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SCREW-SEAL PERFORMANCE IN VACUUM ENVIRONMENT

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SUMMARY

Noncontact seals are being proposed for use in space power systems. These noncontact seals offer reliable operational lifetimes of over 10 000 hours. The leakage rate of mix-bis (mix-phenoxy-phenyl) ether lubricant through a noncontact slinger pump and screw-seal assembly to a simulated space environment was measured. The experimental times ranged from 12 to 100 hours, and the leakage rate extrapolated to 10 000 hours ranged from 0.73 to 2.6 kilograms.

INTRODUCTION

A new class of heat power machinery for operation in space is now under development (ref. 1). In some aspects of design, the vacuum of space can be used to advantage; rotating machinery operating in this environment has no windage losses but requires a seal to prevent excessive losses of the working fluid to space. Machines designed for operation in space are usually intended to have a minimum continuous operating life of 10 000 hours. Friction and viscous losses must be kept to a minimum, and the machine must operate in a zero-gravity environment. Leakage of the working and/or lubricating fluid must be kept low because of the limited inventory that can be carried into space. In some systems, such as SNAP-8, the leakage past the molecular seals is vented to space, thus preventing the lubricant from entering the mercury system or the mercury from entering the lubricant system.

Contact seals can offer low leakage rates, but the 10 000-hour operational life is difficult to assure because of seal wear. Contact seals can, however, be used for static sealing and sealing during startup and shutdown.

Noncontact sealing devices can be used to limit the leakage to space. The screw-type configuration acts as a seal and operates through the spectrum of flow regimes. The Holweck vacuum pump described in reference 2 is an example of a screw configuration operating in the molecular regime.

The objective of this investigation was to measure the leakage rate of the mix-bis (mix-phenoxy phenyl) ether lubricant (hereinafter designated 4P3E-polyphenyl ether) through a noncontact seal to a vacuum. Screw-seal geometries optimized for molecular flow (ref. 2), slow viscous flow (creeping flow) (ref. 3), or transition flow (refs. 4 and 5) were used in this investigation. The molecular leakage to the vacuum environment of 10^{-6} torr from an initial fluid pressure of 10^{-2} torr in the bearing cavity was measured for the different configurations. The operating conditions are considered representative of the anticipated space power-generating systems.

In the course of this investigation, information on the operation of slinger pumps in low-pressure environments was obtained. Operational information on the use of 4P3E-polyphenyl ether in a simulated space-power-system seal and bearing was also obtained.

APPARATUS AND PROCEDURE

Experimental Apparatus

The vacuum seal apparatus elements are shown in figure 1. The high-speed spindle extends into the vacuum tank where the test seal and bearing assembly is located. The relative location of the diffusion pump, vacuum gage, cryogenic baffles and cold trap with respect to the test seal and bearing assembly are shown.

The lubricant used for this investigation was a 4P3E-polyphenyl ether. This fluid is noted for its very low vapor pressure and radiation resistant characteristics. A more detailed summary of 4P3E-polyphenyl-ether properties is included in table I.

A schematic diagram of the experimental apparatus vacuum system and lubrication system is presented in figure 2. Three mechanical pumps and one diffusion pump are used in the vacuum system. The main chamber is pumped by an 8-inch diffusion pump that uses 4P3E-polyphenyl ether and is backed by a mechanical vacuum pump. A cryogenic cold trap on top of the diffusion pump keeps the polyphenyl ether from back-streaming into the main chamber. The bearing cavity and oil tank are pumped by a second mechanical vacuum pump.

The interstage area between apparatus seals 1 and 2 was pumped by the third mechanical pump. The interstage pressure ranged from 10 to 30 millimeters of mercury absolute.

In the lubrication loop (fig. 2), the 4P3E-polyphenyl ether flows from the heated oil tank to the positive displacement pump. The lubricant is then pumped through the supply loop to the experimental apparatus. Approximately one-third of the lubricant passed through a 5-micron porous stainless-steel filter and impinged on the bearing. The remaining lubricant returned to the oil tank.

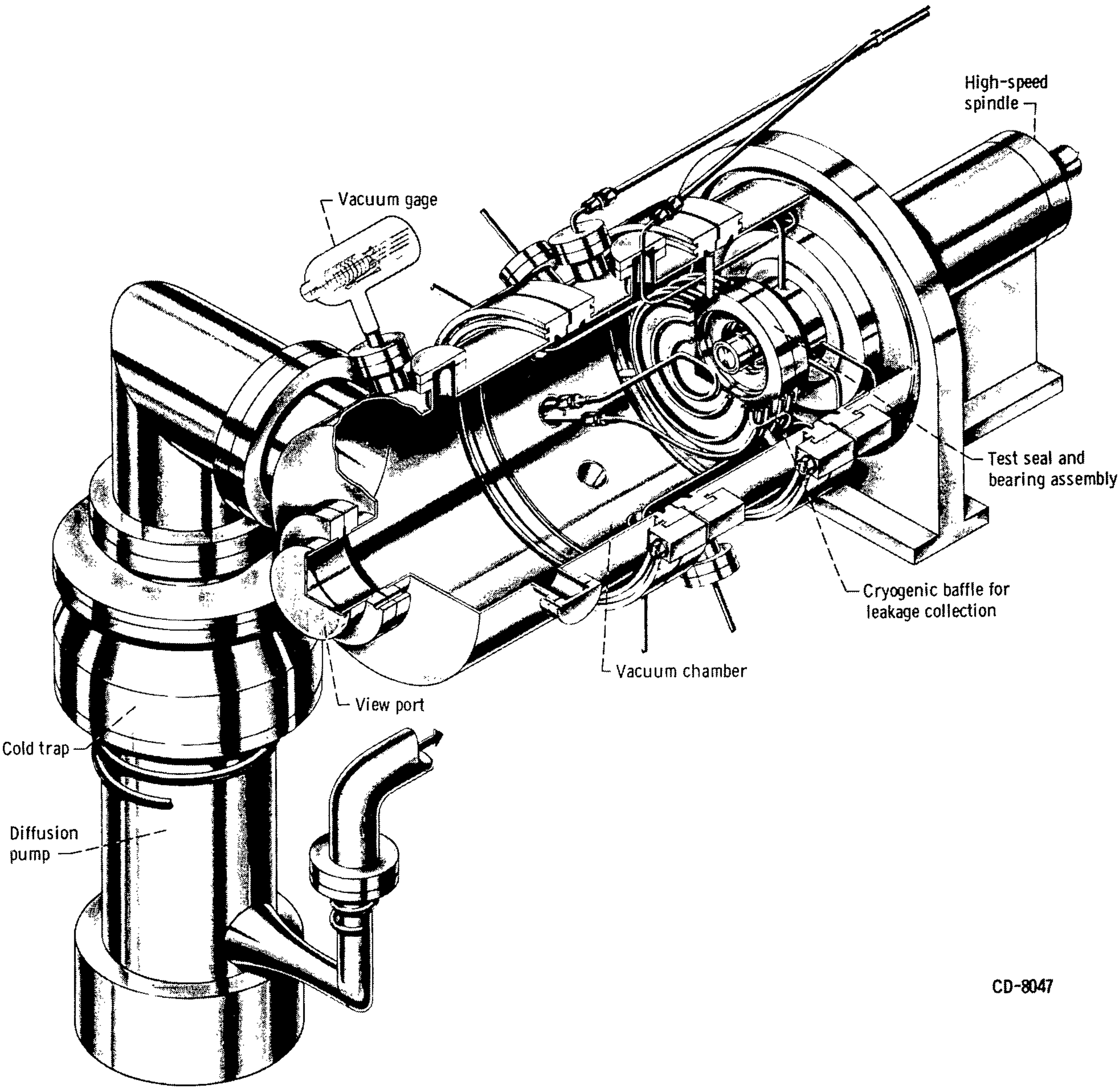


Figure 1. - Experimental apparatus.

TABLE I. - PHYSICAL PROPERTIES OF MIX-BIS (MIX-PHENOXY-PHENYL) ETHER

Property	Value
Isomeric content, percent:	
Meta meta	52.0
Meta para	39.3
Meta ortho	4.6
Ortho para	0.4
Ortho ortho	------
Para para	3.2
Density at 68° F, g/cc	1.1526
Flash point, °F	495
Fire point, °F	555
Pour point, °F	+18
Spontaneous ignition temperature, °F	1050
Phenols, percent	0.049
Halogens, percent	0.019
Viscosity, cs, at -	
210° F	6.27
140° F	20.7
100° F	67.5
Refractive index at 77° F	1.6232
Viscosity increase during 825° F thermodynamic stability test, percent	5.9

From the bearing, the lubricant entered the slinger pumps and was pumped back to the oil tank through the flow-measuring tubes. By closing the bottom of the flow-measuring tube and recording the time to fill the known volume, the lubricant flow rate from each slinger pump was measured.

The experimental seal and bearing assembly is shown in figure 3. Both the front and rear slinger pumps operated with a 0.020-inch radial clearance and a 0.030-inch axial clearance per side.

The condition of the lubricant in the test assembly is indicated in figure 4. The lubricant enters the seal and bearing assembly as a liquid and impinges on the bearing as a jet of liquid. The lubricant then breaks into drops and enters the slinger pumps. In the slinger pumps, the lubricant is again in liquid form with some entrained vapor bubbles. On the screw-seal side of the front slinger, the lubricant vaporizes at the interface, and the vapor migrates to the screw seal where it condenses on the cooler seal housing. Another interface is established in the screw seal where the lubricant vaporizes again and enters the molecular flow regime. The remaining portion of the screw seal offers some resistance to the molecular flow of the lubricant to the low-pressure area.

The slinger element can act as a seal, a pump, or both. In this application, the slingers were primarily pumps, because there was no significant pressure difference across the slinger element. The front slinger prevented a solid head of lubricant from reaching the screw seal and in this way acted as part of the sealing system.

The bearing used in the experimental setup was a size 208 (40 mm) angular contact 13-ball ball bearing fabricated with M50 tool steel with an iron-silicon-bronze separator. The bearing load was 100 pounds axial and 25 to 50 pounds radial.

Experimental Procedure

Before each experimental run, the cryogenic baffle surrounding the end of the test-

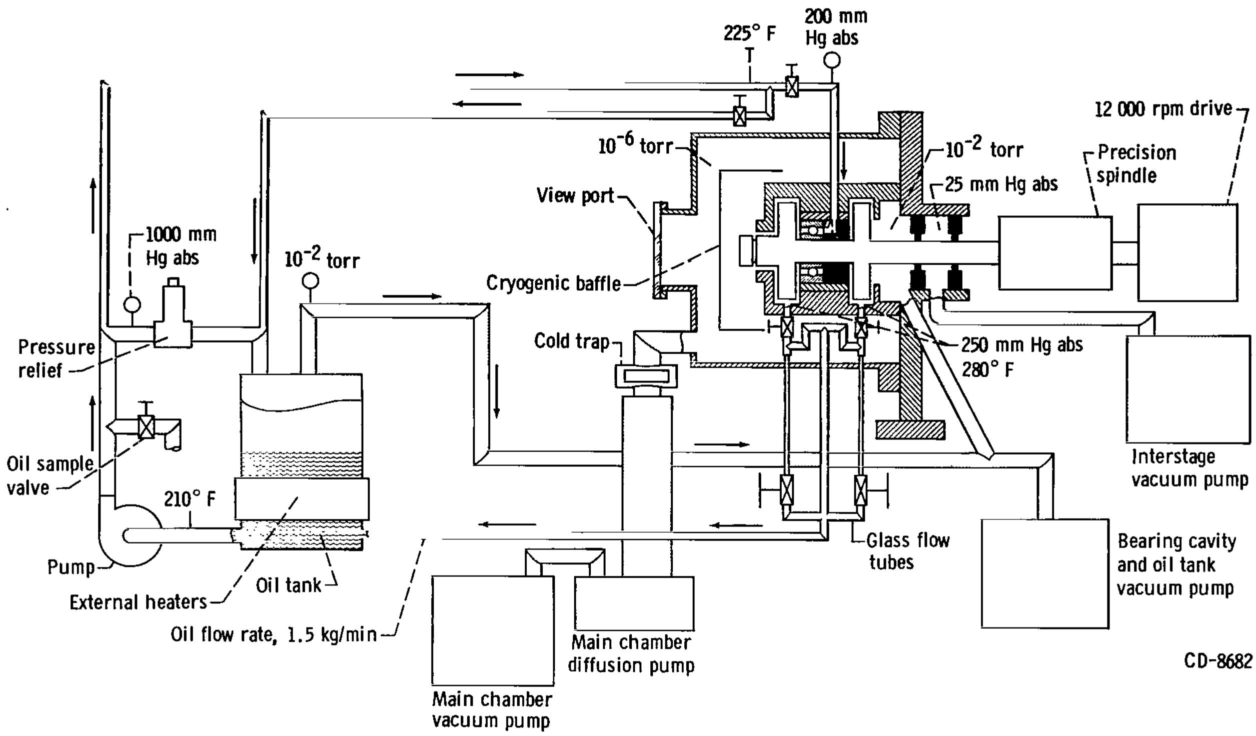


Figure 2. - Schematic diagram of experimental apparatus.

seal assembly was cleaned and weighed. The baffle was installed and the vacuum tank wiped out and assembled.

The lubricant was stored in the oil tank at room temperature and in a vacuum at 2×10^{-2} torr. Prior to use, the oil tank was heated to a temperature of 300° F and evacuated to a pressure of 2×10^{-2} torr in order to degas the 4P3E-polyphenyl ether. The oil loop was then brought up to temperature under a vacuum. Prior to startup, the vacuum chamber was pumped down by the mechanical pump, but not the diffusion pump.

Spindle rotation and lubricant flow to the seal and bearing assembly were started simultaneously. During startup, an observer watched to see that no lubricant dripped off the baffle, which would indicate a spill through the seal.

As soon as a shaft speed of 12 000 rpm and a lubricant flow rate of 1.5 kilograms per minute (200 lb/hr) were established, the diffusion pump and cryogenic baffles were put into operation. Thirty minutes were required to chill the cryogenic baffle and to reach the 10^{-6} torr range in the vacuum tank. Therefore, the time used to calculate the leakage rate commenced from this point.

Shutdown of the experiment started with turning off the diffusion pump and purging the cryogenic baffle. The time used for leakage calculation stopped at this point. In 30 minutes, the pressure in the vacuum tank increased to the 10^{-2} torr range, and the cryogenic baffle used for leakage measurements reached ambient temperature. While

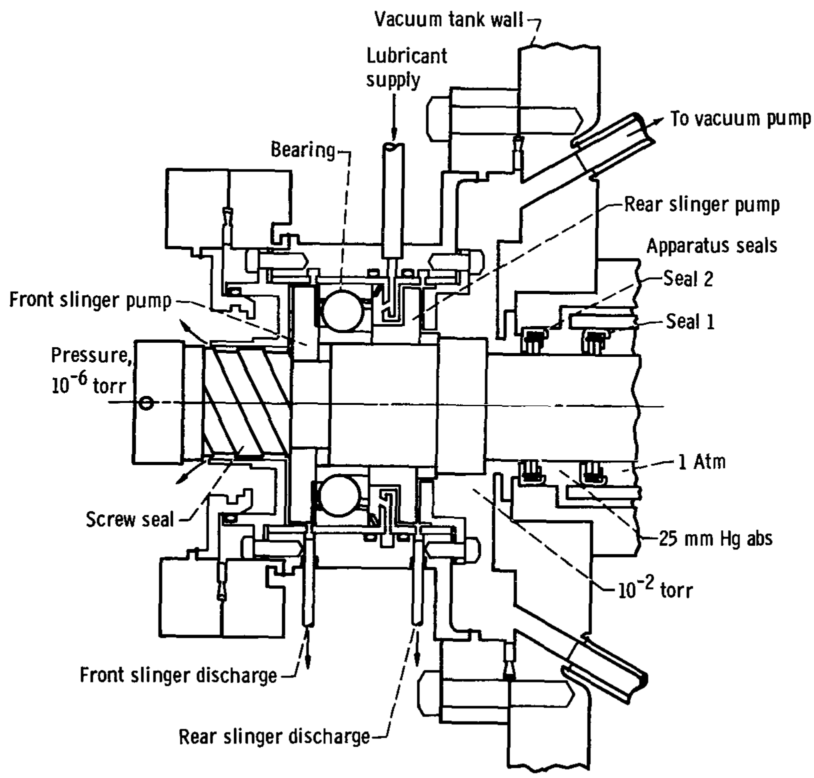


Figure 3. - Experimental seal and bearing assembly.

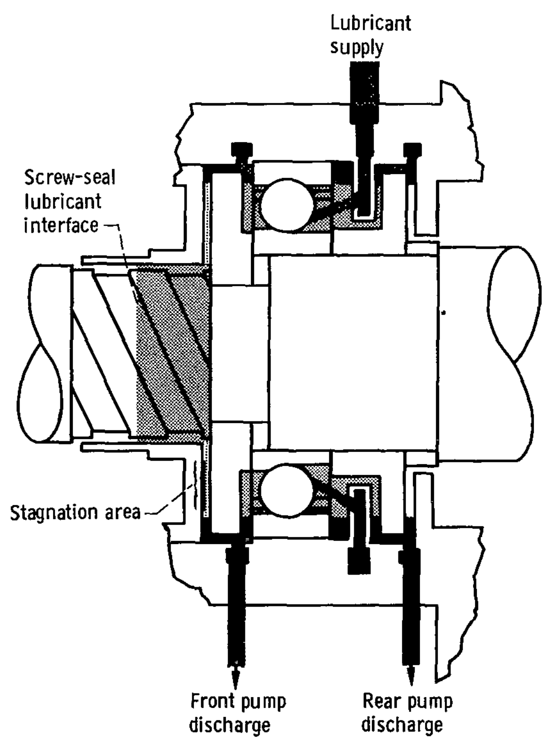


Figure 4. - Experimental assembly illustrating lubricant during operation.

an observer watched for indications of a spill, the lubricant supply was shut off, and 5 seconds later the spindle rotation was stopped.

The vacuum was then released and the cryogenic baffle used for leakage collection was removed and weighed. After an experimental run, the inside of the vacuum tank appeared clean on its polished surfaces. The cryogenic baffle had oil visible only on the side facing the test seal assembly.

Three primary screw-seal configurations were run: the molecular or M-configuration; the slow viscous flow (creeping flow) or V-configuration; and the transition flow or T-configuration. The physical difference in these three configurations can be seen in the sketches and dimensions given in table II.

The first experiment was run in two parts, A and B, and used the M or molecular-flow geometry. The M geometry is similar to a Holweck vacuum pump (ref. 2), except that the surface speed was about one-tenth that of a Holweck vacuum pump.

The second experiment used the geometry optimized for slow viscous flow (creeping flow) of Boon and Tal (ref. 3).

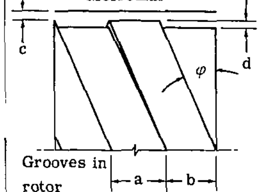
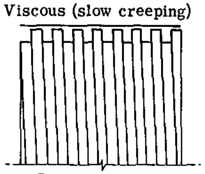
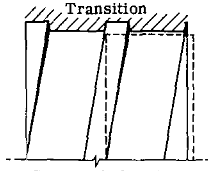
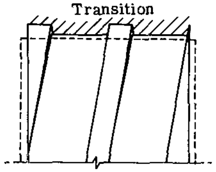
The configuration used for experiments 3 to 6 was the geometry optimized for transition flow (refs. 4 and 5). This configuration used stationary grooves in the housing and a smooth rotor. The stationary groove was chosen because the only other experimental work of similar nature used a stationary groove (ref. 6).

This investigation was conducted with the shaft horizontal in a 1-g gravitational field. In experiments 1 and 2, the groove was in the rotor. Any contents of the groove were subject to an artificial gravity of 2800 g's. In experiments 3 to 6 with the stationary groove in the housing, the 1-g field would aid in reducing the lubricant leakage rate over the zero-gravity condition. During zero-gravity operation, the stationary groove could allow some lubricant drops to migrate down the groove and out to space without any hindrance.

Preliminary work was conducted with vertically oriented, stationary housing grooves. The leakage direction was downward. This arrangement showed that fluid would wind its way down and out of the stationary groove even though the depth of the groove was less than that in experiments 3 to 6. In a 1-g field, the stationary groove configuration of experiments 3 to 6, if oriented vertically with the leakage direction down, could be expected to leak fluid through the seal.

The duration of the experimental runs varied. In experiment 1, the desired run time was 150 hours, which was accomplished in two periods, 50 hours and the other 100 hours. Experimental runs 2 to 6 were of 12 hours' duration, the time previously determined as necessary to collect about 1 gram of leakage. Other independent variables, such as shaft speed, lubricant temperature, lubricant flow rate, were kept constant throughout the experimental series.

TABLE II. - CHARACTERISTICS OF EXPERIMENTAL SCREW-SEAL CONFIGURATIONS

Configuration	Experiment	Groove width, a, in.	Land width, b, in.	Ratio, groove/land	Groove depth, d, in.	Radial clearance, c, in.	Helix angle, φ, deg	Helix starts	Seal length, in.	Rotor nominal diameter, in.	Experiment time, hr	Measured leakage, g	Extrapolated leakage rate, kg/10^4 hr
Molecular  Grooves in rotor	1A	0.320	0.300	1.06	0.004	0.006	23.9	2	1.0	$1\frac{3}{8}$	50	[a]13.003	2.6
	1B	.320	.300	1.06	.004	.006	23.9	2	1.0	$1\frac{3}{8}$	100	9.682	1.0
Viscous (slow creeping)  Grooves in rotor	2	0.060	0.060	1.0	0.080	0.002	2.5	1	1.0	$1\frac{3}{8}$	12	1.202	1.1
Transition  Grooves in housing	3	0.140	0.360	0.39	0.055	0.002	9.5	1	0.5	$1\frac{1}{2}$	12	0.817	0.73
	6	.140	.360	.39	.055	.004	9.5	1	.5	$1\frac{1}{2}$	12	.870	.77
Transition  Grooves in housing	4	0.140	0.360	0.39	0.055	0.002	9.5	1	1.0	$1\frac{1}{2}$	12	1.060	0.96
	5	.140	.360	.39	.055	.004	9.5	1	1.0	$1\frac{1}{2}$	12	.920	.82

[a]Spill during shutdown.

RESULTS

After each experimental run, a quantity of lubricant had collected on the cryogenic baffle, which surrounded the end of the seal and bearing assembly. The fact that the collected lubricant was only on one side of the cryogenic baffle and that the inside of the vacuum tank was still highly polished was good evidence that the collected lubricant passed through the molecular seal during the experimental period.

During each startup and shutdown, observations were made to see if any lubricant spilled through the screw seal. A spill was observed during the shutdown of experiment 1A. Thus, the measured leakage rate experienced during this run was exaggerated because the spilled lubricant was weighed along with the leaked lubricant.

The lubricant leakage results obtained during the experiments are shown in table II. Both the total weight of the leakage in grams and the extrapolated leakage rate in kilograms of lubricant per 10 000 hours are shown. The latter number can be used for direct comparison of experimental runs.

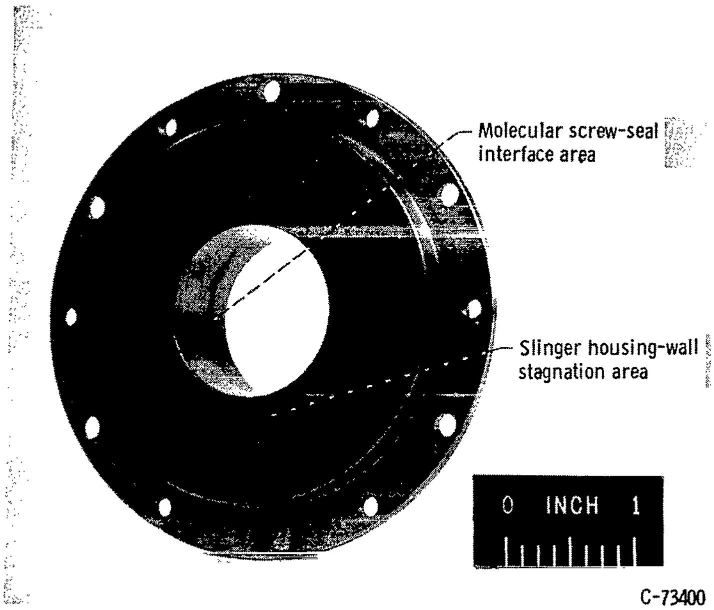
The front end plate after experiments 1A and 1B is shown in figure 5(a). The dark stains occurred in areas where the lubricant evaporated during operation. One stain was located on the vertical housing wall below the molecular seal; another stain was located in the bore of the housing. This latter stain was interesting because it showed that the screw seal operated with fluid engagement over 60 percent of the screw-seal axial length. The remaining 40 percent of the screw-seal axial length consisted of continuum and molecular-flow regimes.

The lubricant is transferred from the slinger interface to the screw seal by several methods. During operation, small drops of lubricant become detached from the slinger interface and migrate to the screw seal. Another method involves lubricant vaporization at the slinger interface and then condensation in the screw seal. A third method by which lubricants transfer is molecular creep along the wall.

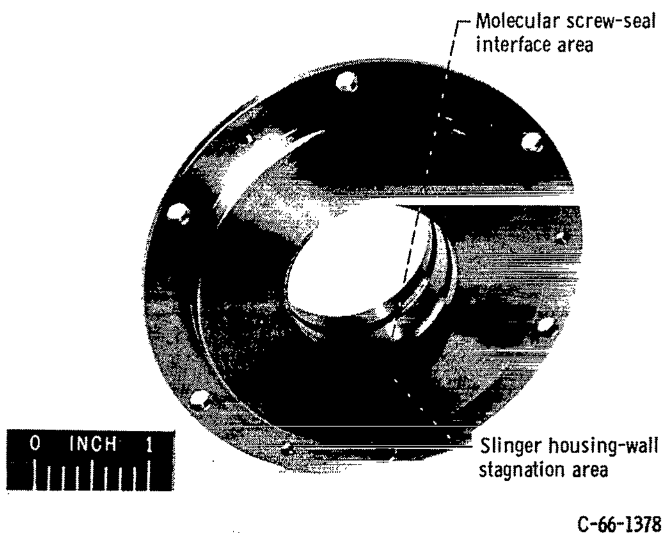
The front end plate containing the stationary housing grooves used in experiments 3 to 6 is shown in figure 5(b). The stain on the vertical slinger wall (similar to that shown in fig. 5(a)) was caused by the excess lubricant in the screw seal running down the slinger wall and vaporizing.

During experiments 3 and 6, the rotor length was 0.50 inch, which would mean that the screw seal (as indicated by the stain in fig. 5(b)) was operating in fluid over 80 percent of its axial length. Thus, in experiments 4 and 5 conducted with a 1-inch-long rotor, the engagement would have been over 40 percent of its axial length.

In experiment 2, a strong stain pattern did not develop because the operating time was only 12 hours in contrast to the results shown in figure 5(a) for a 150-hour run and in figure 5(b) for a 48-hour run. The front end plate from experiment 2 showed a weak stain on the vertical slinger wall similar to that presented in figure 5. Also, no stain on



(a) Plain bore (experiments 1A and 1B).



(b) Helical bore (experiments 3 to 6).

Figure 5. - Front end plate.

the molecular-seal housing bore was evident after experiment 2. The presence of a stain on the vertical slinger housing wall is a good indication that there was fluid in the molecular screw seal similar to that observed in the other experiments. The evidence of fluid in the screw seal and on the slinger housing wall indicates that excessive leakage would occur if the slinger were used as a final seal element in a low-pressure sealing system.

The experimental results indicated that the configuration of the screw seal has little effect on the lubricant leakage rate under the conditions of horizontal shaft and 1-g gravitational field. The experiments showed that lubricant in the liquid form is present in the screw-seal annulus. Preliminary experiments have revealed that a fluid interface in a screw seal is unstable and that small fluid particles detach themselves from the interface. These small particles coalesce into larger drops that can be acted upon by the screw seal and returned to the interface. In stationary grooves under zero-gravity conditions, the small detached particles may be able to wind their way out of the seal and cause an increase in the lubricant leakage rate.

The vapor pressure of 4P3E-polyphenyl ether at 275° F, the temperature of the screw-seal area, is of the order of 10^{-3} torr. Determination of the molecular mean free path under these conditions (ref. 2) indicates that the mean free path of the lubricant molecule is about 0.50 inch.

The low-pressure end of the screw seal acts more as a molecular restriction to the leakage of lubricant molecules than as a dynamic molecular seal. A theoretical calculation of the static case, made by using the molecular beam method (ref. 8) and by assuming an infinite supply of molecules at 10^{-3} torr leaking to a pressure of 10^{-6} torr, resulted in the same order of magnitude of leakage as that measured during the experimental runs.

The slinger elements operated satisfactorily as pumps. The front slinger nominally pumped 0.95 kilogram of lubricant per minute at a pressure rise of 280 millimeters of mercury, and the rear slinger nominally pumped 0.55 kilogram of lubricant per minute at a pressure rise of 186 millimeters of mercury.

The lubricant flow rate to the bearing was 1.5 kilograms per minute. Of this, 63 percent of the lubricant passed through the bearing and was returned by the front slinger pump. The balance splashed off the bearing and returned through the rear slinger pump. No abnormal bearing condition was evident in more than 200 hours of operation at 250° F in the 4P3E-polyphenyl-ether lubricant.

On several occasions during the initial shakedown runs and also during the reported experimental runs, excessive pressure drop across the 5-micron filter was experienced. Examination of the filter showed that it was clogged with a black sludge, chemically analyzed as carbon with trace amounts of iron. Similar sludging of 4P3E-polyphenyl ether has been reported (ref. 7).

SUMMARY OF RESULTS

The leakage rate of mix-bis (mix-phenoxy phenyl) ether lubricant through a noncontact seal to a vacuum was measured for several screw-seal geometries. The following experimental results were obtained:

1. Noncontact screw seals are effective in limiting the losses of the 4P3E-polyphenyl ether lubricants to a low-pressure environment. The leakage rates in a 1-g field extrapolated to 10 000 hours from a 12- to 100-hour experimental time ranged from 0.73- to 2.6 kilograms.

2. Because of the lubricant interface in the screw seal, the screw-seal element should be designed for viscous flow in the high-pressure end and for molecular flow in the low-pressure end.

3. The slinger element functioned effectively as a pump, but it is not suitable as a final seal element of a low pressure sealing system.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, October 27, 1966,
120-27-04-21-22.

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