NASA Technical Memorandum 83529

Overview of Liquid Lubricants for Advanced Aircraft

(NASA-TM-83529) OVERVIEW OF LIQUID LUBRICANTS FOR ADVANCED AIRCRAFT (NASA) 19 p HC A02/MF A01 CSCL 11H
N84-11296
Unclas
G3/27 42460

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Prepared for the
Symposium on Lubricants for Extreme Environments at the
Joint Lubrication Conference
cosponsored by the American Society of Mechanical Engineers and the
American Society of Lubrication Engineers
Washington, D.C., October 4-6, 1982

NASA

E-1740

Overview of Liquid Lubricants for Advanced Aircraft

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ABSTRACT

This presentation is an over-all status report on liquid lubricants for use in current and projected high-performance turbojet engines. Emphasis is placed on the oxidation and thermal stability requirements imposed upon the lubrication system. A brief history is given of the development of turbine engine lubricants which led to the present day synthetic oils with their inherent modification advantages. The status and state of development of some nine candidate classes of fluids for use in advanced turbine engines are discussed. Published examples of fundamental studies to obtain a better understanding of the chemistry involved in fluid degradation are reviewed. Also, alternatives to high temperature fluid development are described. The paper concludes with a discussion of the importance of continuing work on improving current high temperature lubricant candidates and encouraging development of new and improved fluid base stocks.

INTRODUCTION

Development of liquid lubricants for advanced high speed aircraft has been proceeding for a number of years under the sponsorship of the U.S. Armed Forces, NASA, and private industry. The U.S. Air Force has been involved in a sustained and substantial effort in this work at their Materials Laboratory. This paper is concerned with an overall review of the liquid lubricants having potential use in such applications, both military and commercial. The term "Advanced Aircraft" will be defined, for the purposes of this paper, as any aircraft expected to operate above speeds of about Mach 2. Specific examples of such aircraft and engines being developed for their use will in general be avoided because they are beyond the intended scope of this review.

A serious problem with lubricants at aircraft speeds above Mach 2 is that of the high temperature levels reached in the engine lubrication system of advanced aircraft. It is estimated that the bulk oil temperature (BOT) would be about 240° C (400° F) at a speed of Mach 2.5 and about 260° C (500° F) for a Mach 3 speed (1). Difficulties would be expected with lubricant oxidation, thermal-instability, high volatility, and relatively high pour points for low temperature starting.

Figure 1 shows the effect of aircraft speed expressed as Mach Number on the maximum bulk oil operating temperature and the ram air temperature (1). The figure also indicates the status of lubricant development for the various speed ranges. The subsonic to Mach 1.3 range aircraft could operate satisfactorily with a light mineral oil extracted from a petroleum fraction. In the speed range of Mach 1.3 to 2 an ester based fluid, fortified with additives, has been used for the turbine engines in most current military and commercial aircraft.

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For the Mach 2 plus aircraft an earlier MIL-L-9236 specification was proposed using a triester based oil. This has been superceded by a MIL-L-27502 specification for a possible 218° to 246° C (425° to 475° F) BOT using an advanced ester based liquid. To date no candidate oil for this specification has been fully qualified.

It is also noted that above speeds of Mach 2 the ram air temperature increases rapidly and actually exceeds the BOT. As a result, the air can no longer be used as a heat sink to cool the oil, and the problem of holding down BOT is compounded.

The general tentative requirements for an ideal liquid lubricant to operate satisfactorily in future aircraft are shown in Table 1. These requirements conform closely to those of MIL-L-27502, as we will soon see, but they are somewhat more stringent in regard to upper and lower temperature operating limits to allow for operating extremes. This fluid would be the goal of lubricant base developers and fluid formulators for this problem area.

The main approach to the problem of finding this ideal liquid lubricant for high-performance military aircraft has included a search for increased standardization. But this has not been dominated by the overall need for economy as in the case with commercial aircraft. Of course, at the same time there has been a continuing need to find and develop base stocks and additives that resist degradation by oxidation and thermal instability. The overall picture in the past has been one of lubricant standardization within a certain temperature range, followed by the development of a new oil for higher temperatures, followed by a fresh standardization phase to cover the wider temperature range, and so on.

Another approach to this problem area is to use novel systems and general engine design changes to circumvent the deficiencies of available fluids. Some of these ideas will be discussed later.

HISTORICAL REVIEW OF TURBINE ENGINE LUBRICANTS

The jet age and the first real demonstrated need for improved aircraft engine lubricants began in 1930 when Frank Whittle of the Royal Air Force College in England began working on the first practical concept of a gas turbine (2), (3). In 1937 he successfully demonstrated an experimental engine of this design that started a tremendous research and development program for high performance oils.

Prior to and during World War II there was independent development in Germany and the United States of the fluids that form the basis of many of the lubricants used today in the aviation industry. At about the same time that the Whittle engine was being first tested, Dr. Herman Zorn in Germany started a search for oils that would have the outstanding properties of castor oil without its gumming tendencies. From his work there were several triester and diester oils developed that reached the 10 000 tons per year production level by 1944.

Dr. Zorn's counterpart in the United States was Dr. W. A. Zisman and co-workers at the Naval Research Laboratories who independently developed dozens of excellent synthetic ester oils by 1944.

Work has continued to this day on the further development and improvement of ester-based fluids by the Naval Research Lab, the Air Force Materials Lab, and others. Table 2 shows the current specification properties of high performance ester lubricants for turbine engines that have been issued by the Air Force and the Navy (2). These specs are listed in the order of increasing useful engine operating temperatures as indicated by the bulk oil temperatures in the 100 hour Bearing Rig Test, starting with a 177° C (350° F) rating for the MIL-L-7808 oil and going to 240° C (464° F) for the MIL-L-27502 oil. Commercially available products meet the requirements for the three lower temperature oils. In 1962, the Qualified Products List (QPL) for two lubricants of the MIL-L-9236B variety was cancelled. Subsequently, in 1972, this series was superseded by MIL-L-27502 which presently has no oils on its list. However, a newly formulated hindered polyol ester based on polypentaerythritol and developed under the Air Force Materials Laboratory sponsorship has a potentially maximum useful bulk oil temperature (BOT) of 240° C (464° F). This ester is currently undergoing further testing by the U.S. Air Force for possible qualification as a MIL-L-27502 candidate (4), (5).

STATUS OF HIGH TEMPERATURE LUBRICANT DEVELOPMENT

In addition to the extensive development work performed with the esters which has led to their almost exclusive use in present day turbine engines, there has been a number of other organic liquids synthesized and studied in the search for improved lubricants. Just where are we now in the development and production of off-the-shelf high temperature oils? The status of some of the leading candidate classes of fluids that have been considered for this application follow.

Figure 2 gives a listing of nine classes of candidate fluids that will be discussed, and the bar graph indicates the potential operating temperature range for each class. The operating temperature range is herein defined as being bounded on the lower end by the pour point and on the upper end by the maximum useful BOT. Mineral oils are shown as reference fluids. Development and introduction of most of these fluids have occurred over the past thirty years. The more promising higher temperature candidates (i.e., perfluoroethers and triazines) are in relatively early stages of development. Detailed histories of each fluid have been avoided for the sake of brevity in this review. Each could have been the subject of separate reports.

Synthetic Hydrocarbons (-50° to 204° C)

Formulated versions of these long, straight chained polymers were developed to extend the temperature range of petroleum based fluids. They have excellent boundary lubrication properties and rheological characteristics and are available at low cost. However, they have poor fire resistance and are oxidatively stable to only 204° C (400° F) (3). Further development for higher temperature capability is questionable, but they are good candidates for use in an inerted lubrication system.

Superrefined Mineral Oils (-37° to 218° C)

Further refining of mineral oils has produced naphthenic and paraffinic versions of these fluids that has extended the operating temperature range of mineral oils on both ends of the scale, with an upper limit of about 218° C (425° F). Of course they still retain most of the disadvantages of mineral oils, which includes poor fire resistance and high volatility. They are currently not being considered for further development.

Hindered Polyol Ester (-51° to 240° C)

As stated in the previous section, a formulated version of this ester based on pentaerythritol has potential use to a BOT of 240° C (464° F) as a MIL-L-27502 lubricant in a Mach 3 aircaft or similar applications. It has good lubrication ability, fair fire resistance, a foaming problem, and is available only in gallon quantities at this time. Further development to increase its operating range is questionable unless improved base stocks are found. Additional work would be encouraged if the current version was accepted as a MIL-L-27502 oil.

Improved Silicones (-61° to 240° C)

Improved silicone formulations (methyl and trifluoropropyl methyl) show some promise to a maximum temperature of 240° C (464° F). Although they possess outstanding viscosity-temperature properties and are available commercially, they have poor boundary lubrication ability and only fair fire resistance. Although silicone lubricants in general are characterized as having a low rate of oxidation at high temperatures (260° C in this case) where the oxidation rate for this type formulation becomes appreciable, they display poor oxidation tolerance. This is related to their inherent tendency to crosslink during oxidation. Thus, silicone lubricants will increase in viscosity (and form a gel) more than organic lubricants for equal amounts of oxygen intake (3). Also, they have few advantages over the advanced esters, and their potential for further development is unknown.

C-Ethers (-29° to 260° C)

These fluids have oxidative stability up to 260° C (500° F) for a base stock blend of three and four-ring components;the structures are presented in Fig. 3 (6). C-ethers are similar to the polyphenyl ethers except that sulfur provides the link between some of the phenyl rings instead of oxygen. Unformulated C-ethers have fair boundary lubricating ability, fair fire resistance, an inherent copper corrosion problem, surface wetting deficiency, and relatively high pour point (-29° C) and volatility. An extensive formulation and development program by Clark, et al., has produced formulated versions of the fluid with improved lubricating characteristics (7), (8). The C-ethers were found to be inherently better lubricants than an advanced ester and had superior thermal operating potential than two military specification type esters. This was demonstrated in a boundary lubrication study (9), and results are shown in Fig. 4. However, in bench tests of engine bearings at high speeds, insoluble oil oxidation products were formed. This sludge formation caused serious filter-clogging problems (8). It appears that extensive further work would be necessary to determine whether this problem can be eliminated.

Thiophenyl Disiloxanes (-39° to 260° C)

These fluids, blended with C-ethers, were developed to improve the pour point of this type lubricant without sacrificing the other properties of C-ethers (8). Pour points were lowered from -29° C (-20° F) down to almost -39° C (-38° F), but it produced a fluid deficient in lubricating ability and one which was not very receptive to additive treatment. Cost would also be very high. They have the same low potential for further development as the C-ethers.

Polyphenyl Ethers (4° to 288° C)

Aircraft flight experience already exists with at least one version of this fluid, a five-ring polyphenyl ether-base fluid, in an operational military turbine engine. It meets military specification MIL-L-87100. Although it has excellent high temperature stability and very high autoignition temperature, it has a very high pour point of about 4° C (39° F). A trichloroethylene diluent is needed with this fluid to reduce the pour point and make it operational, which greatly limits it use (10)-(12).

Fluorinated Polyethers (-34° to 316° C)

The polyperfluoroalkylether fluids, both the linear and the hexafluoropropylene oxide (HFPO) based varieties, are excellent boundary lubricants. They are non-flammable and possess excellent oxidation stability up to 316° C (600° F). Their problems include low pour points, corrosion with certain alloys at 260° C (500° F), and their rheological properties are difficult to improve because of their complex structures. They are quite costly but are available commercially. The Air Force Materials Laboratory is currently working on a development program for additives to improve the high temperature oxidation stability and corrosion inhibition of this class of fluids. They have high potential if their corrosion problems are solved (12)-(19).

Fluoroether Triazines (-30° to 343° C)

Triazines, having fluoroether side chains, are excellent boundary lubricants, have excellent oxidation stability up to 343° C (650° F), and are non-flammable. They exhibit improved low temperature properties compared to the polyphenyl ethers and are not corrosive at elevated temperatures. Their present problems, high volatility and poor fluidity at low temperatures, are being solved by altering the ratio of carbon to oxygen in the side chains. This fluid class is still in an early development stage and is only available in gram quantitites. Therefore, it is extremely expensive. Even in large scale production it will remain costly, probably ten times that of a C-ether, but reclamation of this type of fluid is not difficult. This could be a very promising high temperature lubricant candidate if its shortcomings are solved by development (12), (20)-(23).

NEED FOR MORE LUBRICANT FUNDAMENTALS STUDIES

In order to design new liquid lubricant base stocks or to improve on the existing ones that were just discussed, it is important to better understand the effect of the physical and chemical properties on their performance at expected advanced turbine engine operating conditions. Also, the mechanisms of thermal and oxidative degradation of lubricants, as they relate to the local high temperature engine environment of lubricated contacts, must be understood in the tribological design of mechanical components. It is not the purpose of this overview paper to enumerate specific suggestions for programs to conduct these fundamental studies to realize the stated objective. However, studies to advance these technologies should include the use of different lubricant base stocks, additives, and the effect of metals on these fluids in different environments.

An excellent example of one such program now in progress is the fluid stability study at Pennsylvania State University under the guidance of Dr. E.E. Klaus. Static thin-film micro-oxidation test apparatus, shown in Fig. 5, (24), (25), is used to evaluate various ester base stocks and other lubricants at temperatures to 245° C (473° F) on catalytic metal surfaces. General oxidation mechanisms, metal-catalyzed variations, and additive-inhibited reactions are being studied. Other data available from prior work include that for mineral oils, synthetic hydrocarbons, polyphenyl ethers, phosphate esters, C-ethers, and organic acid esters. Analytical tools used in the study are ultra-violet, nuclear magnetic resonance, and atomic adsorption spectroscopic techniques, gas chromatography, and high pressure liquid chromatography (HPLC). In addition to furthering the understanding and development of aircraft oils, it is hoped that a simple laboratory test, such as the micro-oxidation test, has the potential to replace both the bulk oxidation and the mockup rig tests, to simulate lubricant degradation chemistry in bearings and gears. Concurrent to and supplemental with the work at Penn State, NASA is performing a fundamental study of lubricant degradation mechanisms of C-ethers and other fluids using these experimental techniques. It has been demonstrated that HPLC and the aforementioned tools can be used effectively as an analytical means to help meet the lubricant developer's goal (26).

An example is shown in Fig. 6 on how HPLC (size exclusion mode) was used to determine the chemical degradation of a MIL-L-27502 candidate ester lubricant from a high temperature (216° C BOT) gas turbine engine test by the U.S. Air Force (27). Analysis indicated depletion of additives and the formation of higher molecular weight material. This higher molecular weight material could be the precursor of sludge and varnish. Such chemical studies could establish decomposition mechanisms of oils and how to inhibit them.

ALTERNATIVES TO HIGH TEMPERATURE FLUIDS

Alternatives to high temperature liquid lubricant development have been used or considered over the past 25 years or so to circumvent deficiencies of available fluids. These include: (1) general engine design considerations to by-pass the fluids shortcomings, (2) use of an inerted lubrication system, and (3) use of a microfog once-through system.

Some Engine Design Considerations

Until fully qualified higher bulk oil temperature lubricants are developed, advanced high speed turbine engine makers have been forced to consider and implement many design changes to meet their immediate demands for coping with higher heat rejection rates. Use of lighter and more heat resistant alloys in engine sumps, increases in heat exchanger efficiency through design and material approaches, and improvements in fuel tank and sump insulation materials have helped solve the problem for earlier engines. Also, methods used to avoid "hot spots" in the engine that cause coking involve design features which provide better thermal barriers. Besides insulation blankets, engine designers have used heat shields and oil jets impinging directly on the sump walls. The potential risk of coking has influenced the development of better oil seals and use of pressurizing air and surface cooling air from external sources. To cope with lubricant volatility at higher operating temperatures and the resulting risk of high oil consumption, vent flow has been reduced by use of carbon seals rather than labyrinth seals and by the use of non-vented sump designs. The use of vent line shut-off valves has been successfully applied and represents a possible compromise between vented and non-vented sump designs (28).

Use of an Inerted Lubrication System

In a conventional open lubrication system, lubricant breakdown is usually by fluid oxidation. The temperature limit for the di-ester formulations most commonly used is about 177° C (350° F), but in the absence of or for very limited oxidation, these oils have thermal stability to about 302° C (575° F) (from isoteniscope data). These data suggest that if oxygen can be restricted in the engine sump, as in an inerted gas blanketed system, the lubricant may have useful stability at temperatures over 93° C (200° F) higher than it does when the system contained substantial amounts of oxygen (29).

Feasibility of using such a system was demonstrated in studies by Sibley, et al., (30)-(32), using five different lubricants in a nitrogen gas inerted system that simulated a Mach 3 aircraft gas turbine engine sump with full scale mechanical components. A schematic of this test sump is shown in Fig. 7 (29). A 125-mm ball bearing with advanced state-of-the-art face contact seals was operated successfully at a bearing speed of 14 000 rpm at an oil temperature of 260° C (500° F) and bearing outer race temperatures in the range of 316° to 427° C (600° to 800° F). Oils that operated satisfactorily during screening tests from 5 to 10 hours included a mixed ester, a synthetic paraffinic fluid, a perfluorinated polymeric oil, and a C-ether fluid. The principal problem in these studies was with excessive leakage of the oil-side bellows face seal. Much development work remains in perfecting such a system for practical application in an engine. Also, the main drawback in use of this system is the need to carry large quantities of nitrogen in an aircraft.

Use of a Microfog Once-Through System

It has been known for some time that an oil-mist once-through lubrication system reduces engine bearing frictional heat significantly by eliminating circulating oil churning at high speeds. At the same time it allows higher bearing operating temperatures since the lubricant can be discarded after use and thermal degradation is of less concern. Also, oil-mist systems have reduced weight and complexity compared to circulating systems, and they are less subject to accidental leaks and plugging of jets and filters (33).

The viability of using such a system with auxiliary air cooling was demonstrated in two separate studies (34), (35) with 46-mm and 125-mm bore bearing test machines. A number of different lubricants were studied at Mach 3 conditions for extended periods over 30 hours. Figure 8 (33) shows some of the results from the 125-mm bearing study which indicates that oil-mist lubrication produces measured heat generation rates that are about one-fourth those of comparable bearings with conventional circulating oil-jet lubrication.

As with the inerted lubrication system, much additional work will be required to perfect oil-mist once-through systems. Optimization is needed for mist size and flow, cooling air flow and application, as well as for nozzle and bearing designs.

CONCLUDING REMARKS AND THE FUTURE

This general overall review of liquid lubricants for advanced aircraft was intended to show the state of development for past and current candidate fluids. It is concluded that there is still a critical need for lubricants to meet all the requirements of the newer high speed aircraft. The perennial question is asked: Where does the lubricant formulator go from here in the search for those elusive high temperature fluids that must operate at higher flight and engine rotative speeds and the resulting higher oil and lubrication system temperatures?

Of course it is important to continue work on improving currently available advanced lubricant candidate fluids by base stock alterations, additive formulation studies, and use of novel systems to improve advanced aircraft operation. However, the point has been reached where more technical innovations in all these areas are needed before that breakthrough is reached.

This is especially true for finding new and better fluid base stocks. Unfortunately, the profit incentive is not there for private industry to invest in significant new fluid development efforts. A concentrated cooperative venture is needed to meet the goals among private industry, universities, and Federal Government agencies, both military and civilian.

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TABLE 1. - REQUIREMENTS FOR AN ADVANCED TURBINE ENGINE HIGH TEMPERATURE LUBRICANT

Physical property	Condition or limit
Viscosity	<15 000 cS at -54° C (-65° F) >1.0 cS at 260° C (500° F)
Compatibility with other materials	-----------
Oxidative stability (potential bulk oil temperature)	260° to 427° C (500° to 800° F)
Evaporation loss, 6.5 hr at 260° C (500° F)	<10 percent
Lubricating ability	Satisfactory results in 100 hr bearing rig test at 260° to 316° C (500° to 600° F) tank temperature (U.S.A.F. specification)
Flash point	260° C (500° F) minimum
Pour point	-54° C (-65° F) maximum
Decomposition	No solid products or excessive deposits in 100 hr bearing test
Foaming	Nonfoaming

TABLE 2. - CURRENT SPECIFICATION PROPERTIES OF ESTER LUBRICANTS FOR MILITARY ENGINES

Property	MIL-L specification number			
	7808 H (1977)	23699 C (1978)	9236 B (1960)	27502 (1972)
Kinematic viscosity, cS at				
260° C (500° F) minimum	---	---	---	1.0
204° C (400° F) minimum	---	---	1.0	----
99° C (210° F) minimum	3.0	5.0-5.5	---	[a]4.0-5.0
38° C (100° F) minimum	Report	25.0	Report	Report
-40° C (-40° F) maximum	---	13 000	---	15 000
-54° C (-65° F) maximum	17 000	---	21 000	----
Pour point, °C (°F) maximum	-59 (-75)	-54 (-65)	-59 (-75)	-54 (-65)
Flash point, °C (°F) minimum	204 (400)	246 (475)	218 (4[illegible]	246 (475)
Autoignition temperature, °C (°F) minimum	---	---	399 (750)	410 (770)
Bearing rig, 100 hr test				
Tank temperature, °C (°F) (bulk oil)	177 (350)	---	218 (425)	[b]240 (464)
Bearing temperature, °C (°F)	260 (500)	---	274 (525)	[b]300 (572)

[a]Estimated.
[b]48 hr test.

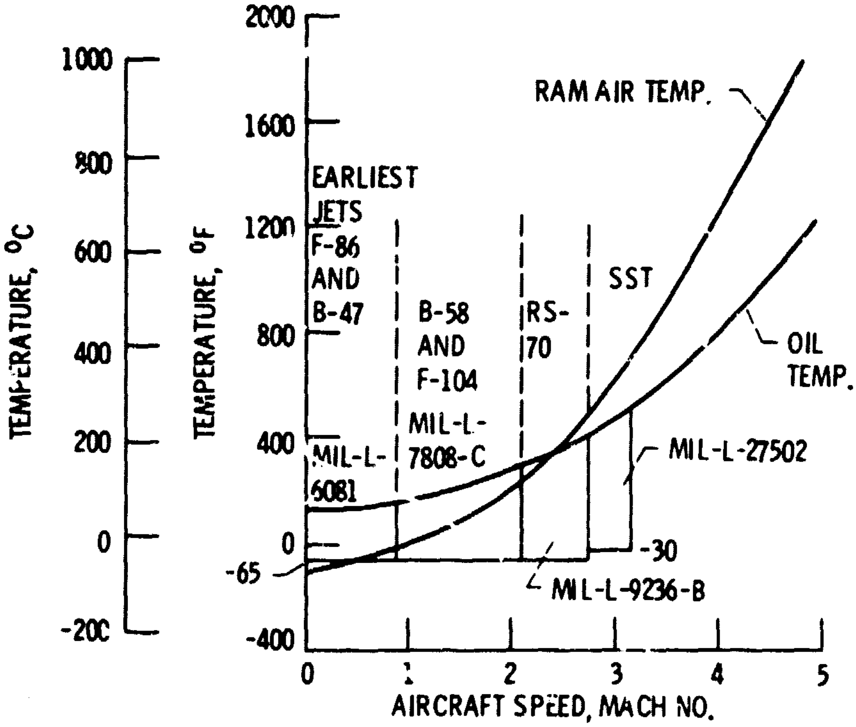
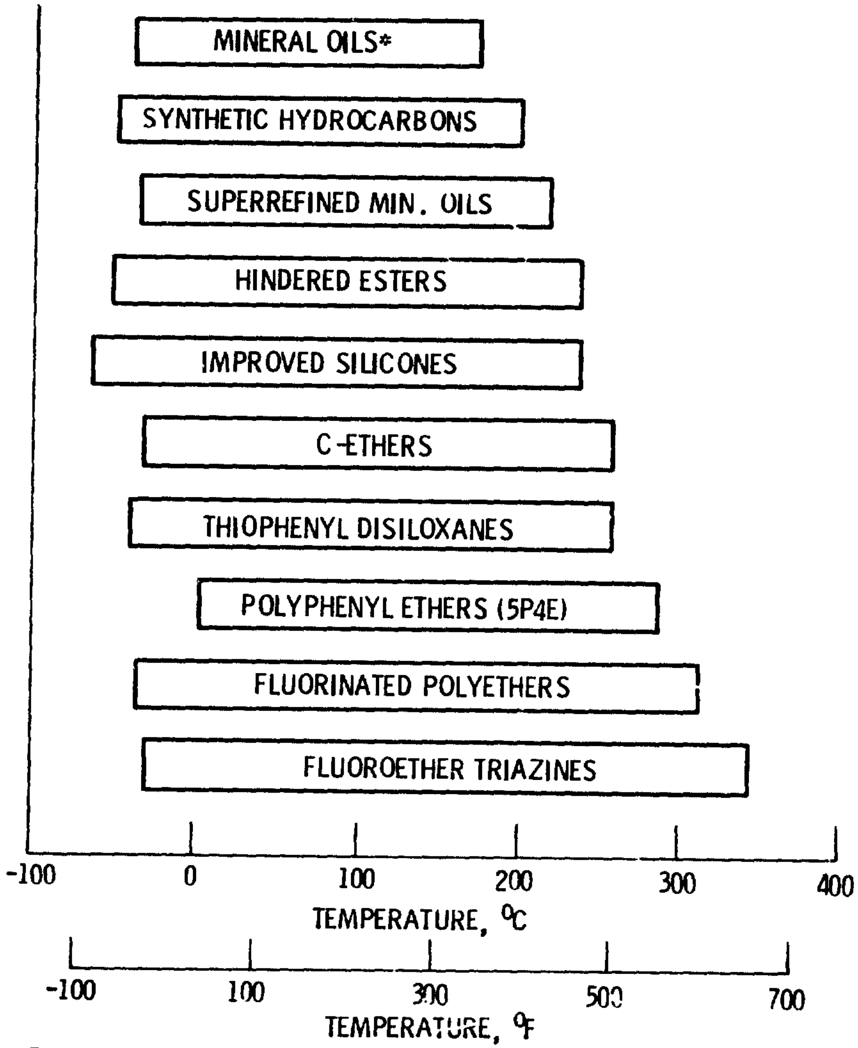
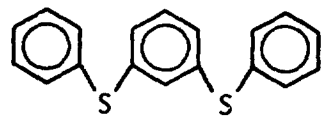


Figure 1. - Effect of aircraft speed on oil operating temperature.

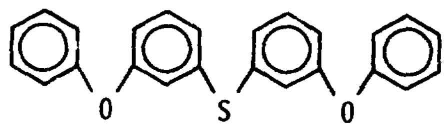


*Reference fluids.

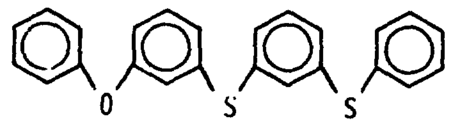
Figure 2. - Operating temperature range for nine classes of high temperature lubricants.



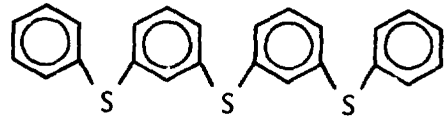
1, 3-bis (phenylthio) benzene



1, 1-thiobis [3-phenoxybenzene]



1 phenoxy-3-[[3-(phenylthio) phenyl] thio] benzene



1, 1-thiobis [3- (phenylthio) benzene]

Figure 3. - Structures of C-ether base fluid components.

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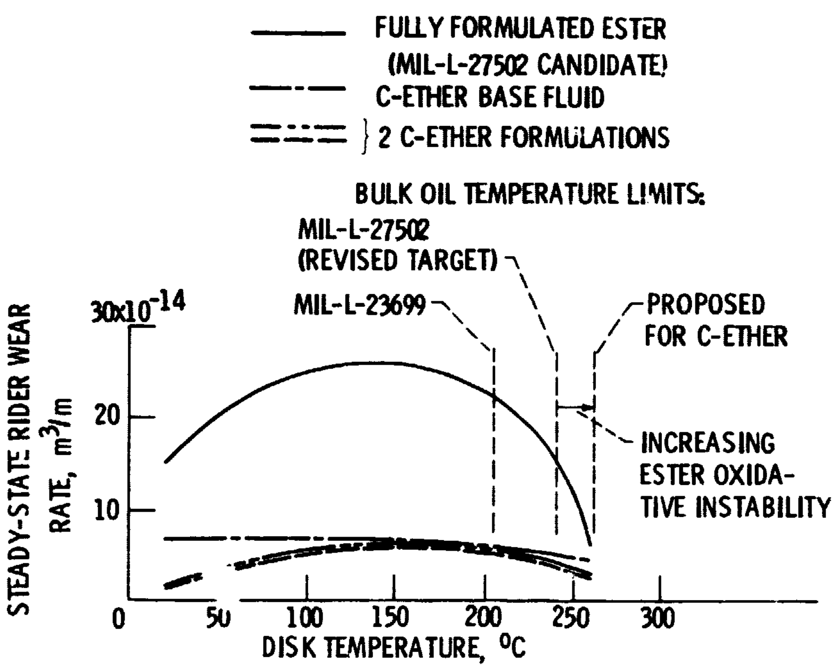

Figure 4. - Steady-state wear as a function of disk temperatures from 20^0 to 260^0 C for a formulated ester and C-ether fluids.

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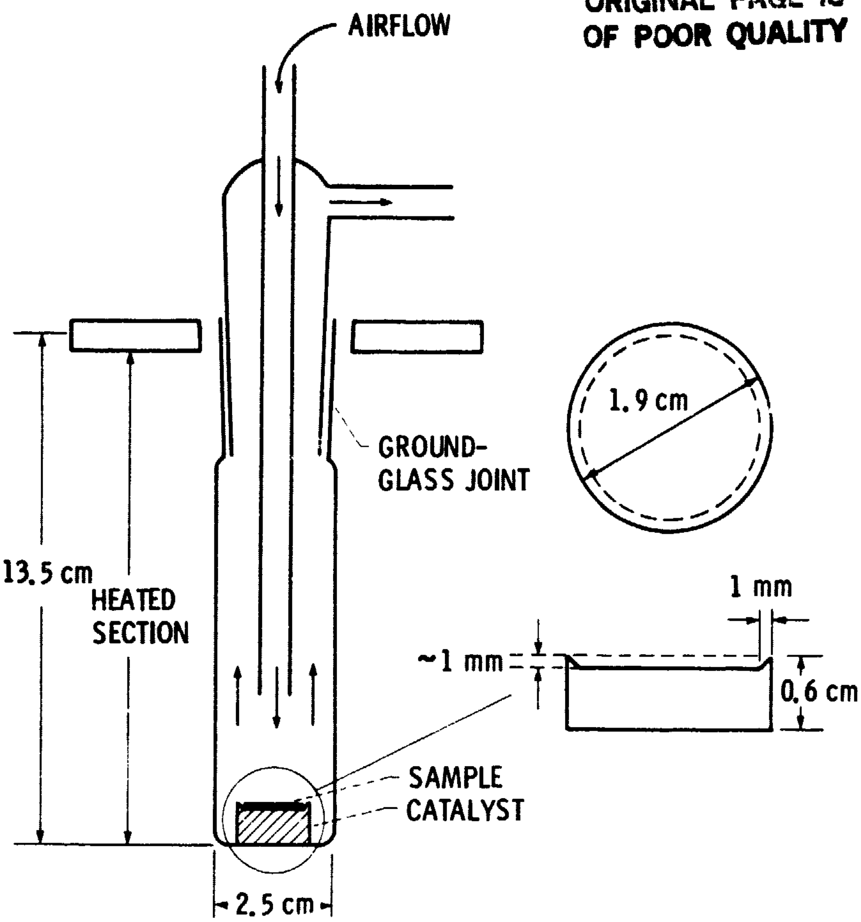

Figure 5. - Micro-oxidation apparatus.

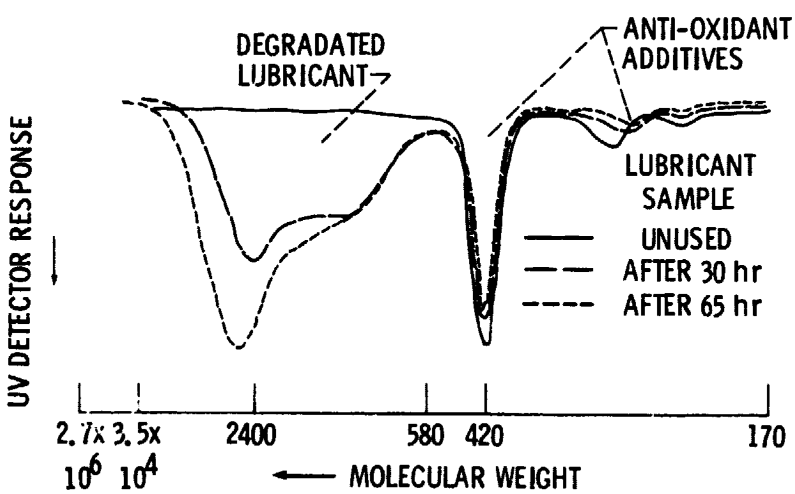

Figure 6. - Size-Exclusion Chromatographic Analysis of MIL-L-27502 Lubricant from a Gas Turbine Engine Test.

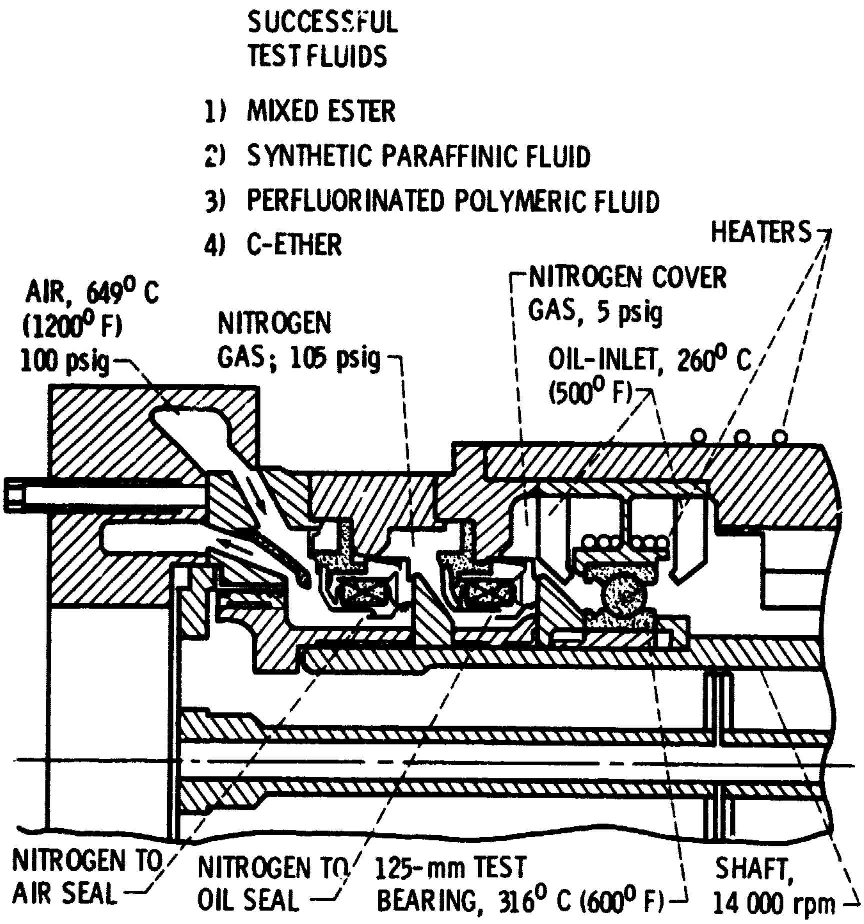

Figure 7. - Inerted Lubrication System in a Simulated Engine Sump.

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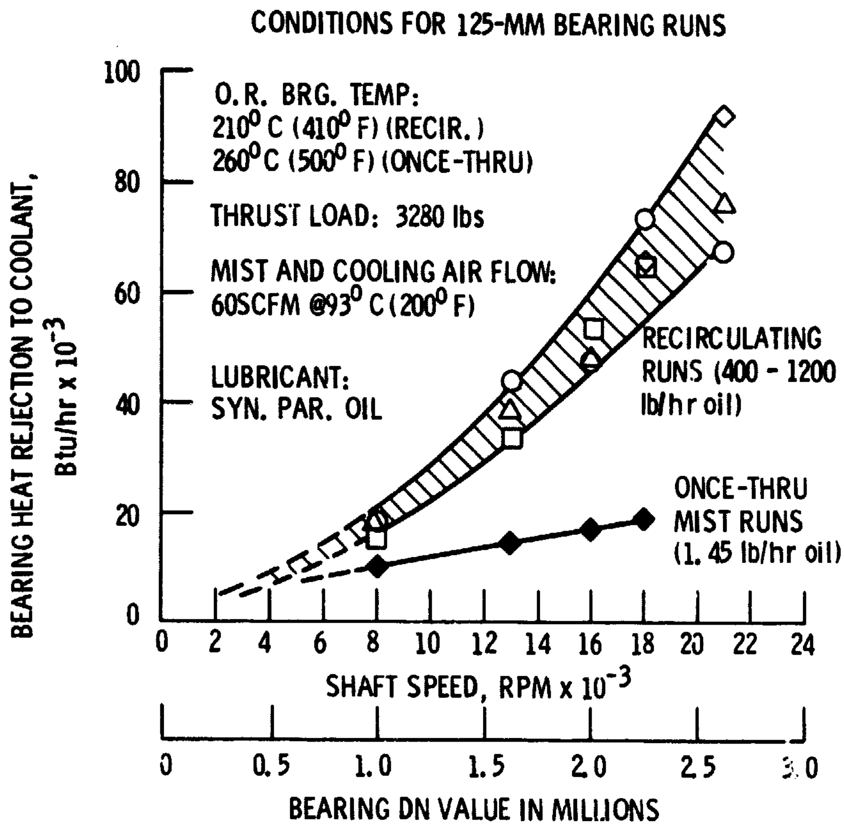

Figure 8. - Bearing heat rejection to coolant for recirculating and once-thru lubrication systems.