NASA Technical Paper 1346

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NOVEMBER 1978

NASA

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Cleveland, Ohio

NASA
National Aeronautics
and Space Administration

Scientific and Technical
Information Office

1978

SUMMARY

Studies were conducted to compare the theoretical results of two NASA Lewis Research Center computer programs for compressible flow across radial face seals with experimental results. These programs were QUASC, for seals with parallel faces and a negligible change in the flow area or cross section due to radial difference, and AREAX, for seals with area change due to either converging or diverging faces or due to an appreciable radial area change. A seal simulator rig with a dam inside diameter of 13.97 centimeters and an outside diameter of 15.24 centimeters was used in the experiment. A nominal clearance of 0.00254 centimeter (0.001 in.) gave ratios of flow length to clearance within the range encountered in seals. Studies were conducted for sealed pressures of 20.7, 41.4, and 62.1 N/m^2 at pressure ratios (ambient pressure/sealed pressure) of 0.9, 0.8, 0.6, 0.4, 0.2, and 0.1.

Both computer programs, QUASC and AREAX, gave results for leakage within 3 percent of the measured values. When theory and experiment were correlated, the calculated loss coefficient, based on measured pressures, ranged from 0.47 to 0.68 for the pressure ratios studied. The calculated pressure profile was within 2.5 N/cm^2 of the experimental values when AREAX was used and within 2.0 N/cm^2 when QUASC was used.

INTRODUCTION

In close-clearance gas-film seals, there is leakage flow of a compressible fluid through a long, thin slot. The ratio of flow length to clearance is usually between 100 and 1000. A schematic of a close-clearance radial face seal is shown in figure 1(a).

In addition to leakage, a major concern, discussed in reference 1, is the equilibrium clearance determined by the balance of opening and closing forces acting on the seal. Therefore a good knowledge of the pressure gradient (profile) along the flow length is required, so that opening force can be predicted reasonably accurately. Accurate determination of opening force is particularly important for close-clearance seals, since small errors in clearance produce a relatively large error in leakage.

Compressible, one-dimensional duct flow, a good basic approximation of flow in seals, is readily handled in an analytical treatment (e.g., ref. 2). The resulting differential equations are solved by numerical methods. This treatment is quite general and handles choked flow and other factors involved in design considerations. A major shortcoming of this model is the lack of knowledge regarding the inlet region effects.

One way to handle inlet effects is to use the Bernoulli equation modified by an empirical loss coefficient (ref. 1). The pressure at the inlet that is calculated in this way is then used in the one-dimensional duct flow model.

At the NASA Lewis Research Center, two computer programs for radial face seals have been developed. These programs are called QUASC (refs. 3 and 4) and AREAX (ref. 5). The basis is a one-dimensional theory using the loss-coefficient method of handling inlet effects. Adiabatic flow is assumed, since the seal dimensions and flow rates normally encountered imply small or negligible heat transfer. Also the seal faces are assumed to be perfectly flat. Both programs handle choked and nonchoked flow. QUASC assumes a constant cross section, normal to the direction of flow, along the flow length; that is, the change in radius is assumed to be negligible compared with the mean radius. AREAX includes the effect of area change due to tilt (axisymmetric convergence or divergence of faces). These programs calculate the leakage, pressure profile, and net seal opening force as well as other factors (e.g., torque and temperature changes due to expansion). The programs assume that the pressure change across the seal acts independently of rotation (ref. 1 discusses the interaction of pressure and rotation).

The objectives of the study were (1) to compare analyses (pressure gradient and leakage) of a seal configuration by QUASC and by AREAX with experimental results over a range of pressure ratios (ambient pressure/sealed pressure P_a/P_s) and (2) to determine the effect of pressure ratios on the inlet loss coefficient.

The tests were conducted in a static (nonrotating) seal simulator rig having a nominal ratio of flow length to clearance of 250, which is typical of seal practice, and a nominal clearance of 0.00254 centimeter. Tests were conducted at nominal sealed pressures of 21, 41, and 62 N/cm^2 and pressure ratios of 0.9, 0.8, 0.6, 0.4, 0.2, and 0.1.

APPARATUS AND PROCEDURE

The flow in the seal simulator rig used is shown in figure 1(b), and a schematic of the instrumentation and flow control system is presented in figure 2. Nominal dam dimensions were the following: inside diameter, 13.97 centimeters; outside diameter, 15.24 centimeters; and step height (from the inlet chamber), 0.64 centimeter. The nominal clearance of 0.0025 centimeter was obtained by inserting a shim stock gasket in the bolt circle area. The dam radial length of 0.640 centimeter gave a length-height ratio of 231, typical of seals. The ratio of step height to clearance permitted neglect of velocity in the inlet chamber when determining inlet effects. Flow rates were determined with a set of two rotameters covering the range of flow rates. Pressures were determined at 12 points across the flow length, in the inlet chamber, and in the outlet manifold. A single pressure transducer coupled to the taps through a rotating port was read with a digital voltmeter. In addition, the inlet and outlet taps were connected to precision pressure gages. Temperatures were determined in the inlet chamber and upstream of the rotameters by thermocouples and read with a digital thermometer.

The rig was supplied with filtered air at a pressure of 103.4 N/cm^2 and exhausted to a vacuum line. The inlet (sealed) and outlet (ambient) pressures in the rig were adjusted with valves. When stable pressures close to the nominal values were indicated by the pressure gages, readings were taken. Flow rate and temperature readings were taken before and after the pressure transducer readings. Also the inlet and outlet pressures were read before and after the pressures in the seal. These readings were compared to reject runs during which appreciable (greater than 1 percent) changes occurred because of air supply fluctuations. For the runs with acceptable changes, the change was assumed to be linear, and the pressure data were adjusted accordingly.

An estimation of the errors in the data used for the analysis is presented in the appendix.

RESULTS AND DISCUSSION

General Character of Pressure Profile

Runs were made at three nominal sealed pressures and six pressure ratios (P_a/P_s), as shown in table I.

Typical plots of $\overline{P}$ (pressure/sealed pressure) across the seal dam are presented in figure 3. One thing to note is that the orifices of taps 1, 2, and 12 (counting from left to right) extend beyond the edges of the dam (compare the tap diameter indicated in fig. 3(a) with the distance of the tap centerline from the edge). Therefore these readings are influenced by pressure outside the seal gap. However, they are of qualitative value in indicating the pressure profile and so are included. A second thing to note is that taps 3, 6, and 9 show pressures below the general trend (noticeable in fig. 3(c)). These taps are located opposite outlet ports, where a higher flow rate and, therefore, a lower static pressure can be expected.

Once a pressure profile is established, the entrance region can be examined. As illustrated in figure 3(a), the 21-N/cm^2 runs show a smooth transition from sealed pressure to viscous flow (constant velocity profile normal to the flow direction), as predicted by references 6 and 7. However, the 41- and 62-N/cm^2 runs, as shown in figures 3(b) and (c), have a minimum pressure in the vicinity of tap 2. This may be a vena contracta effect. The probable explanation of this is that the top surface is basically smooth for some distance ahead of the seal gap. Since the buildup of a boundary layer along a flat plate is inversely proportional to the square root of the Reynolds number, it seems likely that the effect of the vena contracta is negligible for only the 21-N/cm^2 runs (compare Reynolds numbers in table II).

Inlet Loss Coefficient

The viscous portions of the experimentally determined pressure profiles were extrapolated to the inlet (i.d.). The loss coefficients required to give the observed drops from sealed to inlet pressure with AREAX and with QUASC were determined by trial and error. AREAX could not reach a solution for the two higher pressure ratios (0.8 and 0.9), probably because of limitations of the numerical methods used. Although QUASC returned solutions at these pressure ratios, there is reason to think these solutions are subject to limitations in the numerical methods used. For this reason, only the results for pressure ratios of 0.6 and below are considered valid and are presented in table II.

For pressures of 21, 41, and 62 N/cm^2 and pressure ratios of 0.6, 0.4, 0.2, and 0.1, QUASC required loss coefficients between 0.47 and 0.66. For the same range of pressures and pressure ratios, AREAX required loss coefficients between 0.49 and 0.68. Figure 4 presents a plot of loss coefficient as a function of pressure ratio at the three sealed pressures for AREAX (QUASC is consistently lower). These coefficients are affected by pressure and by pressure ratio. At and above 41 N/cm^2, the loss coefficient can probably be predicted on the basis of pressure ratio alone for a given clearance and seal geometry.

Comparison of Calculated Parameters From AREAX and QUASC

The only real difference between the results from QUASC and from AREAX in table II is in the loss coefficients, the maximum difference being less than 5 percent. The leakage rates are nearly the same, and the net forces can be regarded as almost identical.

The Reynolds numbers for QUASC are calculated at the inlet. Those for AREAX are the mean of inlet and outlet values; thus the differences are not significant. With 2300 taken as the highest Reynolds number at which the flow is always laminar, the runs at 21 and 41 N/cm^2 have laminar flow. When the 62-N/cm^2 runs are considered, only the pressure ratios of 0.6 and possibly 0.4 are surely laminar; it is not impossible (considering errors and approximations) that the flow is turbulent at pressure ratios of 0.2 and 0.1.

Comparison of Predicted and Experimental Leakages

Table III compares predicted and experimental leakages. Except for sealed pressures of 41 and 62 N/cm^2 at a pressure ratio of 0.6, the predictions are greater than experimental values. At 21 N/cm^2, both AREAX and QUASC predict a leakage rate within 2 percent of experimental. At 41 N/cm^2, the agreement is within 4 percent.

The worst agreement with experimental leakage values is 8 percent at 62 N/cm^2; the deviation is negative at the 0.6 pressure ratio for 41 and 62 N/cm^2. Otherwise the deviation is positive.

Comparison of Predicted and Experimental Pressure Profiles

Comparisons of experimental pressures with the pressure profile calculated by AREAX are presented in figure 5 for a P_a/P_s of 0.6, 0.4, and 0.2. Taps 1, 2, and 12 are omitted. For a P_s of 21 N/cm^2, predicted pressures are a good match of the experimental, the maximum deviation being within 2.5 N/cm^2. For a P_a/P_s of 0.6 (fig. 5(a)), the match is good at pressures of 41 and 62 N/cm^2 except in the inlet region (taps 3, 4, and 5). For a P_a/P_s of 0.4 (fig. 5(b)), the predicted pressures are somewhat lower (maximum error, 0.2 N/cm^2) than experimental at sealed pressures of 41 and 62 N/cm^2. For a P_a/P_s of 0.2 (fig. 5(c)), the trend is the same. Comparison of the three pressure ratios at sealed pressures of 41 and 62 N/cm^2 shows that predicted pressures are increasingly lower than experimental as pressure ratio decreases. When the net force (represented by the area between a profile and the line $P = P_a$) is considered, it appears by visual examination that the relative error is small, and there is little difference between runs.

Also the readings of tap 12 agree qualitatively with predictions of choking. When AREAX predicts choked flow, tap 12 indicates a pressure that is higher than ambient by a few times the error in the reading. When nonchoked flow is predicted, tap 12 falls within the error range of the ambient pressure.

Pressure predictions by QUASC are so close to those of AREAX that the previous discussion (for AREAX) also holds for QUASC. For most runs, plots of QUASC predictions would be indistinguishable from those of AREAX predictions. The maximum deviation was 2.0 N/cm^2.

SUMMARY OF RESULTS

Calculations obtained from two computer programs (QUASC and AREAX) for determining compressible flow across radial face seals were compared with measured values obtained in a seal simulator rig. The following results were obtained:

1. The loss coefficient varied (from 0.47 to 0.66 for QUASC and from 0.49 to 0.68 for AREAX) over the range of pressure ratios studied. There was not a great difference from the literature. Values for QUASC were consistently about 5 percent below the corresponding values for AREAX.

2. For pressure ratios (ambient to sealed) of 0.6 and lower, AREAX and QUASC predicted leakage rates within 8 percent of experimental.

3. The predicted pressure profiles from AREAX and QUASC were close to experimental values; the maximum difference for QUASC was 2.0 N/cm^2, and for AREAX it was 2.5 N/cm^2.

4. Despite the assumption of negligible area change, QUASC was found to have value in seal analysis, since calculated parameters of leakage, Reynolds number, opening force, and pressure profile agreed closely with the values calculated by AREAX.

5. AREAX and QUASC were unusable above a pressure ratio that is greater than 0.6 but less than 0.8.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, August 1, 1978,
505-04.

APPENDIX - ERROR ANALYSIS

The inlet pressure error was estimated as not greater than 0.5 percent of the sealed absolute pressure for a given run. Also it is suspected that the inlet pressures might be low. For an approximation of leakage error, the classical viscous flow model (ref. 1) is used. It can be presented as $\dot{M} = K\left(P_1^2 - P_2^2\right)/h^3$, where $\dot{M}$ is leakage, P_1 is the inlet pressure, P_2 is the outlet pressure, and h is the clearance. The force generated can be presented as $F = K\left(P_1^2 + P_1P_2 + P_2^2\right)/(P_1 + P_2)$. The resultant error in leakage for P_s of 62 N/cm^2 and a pressure ratio of 0.6 is 2 percent for leakage and 0.4 percent for force. This is the anticipated error in program results due to inlet pressure error.

When calibrated, the rotameters showed noticeable variations from linearity. The low-range rotameter showed a fairly smooth S-curve flow rate plot, which could be matched within 0.5 percent by equations. However, the high-range rotameter had a maximum conversion (of reading to flow rate) error of 2.5 percent.

The pressure transducer readings were checked against a calibrated precision pressure gage, and a conversion accurate to within 0.5 percent above 30 N/cm^2 (within 1 percent at and below 21 N/cm^2) was determined.

The thermocouple readout to the nearest $^{\circ}C$ gives an error of less than 0.5 percent in absolute temperature.

When rotameter readings for pressure and temperature were adjusted, an error of less than 0.5 percent was estimated.

The actual physical dimensions of the dam as well as the clearance were very important to this study. Also distortion of seal gap surfaces must be considered. Although the rig is relatively massive, flexible connections in the outlet manifold were required to avoid noticeable effects of rig distortion on the pressure profile.

Profilometer traces of the seal gap faces of the unassembled rig indicated a combined converging tilt (of top and bottom sections in the direction of flow) of about 0.2 milliradian across the dam and of about 0.3 milliradian across the bolt circle. The top section appeared linear across the dam, but the dam showed barely noticeable convexity (into the gap between the faces) in places.

An investigation of the gap when assembled was conducted by using soft metal pieces which deformed to indicate the clearance profile across the dam. The top surface was greased to prevent adherence of and consequent distortion of the pieces on disassembly. The result indicated nearly parallel surfaces with 0.0028-centimeter mean clearance. However, there was an approximately parabolic convexity into the gap of 0.0003 centimeter between maximum and minimum clearances. After consideration of sources of error, a mean clearance of 0.00277 ± 0.00005 centimeter and a converging tilt of 0.1 ± 0.1 milliradian were determined.

The dam radii were 13.97 and 15.24 centimeters, and the flow length error was less than 1 percent.

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TABLE I. - EXPERIMENTALLY MEASURED LEAKAGES OBTAINED

AT VARIOUS PRESSURES

[Room temperature air; clearance, 0.00254 cm.]

Nominal		Actual[a]			Leakage, kg/min	Sealed temperature, °C
Sealed pressure, P_s, N/cm^2	P_a/P_s	Sealed pressure, P_s, N/cm^2	Ambient pressure, P_a, N/cm^2	P_a/P_s		
21	0.9	20.90	18.43	0.88	0.021	20
	.8	21.10	16.59	.79	.038	20
	.6	20.89	12.39	.59	.060	20
	.4	21.00	8.18	.39	.077	21
	.2	21.05	4.13	.20	.084	21
	.1	20.99	2.09	.10	.085	21
41	0.9	41.60	37.56	0.90	0.074	19
	.8	41.54	33.20	.80	.136	22
	.6	41.69	24.89	.60	.220	↓
	.4	41.49	16.50	.40	.260	↓
	.2	41.49	8.30	.20	.278	↓
	.1	41.29	4.10	.10	.280	↓
62	0.6	62.38	37.41	0.60	0.440	19
	.4	62.14	24.94	.40	.495	↓
	.2	62.12	12.38	.20	.518	↓
	.1	62.34	6.12	.10	.538	↓

[a] ±0.05 N/cm^2.

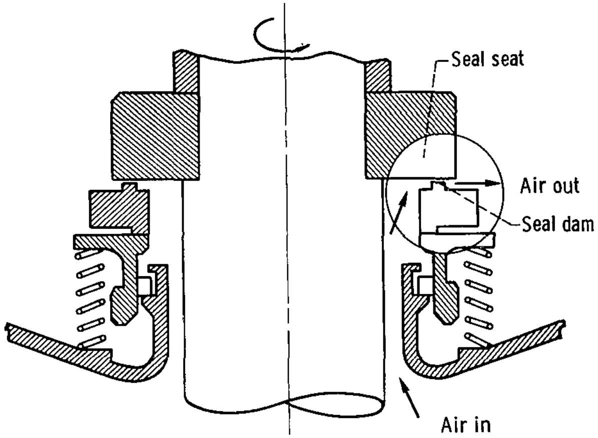
TABLE II. - COMPARISON OF LOSS COEFFICIENT, LEAKAGE, NET FORCE, AND REYNOLDS NUMBER OBTAINED FROM AREAX AND QUASC AT VARIOUS PRESSURES AND PRESSURE RATIOS

Sealed pressure, P_s, N/cm^2	Nominal P_a/P_s	Inlet pressure, P_i, N/cm^2	QUASC				AREAX			
			Required loss coefficient	Leakage, kg/min	Net force, N	Reynolds number	Required loss coefficient	Leakage, kg/min	Net force, N	Reynolds number
21	0.6	20.48	0.605	0.065	129	263	0.628	0.066	129	264
	.4	20.35	.620	.083	208	336	.645	.084	206	340
	.2	20.14	.568	.090	296	364	.593	.091	294	377
	.1	20.29	.656	.092	356	369	.685	.093	355	396
41	0.6	38.42	0.500	0.207	214	837	0.520	0.209	214	849
	.4	37.42	.565	.257	357	1046	.593	.261	355	1078
	.2	37.12	.584	.275	552	1121	.616	.280	548	1219
	.1	37.05	.591	.273	674	1116	.623	.279	670	1220
62	0.6	53.86	0.467	0.370	258	1536	0.491	0.377	257	1570
	.4	52.18	.554	.467	465	1947	.586	.478	461	2031
	.2	52.34	.596	.500	791	2085	.636	.514	787	2291
	.1	52.37	.595	.503	977	2102	.632	.517	972	2306

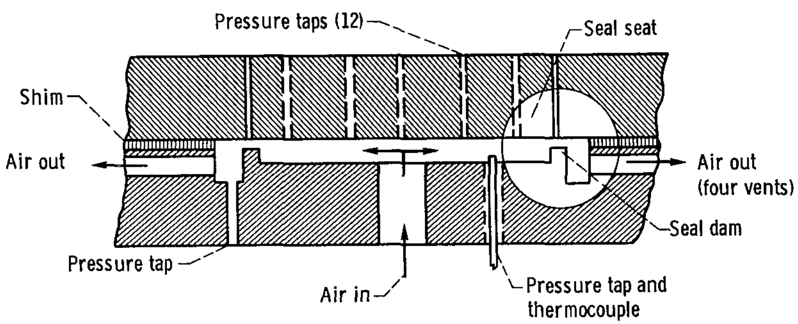
TABLE III. - COMPARISON OF MEASURED LEAKAGE WITH LEAKAGE CALCULATED BY QUASC AND AREAX

[Room temperature air; clearance, 0.00254 cm.]

Sealed pressure, P_s, N/cm^2	Nominal P_a/P_s	$\frac{\text{leakage}_{calc} - \text{leakage}_{exp}}{\text{leakage}_{exp}}$	
		QUASC	AREAX
21	0.6	0.02	0.02
	.4	.02	.02
	.2	.01	.02
	.1	.01	.02
41	0.6	-0.04	-0.03
	.4	.01	.03
	.2	.01	.03
	.1	.00	.02
62	0.6	-0.08	-0.06
	.4	.03	.05
	.2	.05	.08
	.1	.03	.06

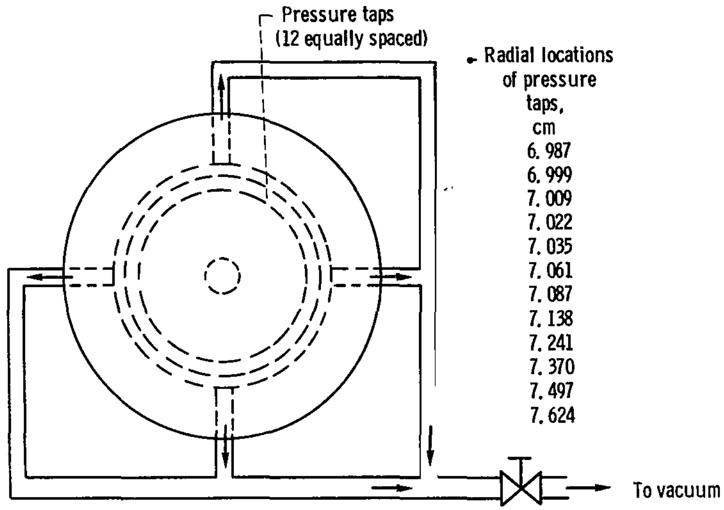


(a) Radial face seal.

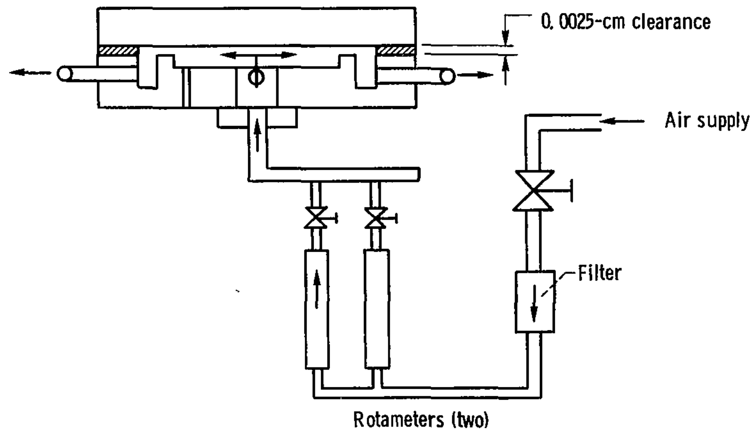


(b) Static flow test rig.

Figure 1. - Flow schematics.



(a) Outlet manifold and dam pressure taps.



(b) Inlet side.

Figure 2. - Facility instrumentation and flow control system.

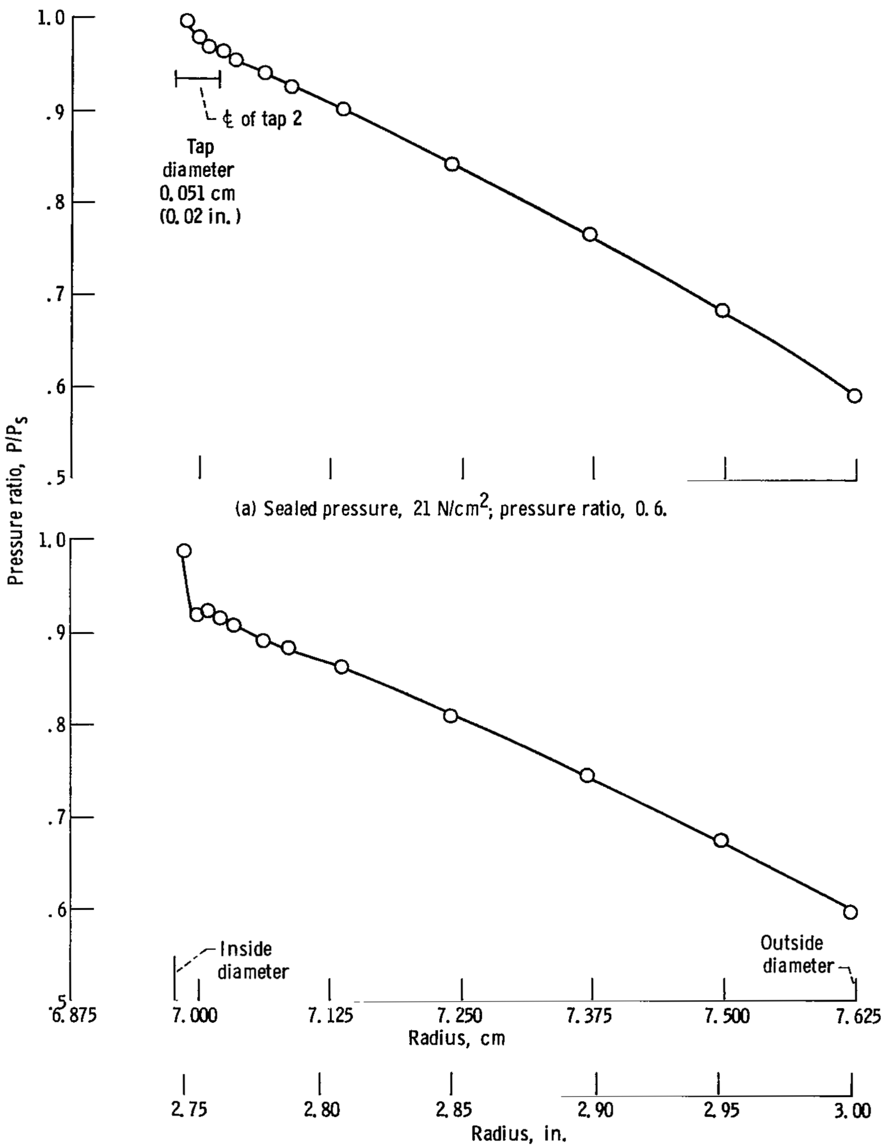
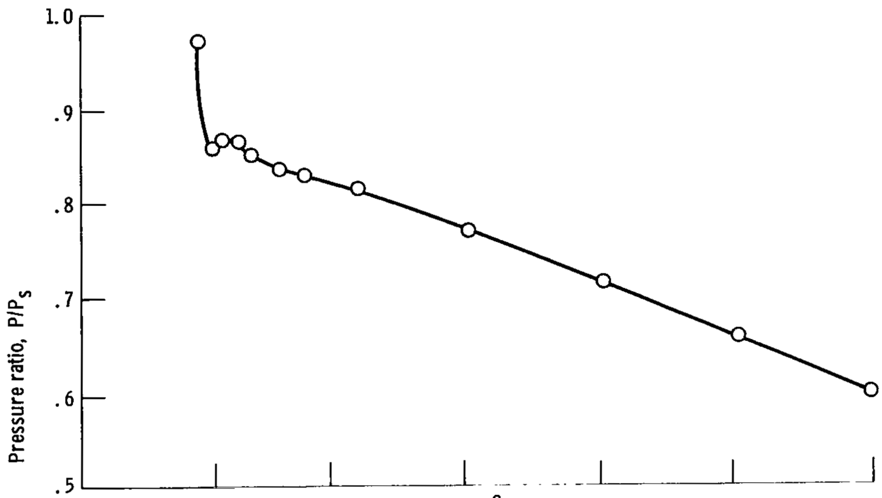
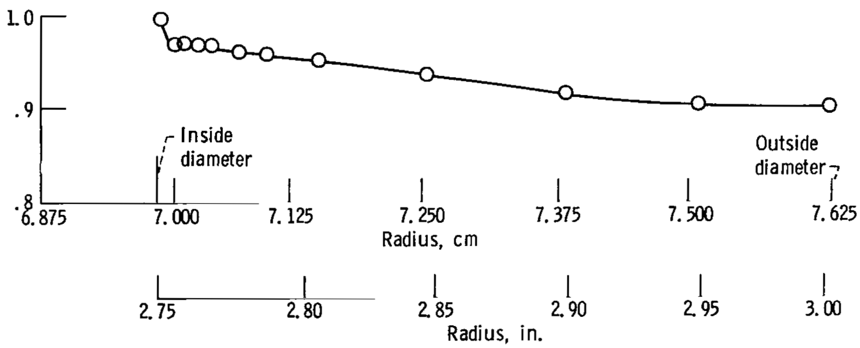


Figure 3. - Typical profiles of P/P_s across dam at several sealed pressures and pressure ratios. Mean clearance, 0.00277 centimeter (0.00109 in.); sealed air at 19^0 to 22^0 C (66^0 to 72^0 F).



(c) Sealed pressure, 62 N/cm^2; pressure ratio, 0.6.



(d) Sealed pressure, 41 N/cm^2; pressure ratio, 0.9.

Figure 3. - Concluded.

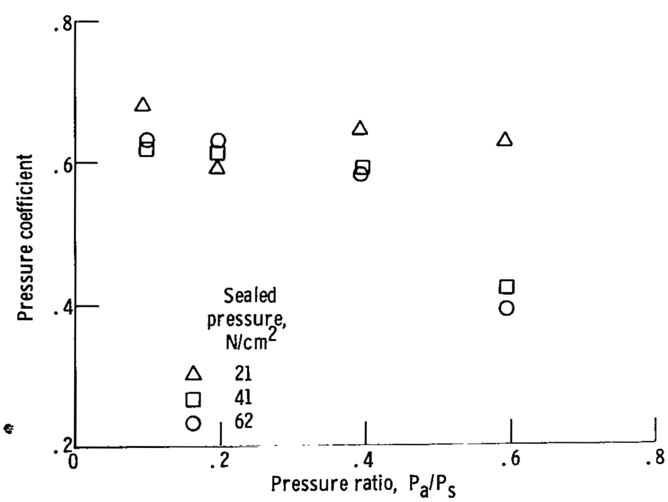
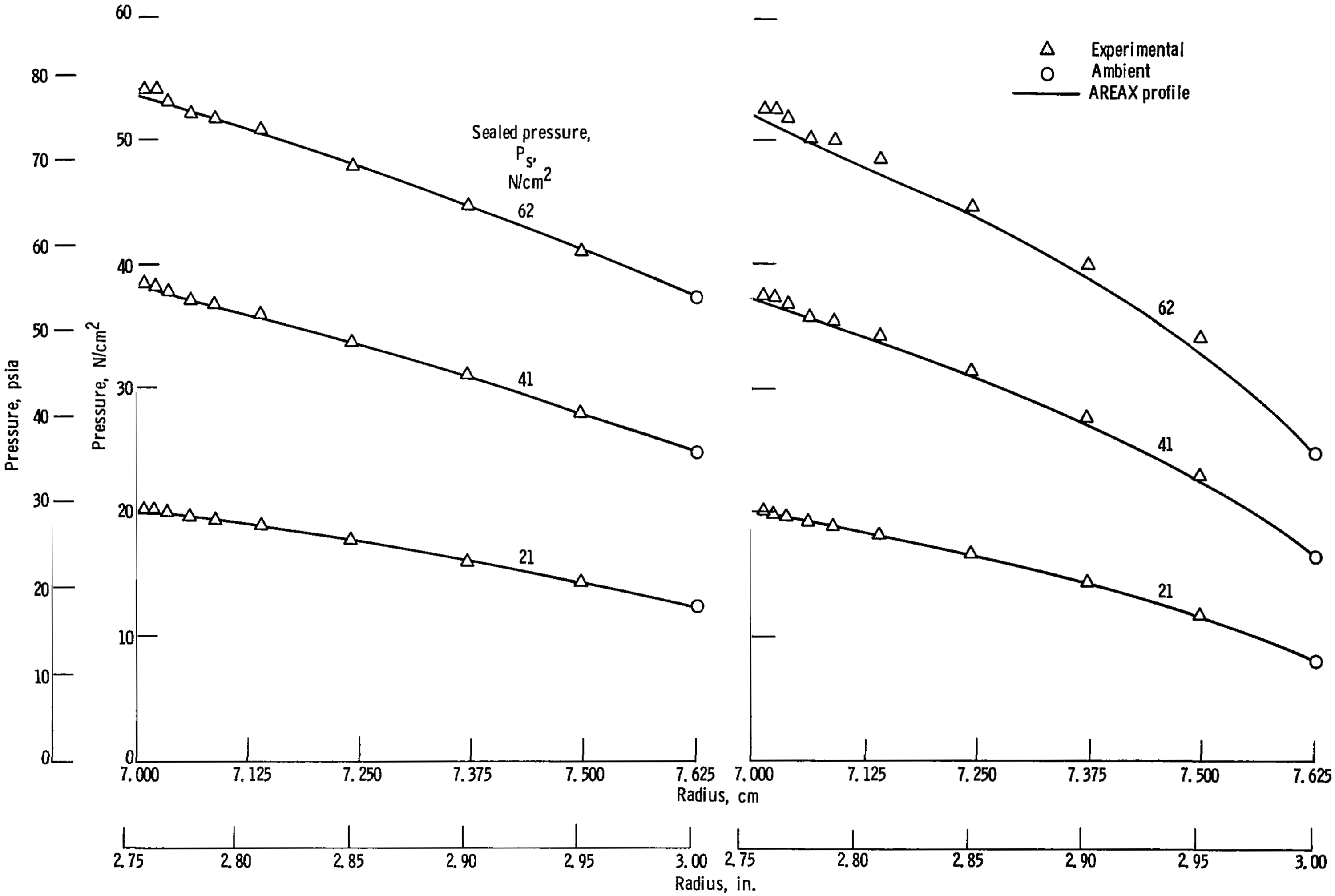


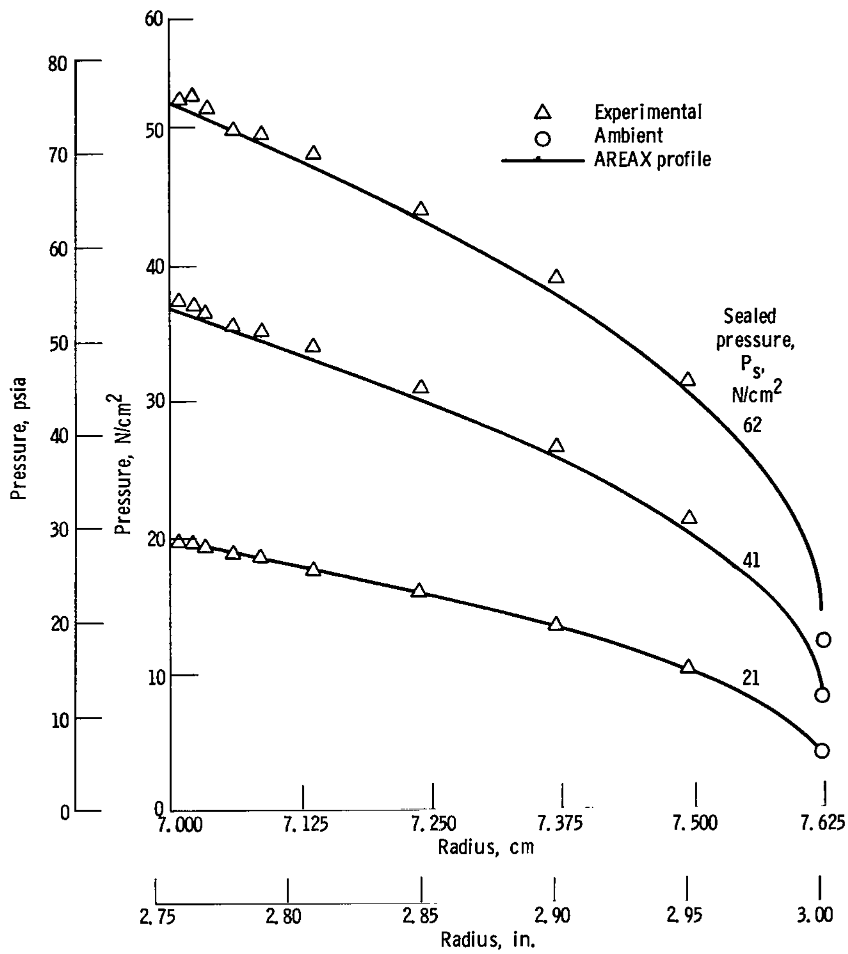
Figure 4. - Loss coefficients required by AREAX to match inlet pressure for test rig (fig. 1). Room-temperature air; clearance, 0.00254 centimeter.



(a) Pressure ratio, 0.6.

(b) Pressure ratio, 0.4.

Figure 5. - Pressure profiles calculated by AREAX compared with experimental results. Clearance, 0.00254 centimeter.



(c) Pressure ratio, 0.2.

Figure 5. - Concluded.

1. Report No. NASA TP-1346	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle COMPRESSIBLE FLOW ACROSS NARROW PASSAGES - COMPARISON OF THEORY AND EXPERIMENT FOR FACE SEALS		5. Report Date November 1978
		6. Performing Organization Code
7. Author(s) Gordon P. Allen, Donald W. Wisander, and William F. Hady		8. Performing Organization Report No. E-9120
		10. Work Unit No. 505-04
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Paper
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

Calculations obtained from two NASA Lewis computer programs for determining compressible flow across radial face seals were compared with measured results obtained in a seal simulator rig at pressure ratios to 0.9 (ambient pressure/sealed pressure). In general, the measured and calculated leakages across the seal dam agreed within 3 percent. The resultant loss coefficient, dependent upon the pressure ratio, ranged from 0.47 to 0.68. The calculated pressures were within 2.5 N/cm^2 of the measured values.

17. Key Words (Suggested by Author(s)) Face seal; Fluid flow; Compressible fluid; Computer analysis; Leakage	18. Distribution Statement Unclassified - unlimited STAR Category 37

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	18	A02

* For sale by the National Technical Information Service, Springfield, Virginia 22161

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