NASA Technical Paper 1583

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JANUARY 1980

NASA

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National Aeronautics
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Scientific and Technical
Information Office

1980

SUMMARY

A segmented, self-acting circumferential seal design for a purge-gas system was analyzed in order to predict performance. A 10-centimeter-diameter seal designed to operate at 500 revolutions per second (157.2 m/sec) and 34.5- or 69-N/cm^2 sealed pressure was analyzed between 300 and 600 rps (94.3 and 188.6 m/sec) and 35 and 86 N/cm^2. Helium at and above room temperature was the sealed fluid.

The analysis predicted noncontact operation over the speed and sealed-pressure ranges studied; test results confirmed this prediction. Qualitative agreement between test and analysis was found despite shortcomings in the analytical model used. The leakage could be reduced and/or the speed and pressure ranges increased somewhat by improving the surface finish and decreasing the pad recess depth.

INTRODUCTION

Segmented circumferential seals are widely used in gas sealing applications such as aircraft turbines. The simplest design has overlapping segments held in an annulus and riding on a shaft. The segments are radially loaded by a garter spring and held against the downstream side of the annulus by a compression spring or springs, as shown in figure 1.

Successful, extended operation of rubbing-contact circumferential seals is restricted to relatively low values of sealed pressure times speed. Rubbing contact causes thermal distortion and wear. A common solution to these disadvantages of rubbing-contact circumferential seals has been to use labyrinth seals. However, labyrinth seals that have sufficient clearance to avoid contact due to vibration, eccentricity, etc., have relatively large leakage rates.

A solution for at least part of the operating pressure range of labyrinth seals is to use close-clearance, hydrodynamic (self-acting) circumferential seals (ref. 1). The addition of self-acting lift-pads to a segmented seal permits noncontact operation (except at startup and shutdown) with minimum leakage.

This report demonstrates noncontact operation of a close-clearance, self-acting circumferential seal and compares predicted performance with experimental data. A 10-centimeter-diameter circumferential seal designed to operate at a sealed pressure of either 34.5 or 69 N/cm^2 and a speed of 50 rps with overspeed to 600 rps was tested at speeds near 500 rps and sealed pressures between 31 and 80 N/cm^2. Then the same seal was analyzed over ranges of 35 to 86 N/cm^2 and 300 to 600 rps (94.3 to 188.6 m/sec). The sealed fluid was helium at approximately room temperature. The conditions of several test runs were analyzed for comparison with the actual results.

APPARATUS

The seal studied was designed and analyzed at the Lewis Research Center. Testing was performed under contract by Rocketdyne Division of Rockwell International.

A schematic of the seal configuration is presented in figure 2. One segment of a similar seal is shown in figure 3. A helium purge prevented mixing of oxidant and fuel vapors. Two identical circumferential seals with different axial orientations were segmented to improve conformance to the shaft. Shrouded, Rayleigh step bearing lift-pads increased seal stiffness (reduced clearance variation) and increased opening force. The segments were retained in position by garter springs (radially) and compression springs (axially). Dimensions of interest are presented in figure 4. There were six segments with three lift-pads of 2:1 recess-land ratio per segment.

Tests consisted of a rapid acceleration (in ~10 sec) to a nominal speed of 500 rps (157.2 m/sec), 6 minutes at test conditions, and rapid braking. Mean values of speeds, pressures, temperatures, and leakage rates were reported.

ANALYSIS

The nominal operating condition was 500 rps and 34.5- or 60-N/cm^2 sealed pressure at 18° C. Sealed pressures of 35, 52, 69, and 86 N/cm^2 and speeds of 300, 400, 500, and 600 rps were analyzed at two recess depths (7.5 and 15 μm) and a downstream pressure of 10 N/cm^2.

The computer program (ref. 2) used to analyze the seal-dam leakage and force was intended for use with a constant-cross-section leakage path. A serious shortcoming was its neglect of rotational shear heating (which can produce a temperature rise on the order of 100° C for adiabatic flow). The program used to analyze the lift-pad force was intended for use with a radial face configuration. However, it was a good geometric approximation because the surface area, mean radius, and width used in the program matched the actual dimensions. Also tests of the program indicated a negligible centrifugal effect on generated force for shrouded pads.

The seal dam was analyzed as a ring of 10-centimeter diameter and 0.051-centimeter axial length. The pad was analyzed for a seal with 18 pads of the dimensions given in figure 4. The effect of the overlap region (fig. 4) was neglected. The closing forces (pressure difference times dam area plus the radial garter spring force) were determined for each sealed-pressure and speed condition. The equilibrium clearance was that at which the sum of the dam and pads opening forces equaled the closing force. The leakage rate was a function of clearance for a given set of operating conditions.

RESULTS AND DISCUSSION

Analysis

The analytical predictions are presented in figure 5. Leakage rates and clearances at the various speeds and sealed pressures are shown for two recess depths. For the region studied, clearances were greater than 2 micrometers. Noncontact operation was expected above this clearance. That is, small machinery variations and thermal gradients could lead to contact at predicted film thicknesses less than 2 micrometers. Therefore, the prediction indicated noncontact operation except at startup and shutdown.

Since the increments of speed and sealed pressure in figure 5 are uniform, it is evident that clearance increased with speed and decreased with pressure. The rate of both changes declined as the independent variable (speed or pressure) rose. The effect of recess depth on clearance decreased appreciably with increasing pressure but increased with increasing speed.

Leakage also increased with speed but went through a maximum as pressure increased. The rate of increase declined as both speed and pressure rose. For increased speed this effect was a result of greater clearance due to a higher opening force. However, for increased pressure the effects of higher density and greater pressure change at first outweighed the effect of decreased clearance. The effect of recess depth on leakage increased with speed and decreased with pressure.

Test Results

Results reported by the contractor did not include clearances. However, wear was measured during periodic inspection of the seals. During a series of checkout runs totaling close to an hour of operation, the seals showed appreciable wear (~2 and 7 μm for the oxidant and fuel sides, respectively). However, the same seal segments showed negligible wear after a further 10 hours of test runs. Evidently, during this 10 hours, there was zero or near-zero wear except during startup and shutdown. Thus, except during the checkout period, the prediction of noncontact at operating conditions is confirmed.

The tests were run with small but significant differences in pressure (sealed and downstream), temperature, and speed. A number of test runs for which these differences should have had little, if any, effect on leakage were selected. Figure 6 shows the effect of pressure drop on leakage rate for the fuel-side seal (7.5-μm recess depth). Predicted results are included for comparison. The reported leakage rates are totals. By using the rule of thumb that half the leakage through a close-clearance seal is through the secondary seal, the actual leakage rate through the seal gap was estimated.

There is considerable data scatter in figure 6. However, the general trend of the test data, for this limited pressure-drop range, was about the same as predicted, although the predicted leakage rates were about three times the mean test estimates. Much of this difference was due to neglect of shear heating in the analysis. Higher temperatures increase flow resistance as a result of higher viscosity and lower density (less mass flow for a given volume flow). For a better comparison, the conditions of three tests at different sealed pressures were analyzed. Conditions and results are presented in table I.

Considering the data scatter in figure 6, there was generally good qualitative agreement between prediction and test results. For both seals, the estimated actual leakage rates are about one-third of the predicted values. Even the highest sealed pressure for the fuel-side seal (table I) shows no worse agreement than that shown in figure 6.

ADDITIONAL REMARKS

During the 10 hours following the checkout runs, both seals operated without contact (as indicated by negligible wear) except at startup and shutdown. The inspection following the checkout runs indicated that the seal mating (inner diameter) surfaces were polished. This is in contrast to the normally matte appearance of machined carbons. Evidently this surface was now smoother than it had originally been. Apparently a successful run-in was at least partly responsible for the subsequent noncontact operation.

This successful operation of the fuel-side seal at about half the customary design clearance suggests a way of either reducing leakage or extending the speed and pressure ranges. First, better surfaces, whether achieved by production or by run-in, will be beneficial. Second, shallower pad recesses will result in a lower equilibrium clearance and a consequent lower leakage. However, previous analysis (unpublished) have predicted that as clearance decreases, the opening force of a shallower recess pad approaches and exceeds that of a deeper recess pad. Therefore only a limited leakage reduction would be expected.

CONCLUSIONS

A segmented, hydrodynamic circumferential seal design for a helium purge seal system was analyzed over ranges of speed and sealed pressure and was also tested.

Comparing analytical and experimental results led to the following conclusions:

1. Noncontact operation (negligible wear) over a 10-hour period confirmed analytical predictions.

2. Qualitative agreement between predicted and measured leakage rates was found despite shortcomings in the analytical models.

3. Leakage could be reduced and/or the speed and pressure ranges extended slightly by improving the surface finish (on the inside diameter of the segments) and by reducing the pad recess depth.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, Sept. 10, 1979,
505-04.

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TABLE I. - COMPARISON OF ESTIMATED ACTUAL AND PREDICTED

LEAKAGE THROUGH SEAL GAP

Test conditions			Oxidant-side seal[a]			Fuel-side seal[b]		
Sealed pressure, N/cm^2	Sealed temperature, K	Speed, m/sec	Downstream pressure, N/cm^2	Experimental leakage, g/sec (c)	Predicted leakage, g/sec	Downstream pressure, N/cm^2	Experimental leakage, g/sec (c)	Predicted leakage, g/sec
76.33	294	157.6	25.65	0.129	0.380	10.55	0.045	0.260
42.54	294	157.4	25.99	.065	.256	12.00	.060	.160
37.58	293	157.6	24.96	.114	.232	12.17	.058	.145

[a]15-μm recess depth.
[b]7.5-μm recess depth.
[c]Estimated as one-half the measured total.

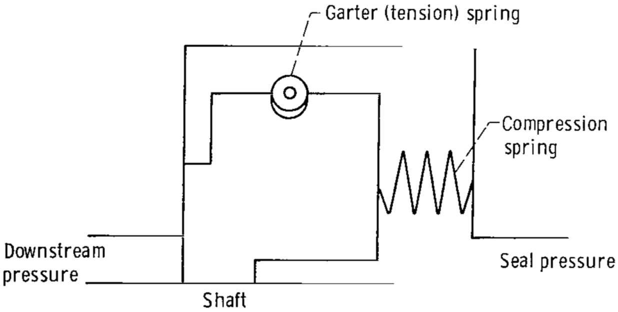


Figure 1. - Basic circumferential shaft-riding seal.

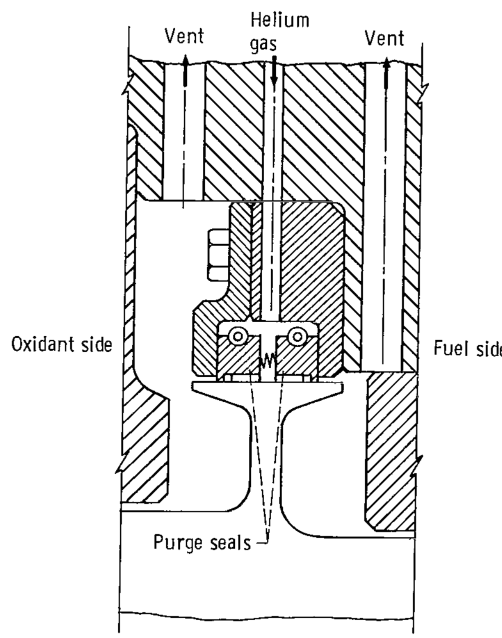


Figure 2. - Schematic of purge-gas sealing system.

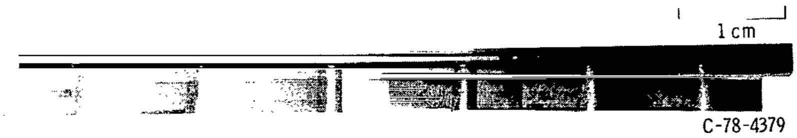


Figure 3. - Typical circumferential seal segment.

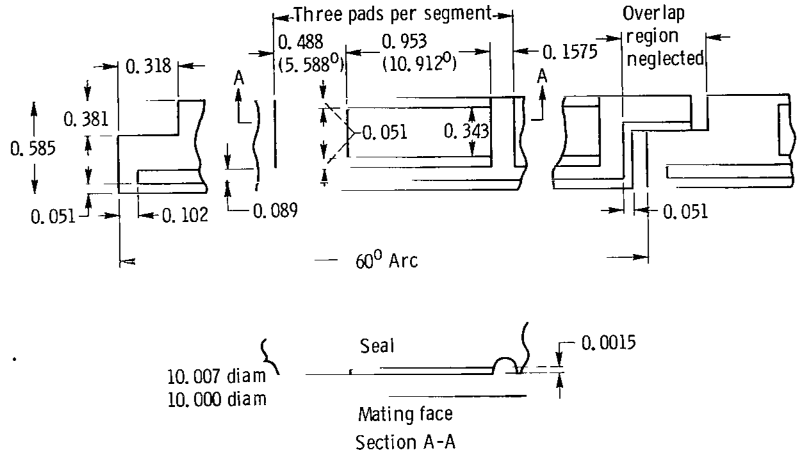
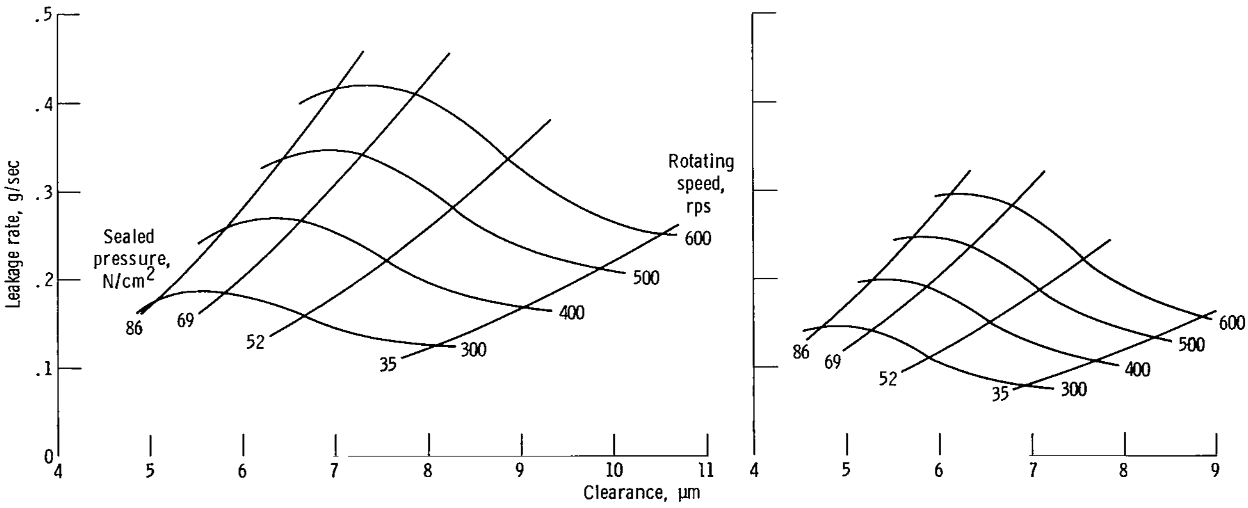


Figure 4. - Dimensions of seal studied. (All dimensions are in centimeters.)



(a) 15-Micrometer recess depth.

(b) 7.5-Micrometer recess depth.

Figure 5. - Predicted performance in sealing room-temperature helium from 1 atmosphere.

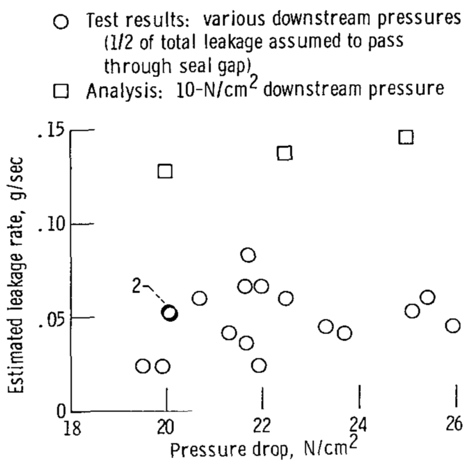


Figure 6. - Effect of pressure drop on leakage rate at about 500 rps (157.2 m/sec) and room temperature for fuel-side seal.

1. Report No. NASA TP-1583	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle SELF-ACTING LIFT-PAD GEOMETRY FOR CIRCUMFERENTIAL SEALS - A NONCONTACTING CONCEPT		5. Report Date January 1980
		6. Performing Organization Code
7. Author(s) Gordon P. Allen		8. Performing Organization Report No. E-154
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135		10. Work Unit No. 505-04
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		13. Type of Report and Period Covered Technical Paper
		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

A segmented circumferential seal with lift-pads for hydrodynamic action was analyzed over ranges of speed and sealed pressure. Predictions were compared with test results. Analysis predicted noncontact operation for speeds as high as 600 revolutions per second at sealed pressures to 86 N/cm^2. Test results confirmed this prediction. There was qualitative agreement between experimental and analytical results.

17. Key Words (Suggested by Author(s)) Circumferential seal Self-acting seal Leakage Fluid flow Computer analysis	18. Distribution Statement Unclassified - unlimited STAR Category 37

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 10	22. Price* A02

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

NASA-Langley, 1980

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Space Administration

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