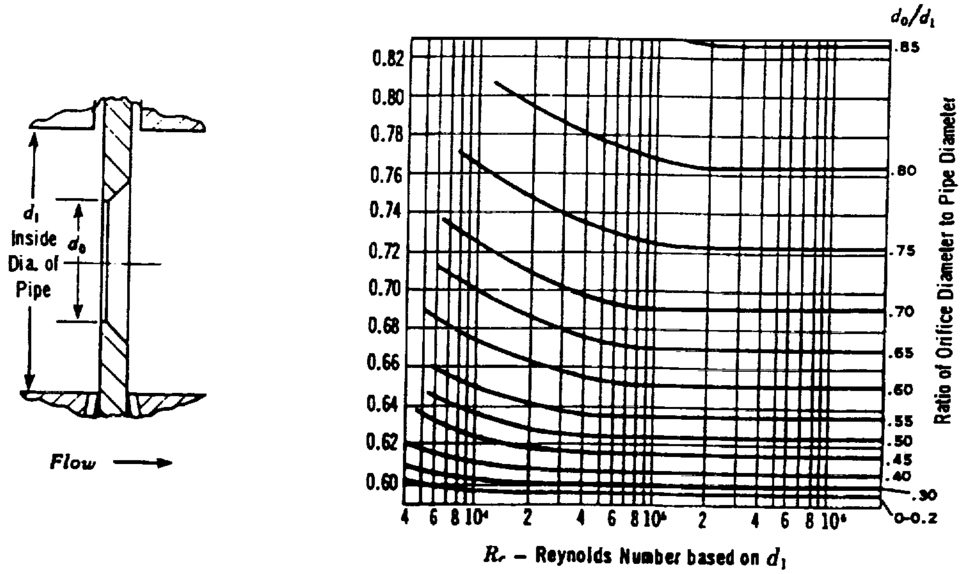


Figure A-3. Flow coefficient C for square-edged orifices.[2]

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1. Dahm, W.K.: Presentation to the NASA/Boeing Technical Interchange Meeting, MSFC, December 20, 1991 (including Figure 1, Choking of Viscous, Adiabatic Pipe Flow).

2. The Crane Company: "Flow of Fluids Through Valves, Fittings, and Pipe." Technical Paper No. 410, Crane Co., Engineering Division, 1961 (used by written permission).

3. Compound V747-75 is a designation of Parker Hannifin Corporation, Parker Seals Division, Parker O-Ring Handbook No. ORD 05700. Viton is a trade name of E.I. DuPont de Nemours Company.

4. Shapiro, A.H.: "The Dynamics and Thermodynamics of Compressible Fluid Flow." The Ronald Press Company, Chapter 6, 1953.

5. NASA/MSFC: "Space Station *Freedom* (S.S. *Freedom*) Seal Flaw Study With Delta Pressure Leak Rate Comparison Test Report." Test report number SSF/DEV/EL91-008, Experiment and Components Test Branch, Systems Test Division, System Analysis and Integration Laboratory.

APPROVAL

SPACE STATION *FREEDOM* SEAL LEAKAGE RATE ANALYSIS AND TESTING SUMMARY: AIR LEAKS IN AMBIENT VERSUS VACUUM EXIT CONDITIONS

By P.I. Rodriguez and R. Markovitch

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

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