NASA TECHNICAL MEMORANDUM

NASA TM X-52867

NASA TM X-52867

AEROSPACE LUBRICATION FOR ADVANCED VEHICLES

by R. L. Johnson and E. J. Manganiello
Lewis Research Center
Cleveland, Ohio U. S. A.

TECHNICAL PAPER proposed for presentation at
German Society of Tribiology Annual Meeting
Essen, Germany, September 22-23, 1970

E-5831

AEROSPACE LUBRICATION FOR ADVANCED VEHICLES

by R. L. Johnson and E. J. Manganiello

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio
U.S.A.

SUMMARY

Lubrication studies at NASA-Lewis Research Center are concerned with the broad scope of problems in aeronautics, space power, rockets and space vehicles. The space shuttle concept provides an advanced problem area including many extremely severe lubrication requirements. Some Lewis lubrication studies pertinent to the shuttle are reviewed with special reference to the airbreathing engines where requirements are similar to those for future aircraft. The trends in airbreathing engines are toward more severe conditions such as higher rotative speeds and higher temperatures with the shuttle adding special seal problems. Some data on lubrication methods for use at higher temperatures and speeds indicate promise for mist systems and inerted or closed systems. Main-shaft face type seals with Rayleigh step lift-pad geometry perform well under extreme conditions. Lubricant limitations are described and successful operation at high temperatures is reported. A synthetic paraffin liquid lubricant provided extended operation of engine bearings at 650° F (343° C) in an inerted atmosphere and a CaF_2 base solid lubricant allowed operation of ball bearings to 1500° F (816° C) for periods up to 150 hours. Improvements in application of MoS_2 by vacuum deposition methods give evidence that the stalwart lubricant of past space vehicles can have the extended durability needed for the shuttle and space stations.

INTRODUCTION

The NASA-Lewis Research Center is primarily a propulsion and power systems oriented laboratory with general research and development programs to serve the needs of aeronautics, space power, rockets and space vehicles. Advanced lubrication research is conducted at Lewis to answer the immediate and anticipated needs for those general programs. This paper will review several elements of our lubrication activity with special reference to lubrication problems for advanced aircraft engines.

One of NASA's newer programs now being considered is that of the earth orbit shuttle (ref. 1). That program area is of particular interest
CS-54260 with regard to lubrication technology. The shuttle (fig. 1) combines

all the most severe problems of aircraft, chemical rockets and spacecraft. The piggyback orbiter and the booster will take off as a conventional rocket in the vertical attitude. After achieving a staging velocity of about 9000 feet per second (2743 meters per second) the two elements will separate and the booster returns to earth landing like a conventional aircraft. The orbiter will proceed into a space orbit to perform various types of missions possibly to rendezvous with a space station and function in space for periods of time of up to 30 days. The earth orbit shuttle will then achieve a routine re-entry and landing after the orbital flight. The vehicles will re-enter the earth's atmosphere under conditions to minimize aerodynamic heating, and they may have a cross range in excess of 1000 miles (1609 kilometers). Although the re-entry heating will be minimized, it is still likely that the temperatures of the aerodynamic surfaces will exceed 2000° F (1093° C). It is quite apparent that the lubricated surfaces exposed to both extended time in space vacuum and to high temperature re-entry of the earth's atmosphere for the period of time necessary for the stipulated cross range will have unique problems.

It is the objective of this paper to discuss the advancing lubrication technology being developed at NASA-Lewis Research Center using the shuttle problem as a reference framework.

DISCUSSION

Airbreathing Engine

Advanced airbreathing engines are being considered for use with both the booster and orbiter vehicle of the shuttle. Engine capabilities might be required for landing, go-around, and ferrying. The engines will likely be in a closed compartment but still might be expected to have exposure to space vacuum while in orbit. Later the engines may be exposed to high temperatures during re-entry. The most advanced engines available will most likely be utilized. An engine representative of existing commercial engines that are being considered for application in the booster is the Pratt and Whitney's JT-9D. This engine is now operating in the Boeing 747 transport. If we compare that engine with the JT-3D engine used in many of the present day transports we can see that there has been substantial advancement
CS-54878 in aircraft engines in recent years. Figure 2 illustrates this development showing the size comparison of the JT-3D engine to the

present day JT-9D engine with the JT-3D scaled up to provide the equivalent thrust of the JT-9D. It is quite apparent that significant advancements have been achieved. Important aspects of the improved performance have been greatly simplified bearing lubrication systems (ref. 2) and increased rotative speeds. The latter will be a continuing trend in the engines of the immediate future. The trend illustrated
CS-54798 in figure 3 shows the current surface speeds for mainshaft seals being upwards of 420 feet per second (128 meters per second) (ref. 3) and the DN value (bore diameter of bearing in mm times speed in rpm) of mainshaft bearings being upwards of 2.2 million DN (ref. 4).

As engines are operated at higher rotative speeds, the problems of lubricant stability become correspondingly more severe. Additional effects of higher rotative speeds on the lubricant is illustrated by
CS-53491 data of figure 4. These data from SKF Industries (NASA contract NAS3-6267) show the relative power loss of a simulated full-scale engine bearing and seal assembly as a function of viscosity for several lubricants with a 125-mm bore ball bearing. The power loss, as expected, increases with the viscosity of the lubricant. The type II ester lubricant was run not only at 14 000 rpm (1.75 million DN) but also at higher speeds. Operation at 20 000 rpm (2.5 million DN) caused a 50 percent increase in power loss over that experienced at 14 000 rpm. These data were all obtained with one gallon per minute (0.23 cubic meters per hour) of oil circulating through the bearing and seal assembly.

A very promising approach to lubricating aircraft engine components at higher rotative speeds may be that of using a mist once-through lubrication system. Minute quantities of lubricant are used in a mist system and are introduced in a gas stream to the lubricated part and subsequently dumped overboard. In that case, however, it may be necessary to introduce supplemental gas cooling of the lubricated parts. Data (fig. 4) for the synthetic paraffin using both the circulating system and the mist lubrication system at 14 000 rpm indicate that the power loss in the assembly for mist lubrication was about 1/3 that for the circulating fluid. Although the necessity for supplemental cooling may seem objectionable, it is more efficient to use gas cooling on components operating at very high surface speeds than for static or slowly moving parts. Some design experience indicates that gas cooling of mist lubricated mechanical components is indeed a feasible approach for future aircraft engines. The data of figure 4 were obtained with outer race bearing temperatures of 600° F (316° C) for the circulating system with the bulk lubricant temperature at 500° F (260° C). Operation of these fluids under such conditions would not be possible without using an inerted lubrication system.

CS-53494 As illustrated in figure 5, and discussed further in reference 5, the limiting temperatures for various lubricants can be substantially extended if the lubrication system is closed and inerted rather than open to the atmosphere. These data show the limiting temperatures for the use of a number of organic lubricants in an open system where there is air available to the lubricant and in a closed system where there is no substantial amount of oxygen available to the lubricant. These data were obtained from oxidation studies and from thermal stability studies using an isoteniscope. Comparisons suggest that inerting can allow 150-200° F (83-111° C) higher temperature levels over those permissible if the lubrication system is open to the atmosphere.

CS-53496 Figure 6 is a photograph of a 125-mm bore bearing assembly after operating 250 hours at 650° F (343° C) with 500° F (260° C) oil-in temperature. This operation utilized a synthetic paraffin lubricant and employed inerting with a gaseous nitrogen cover. The lubricated surfaces of the ball bearing are in excellent condition. To obtain similar results in an open system it would be necessary to restrict the temperatures of the bearing to about 500° F (260° C) and the oil-in temperature to about 350° F (177° C). Similar results can be demonstrated for several lubricants and indeed indicate the feasibility of closed and inerted lubrication systems for high temperature operation. It is likely a closed lubrication system will be needed with the airbreathing engines of the shuttle vehicle for several reasons beside that of high temperature operation.

One of the important characteristics of the shuttle vehicle is that it must be reusable. Present plans call for the shuttle vehicle to operate
CS-53548 through 100 flight cycles or more without major maintenance. Figure 7 shows the effect of using various lubricants on the endurance of bearings operating at 600° F (316° C) in an inerted environment. The synthetic paraffin showed superior performance compared with other high temperature lubricants giving bearing lives many times the AFBMA (Anti-Friction Bearing Manufacturers Association) predicted life for that bearing under more nominal conditions.

Improved mainshaft and other seals are essential for engines exposed to
CS-47729 vacuum and high pressure operation or inerting (ref. 6). As figure 8 shows there are substantial differences in the leakage for various types of seals over a range of pressures. The leakage for the labyrinth type seal is very high compared with that for the conventional face seal. The conventional face seal, however, fails to operate at more extreme conditions of pressure as indicated by accelerated leakage rates that occurs with rapid surface deterioration (wear). An approach that has promise for extreme operation, however, involves the use of auxiliary

lift pads adjacent to the seal dam on what otherwise appears to be a
conventional face type seal. More details on the lift pad seal con-
CS-47726 figuration are shown in figure 9 and described in reference 7. This
configuration utilizes shrouded Rayleigh step lift pads and has been
CS-53424 subjected to extensive investigation. Figure 10 is a photograph of
the carbon face of a lift pad seal configuration after more than three hundred hours of operation with pressures in the range of 200-280 pounds per square inch (138-193 N/cm^2), sealing air at 1000° F (538° C), and with surface speeds in the range of 400-450 feet per second (122-137 meters per second). A conventional face seal, under these same conditions, shows excessive wear; hence, it cannot be used. Examination of figure 10 suggests that there was very little wear or other surface disturbance on this lift pad seal. Some minor score marks occurred as a result of debris coming through the seal. The lift pads were initially less than 0.001-inch (0.0025-cm) deep and; therefore, it is quite apparent there was very little wear on this seal face. The hydrodynamic gas action is sufficient so that this seal is supported on a thin gas film and is rarely in contact with the mating surface. Even under conditions normally associated with idle operation in an aircraft engine this seal face would be supported by gas film rather than in solid contact.

Vehicle

A very important problem for supersonic aerodynamic vehicles is the heating that occurs as a result of stagnation temperatures. The shuttle will utilize aerodynamic controls during re-entry and landing. The skin temperatures of aerodynamic surfaces during re-entry may exceed 2000° F (1093° C). Airframe bearings for those aerodynamic control surfaces will likely encounter temperatures of 1600° F (871° C) or higher. Solid lubricants offer a solution to the lubrication of such high temperature airframe bearings (ref. 8).

Figure 11 shows the effect of temperature on solid lubricant performance as indicated by friction coefficient. These data were obtained with thin bonded films sliding in air between concentrated contacts. It is quite apparent that molybdenum disulfide cannot perform over the temperature region required even with potential improvements possible with additives. Neither can a relatively newly used solid lubricant graphite monofluoride which offers some increased temperature potential (ref. 9). The solid lubricant that appears to have promise for this program area is calcium fluoride. Reference 8 reports experience with CaF_2 as a lubricant in air. Data on the evaporation and decomposition of lubricating materials also shows that CaF_2 has excellent potential for use
CS-53488 in vacuum (fig. 12).

Calcium fluoride can also be used to lubricate ball bearings effectively. The lubricant is applied as a fused coating on the bearing
CS-45783 cages. Figure 13 is a photo of a 20-mm bore ball bearing operating at red heat (1450° F (788° C)) with CaF_2 as the lubricant. Calcium fluoride from the cage transfers to the running surfaces of the races and provides effective lubrication. Bearings of this type have been run at temperatures of 1500° F (816° C) for periods of up to 150 hours without failure. Similarly these bearings have been run at 1200° F (649° C) for periods of up to 1000 hours without failure. Calcium fluoride lubricated bearings can function well in vacuum or in air and at high temperatures and thus appear to have excellent capabilities for airframe bearings to be used in the space shuttle.

New vacuum deposition methods (ref. 10) and composite materials (ref. 8) give greater utility for solid lubricants. For example, MoS_2 which is one of the standard lubricants for space mechanical components can be applied without bonding agents using r-f or d-c sputtering. Figure
CS-51197 14 shows relative endurance life in vacuum for several films. The burnished and bonded MoS_2 films that have served well on many spacecraft are compared with the performance of the vacuum deposited films. The vacuum deposited films offer attractive potential for use in the extended and repeated operation of shuttle vehicles.

Rocket Engine

The rocket engine lubrication problems for the shuttle are similar to present rocket engines utilizing the same propellants. Present upper stage engines predominantly utilize hydrogen as the fuel and oxygen as the oxidant. These are the likely propellants for the rocket booster engines of the shuttle. Liquid oxygen is a relatively good lubricant for slider materials. Critical slider locations for lubrication occur in the rolling contact bearing cage locating surfaces and in the cage ball pockets (ref. 11). They occur at the sliding interface between nose pieces and their mating surface. Liquid hydrogen is a very poor lubricant. It has the viscosity at its boiling point that is about equivalent to air at room temperature. With activation by friction energy hydrogen tends to chemically reduce the surface oxides that are often necessary to prevent wear and seizure of metals in sliding contact. About the only function of a lubricant that liquid hydrogen can fill is that of a coolant. It has been learned, however, that it is possible to utilize transfer films of solid lubricating materials for the lubricating function in liquid hydrogen with that propellant providing the cooling.

CS-54799 Figure 15 shows the relative wear and friction for the combinations of treated carbons used in face type seals and the PTFE or teflon filled with 15 percent glass fibers and containing 5 percent graphite. The latter material is used as the cage material for rolling contact bearings used in liquid hydrogen turbopumps. An improved material is now available for use in seal and bearing applications. That material is teflon reinforced with laminated graphite fabric. The performance with regard to wear and friction shown in figure 15 illustrates that this material should have improved life in friction applications such as in bearings or seals (ref. 12)

The primary distinguishing characteristic between present engines and shuttle rocket engines is the requirement for longer and repeated cycles of operation. Also it is very likely that the rocket engines used will have higher pressure systems. With the higher operating pressures, sealing becomes more critical in the rocket engine turbopumps. It is anticipated that the present conventional face type seals will be replaced with the self-acting lift geometry type previously described for aircraft engines. Because of their self-acting (hydrodynamic) configuration, the lift-pad can be used with high pressure fluids without danger of catastrophic wear and surface failure that would most certainly be experienced with conventional face seals.

The manner of increased endurance operation for the rocket engines to be used on the shuttle is extremely important. Whereas a conventional rocket engine would have its total life measured in minutes, the rocket engines for the shuttle will have to survive perhaps 100 cycles of operation, and the total life requirement will be measured in hours. It will be necessary to verify that the self-acting seal geometries described previously can operate for extended periods of time without failure. Also, it is important to verify that the endurance of present propellant-cooled bearings with self-lubricated cages is satisfactory. The use of graphite laminated reinforced teflon to replace the glass fiber reinforced teflon as illustrated in figure 15 may be an important step toward achieving this extended life.

CONCLUDING REMARKS

The proposed shuttle vehicle provides challenging applications for the most advanced lubrication technology available. Several areas of NASA lubrication research have been described that may contribute to the solution of these challenging shuttle problems.

REFERENCES

1. Faget, Max: Space Shuttle: A New Configuration. Astronautics and Aeronautics, vol. 8, no. 1, Jan. 1970, pp. 52-61.

2. Reynolds, H.W., Jr.; and Moore, R.E.: Evaluation of the Pratt and Whitney Aircraft JT9D Engine Oil System. Paper presented at SAE Air Transportation Mtg., April 21-24, 1969, New York. (Also Esso Air World, vol. 21, no. 6, May/June 1969, p. 147).

3. McKibben, A.H.; and Parks, A.J.: Aircraft Gas Turbine Mainshaft Face Seals--Problems and Promises. Presented at 4th International Conf. of Fluid Sealing, Philadelphia, Penna., May 5-8, 1969. ASLE Special Publication SP-2, pp. 28-35.

4. Rumbarger, J.H.; and Dunfee, J.D.: Survey of the State-of-the-Art for the Design of High Speed Rolling Element Bearings Used in Gas Turbine Engines. The Franklin Institute Research Labs Final Report F-C2138-1, vol. 1 for Naval Air Propulsion Test Center, Contract N00156-68-C-0330.

5. Loomis, W.R.; Townsend, D.P.; and Johnson, R.L.: Lubricants for Inerted Lubrication Systems in Engines for Advanced Aircraft. SAE paper 680317, May 1968.

6. Johnson, R.L.: Loomis, W.R.: and Ludwig, L.P.: Performance and Analysis of Seals for Inerted Lubrication Systems of Turbine Engines. NASA TN D-4761, 1968.

7. Johnson, R.L. and Ludwig, L.P.: Shaft Face Seal With Self-Acting Lift Augmentation for Advanced Gas Turbine Engines. NASA TN D-5170, 1969.

8. Sliney, H.E. and Johnson, R.L.: Preliminary Evaluation of Greases to 600° F and Solid Lubricants to 1500° F in Ball Bearings. NASA TN D-4652, 1968.

9. Fusaro, R.L. and Sliney, H.E.: Preliminary Investigation of Graphite-Fluoride $(CF_x)_n$ as a Solid Lubricant. NASA TN D-5097, 1969.

10. Spalvins, T.: Energetics in Vacuum Deposition Methods for Depositing Solid Film Lubricants. NASA TM X-52549, 1969.

11. Brewe, D.E.; Scibbe, H.W. and Anderson, W.J.: Film-Transfer Studies of Seven Ball-Bearing Retainer Materials in Hydrogen Gas. NASA TN D-3730, 1966.

12. Wisander, D.W. and Johnson, R.L.: Friction and Wear of Nine Selected Polymers with Various Fillers in LH_2. NASA TN D-5073, 1969.

E-5831

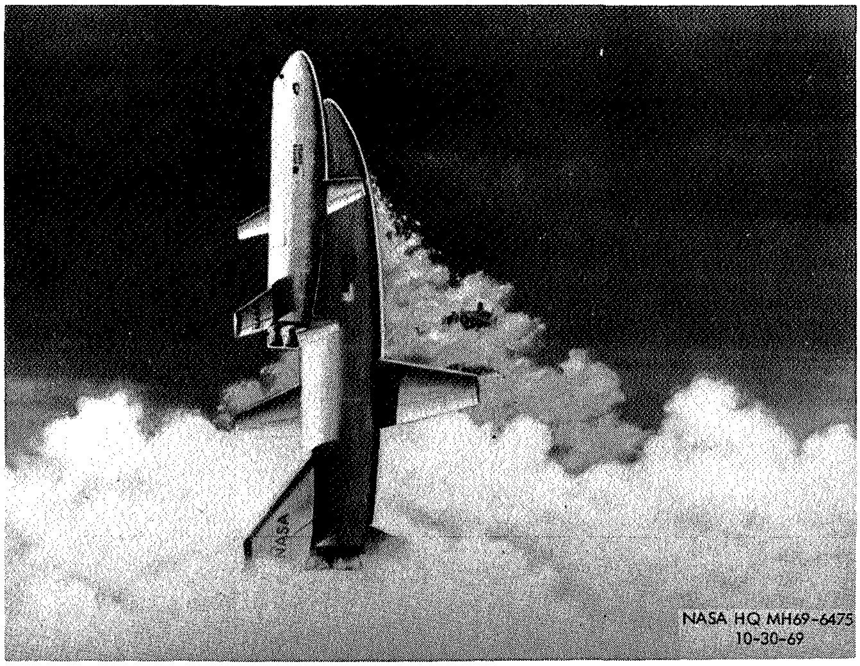

Figure 1. - Earth orbit shuttle.

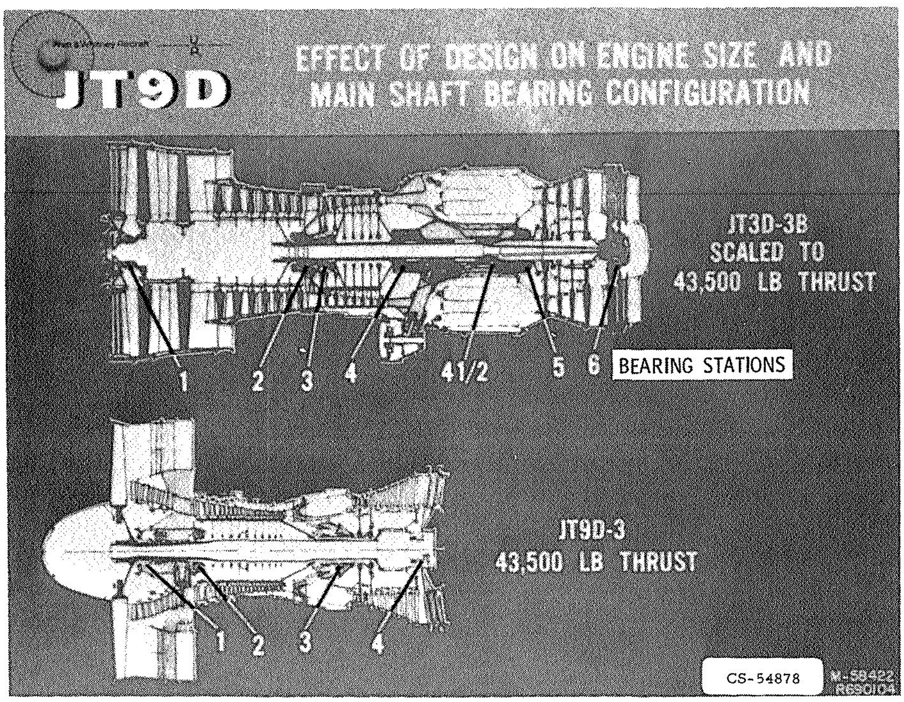

Figure 2.

E-5831

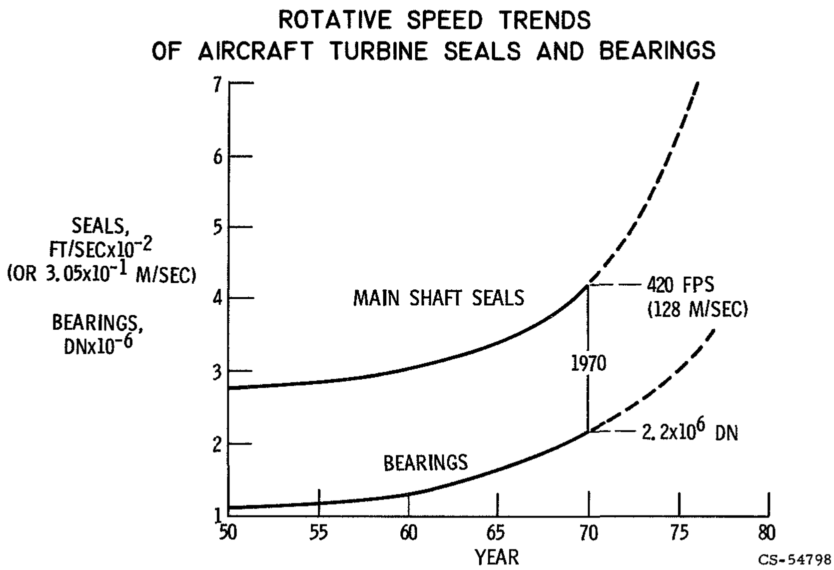

Figure 3.

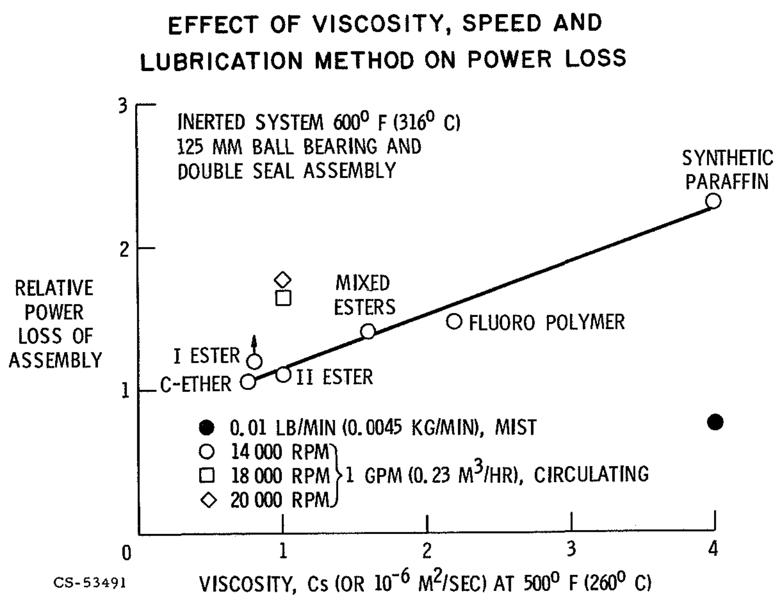

Figure 4.

E-5831

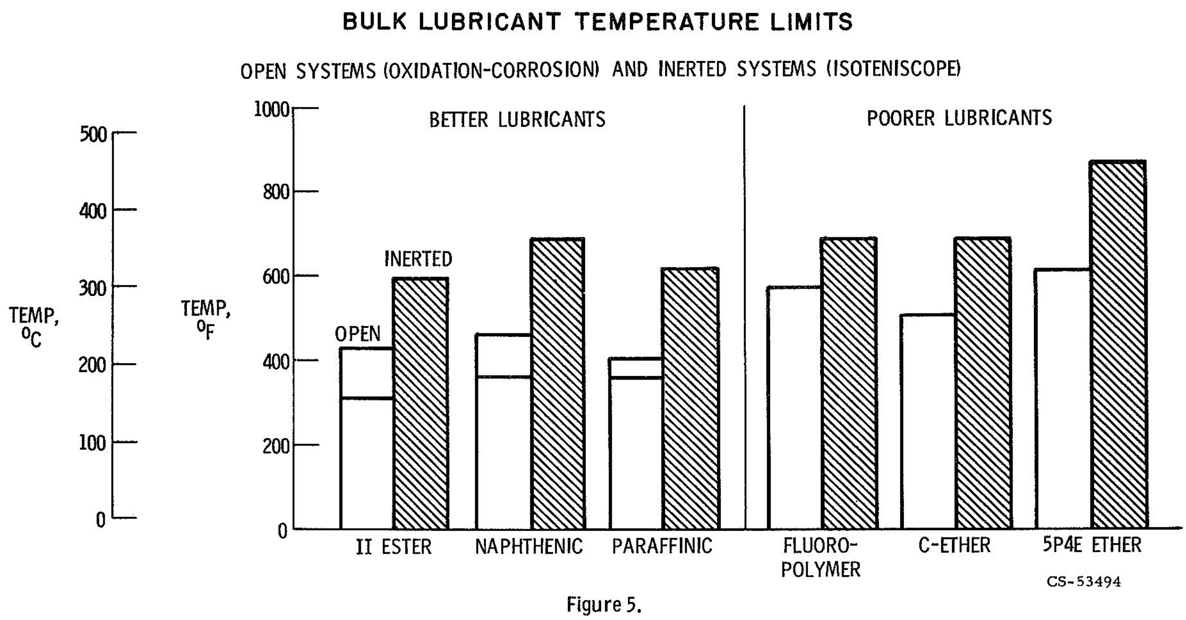

Figure 5.

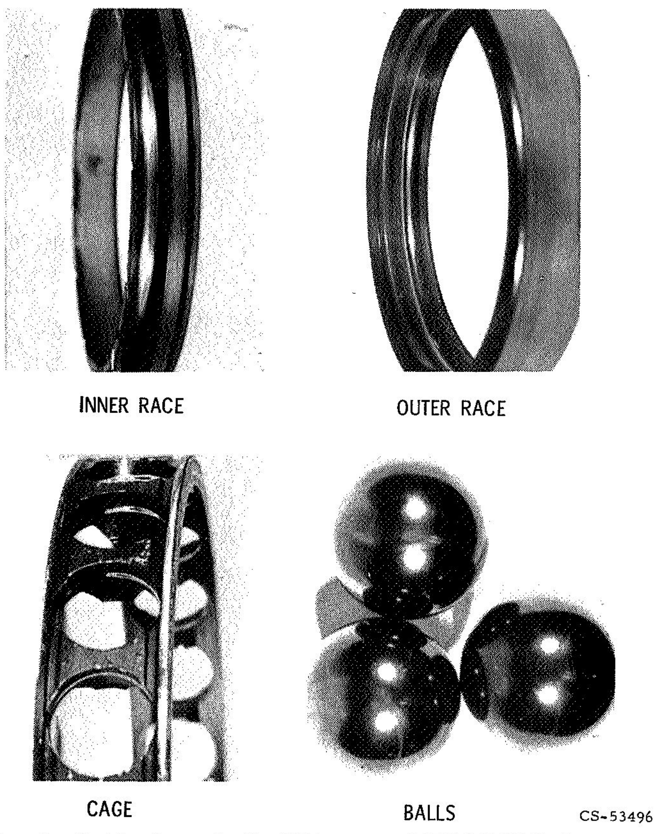

Figure 6. - Test bearing parts after 230 hour run at 650° F (343° C) with synthetic hydrocarbon oil. N_2 atmosphere.

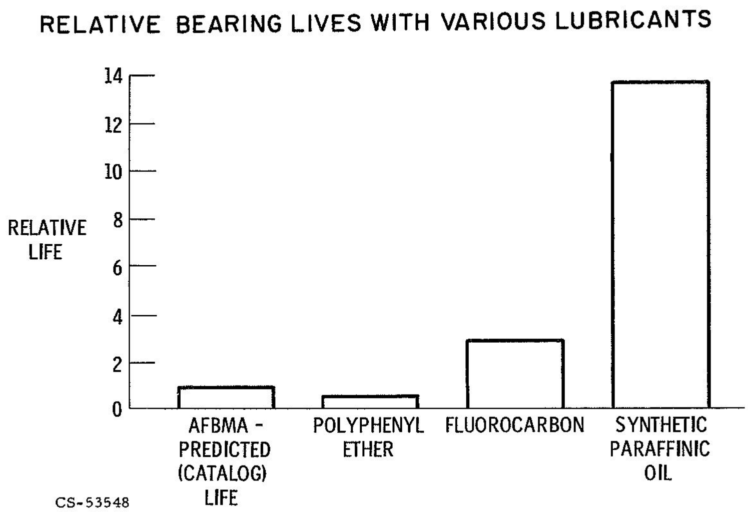

Figure 7.

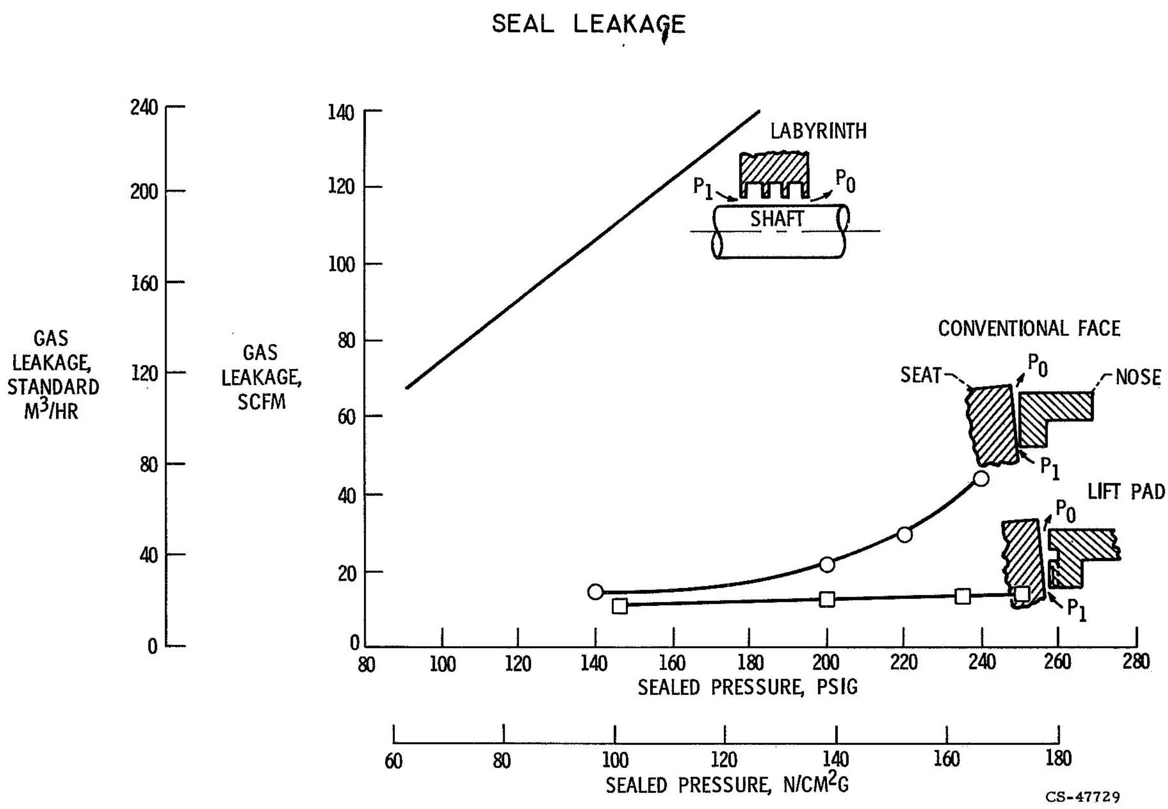

Figure 8.

NOSE FACE WITH SELF-ACTING BEARING

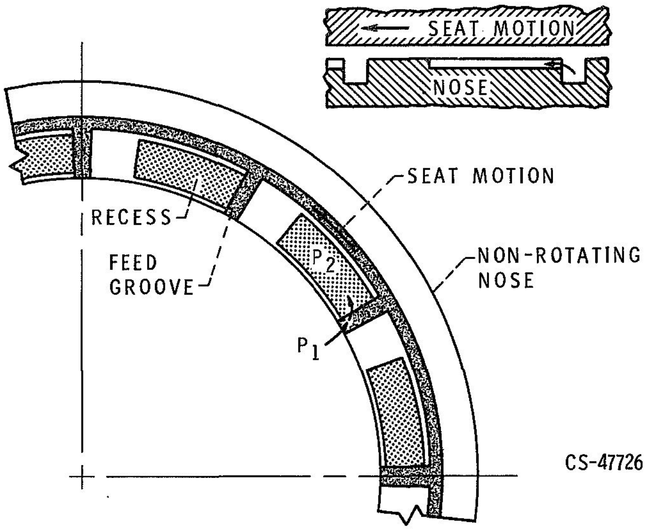

Figure 9.

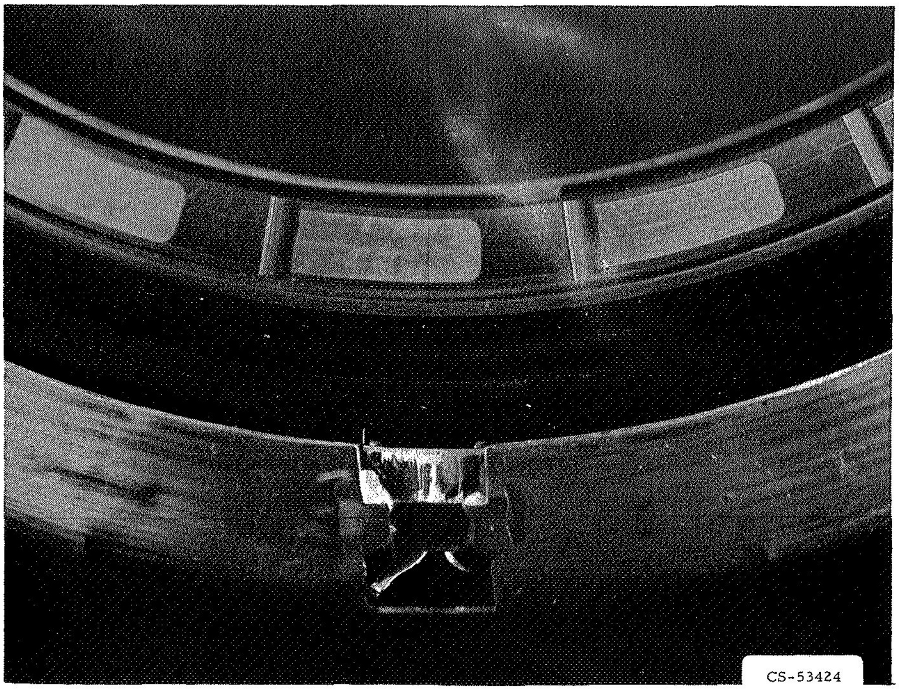

Figure 10. - Lift pad seal carbon face after 330 hours testing at pressure of 200 psi (138 N/cm^2), sealing air at 1000° F (538° C), and surface speed of 400 fps (122 M/sec).

E-5831

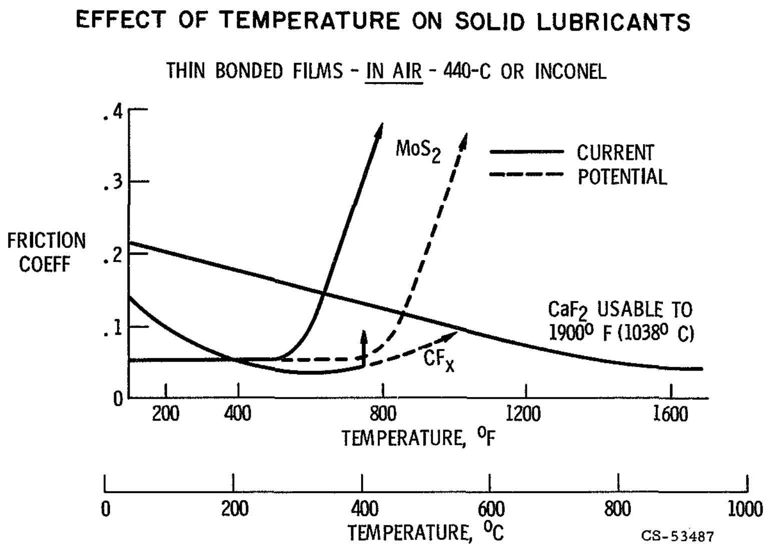

Figure 11.

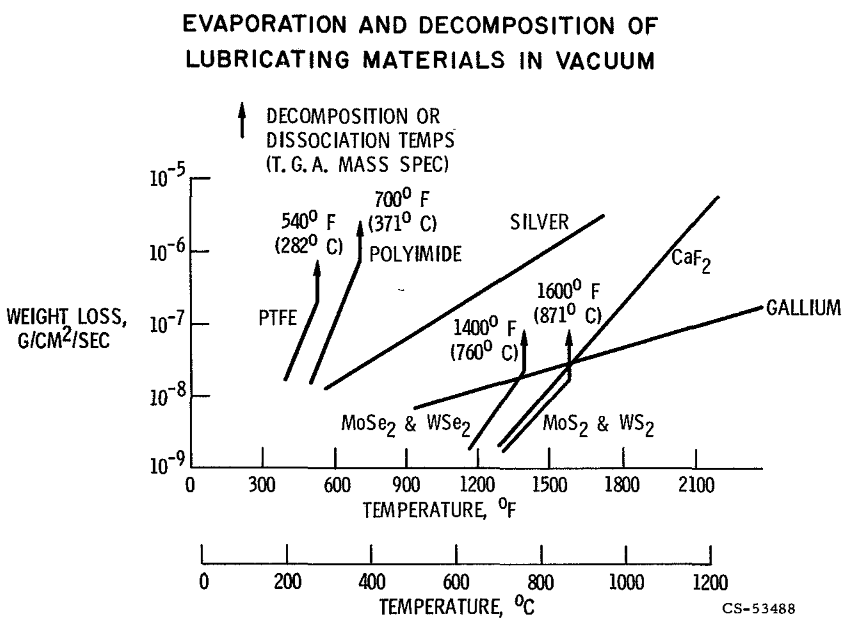

Figure 12.

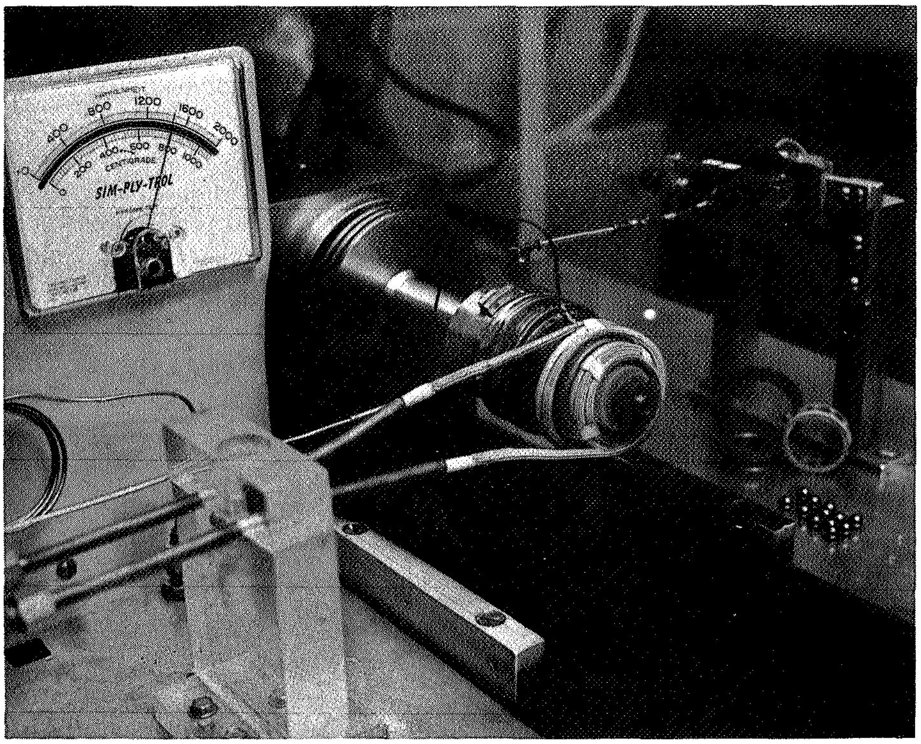

Figure 13. - High temperature bearing test. CS-45783

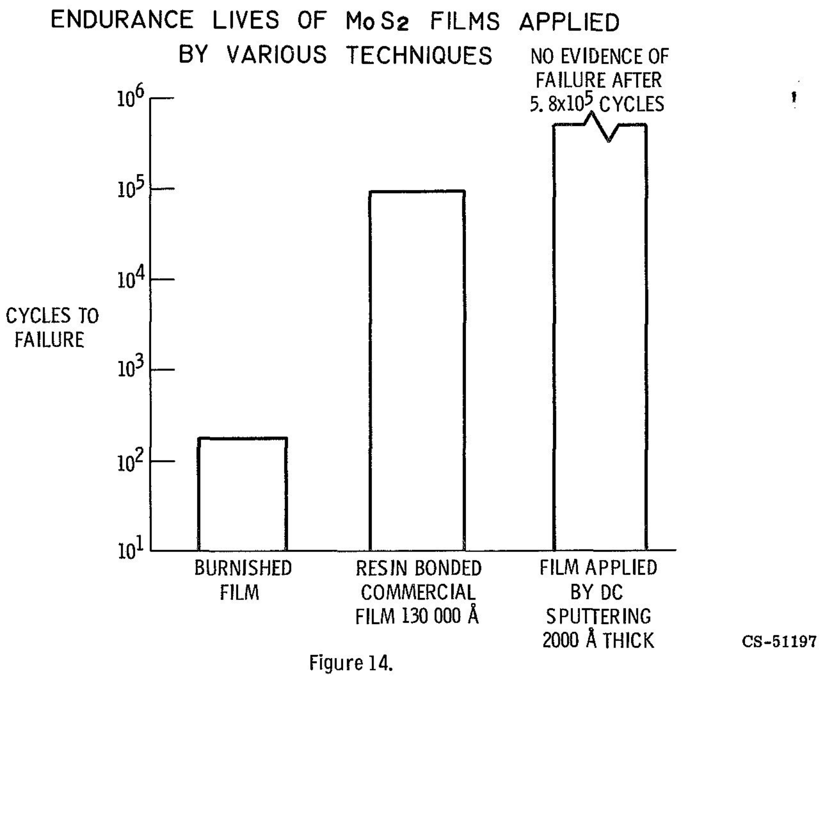

Figure 14.

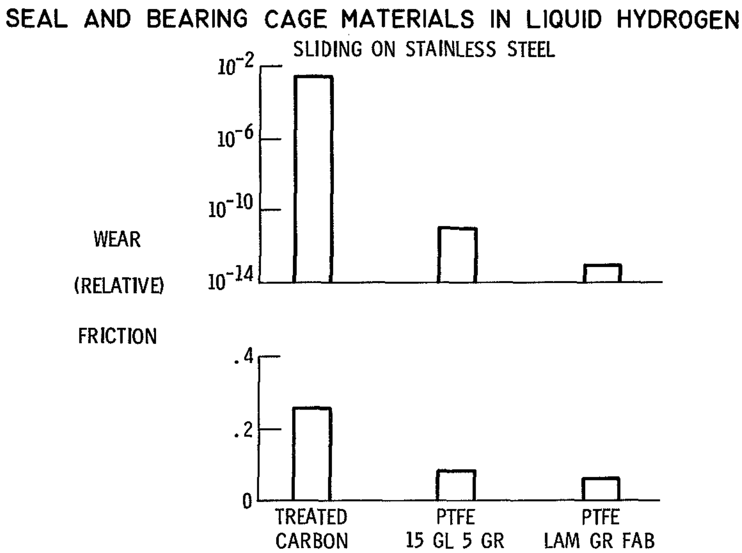
SEAL AND BEARING CAGE MATERIALS IN LIQUID HYDROGEN
SLIDING ON STAINLESS STEEL
WEAR
(RELATIVE)
10^{-2}
10^{-6}
10^{-10}
10^{-14}
FRICTION
.4
.2
0
TREATED CARBON
PTFE 15 GL 5 GR
PTFE LAM GR FAB

Figure 15.