ADVANCED LUBRICATION TECHNIQUES

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The following discussion covers some of the more unconventional approaches being explored to meet anticipated lubrication requirements for liquid rocket engines and flight vehicle power equipment.

Propellant Lubrication

One of the more serious considerations in lubricating turbo pumps for liquid rocket engines is that of lubricant-propellant compatibility. This problem dictates the use of elaborate seals and, in the case of cryogenics, the use of lubricant heaters adds to the system's complexity. We should explore the possibility of completely eliminating the turbopump oil system by lubricating the gears and bearings with the propellants being employed in the system. Results of a recent program have revealed that this lubrication approach is entirely feasible for both bearings and gears within certain limitations. Tables 1 and 2 summarize the results obtained.

The bearing tests were all performed on 45 mm I.D. ball bearings at 25,000 RPM under a 330 lb thrust load for a one-hour duration when attainable. The ball and race materials were 440-C and the cages were glass supported teflon. In general, all of the propellants performed staisfactorily in the bearing tests except the amines (UDMH, EDA, N_20_4) which were very poor. Based on simplified friction and wear screening test data, however, it is recommended that these propellants be evaluated further with other bearing materials such as berylco-25 and Ni or Co base alloys.

The gear tests were made with a 5-inch diameter gear and a 25-degree pressure angle. The tests operated at a pitch line velocity of 8000 fpm under loads of 500 ppi and 1000 ppi and 1000 ppi for durations of 15 minutes and 60 minutes respectively when attainable. The performance of propellant lubricated gears revealed that the same five propellants were generally satisfactory lubricants although not necessarily on the same gear materials. For example, while 440-C was a good material for RP-1, N_20_4, and IRFNA, it was found that the 9310 performed better in LH_2 and $L0_2$. This is primarily attributed to the brittleness at cryogenic temperatures of 440-C and to a lesser extent nitralloy 135M. In no case did the amines perform well in gears; 440-C gears were especially poor, however, marginal performance could be attained under light loads when berylco-25 gears were used with the amines.

This program is being continued with the effort concentrated on finding gear and bearing materials which have good rolling and sliding characteristics in a 50 percent mixture of UDMH and hydrazine which is the fuel for Titan II.

Positive Displacement Lubrication

In the low horsepower range (<10 HP) a flight vehicle power source which appears competitive with the small gas turbines is the positive displacement engine. This type power source could be of the vane pump or piston type and driven by hot exhaust gases from either mono or bi-propellants such as hydrazine or hydrogen-oxygen. A stringent lubrication problem arises since the driving gas temperatures are around 1500°F and, unlike a normal air-breathing engine, there is no air cooling cycle; thus the rubbing surfaces soon attain an equilibrium temperature approaching that of the driving gas temperature. The problem then boils down to providing a means of lubricating sliding surfaces under the conditions given in table 3.

These conditions pretty well rule out the use of conventional organic lubricants and thus various inorganic solid lubricants are being investigated. Various lubricants are not only being explored but various materials of construction as well, since the lubricant cannot be considered independently of the sliding metals. A tentative list of some of the structural materials and lubricants to be evaluated are shown in tables 4 and 5. Examples of some of the proposed materials of construction are molybdenum, nickel, and cobalt base alloys; titanium and chromium carbide nickel cermets; aluminum oxide, B_4C-TiB, and SiC-B_4C ceramics; graphite; and various flame platings. Examples of some of the lubricants that will be investigated are sulfur family binaries such as MoS_2, PbSe, and Ag_2Te; ternary compounds such as $MgS0_4$, $PbMo0_4$, or $PbCr0_4$; soft glasses; pure metals such as Cu or Ag; graphite, and certain polymeric materials which display unusually high thermal stability.

Lubricating Powders Entrained in Gas

In an attempt to raise the maximum temperature capability of high speed ball bearings various techniques were employed using lubricants other than conventional organic materials, which are inherently unstable at temperatures above 1000°F. Of the various techniques investigated the use of lubricating powders entrained in a gas carrier have demonstrated the best performance towards meeting the objective of 10 hours operation from room temperature to 1200°F, 50,000 rpm, and 100 lb load.

Table 6 lists the more successful test results obtained to date and the lubricants utilized. The bearings were cast and wrought, 20 mm bore and mostly constructed of either TiC or cobalt alloys. It was found that even the best of the single constituent lubricant powders did not perform well over the entire temperature range. Several lubricant powder mixtures were evaluated to find combinations which performed well throughout the temperature range. Molybdenum disulphide + phthalocyanine entrained in nitrogen and graphite + Cd0 carried in air were the most successful combinations evaluated. Such a lubrication scheme could be applied to the flight vehicle power systems for such concepts as Dyna-Soar or SLAM (a supersonic low altitude missile) where the equilibrium bearing temperatures would readily reach 1200°F or higher unless cooling was provided.

Gas Lubricated Bearings

Another approach to obtaining high temperature lubrication is the use of gas lubricated bearings. Ironically one of the reasons gas bearing lubrication is an attractive prospect for high temperature applications is that the viscosity of the lubricant (gas) increases with temperature, which means, all other things being equal, that higher loads can be supported as the temperature increases.

In addition to the high temperature advantage there are other desirable characteristics of gas lubricated bearings - particularly their complete stability to high radiation dosages, their increased load capacity at higher speeds, and their extremely low power requirement. Gas bearings have definite limitations and before any serious consideration is given to their utilization in hardware equipment one must first determine that the requirements are within the gas bearing capacities particularly with respect to load and gas flow.

There are several flight vehicle power applications involving light loads where one can envision a sufficient supply of gas to make the use of gas bearings appear feasible. For example, in a high mach ramjet there would be an abundant supply of high temperature, high pressure air; in a non air-breathing application where the flight vehicle power unit is driven by decomposition gases of a propellant such as hydrazine, there would also be a high temperature, high pressure supply of exhaust gas available. It is also conceivable that the self-acting bearing could be used in certain applications where the whole bearing environment could be enclosed and pressurized with only a small make-up bottle needed to handle small amounts of leakage.

To determine experimentally the maximum load carrying capacity of gas bearings under conditions representative of typical flight vehicle power equipment, the performance of various bearing designs at speeds up to 65,000 RPM and temperatures to 1500°F has been studied under contract. The results to date have shown that at least a 5-pound load can be carried on a 2-inch by 1.5-inch diameter bearing at all temperatures up to 1500°F and all speeds up to 65,000 RPM with gas flow rates slightly less than 5 pounds per hour at the extreme conditions of temperature and speed. These tests were conducted on flame plated Inconel-X bearings using nitrogen gas as the lubricant. Future plans are to extend the capability of the rig by building an all ceramic test bearing. This should permit operation at temperatures up to 2200°F with an oxidizing gas such as air as well as inert gases. In addition gases of widely differing viscosities and densities such as He, A, and CF_4 will be employed to study the effect of these properties on bearing performance and load carrying ability.

Liquid Metal Lubrication

There are certain types of power equipment, namely the closed loop space power equipment which must be lubricated with the working fluid itself. The schematic shown in figure 1 is a simplified illustration of the operation of a single loop closed cycle system. The working fluid (for example, mercury, potassium, or rubidium) is vaporized in a heat source such as a nuclear or solar boiler, the hot vapor is then expanded to drive a turbine which directly drives a generator; the exhaust vapor is condensed in a heat exchanger or radiator and pumped back into the heat source. These systems are designed to operate for long duration satellite and space vehicle applications. As one can well imagine, the use of a conventional oil system is prohibitive since adequate sealing cannot be provided for durations of 1 year or more. Consequently, the working fluid itself must be used as the lubricant. For example, a small portion of the liquid phase of the working fluid could be diverted to the bearings after leaving the pump. The temperature of the liquid going into the bearings would be somewhere between 500°F and 1200°F depending on the system design and the particular working fluid being used.

The relative performance of various liquid working fluids in journal bearing is being investigated with particular emphasis on potassium and rubidium. The test conditions and objectives of this investigation are given in table 7.

The overall objective is to provide a means of satisfactorily operating under typical hardware conditions for long durations. The results to date have been preliminary in nature. The test rig and its support system has been checked out on liquid potassium and appears to be operating satisfactorily. Tests using various test bearing sizes and designs will be evaluated next. The test rig is constructed of stainless steel. The test bearings consist of a chrome plated stainless steel shaft with bearing sleeve inserts of various materials such as aluminum bronze, silicon bronze, graphite, etc. Aside from the potential corrosion problem and the problem of bearing performance using these liquid metals another problem which could prove to be a serious limitation for extremely long life (10,000 hours or more) is that of erosion, particularly with a high density liquid metal such as mercury.

Vapor Bearing Lubrication

An alternate method of accomplishing closed loop bearing lubrication is to utilize a small portion of the high temperature, high pressure vapor phase of the working fluid as it leaves the boiler. In other words, vapor bearing lubrication is a complicated cousin of gas bearing lubrication. Some of the additional problems of lubricating with an alkali metal vapor rather than a gas are (1) corrosion and the associated problems of jamming, scarring, and clogging resulting from corrosion products debris, and (2) liquid condensation occurring within the bearing due to transient temperature and/or pressure changes; it is not certain what effect this condensate would have, although it is probable that the presence of liquid in the bearing would destroy the supporting gas film.

Despite these anticipated problems there are several important advantages that could be realized by using vapor bearings; particularly those of reduced erosion and wear which should aid in attaining long life. Less cooling would be required, since the bearings could be operated at approximately the same temperature as the vapor (from 1200°F to 1800°F depending on the fluid and system). Other advantages, particularly with respect to long life operation, are those of low friction and low horsepower consumption.

There are two other lubrication schemes which appear worthy of additional research. One of these is magnetic bearings, that is, bearings supported by a magnetic field. Although there are several operational disadvantages with magnetic bearings namely low load carrying capacity and instability; however, with sufficient development there would be some distinct advantages, particularly at cryogenic temperatures where power losses would be very low.

The other type is electrostatically supported bearings. Electrostatic bearings offer a possible solution to the lubrication problem associated with electrostatic generators. The high vacuum of space is an ideal environment for operating an electrostatic generator, but it poses a severe lubrication or sealing problem. If, however, electrostatic bearings could be used, the advantages would be obvious. Not only is an abundance of electrostatic electricity available, but the high vacuum of space becomes a definite asset.

In summary there are several applications in which the use of organic lubricants create definite limitations to the system. There are, however, unconventional lubrication techniques which, if sufficiently explored and developed, could unveil capabilities presently far beyond today's state of the art and in some cases even beyond ones imagination. To accomplish this unveiling, the "Conventionalism Barrier" must be broken and new lubrication techniques explored with uninhibited vigor.

Government sponsored research has only scratched the surface. There are still many challenging research avenues which need exploration. We sincerely hope that the challenge will be accepted.

LIST OF ABBREVIATIONS

UDMH	Unsymmetrical dimethylhydrazine
EDA	Ethylenediamine
N_2O_4	Nitrogen tetroxide
RP-1	Low-cut hydrocarbon, essentially kerosene
IRFNA	Inhibited red fuming nitric acid
LH_2	Liquid hydrogen
LO_2	Liquid oxygen
N_2H_4	Hydrazine

REFERENCES

1. Butner, M.: "Propellant Lubrication Properties Investigation" WADD TR 61-77.

2. Amateau, Krause, Orcutt, Glaeser, Allen: "Development of Lubricants for Positive Displacement Power Sources from 1200°F to 1500°F," Progress Reports Nos. 1 & 2, Contract AF 33(616)-7568, Directorate of Materials and Processes.

3. Wilson and Gray: "The Development of Lubricants for High Speed Rolling Contact Bearings Operating over the Range of Room Temperature to 1200°F," WADD TR 60-732, January 1961.

4. Macks, F : "Gas Lubrication of Radial and Thrust Bearings at Very High Temperatures, High Speeds and Low Lubricant Flow Rates," WADD TR 61-83, February 1961.

5. Contracts AF 33(616)-6860 and AF 33(616)-8328 "Liquid Metal Lubrication of Journal Bearings", Directorate of Materials and Processes.

6. Contract AF 33(616)-8082, "Metal Vapor Lubrication of Thrust Bearings", Directorate of Materials and Processes.

TABLE I

PROPELLANT LUBRICATED BALL BEARINGS

MATERIALS

RACES AND BALLS: 440-C

CAGES: GLASS SUPPORTED TEFLON

PERFORMANCE

GOOD	POOR
RP-I	EDA
LH-2	UDMH
LO_2	N_2H_4
N_2O_4	
IRFNA	

TABLE 2

PROPELLANT LUBRICATED GEARS

PROPELLANT	PERFORMANCE		
	GOOD	FAIR	POOR
RP-I	NIT. 135 M 440-C 9310		BERYLCO 25
LH_2	9310	NIT. 135 M 9310 vs. NIT. 135 M	440-C BERYLCO 25
LO_2	9310 NIT. 135 M	440-C	BERYLCO 25
N_2O_4 IRFNA	440-C		
EDA		BERYLCO 25	440-C
UDMH		BERYLCO 25	440-C
N_2H_4		BERYLCO 25 BERYLCO 25 vs. 440-C	440-C

TABLE 3

POSITIVE DISPLACEMENT LUBRICATION REQUIREMENTS

MOTION: RECIPROCAL AND ROTATIONAL SLIDING
SPEED: UP TO 80 FT/SEC
TEMPERATURE: UP TO 1500°F
LOAD: UP TO 50 PSI
ENVIRONMENT: INERT, REDUCING, OR OXIDIZING
ENVIRONMENTAL PRESSURE: 0.5 TO 1000 PSIA
DURATION: UP TO 300 HRS.

TABLE 4

CANDIDATE STRUCTURAL MATERIALS

ALLOYS	CERMETS	CERAMICS	FLAME PLATINGS
Mo Base	TiC - Nickel	$B_4\acute{C}$ - TiB	Al_2O_3 on Hastelloy W
Ni Base	CrC - Nickel	SiC - B_4C	
Co Base			

TABLE 5

CANDIDATE LUBRICANTS

SULFUR FAMILY	TERNARY COMPOUNDS	PURE METALS	GRAPHITE	POLYMERIC MATERIALS
MoS_2	$MgSO_4$	Cu		
PbSe	$PbCrO_4$	Ag		
Ag_2Te	$PbMoO_4$			

TABLE 6

UNCONVENTIONAL BALL BEARING LUBRICATION

BEARINGS

20 mm bore TiC or Cobalt Alloy

CONDITIONS

30,000 RPM, 100 lb thrust, 10 hours
80°F through 1200°F

LUBE	CARRIER	PERFORMANCE
MoS_2	Nitrogen	High Friction in 800 to 1000°F Range
MoS_2 - PCH_2	Nitrogen	Good
Graphite - CdO	Air	Good

TABLE 7

LIQUID METAL LUBRICATION

TEMPERATURE: ROOM TEMPERATURE OR MELTING POINT UP TO 1200° F

BEARING SIZES: L/D = 2 OR LESS; DIAMETER = 1.0 IN.

BEARING SPEEDS: UP TO 36,000 RPM

BEARING DESIGNS: SELF-ACTING, EXTERNALLY PRESSURIZED

RADIAL LOADS: UP TO 100 LBS

LUBRICANTS: MERCURY

POTASSIUM

RUBIDIUM

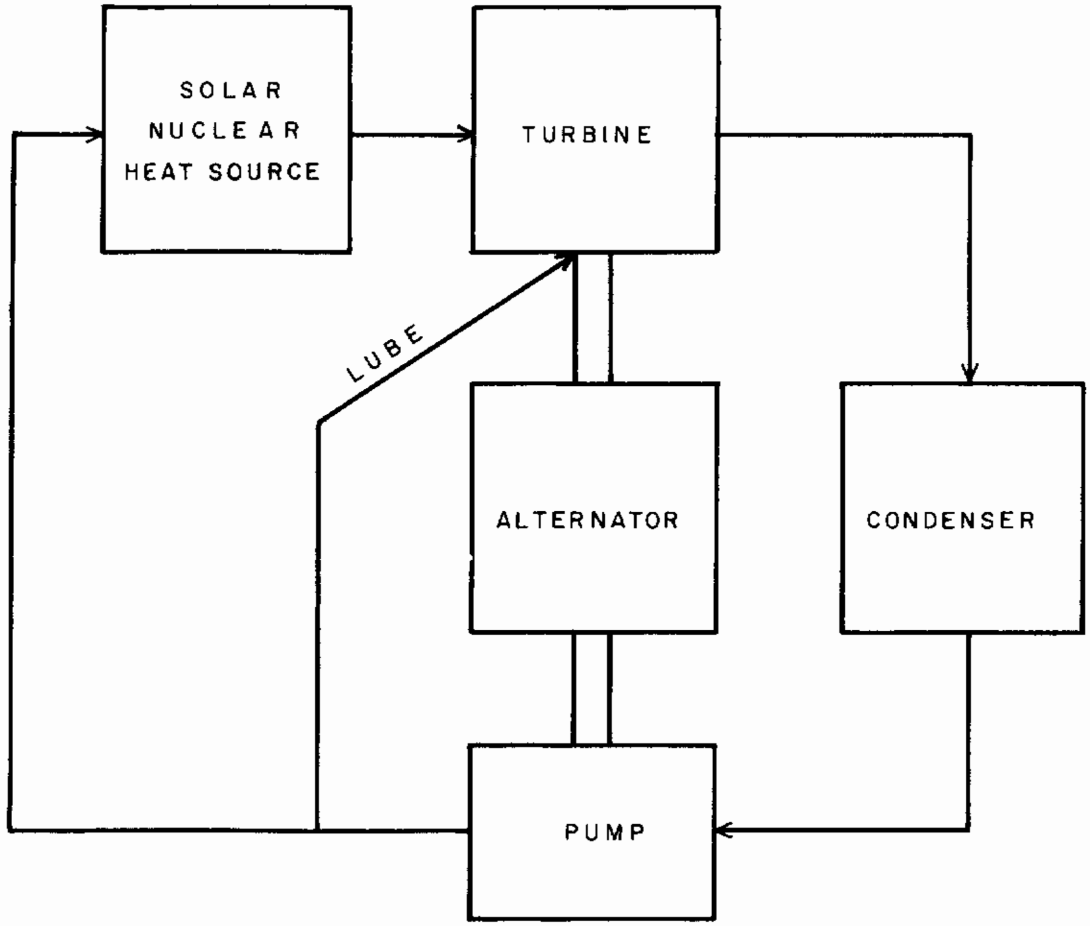
SOLAR
NUCLEAR
HEAT SOURCE
TURBINE
LUBE
ALTERNATOR
CONDENSER
PUMP

Figure 1.