ROCKET ENGINE AND FLIGHT VEHICLE POWER LUBRICATION REQUIREMENTS

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ABSTRACT

This paper describes some of the key lubrication requirements associated with rocket engines and flight vehicle power equipment and the various techniques being explored to meet these requirements. Concerning rocket engines, the discussion covers the problem of standardizing a test method for determining the impact sensitivity of lubricants with liquid oxygen and the requirement for a low viscosity, high gear load oil for turbopump applications. Concerning flight vehicle power, a discussion is presented on the various methods meriting research effort in addition to conventional lubricants - such as gas bearings, vapor-lubricated bearings, liquid-metal lubricated bearings, electrostatic bearings, etc.

The primary lubrication requirements for liquid rocket engines can be summed up in a few brief words: short duration, compatibility, and high power. Short duration is obvious since operational times are measured in minutes, and even though there are numerous static check-out firings, the total cumulative operational time on any one engine will never exceed a few hours.

The compatibility requirement has undoubtedly been given the most attention. Even though liquid oxygen has been in very wide usage as a rocket oxidizer for several years, there still seems to be quite a mystery in trying to determine what or when a material is compatible with liquid oxygen. Most of industries'efforts to date have been utilizing impact test rigs to establish compatibility, but there is much disagreement on the data generated by these test rigs. Tentatively, the Air Force has adopted the ABMA rig as the standard impact test apparatus. Mr. Burl Baber will give more information about this test rig tomorrow.

It might be of interest, however, to review the results of a recent cooperative testing program that had been conducted to determine how closely laboratories agree when impact-testing the same fluids. You may recall that the results of Cooperative Program No. 1 indicated very little agreement between laboratories on the five reference fluids. Unfortunately, we had no way of knowing which laboratories were correct, since the relative sensitivity of each reference fluid was not accurately known.

Therefore, for Cooperative Program No. 2, three fluids were selected which could be rated with reasonable accuracy into three categories: least sensitive, most sensitive and in-between. This was achieved by making each of the three reference fluids a blend of different percentages of a reactive oil (Ucon LB 65)* and a non-reactive fluoronated oil (Halocarbon 11-14). Table 1 gives a breakdown on the exact composition.

In addition to using new reference fluids, other changes to improve reproducibility were adopted in Cooperative Program No. 2. The test specimen cups and striker pins furnished to each participating laboratory were each made from the same material and production lot, and the surface conditions were closely controlled with respect to smoothness and parallelness.

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*This should not be misconstrued that all Ucon fluids are reactive with LOX.

TABLE 1. COMPOSITION OF REFERENCE FLUIDS USED IN LOX IMPACT COOPERATIVE PROGRAM NO. 2

Anticipated Reactivity	Code	Ucon LB 65	Halocarbon 11-14
Least	IID	30%	70%
Medium	IIE	50%	50%
Most	IIF	70%	30%

In general, the results of Cooperative Program No. 2 (Fig. 1) shape up this way:

(1) The general trend of the data is that, as anticipated, sample IID is the least reactive. However, in all but a few cases samples IIE and IIF appeared about the same.

(2) Two disturbing exceptions are that while most of the laboratories rated IID as having a threshold value of 60 ft-lb or higher, WADD and SwRI both rated IID less than 20 ft-lb. A possible explanation for this might be the difference in interpretation of a char mark. For example, out of a total of 86 reactions recorded by SwRI, 51 were char marks or about 59%; WADD recorded 15% char marks. This corresponds to an average of only 5% char marks recorded by the other laboratories. This suggests that perhaps a more precise means of defining a detomation is needed.
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(3) Of most significance, however, is the fact that the overall trend of the data shows a definite improvement toward being able to correlate the results of one laboratory with another.

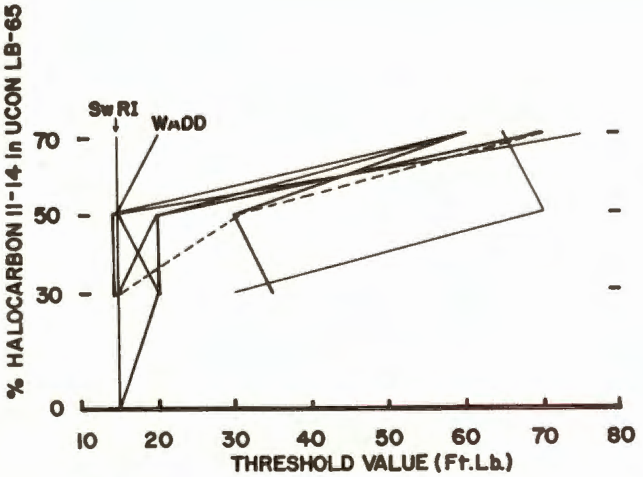

FIGURE 1. LOX IMPACT COOPERATIVE PROGRAM NO. 2 TEST RESULTS

Of course, there are compatibility problems other than those of liquid oxygen. Any of the strong oxidizers such as H_2O_2, N_2O_4, ClF_3, liquid fluorine, etc., and even some of the propellant fuels such as UDMH, hydrazine, pentaborane, etc., each pose a compatibility problem uniquely its own. It is felt that much of the testing experience and test procedure refinements developed in conjunction with liquid oxygen compatibility using the ABMA test rig will be applicable to these other propellants, and that only a minimum number of changes will be required to accommodate the new propellants.

The status of the ABMA impact test rig is that all of the design details have been finalized. A tentative detailed test procedure for using the ABMA impact test to determine the LOX compatibility of oils, greases, solvents, solids, and dry films has been prepared and distributed to industry for review and coordination. The final official version of the test procedure should be available by the early part of 1961.

The other primary requirement I mentioned was that of high power; namely high power transmission through the gear box of the propellant turbopump. A typical rocket engine, for example, might require a 3 to 1 gear reduction from the 25,000 rpm of the gas turbine drive to about an 8000 rpm propellant pump speed. Load transmission requirements might be on the order 4000 hp which, according to some designs where minimum gear weight is necessary, corresponds to a unit loading of about 4000 pounds per inch of tooth face width. Unit loadings can be designed to be much lower, but only at the expense of increasing gear size and weight. Since it is anticipated that future rocket engine turbopumps might be transmitting on the order of ten times as much power (say, 40,000 hp), it behooves us to review what oils are available or will be required to fulfill these high gear load requirements.

At least two military specification oils have load carrying capacity in excess of 3500 lb/in: MIL-L-6086 (a mineral oil) and MIL-L-25336 (a synthetic oil). Although both of these fluids can be used as turbopump oils, they do have their shortcomings. For example, MIL-L-6086 has a high pour point and requires kerosene dilution for -30°F ambient temperature start up, and is fairly volatile at operating temperatures and pressures. MIL-L-25336, on the other hand, has excellent volatility characteristics and a good viscosity index, but it is still a heavier oil than is desired for the low temperatures. There is another important consideration which must be given to turbopump oils; that is storage stability. Herein lies the primary shortcoming of the MIL-L-25336 oil, it is not sufficiently stable in storage, a characteristic more often common to synthetic oils than to mineral oils.

Storage stability may seem like an unusual requirement for an oil which has a total operational life of only a few hours at the most, but the requirement stems from the fact that many rocket engines will remain in storage for several years with only periodic static check-out firings. Likewise, the operating oil should remain sufficiently stable in storage so that none of its desirable operating characteristics will be adversely affected.

To get the ball rolling toward developing a turbopump lubricant specification, a small survey was conducted to solicit comments from oil and chemical manufacturers on a tentative set of specification limits proposed by WADD. Table 2 gives a tabulation of the proposed set of tentative specification limits which also includes some of the recommendations submitted by industry.

You may note that the viscosity of this oil is quite low in order to provide good pumpability at -30°F. The low viscosity at high temperature should not be a problem since the maximum operating temperature is not expected to be over 250°F which would correspond to about 1.5 cs. The flash point of 250°F is rather high for a mineral oil of this viscosity, but not so high as to exclude their use. The Ryder gear value is based on the relative rating system, and the tentative limits utilize a sliding scale technique so as to provide a minimum rating equivalent to 3500 lb/in. Rubber swell and foaming are about the same as in the MIL-L-25336 specification. Evaporation loss may be difficult to meet with a mineral oil, but the limit of 30% should not necessarily prohibit their use. The corrosion and oxidation test may be a problem from a corrosion standpoint, depending on the reactivity of the gear load additive employed. Storage stability, of course, will be one of the most stringent requirements in the specification. The oil will be required to meet all of the specification limits after storage for one year in the WADD Tropical Storage Room and after two years in normal field service storage. It is hoped that a shorter duration, accelerated storage test can eventually be developed to facilitate qualification testing. The bearing stabilization test will not be severe, requiring only that the bearing temperature stabilize. Good preservative characteristics would also be extremely desirable, but it may not be possible to develop a combined package having both high gear load capacity and good corrosion preservative properties.

Another consideration that should be taken into account with respect to these high gear load turbopump oils is that of compatibility with the oxidizer. In most current designs the oil and the oxidizer are separated by an elaborate series of seals which have been doing a fairly good job of

TABLE 2. TENTATIVE TURBOPUMP LUBRICANT SPECIFICATION

Tests	Conditions	Tentative Limits
1. Viscosity	210°F	2.0 cs
	-30°F	500 cs
2. Pour Point		-50°F max
3. Flash Point		250°F min
4. Ryder Gear	Standard 165°F	
	1 gear	143%
	2 gears	139%
	3 gears	136%
	4 gears	134%
5. Rubber Swell	H Stock	5% min, 35% max
6. Foaming	75°F	100 ml to 0 in 300 sec
	200°F	25 ml to 0 in 180 sec
	75°F	100 ml to 0 in 300 sec
7. Evaporation	5 hours, 250°F	30%
8. Corrosion and Oxidation	250°F, 168 hrs	
	Cu	±0.4
	Ag	±0.2
	St	±0.2
	Al	±0.2
	Mg	±0.2
	Viscosity Change	-5% to 20%
	Neut. No. Change	2.0 max
	Original Neut. No.	1.0 max
9. Storage Stability	WADD Tropical Room	1 year
	Field Service	2 years
10. WADD Bearing Stabilization	To be established	To be established
11. Preservative Test	To be established	To be established

preventing the oil and oxidizer from mixing. It would be desirable, however, to use an oil which was completely inert or compatible with the oxidizer.

The only such readily available fluids known are halogenated oils. Some of these oils also possess the high load carrying capacity needed, but very few have the desired corrosion characteristics. A few companies have been working toward developing suitable corrosion inhibitor additives, and tests to date have been very encouraging. But so far a fluid has not yet been found which possesses a combination of all the desired key properties: high gear load, good corrosion inhibition, good viscosity and lubricating characteristics, and, of course, compatibility with the oxidizer. Table 3 presents a tabulation of some of the LOX-compatible lubricants which have been evaluated to date. If we are successful in finding compatible fluids which have all of the necessary desirable lubricant properties, another specification will be written covering LOX compatible turbopump oils.

TABLE 3. LOX-COMPATIBLE TURBOPUMP LUBRICANTS

Oil	LOX-Compat	Ryder Gear Load	Lubricity	Corrosion Resistance*
A	Yes	78%	Good	Very Poor
B	Yes	166%	Good	Very Poor
C	Yes	122%	Fair	Very Good
Goal	Yes	139%	Good	Good

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*Good corrosion resistance is defined as equivalent to MIL-L-7808.

In addition to our work on these two specifications, there is still another approach which the hardware industry is seriously considering, and that is utilization of the actual propellants themselves as the lubricant, in other words, propellant lubrication. This technique is currently being employed in certain hardware development programs using liquid oxygen and liquid hydrogen as the lubricants. This afternoon Mr. Myles Butner will describe Rocketdyne's Air Force contract activities, where the lubricating capability of various propellants is being determined in both gears and bearings as well as a simplified screening test.

The other area of concern is that of providing lubricants and lubrication techniques for flight vehicle power systems, such as those described by Mr. Reuben Retz. The flight vehicle power systems requiring lubrication are of the mechanical conversion type and conveniently fall into two categories both with respect to type and application. First, there is the open-cycle power source, defined as that type where the hot driving gases are exhausted and not returned again to the system. The open-cycle type is normally used for short or medium durations (less than 300 hrs) in boost glide vehicles such as Dyna-Soar, high Mach ramjets such as SLAM (a supersonic low-altitude missile), or short-duration satellites requiring more power than is feasible with batteries or solar cells.

Since the hot driving gases run in the 1200 to 1800°F temperature range, the turbine support bearings tend to reach equilibrium temperatures above 1000°F, unless external cooling is provided. Therefore, we have been investigating various lubrication techniques which could provide a satisfactory and practical means of operating at these temperatures and also at typical operating speeds of 20,000 to 60,000 rpm.

Of the various approaches one could explore, those shown in Table 4 appear to be the most promising. The first approach, of course, is to lubricate the bearings with conventional lubricants and provide the necessary external cooling. This technique has been used in the past almost exclusively. Although promising higher temperature lubricants such as the polyphenyl ethers are becoming available and may very well find applications in this type of hardware, undesirable external cooling will still be required. Therefore, additional approaches are being explored which, hopefully, would not require any external cooling.

TABLE 4. OPEN-CYCLE POWER SYSTEM LUBRICATION APPROACHES

1. Conventional Lubricants Plus Cooling
2. Powdered Solid Lubricants Entrained in Gas Carrier
3. Reactive Gases
4. Powdered solids in reactive gas carrier
5. Gas-lubricated bearings

One method is that of lubricating rolling-contact bearings with powdered solid lubricants entrained in a gaseous carrier or the use of reactive gases or combinations of both. Tomorrow Mr. Donald Wilson of the Stratos Division will describe in more detail the various operational problems encountered and test data generated while studying these lubrication techniques under Air Force contract. In general, the overall objective of the program is to attain an operating capability of 50,000 rpm on 20-mm ball bearings throughout the temperature range of room temperature to 1200°F for durations of 10 or more hours.

Another method of lubrication holding promise for high-speed, high-temperature operation is that of gas lubricated bearings. Gas bearing lubrication has been receiving much more attention in recent years as evidenced by the large and growing number of companies sponsoring their own research programs; although most of these programs have not been concerned with high temperatures.

Ironically, one of the reasons gas bearing lubrication becomes an attractive prospect for high-temperature applications is that the viscosity of the lubricant (gas) increases with an increase in 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 consumption. But one must also realize at the start, that gas bearings have definite limitations and before any serious consideration is given to their utilization in hardware equipment, one must first determine that his requirements are within the gas bearing ball park - particularly with respect to load and gas flow.

There are several ways that one could envision a practical means of having sufficient gas supply available to make gas bearings 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 a power unit might be driven by hot monopropellant or bipropellant exhaust gases, again, there would 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 pressure bottle needed to handle small amounts of leakage. Tomorrow afternoon Mr. Fred Macks of Tribo-Netics Laboratories will describe the scope and results to date of their Air Force contract efforts in this area.

The remaining open-cycle power system type posing severe lubrication requirements is the positive displacement power unit. In this type of power generator, expanding hot gases (from solid, mono, or bipropellants) are used to drive a piston in reciprocating motion or a vane pump in rotational motion. The main problem is that of high-speed sliding motion (up to 80 ft/sec) and high temperatures (1200 to 1500°F). These temperatures are considered fairly realistic since there are no air cooling cycles similar to those normally experienced in an air-breathing piston engine. In most cases the exhaust gases are reducing in nature, for example, hydrazine produces nitrogen, hydrogen and ammonia; a notable exception being hydrogen peroxide which produces an oxidizing atmosphere.

A program has been initiated with Battelle Memorial Institute to study this problem for the Air Force. A test rig designed to evaluate various lubricants and construction materials is now being fabricated and should be completed and ready for initial testing by around the end of December 1960. Examples of some of the lubricants which will probably be evaluated are sulfur family binaries such as MoS_2, PbSe; AgTe; ternary compounds such as $MgSO_4$ or $PbCrO_4$; soft glasses; pure metals such as Cu or Ag; graphite; and certain polymeric materials which display unusually high thermal stability.

Now, I mentioned that there were two main types of flight vehicle power systems and I have been discussing thus far only the open-cycle type. The other main type is that of the closed cycle or closed loop, as it is frequently called. A schematic of a typical single-loop closed system which may be familiar to you is shown in Figure 2. Briefly, 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 then condensed in a heat exchanger or radiator and pumped back into the heat source. The closed-cycle power systems are designed for long duration satellite and space vehicle applications. As you can well imagine, unless dynamic seals are utilized which have essentially zero leakage rates for long durations, a conventional oil lubrication system is prohibited from use in this type of equipment. Consequently, there is only one feasible method for providing bearing lubrication - namely to utilize the working fluid itself 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 to 1200°F depending on the system design and the particular working fluid being used.

In addition to several hardware equipment development contracts, there are two other programs sponsored by WADD which should provide additional information on the subject of liquid-metal lubrication. One program is with North Carolina State College with the primary objective of seeing if liquid-metal bearings follow the same theory as would be expected of such low viscosity

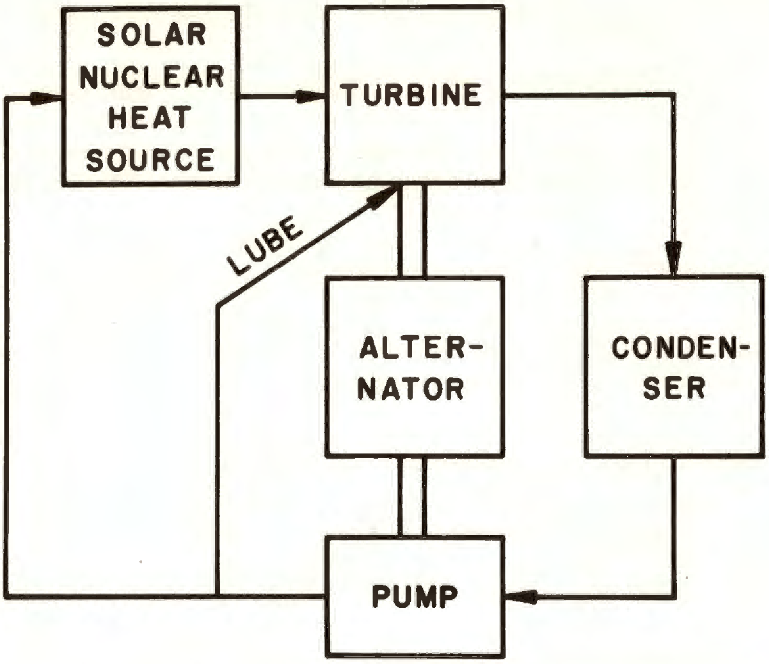

FIGURE 2. TYPICAL SINGLE-LOOP CLOSED SYSTEM

fluids and also of studying the area of boundary lubrication with liquid metals. The other program is with Sundstrand Turbo where the lubricating characteristics of various potential working fluids are to be evaluated in bearings under the conditions shown in Table 5. Upon learning more of the general effects of operating conditions on bearing performance, it is intended to conduct longer duration tests (500 hours or more) to determine the effects of operating conditions on bearing life in terms of wear, dynamic erosion, corrosion, etc. The ultimate goal of this work is to establish broad information which can be generalized to aid in the design of systems requiring maintenance-free operation for 10,000 hours or more. Tomorrow Mr. Reemsynder of Thompson Ramo Wooldridge will cover some of his work on hydrosphere bearings lubricated with liquid mercury. The progress of TRW and others clearly illustrates that liquid-metal lubricated bearings offer just cause for optimism that 10,000 hours can be attained or even exceeded.

TABLE 5. WORKING FLUID LIQUID PHASE LUBRICATION

Temperature: Room temperature or melting point up to 1200°F

Bearing Sizes: L/D = 1
L/D = 2

Bearing speeds: Up to 24,000 rpm

Radial Loads: Up to 50 lb

Lubricants:

- Mercury
- Potassium
- Rubidium
- Aluminum Bromide

Duration: Up to 500 hours

An alternate method of accomplishing closed-loop bearing lubrication with the working fluid is to utilize the vapor phase of the fluid instead of the liquid phase. In other words, vapor bearing lubrication, a complicated cousin of gas bearing lubrication. Some of the additional problems of lubricating with an alkaline 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 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 extremely long life. Less cooling would be required, since the bearings could be operated at approximately the same temperature as the vapor (from 1200 to 1800°F depending on the fluid). Another advantage, particularly with respect to long life operation, is that of low friction and low power consumption.

There are two other lubrication schemes which may be worthy of research effort to establish their maximum capabilities and limitations. One of these is magnetic bearings, that is, bearings supported by a magnetic field. Although there are many operational difficulties with magnetic bearings including low load carrying capacity and instability, with sufficient development there may be some distinct advantages - particularly at cryogenic temperatures where power losses would be very low.

The other type would be that of 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 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 environment becomes a definite asset, rather than an almost insurmountably. difficult problem.

This pretty well sums up our rocket engine and flight vehicle power lubrication requirements and the various lubrication schemes which we are exploring or considering to meet these requirements. I know that many of you who are associated with the chemical and petroleum business must be wondering by now, with all this talk about magnetism, static electricity, liquid metals, and gas bearings, where can you be of help? Except perhaps for working fluid lubricated bearings, most of the lubrication techniques I have described are still considered extremely high risk areas. This means, Gentlemen, that conventional lubricants are still going to be urgently needed and, I assure you, widely employed in many applications for a long time to come - particularly when you are able to continue meeting the challenges of higher operating temperatures and other severe conditions.