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TORQUE AND LEAKAGE RATES OF  
VARIOUS LUBRICATED LIP SEAL  
DESIGNS AT A PERIPHERAL VELOCITY  
OF 120 FEET PER SECOND

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and Robert L. Johnson*

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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## ABSTRACT

Lip-type shaft seals were run at peripheral velocities representative of requirements in mechanical components for rocket engines. The seals with butyl rubber lips had prominent wear-in torque peaks that were attributed to lip temperature rise and subsequent lip shrinkage (Gow-Joule effect). This effect could cause sudden failure; gradual wear-in, however, reduced failure probability. The seals with glass-filled polytetrafluoroethylene lips also exhibited wear-in torque peaks. The seals with graphite-filled polytetrafluoroethylene lips exhibited low leakage and good wear characteristics. Running torques of the various lip seal types were similar to that of a segmented-carbon shaft seal. For butyl and graphite-filled polytetrafluoroethylene lip seals, the dynamic gas leakage rates were similar to the static leakage rates.

# TORQUE AND LEAKAGE RATES OF VARIOUS LUBRICATED LIP SEAL DESIGNS

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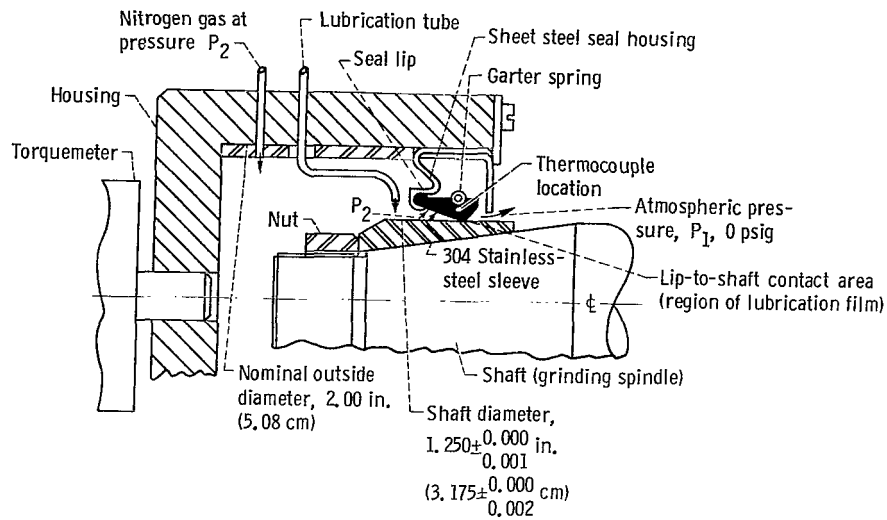
Lewis Research Center

### SUMMARY

Some mechanical components of rocket vehicles use lip-type shaft seals to prevent leakage of bearing and gear lubricants. Although required seal life is only several hours, the sliding velocity is high and data on seal life, leakage, and heat generation is of interest. Various lip seal designs were run at speeds (24 000 rpm) representative of rocket vehicle mechanical components. Running torques and lip temperatures were continuously recorded in short-term runs to 600 seconds with zero pressure differential across the seal. Starting torques and leakage rates were checked at pressures to 14 psig (9.65 N/cm<sup>2</sup> gage). The lip orientation used produced a lip radial force that decreased as pressure increased. The seals with a butyl rubber lip exhibited prominent wear-in torque peaks that were attributed to lip temperature rise and subsequent lip shrinkage (Gow-Joule effect). These torque peaks could lead to sudden failure (burnout); gradual wear-in, however, reduced the probability of failure. Seals with a glass-filled polytetrafluoroethylene lip also exhibited wear-in torque peaks; several sudden failures occurred. The seal with a graphite-filled polytetrafluoroethylene lip exhibited low leakage rates and good wear performance. Running torques of the various seals were similar to that of a segmented-carbon shaft-riding seal. For the butyl rubber and graphite-filled polytetrafluoroethylene lip seals, the dynamic gas leakage was similar to the static leakage.

### INTRODUCTION

Operational service time of the order of several hundred seconds at high shaft speeds (i. e., 24 000 rpm) is typical of the requirements of some rotating mechanical components for rocket engines. With the addition of the ground checkout time, the total



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Figure 1. - Lip seal apparatus ( $P_2 > P_1$ ).

rotating operational time could be only several hours. For these conditions of high speed and short operating time, elastomeric lip seals have been used in turbopumps for rocket vehicles. Figure 1 shows a typical seal with an elastomeric lip. Usually the seal consists of a sheet steel housing which is press fitted in the housing of the turbopump. This sheet steel housing carries the elastomeric lip which is loaded against the shaft by a garter-type spring and/or by the interference fit between the lip and the shaft. In general, the seal surface speeds are high ( $> 100$  ft/sec or  $30.5$  m/sec), and the amount of energy dissipated by the rubbing contact is necessary for calculation of a heat balance or thermal map of the mechanical component. For example, the heat generated by a seal next to a bearing could effect a change in the bearing internal clearance. Thus, some information on seal running torques is of interest. Further, during ground check out and before flight, the seal condition is checked by pressurizing the seal and measuring the gas leakage; thus some data on seal wear and static leakage ratio are of interest.

Manufacturers of lip seals usually state seal operational capacity in terms of limiting shaft surface velocity and pressure differential; these limiting figures usually apply to operational usage of hundreds or thousands of hours, and manufacturers give an approximate maximum useful operation velocity of  $50$  feet per second ( $15.2$  m/sec) for a synthetic rubber lip seal. No data are given by manufacturers on the limiting speeds or pressures for a useful life of several hours.

The useful life of a lip seal is dependent on the extent to which a lubrication film is formed between the lip and the shaft surface and on the seal lip temperature. Studies on

the lubrication of synthetic rubber shaft seals (ref. 1) indicate that full-film lubrication can exist and that the film thickness was of the order of 0.0001 inch (0.00025 cm) thick. No mechanism for film formation was postulated, but the higher velocities (27 ft/sec or 8.2 m/sec) produced larger film thicknesses than the low-velocity (0.3 ft/sec or 0.09 m/sec) runs. This suggests that high peripheral velocities may not be detrimental to wear life. The film formation is probably associated with small (micro) slider bearing geometries formed from the elastic deformation of the lip material in conjunction with surface roughness and waviness. Similar microasperity lubrication of face seals is discussed in reference 2. However, as compared with face seal, the seal lip material has a much lower elastic modulus; therefore, local elastic deformation of the sliding interface can more readily occur under the action of hydrodynamic forces.

These elastic deformations are conducive to formation of a lubricant film between the lip and shaft; however, the data of reference 3 suggest considerable detrimental velocity effects. As velocities increase, out-of-round shaft geometry causes local gaps between the lip and the shaft surface because the lip cannot respond to the frequency of the shaft disturbances. In addition, seal interface temperature, a factor that affects film thickness, is dependent on the shaft surface velocity.

The objectives of this study are to (1) measure seal torque and gas leakage rates of various lip seal designs and (2) compare the wear of the various seals.

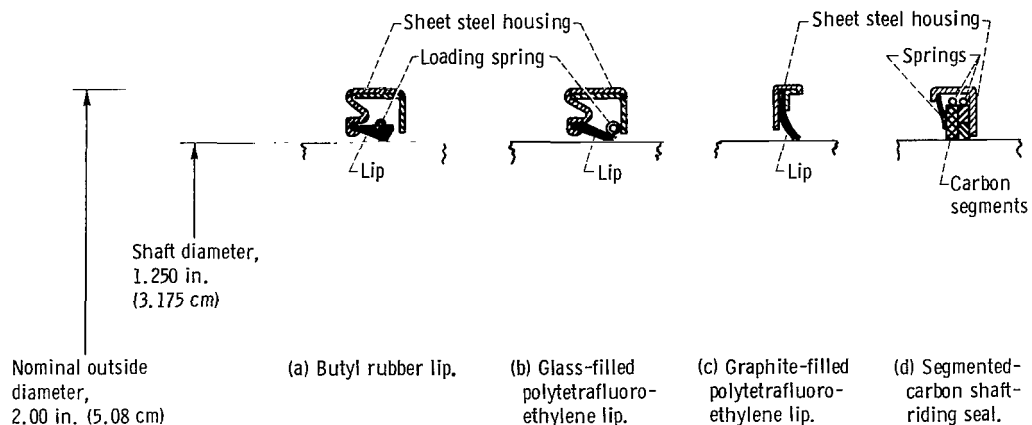
The lip seals were operated at peripheral velocities of 120 feet per second (36.6 m/sec) in an oil-mist, nitrogen-gas atmosphere. Running torque, static torque, and gas leakage rates were measured at various pressures (from zero pressure differential to applied pressures that tended to reduce the lip contact force). The seal lip materials were butyl rubber, glass-filled polytetrafluoroethylene, and graphite-filled polytetrafluoroethylene. A segmented-carbon shaft-riding seal was used as the basis of comparison.

## APPARATUS AND PROCEDURE

A schematic diagram of the apparatus used to evaluate the various lip seals is shown in figure 1. The seal lip ran against a 304 stainless-steel sleeve that was mounted on the stub end of a grinding spindle. The sleeve had a 1.250-inch (3.17-cm) nominal diameter and a 4- to 8-microinch ( $10.2 \times 10^{-6}$  to  $20.3 \times 10^{-6}$ -cm) plunge-ground (no axial grinding motion) and polished surface finish. The maximum dynamic runout was 0.001 inch (0.0025 cm) as measured by a capacitance probe. A lubricating mist was produced by dripping the lubricant (a synthetic diester, MIL-L-7808) on the rotating shaft at the rate of 1 cubic centimeter per minute. The test seal was supported by a housing that in turn was supported by a torque-meter with a 50-inch-ounce (35.3-cm-N) capacity. In some

cases, the runs were made with zero pressure differential; in other cases, the seal was pressurized (nitrogen gas) to reduce the lip contact force (see fig. 1). This procedure is the opposite of the conventional mode of operation in which the seal assembly is such that the sealed pressure tends to increase the contact force. However, in some short-term applications, such as in components for rocket vehicles, applying the seal in the pressure unloading configuration is sometimes used so that the seal prevents gross lubricant leakage and allows the case to vent as the altitude of the vehicle increases. Measurement of starting torque and leakage provided a relative gage of lip contact force. Shaft speed (24 000 rpm) was monitored by a magnetic pickup. Leakage was measured by a wet-test gas flowmeter, and the torque was continuously recorded on magnetic tape. In some runs, a thermocouple was attached to or embedded in the seal lip (see fig. 1).

A schematic diagram of the test seals, typical commercial seals, is shown in figure 2. The approximate cross sections of the seals with butyl rubber lips of 80 duro-



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Figure 2. - Seal types evaluated.

meter hardness and the seals with glass-filled polytetrafluoroethylene (80 percent polytetrafluoroethylene) lips are shown in figures 2(a) and (b), respectively. These seals are loaded by a garter spring. Figure 2(c) shows the approximate cross section of the seal with a graphite-filled polytetrafluoroethylene lip. Mechanical springs for lip loading were not used in this design. The approximate cross section of a segmented-carbon shaft-riding seal that was run for comparative purposes is shown in figure 2(d). No external heat was used; thus, the lip temperature rise was attributed to frictional heat generated at the sliding interface.

## RESULTS AND DISCUSSION

### Seal Running Torque and Temperature

Seal with butyl rubber lip. - The torque and temperature variation during running time for butyl rubber lip seals operating at zero pressure differential and a velocity of 120 feet per second (36.6 m/sec) is shown in figures 3 and 4. The traces of figure 3 are typical of seals that failed suddenly after several minutes of operation. The sudden failure was postulated to be a result of seal lip shrinkage. Shrinkage is known to occur in heated rubber materials under tensile stress (Gow-Joule effect). When assembled on the shaft, the lip is in tension and exerts a radial force against the shaft. Shaft rotation causes frictional heat generation at the sliding interface, and this heat can increase the lip tension (and radial force). More tension leads to more heat, and sudden failure can be induced. In contrast, the torque and temperature traces in figure 4 are for a seal that did not fail, probably because the initial lip inside diameter was larger and the radial lip force lower than that of the run shown in figure 3. The steep rise in torque (at

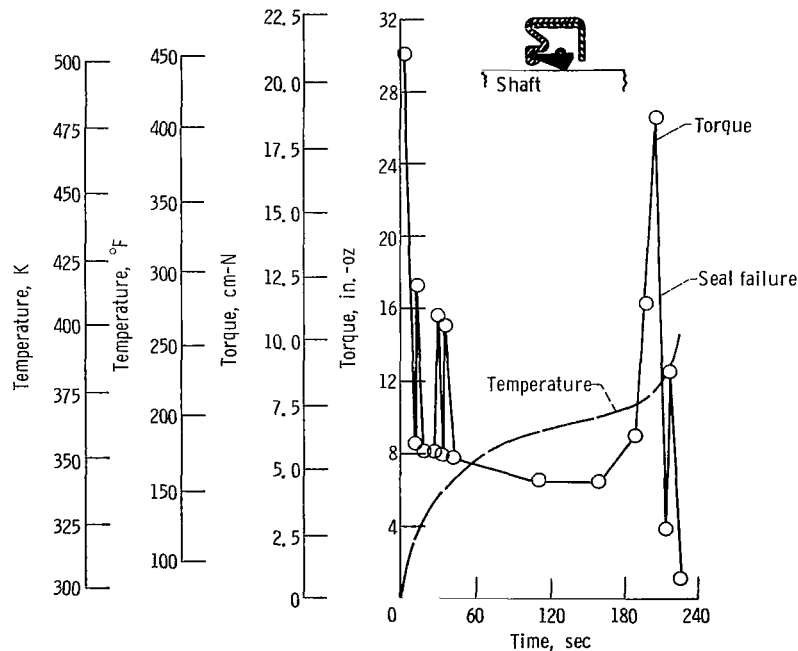


Figure 3. - Seal running torque and lip temperature as function of operating time. Lip material, butyl rubber; shaft surface velocity, 120 feet per second (36.6 m/sec); MIL-L-7808D lubricant rate, 1 cubic centimeter per minute; initial lip inside diameter, 1.170 inches (2.972 cm); pressure differential, zero.



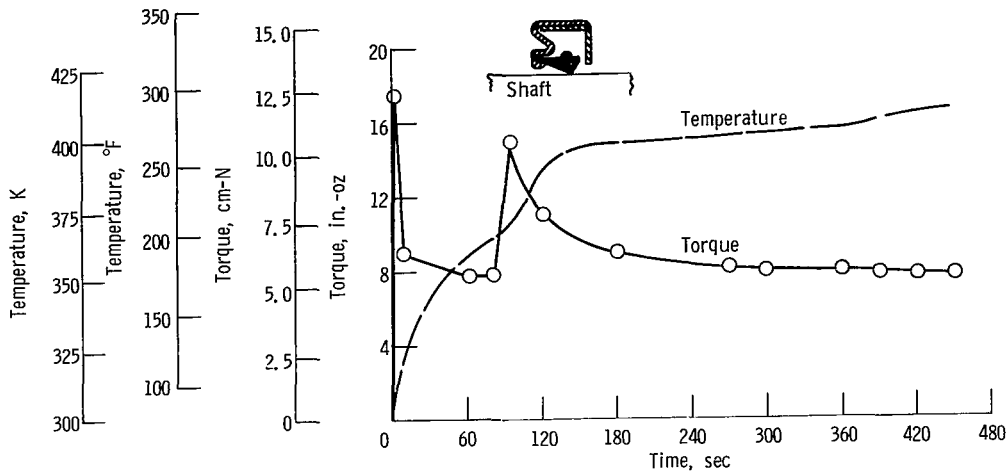


Figure 4. - Seal running torque and lip temperature as function of operating time. Lip material, butyl rubber; shaft surface velocity, 120 feet per second (36.6 m/sec); MIL-L-7808D lubricant rate, 1 cubic centimeter per minute; initial lip inside diameter, 1.180 inches (2.997 cm); pressure differential, zero.

85 sec) was typical of the seals with butyl rubber lips. The steep rise and subsequent decrease were postulated to be the result of lip shrinkage followed by a small amount of wear-in (corrective wear), after which the seal operated satisfactorily (as evidenced by the small amount of lip wear measured at the end of the test). The lip wear was determined by the width of the lip contacting the shaft; in this case, the lip was 0.025 inch (0.0635 cm) wide after operation. It should be noted that the lip temperature, measured 0.03 inch (0.076 cm) from the contact, is high (280° F or 410.9 K) under this type of operation.

An additional run in which the lip contact force was decreased by an increase in pressure differential provided added evidence of the postulated corrective-wear theory. The run (fig. 5) was started with a pressure differential of 8 psig (5.5 N/cm<sup>2</sup> gage), and considerable gas leakage (5200 standard cu cm/min) occurred because of the reduced lip contact force. The important point noted was the sudden increase in torque and subsequent decay each time the pressure differential was decreased. Each reduction in pressure differential was accompanied by a corresponding increase in torque because of the increase in lip contact force.

Further evidence of the corrective-wear process, for the seals with butyl rubber lips, is provided in figure 6, which shows the torque variation with time for a sequence of runs. In the first run of 60 seconds, the peak torque during acceleration to 120 feet per second (36.6 m/sec) shaft surface velocity was 30 inch-ounces (2.12 cm-N). A torque rise near the end of run 1 is similar to that shown in figure 4 and suggests that the corrective wear process had been induced by lip shrinkage that accompanied the lip tem-

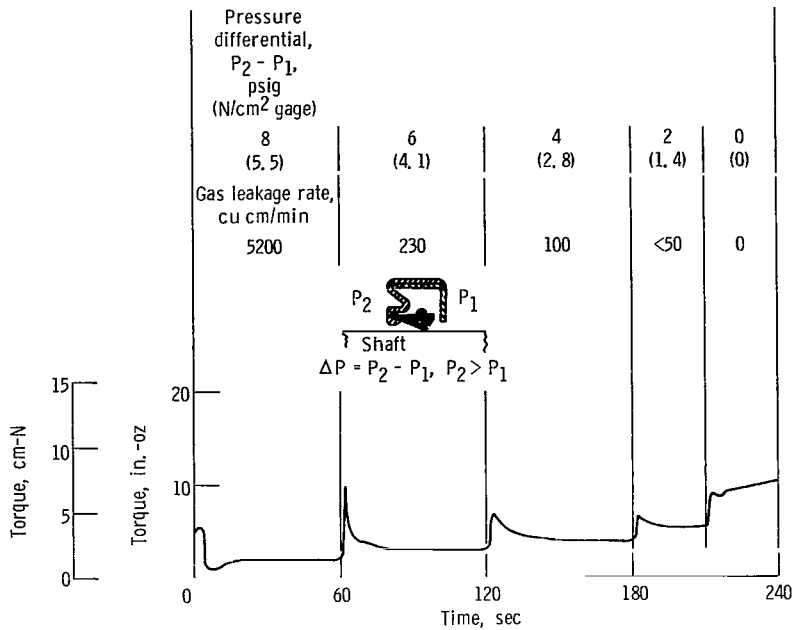


Figure 5. - Seal running torque as function of operating time and pressure differential. Lip material, butyl rubber; shaft surface velocity, 120 feet per second (36.6 m/sec); MIL-L-7808-D lubricant rate, 1 cubic centimeter per minute.

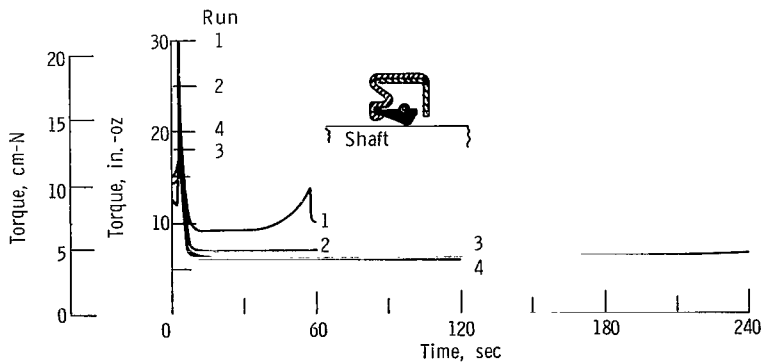


Figure 6. - Seal running torque as function of operating time and number of runs. Lip material, butyl rubber; shaft surface velocity, 120 feet per second (36.6 m/sec); MIL-L-7808-D lubricant rate, 1 cubic centimeter per minute; pressure differential, zero.

perature rise. After cool down, the second run of 60 seconds duration exhibited lower peak torque than the first run; no corrective wear occurred near the end of the second run as with the first run, and the running torque was lower than that for the first run. The third and fourth runs showed continued evidence of wear, in that both had lower peak torques and running torques than runs 1 and 2.

Seal with glass-filled polytetrafluoroethylene lip. - The torque and temperature variation for a glass-filled polytetrafluoroethylene seal operating at zero pressure differential at 120 feet per second (36.6 m/sec) is shown in figure 7. An erratic torque

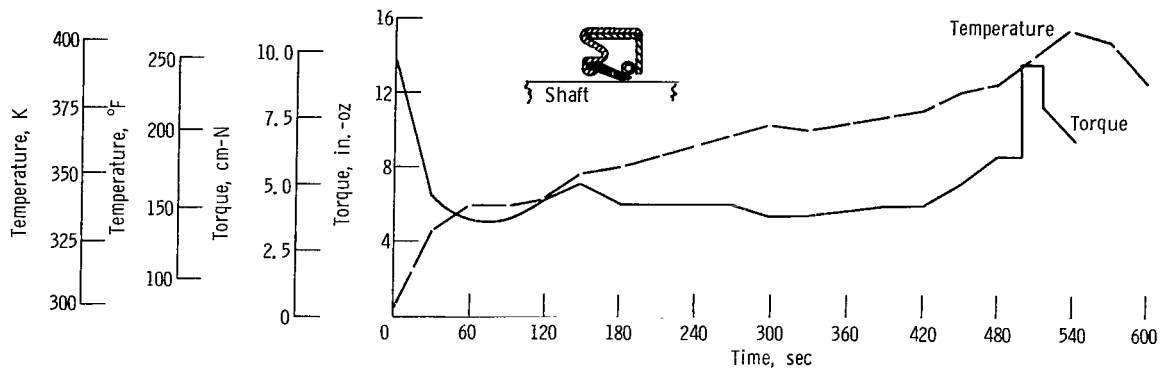


Figure 7. - Seal running torque and lip temperature as function of operating time. Lip material, glass-filled polytetrafluoroethylene; shaft surface velocity, 120 feet per second (36.6 m/sec); MIL-L-7808D lubricant rate, 1 cubic centimeter per minute; initial lip inside diameter, 1.230 inches (3.124 cm); pressure differential, zero.

surge occurred near the end of 540 seconds of operation; this torque is unexplained. In additional runs (fig. 8) in which the pressure differential was decreased in steps from an initial value of 14 psig (9.6 N/cm<sup>2</sup> gage), the torque indicated a small wear-in effect. Each time the pressure differential was reduced (thus increasing the lip contact force), the torque increased slightly and then decayed slowly with increased running time. Compared with the rubber butyl lip seal design, glass-filled polytetrafluoroethylene lip exhibited a running torque that was less sensitive to changes in pressure differential. This relative insensitivity is probably the result of the greater stiffness of the filled polytetrafluoroethylene and the lip geometry differences.

Further evidence of the wear-in process is provided in figure 9, which shows the running torque as a function of time for a sequence of four runs. The first run exhibited a torque peak (50 in.-oz or 35.3 cm-N) that is probably the result of a wear-in process. Succeeding runs (2, 3, and 4) with the same seal had lower starting torques than the first run and had no torque peaks.

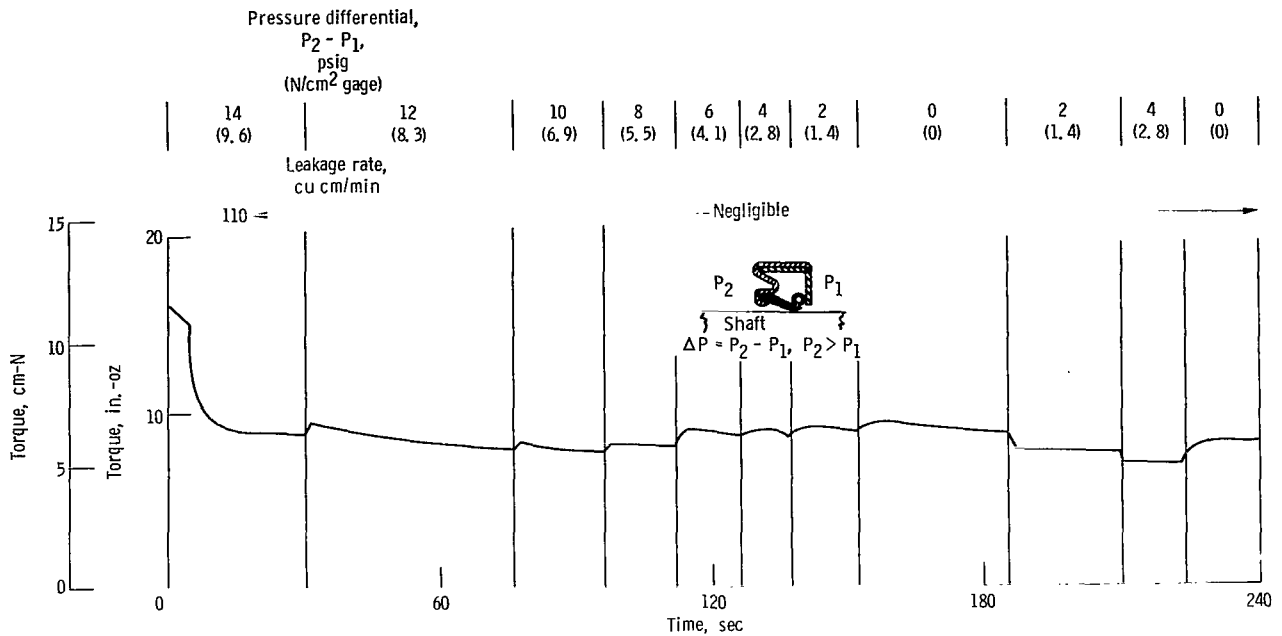


Figure 8. - Seal running torque and lip temperature as function of operating time and pressure differential. Lip material, glass-filled polytetrafluoroethylene; shaft surface velocity, 120 feet per second (36.6 m/sec); MIL-L-7808D lubricant rate, 1 cubic centimeter per minute.

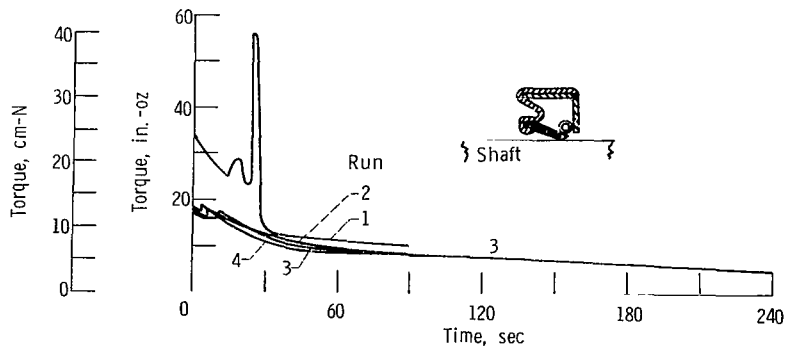


Figure 9. - Seal running torque as function of time and number of runs. Lip material, glass-filled polytetrafluoroethylene; shaft surface velocity, 120 feet per second (36.6 m/sec); MIL-L-7808D lubricant rate, 1 cubic centimeter per minute; pressure differential, zero.

Seal with graphite-filled polytetrafluoroethylene lip. - The torque and temperature variation for a seal design with a graphite-filled polytetrafluoroethylene lip at zero pressure differential and 120 feet per second (36.6 m/sec) is shown in figure 10. The starting torque of approximately 24 inch-ounces (16.9 cm-N) was attributed to a lip contact forced judged to be high. During the run, the torque was erratic and high initially; however, the torque leveled off to a constant value of 10 inch-ounces (7.1 cm-N) after 350 seconds of operation. The thermocouple cemented to the side of the lip registered a temperature of 275° F (408.2 K) at the end of the run.

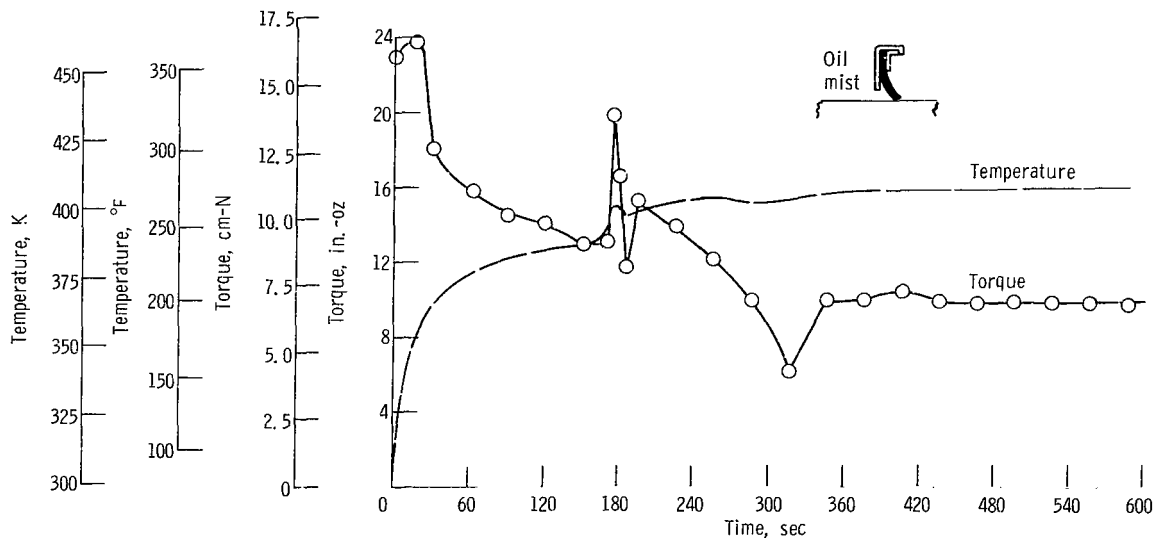


Figure 10. - Seal running torque and lip temperature as function of operating time. Lip material, graphite-filled polytetrafluoroethylene; shaft surface velocity, 120 feet per second (36.6 m/sec); MIL-L-7808D lubricant rate, 1 cubic centimeter per minute; initial lip inside diameter, 1.173 inches (2.979 cm); pressure differential, zero.

Segmented carbon seal. - As a basis of comparison, the running torque of a segmented-carbon shaft-riding seal was measured (fig. 11). Each decrease in pressure resulted in a corresponding decrease in running torque. Since the pressure differential acts to increase the contact force between the carbon and the shaft, the relation of torque as a function of pressure shown in figure 11 should be anticipated. The torque trace shows that the segmented carbon seal does not have the marked fluctuations in torque that occurred for the seal design with butyl rubber and filled polytetrafluoroethylene lips. However, the running torque at zero pressure differential is not significantly different from that for the lip seals.

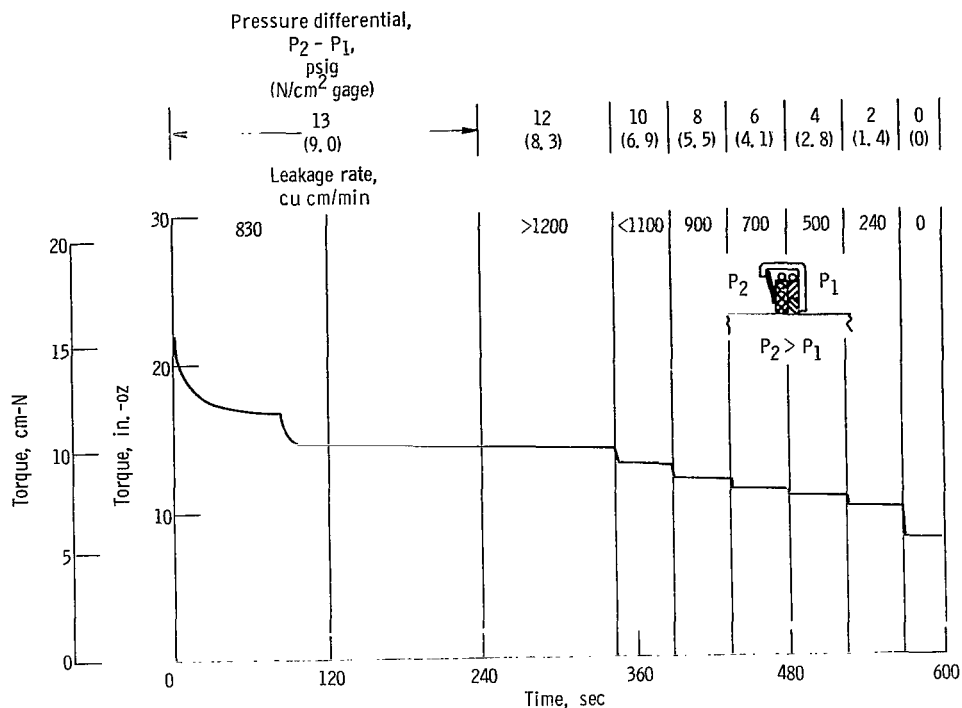
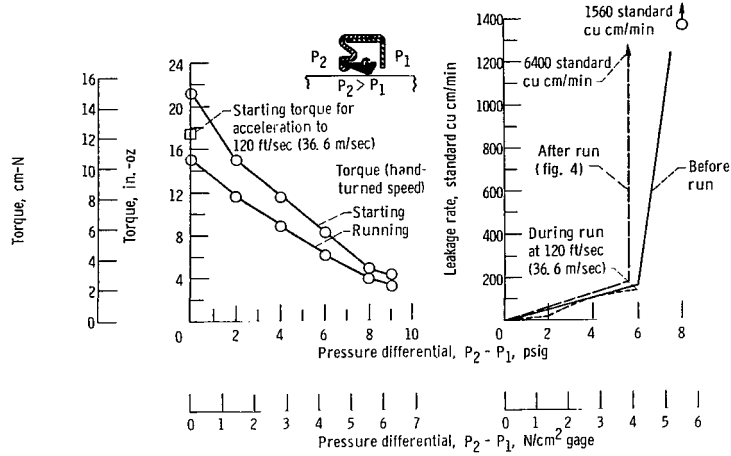


Figure 11. - Seal running torque and gas leakage rate as function of time and pressure differential. Seal material, carbon-graphite; shaft surface velocity, 120 feet per second (36.6 m/sec); MIL-L-7808D lubricant rate, 1 cubic centimeter per minute; sealed gas, nitrogen (room temperature).

## Starting Torque, Leakage, and Wear

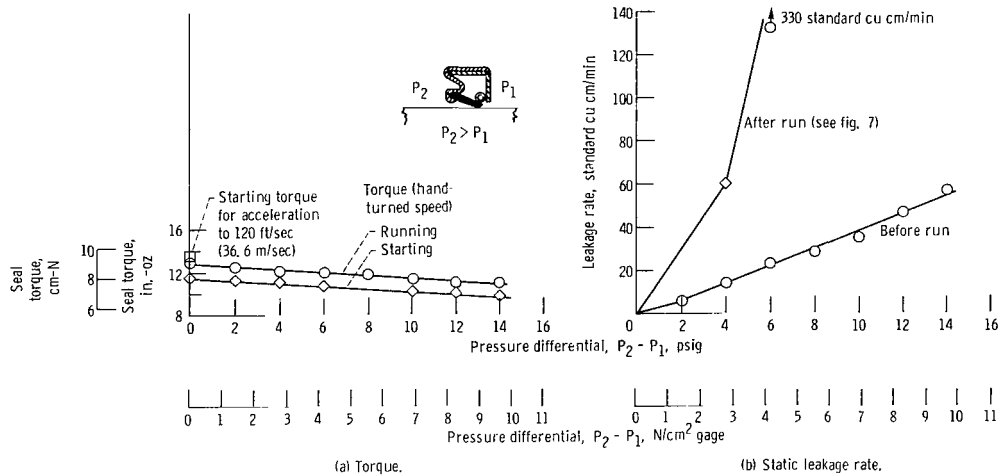
Seal with butyl rubber lip. - Starting torque for hand-turned startup is plotted in figure 12(a) for various sealed gas pressures. Also plotted in figure 12(a) is the running torque at hand-turned speeds. As would be expected, this slow-speed running torque is somewhat less than the breakaway torque.

Static leakage rates measured at the time the starting torque values were determined (before running at 120 ft/sec or 36.6 m/sec) are shown in figure 12(b). The curve for static leakage indicates a gradual increase in leakage as pressure differential increases to 6 psig (4.1 N/cm<sup>2</sup> gage); between 6 and 8 psig (4.1 and 5.5 N/cm<sup>2</sup> gage), the marked increase in leakage rate indicates that the seal leakage gap has significantly increased. This point was termed the lip-opening pressure. After running at 120 feet per second (36.6 m/sec), the lip-opening pressure occurred at 5.6 psig (3.9 N/cm<sup>2</sup> gage) compared with 6 psig (4.1 N/cm<sup>2</sup> gage) before running. This lower lip-opening pressure was attributed to wear that was measured as an 0.021-inch (0.032-cm) increase in diameter. Also plotted in figure 12(b) is the curve for the gas leakage rate at 120 feet per second (36.6 m/sec). The comparison of leakage rates



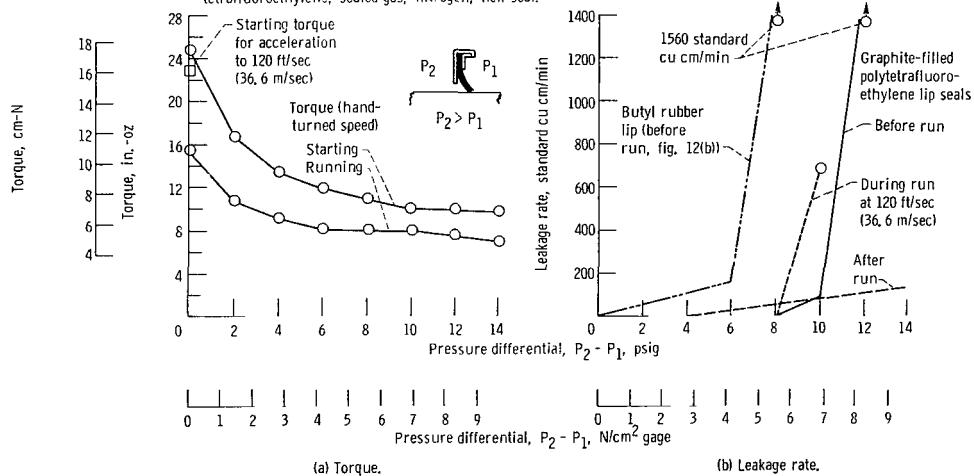
(a) Torque. (b) Leakage rate.

Figure 12. - Seal starting torques and gas leakage rate as function of pressure differential. Lip material, butyl rubber; initial lip inside diameter, 1.180 inches (2.997 cm); sealed gas, nitrogen; new seal.



(a) Torque. (b) Static leakage rate.

Figure 13. - Seal starting torques and gas leakage rate as function of pressure differential. Lip material, glass-filled polytetrafluoroethylene; sealed gas, nitrogen; new seal.



(a) Torque. (b) Leakage rate.

Figure 14. - Seal starting torques and gas leakage rate as function of pressure differential. Lip material, graphite-filled polytetrafluoroethylene; sealed gas, nitrogen; new seal.

shown in figure 12(b) shows that the dynamic leakage is similar to the static leakage at seal pressures to 6 psig ( $4.1 \text{ N/cm}^2$  gage). Dynamic leakage was not determined for pressures greater than 6 psig ( $4.1 \text{ N/cm}^2$  gage).

Seal with glass-filled polytetrafluoroethylene lip. - The starting torque values of the glass-filled polytetrafluoroethylene seals are shown in figure 13(a). In comparison with the butyl rubber lip seal, the glass-filled polytetrafluoroethylene seal does not exhibit a lip-opening pressure (before running) in the differential pressure range of 0 to 14 psig (0 to  $9.6 \text{ N/cm}^2$  gage). Also, for any given pressure, the leakage rates are lower (fig. 13(b)) than that for the seal with a butyl rubber lip. These lower rates may be attributed to the greater bending stiffness of the filled polytetrafluoroethylene lip. After running, the leakage rate was significantly greater than that before running; this increase was attributed to the 0.014-inch (0.035-cm) diametral wear. Two other runs with new seals ended in failure after 15 seconds of operation; thus this seal design had high failure probability under these conditions of operation.

Seal with graphite-filled polytetrafluoroethylene lip. - The starting torques of the graphite-filled polytetrafluoroethylene seals are shown in figure 14(a). Comparison with the torques for the butyl rubber seal (fig. 12(a)) shows that the pressure does not unload the lip contact pressure as readily, and, therefore, the leakage is less (fig. 14(b)); the leakage curve of the butyl rubber seal (fig. 12(b)) is included for comparison in figure 14(b). The seal lip-opening pressure occurred between 10 and 12 psig ( $6.9$  to  $8.3 \text{ N/cm}^2$  gage) before running. After the run, the seal did not open in the range of 0 to 14 psig ( $9.6 \text{ N/cm}^2$  gage), and the leakage rates were the lowest of the three seal designs evaluated. The change in diameter (permanent set plus wear) was 0.047 inch (0.119 cm). In two other runs with new seals, the leakage and torque results were similar to that shown in figure 14. One of these runs was made without lubrication. In general, the graphite-filled polytetrafluoroethylene seal exhibited good wear and the lowest leakage rate of the three types of lip seals evaluated. (This evaluation is based on the total designs and not materials alone.)

The data suggest that the seal design with a graphite-filled polytetrafluoroethylene lip may be useful for very low-leakage sealing against a small pressure differential (to 8 psig or  $5.5 \text{ N/cm}^2$  gage) applied so as to reduce the lip contact force. However, long-term storage and running, in which cold flow of the lip material is important, has not been evaluated in this study.

## SUMMARY OF RESULTS

Lip seals of various types were run to peripheral velocities of 120 feet per second (36.6 m/sec). Torque and lip temperature were continuously recorded during short-



term (to 600 sec) operation with zero pressure differential across the seal. Starting torques and leakage rates were checked at pressure differentials to 14 psig (9.6 N/cm<sup>2</sup> gage). The pertinent results apply to the seal design as a whole and not solely to lip materials.

The following results were obtained with respect to the seal running torque:

1. The seal with the butyl rubber lip exhibited a prominent wear-in torque peak. This wear-in torque was postulated to be associated with lip shrinkage due to heating (Gow-Joule effect). This lip shrinkage can lead to sudden failure at the shaft velocities employed, but gradual wear-in decreased the probability of failure.

2. Seals with glass-filled polytetrafluoroethylene lips also exhibited a wear-in process and high failure probability under some of the test conditions.

3. Seals with graphite-filled polytetrafluoroethylene lips had erratic and high wear-in torques that were attributed to the high initial lip contact force characteristic of this seal type.

4. In general, lip-seal running torques (after the wear-in process) were similar to that for segmented-carbon shaft-riding seals.

The following results were obtained with respect to leakage and wear:

5. The seal with a graphite-filled polytetrafluoroethylene lip exhibited the lowest leakage rate and good wear characteristics.

6. Dynamic gas leakage was similar to the static leakage for the seal designs with butyl rubber lips and graphite-filled polytetrafluoroethylene lips.

Lewis Research Center,

National Aeronautics and Space Administration,

Cleveland, Ohio, March 5, 1969,

120-27-04-21-22.

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