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SUMMARY

An overview of liquid lubricants for use in current and projected high-performance turbojet engines is discussed. Chemical and physical properties are reviewed with special emphasis 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 that led to the present-day synthetic oils with their inherent modification advantages. The status and state of development of some 11 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. 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 the development of new and improved fluid base stocks.

INTRODUCTION

The development of liquid lubricants for advanced, high-speed aircraft has been proceeding for several years under the sponsorship of the Defense Department, NASA, and private industry. The U.S. Air Force effort at their Wright Research and Development Center has been sustained and substantial. NASA's program is being conducted at the Lewis Research Center. This paper presents a review of the liquid lubricants currently used and those that have potential for use in future advanced aircraft, both military and commercial.

One problem that occurs when we try to obtain greater aircraft efficiency or to operate aircraft at higher speeds is that the engine lubrication system must be made operable at yet higher temperature levels. It is estimated that the bulk oil temperature would be about 204°C (400°F) at Mach 2.5 and about 260°C (500°F) at Mach 3 (Ref. 5). Difficulties that can be expected when liquid lubricants operate at these temperatures are 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 (Ref. 5). 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 for short periods and regular oil changes. In the Mach 1.3 to 2 speed range an ester-based fluid, fortified with additives, is used for the turbine engines in most current military and commercial aircraft.

For the Mach 2 plus aircraft an earlier MIL-L-9236 specification was proposed using a triester-based oil. The use of this oil has been discontinued and superseded by MIL-L-27502 specification for a possible 218°C to 246°C (425°F to 475°F) bulk oil temperature using an ad-

vanced, ester-based liquid. To date no lubricating oil for this specification has been fully qualified.

It also should be mentioned, that above Mach 2, the ram air temperature increases rapidly and actually exceeds the bulk oil temperature. Because the air can no longer be used as a heat sink to cool the oil, the problem of holding down bulk oil temperature is compounded.

The tentative consensus requirements for an ideal liquid lubricant for future commercial advanced aircraft are shown in table I. The requirements shown there conform closely to those of MIL-L-27502 but have more stringent upper and lower operating temperature limits to allow for greater operating extremes. A fluid meeting these requirements is a goal of lubricant base oil developers and fluid formulators.

The main approach to the problem of finding an ideal liquid lubricant for high-performance military aircraft has included a search for increased standardization. But the search has not been dominated by the overall need for economy, as is 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 the high-temperature lubrication 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 in the paper.

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 (Refs. 24 and 40). In 1937 his successful demonstration of an experimental engine of this design started a tremendous research and development program for high-performance oils.

Before and during World War II independent development of fluids in Germany and the United States formed the basis of many of the lubricants used today by the aviation industry. While 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 several triester and diester oils were developed that, by 1944, reached the 10 000 tons per year production level. Dr. Zorn's counterpart in the United States was Dr. W.A. Zisman and his coworkers at the Naval Research Laboratories who independently developed dozens of usable synthetic ester oils by 1944.

Work has continued to this day on the improvement of ester-based fluids by the Naval Research Laboratory, the Air Force Materials Laboratory, and others. Table II shows the specification properties of high-performance ester lubricants for turbine engines that have been issued by the Air Force and the Navy (Refs. 51 to 54). These specifications are listed in the order of increasing useful engine operating temperature, as indicated by the bulk oil temperature, in the 100-hr bearing rig test, starting with a 177°C (350°F) rating for the MIL-L-7808J oil and going to 240°C (464°F) for the MIL-L-27502 oil. Commercially available products meet the requirements for the two lower temperature oils.

A formulated neopentyl polyol ester blend, developed under the Air Force Materials Laboratory sponsorship, has a potentially maximum useful bulk oil temperature (BOT) of 240°C (464°F) (Refs. 4 and 11). The oil was tested by the Aero Propulsion and Power Laboratory at Wright-Patterson Air Force Base for 100 hr in a full-scale J57-P29W engine test in accordance with MIL-L-27502. The results are discussed in Ref. 4. Overall the results were

considered favorable and indicated that this oil formulation has excellent potential for high-temperature turbine engine applications not requiring -51°C (-60°F) low-temperature startup capability.

STATUS OF HIGH-TEMPERATURE LUBRICANT DEVELOPMENT

Besides the extensive development work performed with the esters, which has led to their almost exclusive use in present-day turbine engines, several other organic liquids have been 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 the leading candidate classes of fluids for this application follow.

Figure 2 lists 9 of the 11 classes of candidate fluids that will be discussed. The bars indicate the potential operating temperature range for each class. Mineral oils are shown as reference fluids. The operating temperature range is defined as being bounded on the lower end by the pour point and on the upper end by the maximum useful bulk oil temperature. Development and introduction of most of these fluids have occurred over the past 40 years. The more promising higher temperature candidates (i.e., perfluoropolyethers and perfluoroether triazines) are still being developed. Detailed histories of each fluid have been avoided for the sake of brevity in this review. Each could have been the subject of a separate report.

Synthetic Hydrocarbons (-50°C to 204°C)

Formulated versions of these long, straight-chained polymers were developed to extend the temperature range of petroleum-based fluids. Synthetic hydrocarbons have excellent boundary lubrication properties and rheological characteristics and are available at low cost. However, they have poor fire resistance and are oxidatively stable only to 204°C (400°F) (Ref. 24). Further development for higher temperature capability is questionable, but they are good candidates for use in an inerted lubrication system.

Polyalphaolefins (PAO) (-46°C to 204°C)

Polyalphaolefin fluids are based on the oligomerization of alphaolefins. They were developed in the late 1960's and early 1970's as fire-resistant hydraulic fluids in the Materials Laboratory at the Wright-Patterson Air Force Base (Refs. 22 and 80). The fluids have a low operation temperature of -46°C (-50°F) and an upper operation temperature of 204°C (400°F). The fluids have very good fire resistance both to ignition and to the propagation of fires. They are extremely attractive for hydraulic system use (as a base stock for military specification MIL-H-83282) because of their availability and low cost.

Silhydrocarbons (SiHC) (-65°C to 175°C)

Silhydrocarbon fluids were developed in the late 1970's in the Materials Laboratory at the Wright-Patterson Air Force Base. They have excellent thermal stability, viscosity index, and low-temperature flow characteristics (Refs. 70 and 80). They were called silhydrocarbons to reflect the hydrocarbon behavior characteristics without the hydrolytic instability of silicate ester fluids or the poor bulk modulus properties of silicones. These fluids have oxidative stability to 175°C (347°F) and a flash point of 227°C (441°F). Their shear stability is excellent. The

fluids are candidates for use in military aircraft hydraulic systems where fire resistance and low-temperature operation are major requirements. Availability and relatively high cost are concerns.

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

The further refining of mineral oils has produced naphthenic and paraffinic versions and 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). Unfortunately, these superrefined oils retain most of the disadvantages of mineral oils, which include poor fire resistance and high volatility. They are not currently being considered for further development.

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

As stated previously, a formulated version of the neopentyl polyol ester, based on pentaerythritol, has potential use to a bulk oil temperature of 240°C (464°F) as a MIL-L-27502 lubricant in a Mach 3 aircraft or similar application. It has good lubrication ability and fair fire resistance. But it has a foaming problem and is available only in relatively small 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 were accepted as a MIL-L-27502 oil.

Improved Silicones (-61°C to 240°C)

Improved silicone formulations (methyl and trifluoropropyl methyl) show some promise at maximum temperatures of 240°C (464°F). Although these fluids possess outstanding viscosity-temperature properties and are available commercially, they have poor boundary lubrication ability and only fair fire resistance. Silicone lubricants, in general, have a low rate of oxidation up to 240°C (464°F). At higher temperatures their oxidation rate is appreciable, and they display increasingly poor oxidation resistance. Their inherent tendency to crosslink during oxidation causes greater viscosity (forming a gel) than organic lubricants for equal amounts of oxygen intake (Ref. 24). They have few advantages over the advanced esters. And their potential for further development is unknown.

C-Ethers (-29°C to 260°C)

C-Ethers fluids have good 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 (from Ref. 46). 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 (Refs. 12 and 13). The C-ethers were found to be inherently better lubricants than an advanced ester and to be superior in thermal operating potential to two military specification type esters. This was demonstrated in a boundary lubrication study (Ref. 47), and the 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 (Ref. 13). It appears that extensive further work would be necessary to determine whether this problem can be eliminated.

Thiophenyl Disiloxanes (-39°C to 260°C)

Thiophenyl disiloxane fluids blended with C-ethers were developed to improve the pour point of disiloxanes without sacrificing the other properties of C-ethers (Ref. 13). Pour points were lowered from -29°C (-20°F) to almost -39°C (-38°F), but it produced a fluid that was deficient in lubricating ability and not very receptive to additives. The cost would also be very high. They have the same low potential for further development as the C-ethers.

Polyphenyl Ethers (4°C to 288°C)

Aircraft flight experience already exists with at least one version of this fluid, a five-ring polyphenyl ether-based 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), which greatly limits its use (Refs. 29, 32, and 55). A trichloroethylene diluent is needed with this fluid to reduce the pour point, which greatly limits its use (Refs. 29, 32, and 55).

Perfluoropolyethers (-34°C to 316°C)

The most promising chemical class of fluids for future high-temperature gas turbine engine lubricants is the perfluoropolyethers (PFPE). They possess inherent oxidative stability, good thermal stability, very low volatility, chemical inertness, and high radiation resistance and are nonflammable (Refs. 4, 11, 23, 32, 62, 69, and 80). The main problems with PFPE's are that they tend to chemically breakdown under boundary lubrication with certain metals or alloys and that their rheological properties are difficult to improve because of their complex structures.

Recently several studies have been conducted to investigate the breakdown of these fluids under lubricating or oxidizing conditions. Jones et al. (Refs. 37 and 38) have performed thermal oxidative stability studies on unbranched PFPE fluids at 288°C (550°F) in oxygen in the presence of titanium, aluminum, and the alloy Ti(4Al,4Mn). Degradation occurred, and the mechanism of degradation was by chain scission. The Ti(4Al,4Mn) induced more degradation than the other metals. Morales (Ref. 56) has shown that various other materials can catalytically cause the degradation of these fluids. His tests involved the heating of a thin film of the fluid on the material for 30 minutes in dry air at 345°C (653°F). The material that caused the greatest degradation was 440C bearing steel. Carré (Refs. 9 and 10) has inferred that iron fluoride (FeF_2) can form in the absence of oxygen under boundary lubrication conditions through the interaction of PFPE with steel surfaces.

Mori and Morales (Ref. 59) evaluated several of these fluids under sliding conditions in a vacuum chamber. They found that the fluid that contained the acetal group decomposed, giving off gaseous products, while the others did not. Analysis after the tests revealed that all the tested fluids formed metal fluorides on the sliding surfaces. They concluded that the tribological reaction of the PFPE is mainly affected by the activity of mechanically formed fresh surfaces of metals rather than by the heat generated at the sliding contacts. These and other studies indicate that either passivating additives need to be found for these fluids or bearings need to be made from materials that do not cause the fluids to catalytically decompose.

A major difficulty with PFPE fluids is that conventional oil additives are not soluble in

these fluids. The Air Force Materials Laboratory at the Wright Research and Development Center is currently developing additives to improve the high-temperature oxidation stability and corrosion inhibition PFPE's. An additional problem with these fluids is that they are very expensive; however, they are available commercially. They have significant potential if their corrosion and decomposition problems can be solved.

Fluoroether Triazines (-30°C to 343°C)

Triazines with fluoroether side chains are excellent boundary lubricants, have excellent oxidation stability up to 343°C (650°F), and are nonflammable. They exhibit better low-temperature properties than the polyphenyl ethers and are not corrosive at high 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 quantities. Therefore, it is extremely expensive. Even in large-scale production it will remain costly, probably 10 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 (Refs. 3, 25, 32, 68, and 75).

LUBRICANT PHYSICAL AND CHEMICAL PROPERTIES

When choosing a liquid lubricant for use in advanced aircraft, it is especially important to determine the operational conditions to which it will be exposed. This is true since the various chemical classes of liquid lubricants behave differently under different operational conditions. For example, if the lubricant were not exposed to air, one would not be concerned with the oxidation properties of the lubricant. Many other properties should also be taken into consideration such as bulk modulus, density, pour point, etc. Table III (from Ref. 82) lists lubricant properties and the environmental areas where they are important. The ensuing paragraphs will discuss some of the more important physical and chemical properties in relation to the following six classes of lubricants: Paraffinic mineral oils (PMO), silahydrocarbons (SiHC), polyalphaolefins (PAO), polyolesters (PE), polyphenylethers (PPE) and two types of perfluoropolyethers (PFPE), branched and linear.

Thermal Stability

The term "thermal stability" is often used to describe the stability of the lubricant in the absence of oxygen. Table IV (from Ref. 76) presents thermal stability data on six classes of liquid lubricants. These data were obtained by sealing a 12.7-mm-diameter ball and 20 ml of fluid in a stainless-steel tube. Three metals were evaluated: 52100 steel, naval bronze, and M-10 steel. After specimen insertion, the oxygen was displaced from the tube with dry nitrogen. The tube was then sealed and heated to a specified temperature for 6 hr. After cooling to 25°C (77°F), the specimens were analyzed. The degree of fluid degradation was determined by changes in oil viscosity and acid number and by the weight change of the metal specimens. The relative ranking of the fluids based on thermal stability was PPE > SiHC > PFPE > PMO > PAO > PE.

Corrosion-Oxidation Stability

The six fluids mentioned in the last section were also evaluated for their corrosion-oxidation stability. The method used is described in the Federal Test Method Standard, 791b, Method 5308. A smaller scale version of this method is described in Ref. 70. After testing, the fluids were evaluated for changes in viscosity at 40°C (104°F), for acid number, and for the amount of fluid loss. Metal specimens were evaluated for changes in weight. The results of this study are shown in table V (from Ref. 76). The relative ranking of the fluids based on corrosion-oxidation stability was PFPE \approx PPE > PE > PAO \approx SiHC \approx PMO.

Pour Point

The pour point of a lubricating oil is the lowest temperature at which it will pour or flow when chilled. Pour point generally provides an indication of the lowest temperature at which the fluid can be used. Mostly, though, the lowest use temperature for a specific application is defined in terms of the fluid viscosity needed for a particular application.

In general, viscosity is dependent on the molecular weight of the fluid. The six classes of fluids can be formulated with different molecular weights, each with a different viscosity. To make a valid comparison Snyder (Ref. 76) used the pour points of similar viscosity fluids from each of the six fluid classes. The method used was ASTM D97. The results are shown in table VI (from Ref. 76). On the basis of pour points, the fluid classes were ranked as follows: linear PFPE \approx SiHC \approx PE > PAO > PMO > branched PFPE \gg PPE.

Density

The density of a substance is the mass per unit volume at a standard temperature. Since density changes with temperature, it is determined at a controlled temperature and then corrected to a standard temperature by use of special tables. The densities of the six classes of fluids mention in this section are given in table VII (from Ref. 76). Since, in aerospace applications, high density is not desirable because of increased weight, the relative ranking of the fluids according to density is PAO \approx SiHC \approx PMO \approx PE \approx PPE > PFPE.

Bulk Modulus

A measure of a fluid's resistance to compression is the bulk modulus value. A fluid with low bulk modulus is more compressible than one with a high bulk modulus. Table VIII (from Ref. 76) gives the bulk modulus for the six classes of fluids. There is very little difference in bulk modulus for the PMO, SiHC, PAO, and PE fluids. But the bulk modulus of PPE is considerably higher, and that of PFPE very much lower.

NEED FOR MORE LUBRICANT FUNDAMENTALS STUDIES

To design new liquid lubricant base stocks or to improve the existing ones, it is important to understand better the effect of the physical and chemical properties on fluid 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 to give specific suggestions for conducting these fundamental studies. However, we do suggest that such studies include the use of different lubricant base stocks and additives and the effect of metals on these fluids in different environments.

An excellent example of a fundamental studies program was the fluid stability study conducted at Pennsylvania State University under the guidance of Dr. E.E. Klaus (Refs. 15 and 45). In this study, a static thin-film micro-oxidation test apparatus (Fig. 5) was 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 were studied. Analytical tools used in the study were ultra-violet, nuclear magnetic resonance, and atomic adsorption spectroscopic techniques, gas chromatography, and high-pressure liquid chromatography (HPLC).

Besides furthering the understanding and development of aircraft oils, it is hoped that a simple laboratory test, such as the micro-oxidation test, can replace both the bulk oxidation and the mockup rig tests to simulate lubricant degradation chemistry in bearings and gears. In addition to the Penn State studies, NASA has also performed 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 (Ref. 36).

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 bulk oil temperature) gas turbine engine test by the U.S. Air Force (Ref. 36). Analysis indicated the depletion of additives and the formation of higher molecular weight material. This higher molecular weight material could be the precursor of sludge and varnish. Chemical studies such as these 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 35 years or so to circumvent deficiencies of available fluids. These include (1) designing engines to accommodate the fluid's shortcomings, (2) using inerted lubrication systems, and (3) using microfog once-through systems.

Some Engine Design Considerations

Until fully qualified, higher bulk-oil-temperature lubricants are developed, advanced high-speed turbine engine makers are forced to 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 helped solve the problem for earlier engines. Also, methods used to avoid engine "hot spots," which cause coking, involve design features that provide better thermal barriers. Besides insulation blankets, engine designers have used heat shields and oil jets impinging directly on the sump walls. The risk of coking has influenced the development of better oil seals and the use of pressurizing air and surface cooling air from external sources. To cope with lubricant volatility at higher operating temperatures and with the resulting risk of high oil consumption, vent flow has been reduced by use of carbon face contact seals rather than labyrinth seals and by the use of

nonvented sump designs. Vent line shutoff valves have been successfully applied and represent a possible compromise between vented and nonvented sump designs (Ref. 79).

Use of an Inerted Lubrication System

In a conventional, open lubrication system, lubricant breakdown is usually by oxidation. The temperature limit for the diester formulations most commonly used is about 177°C (350°F), but in the absence of, or for very limited oxidation, these oils have satisfactory 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 inert-gas-blanketed system, the lubricant may have useful stability at temperatures over 93°C (200°F) higher than it does when the system contains substantial amounts of oxygen (Ref. 48).

The feasibility of using such a system was demonstrated in studies by Sibley et al. (Refs. 27, 28, and 64) 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 (Ref. 48). 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 at bearing outer race temperatures from 316°C to 427°C (600°F to 800°F). Oils that operated satisfactorily during screening tests from 5 to 10 hr 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.

Microfog Once-Through Systems

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 since thermal degradation is of less concern. Also, oil-mist systems have lower weight and complexity than circulating systems, and they are less subject to accidental leaks and plugging of jets and filters (Ref. 49).

The viability of using such a system with auxiliary air cooling was demonstrated in separate studies (Refs. 66 and 67) with 46-mm-bore and 125-mm-bore bearing test machines. Several lubricants were studied at Mach 3 conditions for periods over 30 hr. Figure 8 (Ref. 49) shows some results from the 125-mm bearing study which indicate that oil-mist lubrication produces measured heat generation rates that are about one-fourth those of comparable 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 airflow and application, as well as for nozzle and bearing designs.

CONCLUDING REMARKS AND THE FUTURE

This review of liquid lubricants for advanced aircraft has shown the state of development for past and current candidate fluids. There is still a critical need for lubricants to meet the requirements of the future higher speed aircraft. The perennial question asked is: Where does the

engine designer go in the search of those elusive high-temperature fluids that must be used to operate at higher flight and engine rotative speeds as well as the resulting higher oil and lubrication system temperatures?

It is important to continue work on improving current advanced lubricant candidate fluids by altering base stocks, by formulating new additives, and by using novel systems to improve aircraft operation. However, the point has been reached where more innovative technical concepts (in all these areas) are needed if breakthroughs are to be achieved. 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 research venture among private industry, universities, and federal government agencies (both military and civilian) is needed if we are to meet future lubrication goals.

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TABLE I. - 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 °C to 427 °C (500 °F to 800 °F)
Evaporation loss after 6.5 hr at 260 °C (500 °F)	<10 percent
Lubricating ability	Satisfactory after 100-hr bearing rig test at 260 °C to 316 °C (500 °F to 600 °F) tank temperature (USAF) specification
Flash point (min)	260 °C (500 °F)
Pour point (max)	-54 °C (-65 °F)
Decomposition	No solid products or excessive deposits in 100 hr bearing test
Foaming	Nonfoaming

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

Property	Specification number			
	7808 J ^b (1982)	23699 D (1990)	9236 B ^c (1960)	27502 (1972)
Kinematic viscosity, cS at—				
260°C (500°F) min	-----	-----	-----	1.0
204°C (400°F) min	-----	-----	1.0	-----
99°C (210°F) min	3.0	5.0 - 5.5	-----	4.0 - 5.0 ^d
38°C (100°F) min	Report	25.0	Report	Report
-40°C (-40°F) max	-----	13,000	-----	15,000
-54°C (-65°F) max	17,000	-----	21,000	-----
Pour point (max), °C (°F)	(e)	-54 (-65)	-59 (-75)	-54 (-65)
Flash point (min), °C (°F)	204 (400)	246 (475)	218 (425)	246 (475)
Auto-ignition temperature (min), °C (°F)	-----	-----	399 (750)	410 (770)
Bearing rig, 100-hr test tank temperature (bulk oil), °C (°F)	177 (350)	200 (390)	218 (425)	¹ 240 (464)
Bearing temperature, °C (°F)	260 (500)	-----	274 (525)	¹ 300 (572)

*From Refs. 51 to 54.

^bExpected to be replaced soon (1991 or 1992) with the K spec requiring viscosities of 4.0 cS, min, at 99°C (210°F) and 20 000 cS, max, at -51°C (-60°F) for a -51°C to 204°C (-60°F to 400°F) lubricant.

^cDiscontinued and superseded by MIL-L-27502 in 1972.

^dEstimated.

^eNo longer a requirement

¹48-hr test.

**TABLE III—LUBRICANT PROPERTIES AND
AREAS OF IMPORTANCE***

Property	Environmental application
Foaming	Gears and circulation
Bulk modulus	High pressure
Vapor pressure	High temperature and/or vacuum
Miscibility	Compatibility - additives and seals
Gas solubility	Cavitation, boundary lubrication
Heat capacity	Heat transfer
Thermal conductivity	Heat transfer
Freezing point	Starting
Viscosity and viscosity index	Hydrodynamic lubrication
Pressure viscosity	Elastohydrodynamic lubrication
Work of adhesion	Boundary lubrication
Thermal stability	Inert atmospheres
Oxidation stability	Ordinary atmospheres
Corrosion	Metals

*From Ref. 82.

TABLE IV—THERMAL STABILITY DATA*

Fluid class	Temperature, °C	Viscosity change at 40 °C, percent	Acid number change, mgKOH/g	Metal weight change, mg/cm		
				52100	Naval bronze	M 10
Mineral Oil	370	-39	<0.1	-0.1	-0.17	-0.05
Silahydrocarbon	370	-11.5	<0.1	0.00	0.00	0.00
Polyalphaolefin	370	-63	0.1	0.00	-0.13	-0.06
Polyol ester	370	(b)	166	-35.0	-27.0	-33.0
	315	<0.1	7.1	-0.22	-0.48	-0.35
Polyphenylether	370	-2.2	<0.1	+0.02	-0.33	-0.08
Perfluoropolyether:						
Branched	370	-2.5	<0.1	+0.12	+0.10	+0.08
Linear	370	-38.0	7.0	+0.25	+0.44	+0.15
	315	-6.4	<0.1	+0.01	+0.35	+0.15

*From Ref. 76.

^bSolids generated prevented determination.

Table V—CORROSION OXIDATION STABILITY DATA*

Fluid Class	Additives	Test method temperature, °C	Viscosity change at 40 °C, percent	Acid number change, mgKOH/g	Fluid loss, percent	Metal weight change, mg/cm ²					
						Ag	440C	350	Ti	Cu	
Mineral Oil	0.75% Hindered Phenol, 1% TCP	^b 175	+ 9.0	+ 1.9	1.9	Ag	<0.1	<0.1	<0.1	<0.1	<0.1
						440C	<0.1	<0.1	<0.1	<0.1	<0.1
						350	<0.1	<0.1	<0.1	<0.1	<0.1
						Ti	<0.1	<0.1	<0.1	<0.1	<0.1
Silahydrocarbon	1% Hindered Phenol, 3% TCP	^b 175	+ 2.6	+ 0.44	0.4	Ag	<0.1	<0.1	<0.1	<0.1	<0.1
						440C	<0.1	<0.1	<0.1	<0.1	<0.1
						350	<0.1	<0.1	<0.1	<0.1	<0.1
						Ti	<0.1	<0.1	<0.1	<0.1	<0.1
Polyalphaolefin	0.5% Hindered Phenol, 1% TCP	^b 175	+ 1.3	<0.1	0.3	Ag	<0.1	<0.1	<0.1	<0.1	<0.1
						440C	<0.1	<0.1	<0.1	<0.1	<0.1
						350	<0.1	<0.1	<0.1	<0.1	<0.1
						Ti	<0.1	<0.1	<0.1	<0.1	<0.1
Polyol Ester	1% PANA, 0.5% TCP	^b 175	+ 8.6	<0.1	0.4	Ag	<0.1	<0.1	<0.1	<0.1	-0.6
						440C	<0.1	<0.1	<0.1	<0.1	<0.1
						350	<0.1	<0.1	<0.1	<0.1	<0.1
						Ti	<0.1	<0.1	<0.1	<0.1	-1.9
Polyphenylether	NONE	^c 315	+14.4	<0.1	1.5	Ag	<0.1	<0.1	<0.1	<0.1	+0.1
						440C	<0.1	<0.1	<0.1	<0.1	<0.1
						350	<0.1	<0.1	<0.1	<0.1	<0.1
						Ti	<0.1	<0.1	<0.1	<0.1	<0.1
Perfluoropolyether: Branched Linear	0.5% Nickel bis(Phenyl-5-nitrososalicyclamine)	^c 288	+7.2	<0.1	1.4	Ag	<0.1	<0.1	<0.1	<0.1	<0.1
						440C	<0.1	<0.1	<0.1	<0.1	<0.1
						350	<0.1	<0.1	<0.1	<0.1	<0.1
						Ti	<0.1	<0.1	<0.1	<0.1	<0.1
Perfluoropolyether: Branched Linear	41% P-3	^d 288	+ 2.3	<0.1	0.5	Ag	<0.1	<0.1	<0.1	<0.1	<0.1
						440C	<0.1	<0.1	<0.1	<0.1	<0.1
						350	<0.1	<0.1	<0.1	<0.1	<0.1
						Ti	<0.1	<0.1	<0.1	<0.1	<0.1

*From Ref. 76

^bFederal Test Method Standard 791b, Method 5308, test run for 48 hr.

^cSame as above but test run for 24 hr.

^dDescribed in Ref. 70.

*Microscale test described in Ref. 70; test run for 24 hr.

TABLE VI—FLUID POUR POINT DATA*

Fluid class	Pour point, °C
Paraffinic mineral oil	≈ -50
Silhydrocarbon	< -60
Polyalphaolefin	≈ -60
Polyol ester	< -60
Polyphenylether	+5
Perfluoropolyether	
Branched	-30
Linear	< -60

*From Ref.76.

TABLE VII—FLUID DENSITY DATA*

Fluid class	Density at 16 °C, g/cc
Paraffinic Mineral Oil	0.844
Silhydrocarbon	0.816
Polyalphaolefin	0.825
Polyol Ester	0.992
Polyphenylether	1.20
Perfluoropolyether	
Branched	1.88
Linear	1.87

*From Ref. 76.

TABLE VIII—BULK MODULUS*

[Isothermal secant at 38°C, 21,000 kPa]

Fluid class	Bulk modulus, kPa
Paraffinic mineral oil	1,530,000
Silhydrocarbon	(Not determined)
Polyalphaolefin	1,230,000
Polyol ester	1,790,000
Polyphenylether	2,540,000
Perfluoropolyether:	
Branched	979,000
Linear	835,000

*From Ref. 76.

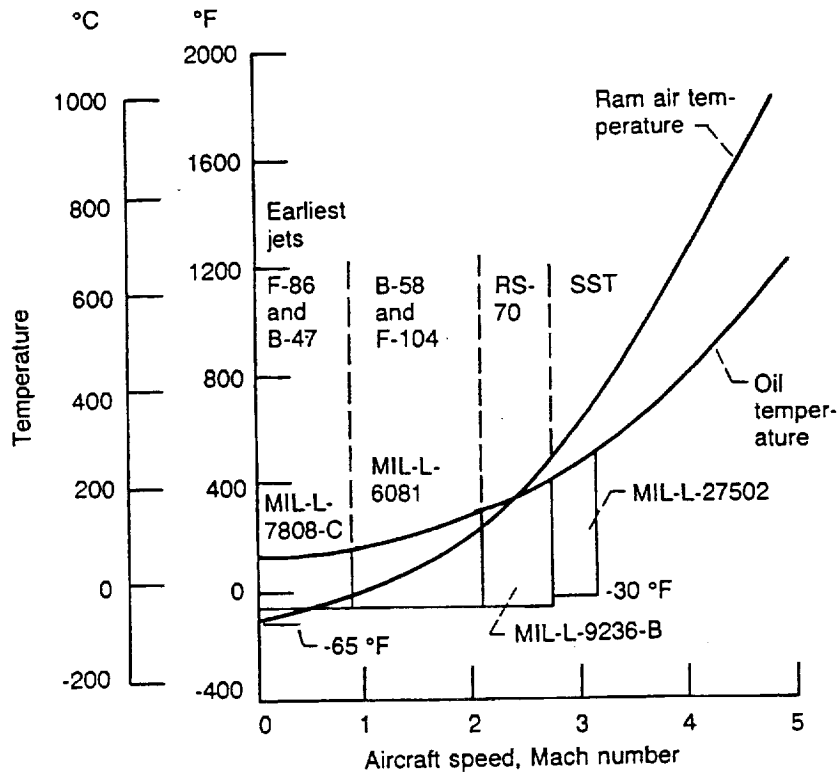


Figure 1 . - Effect of aircraft speed on oil operating temperature.

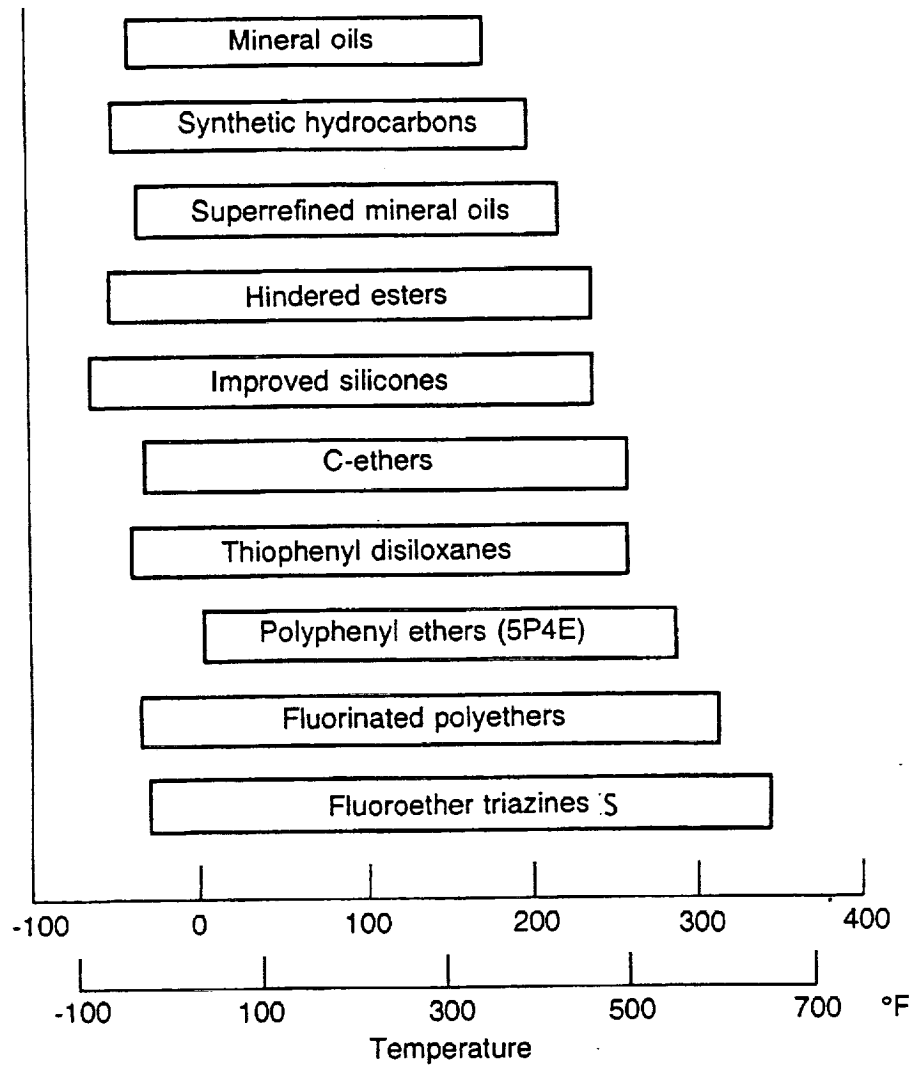


Figure 2. - Operating temperature range for nine classes of high temperature lubricants.

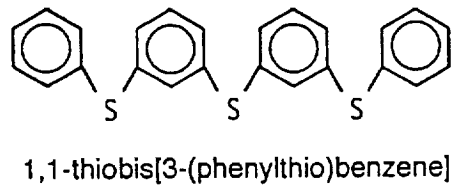
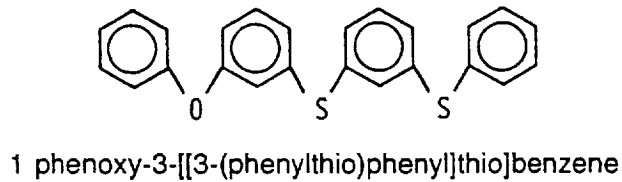
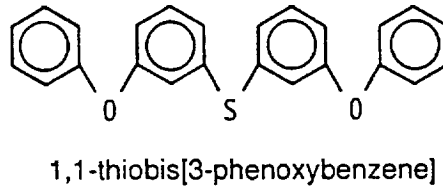
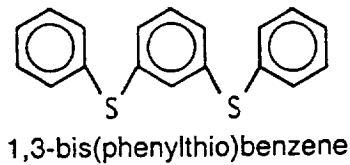


Figure 3. - Structures of C-ether base fluid components.

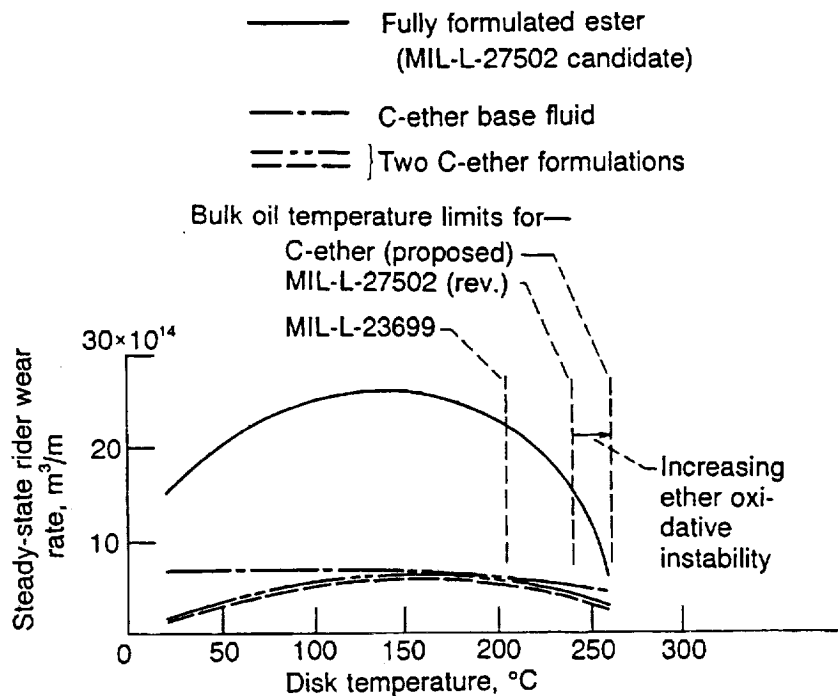


Figure 4. - Steady-state wear as a function of disk temperatures from 20 to 260 °C for a formulated ester and C-ether fluids.

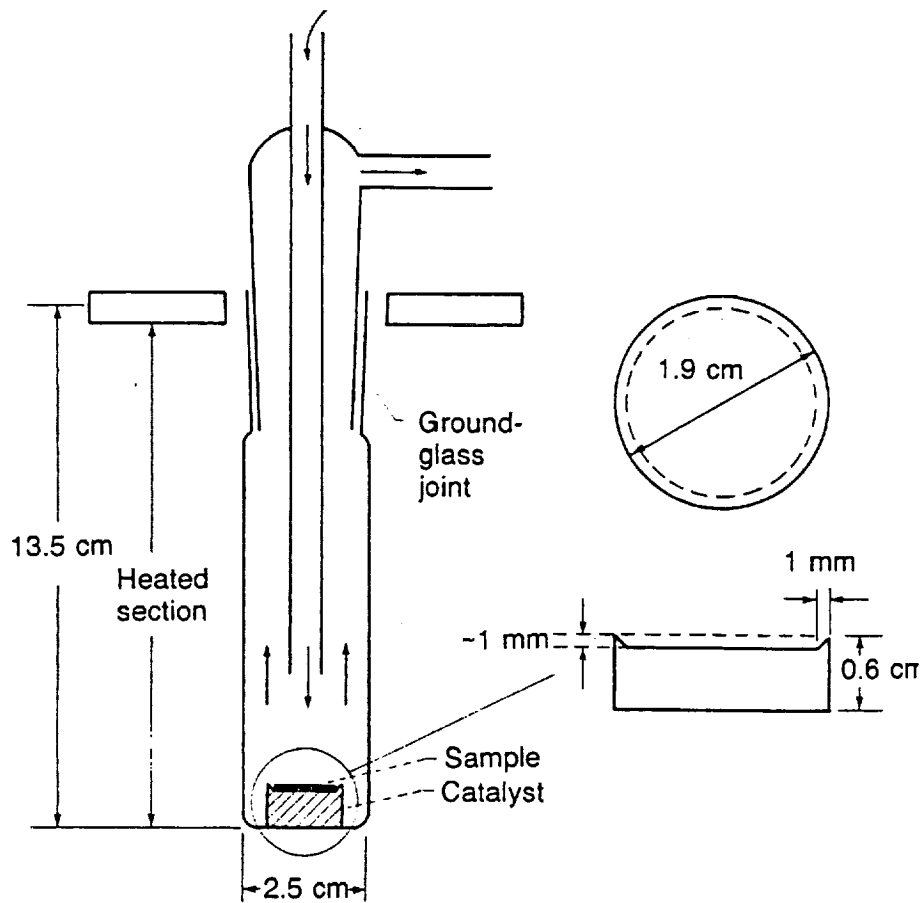


Figure 5. - Micro-oxidation apparatus.

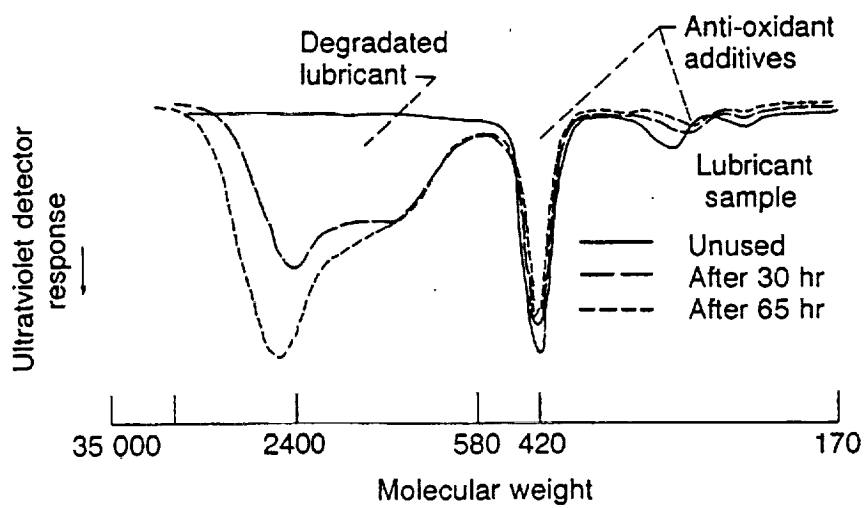


Figure 6. - Size-exclusion chromatographic analysis of MIL-L-27502 lubricant from a gas turbine engine test.

Successful test fluids

- (1) Mixed ester
- (2) Synthetic paraffinic fluid
- (3) Perfluorinated polymeric fluid
- (4) C-ether

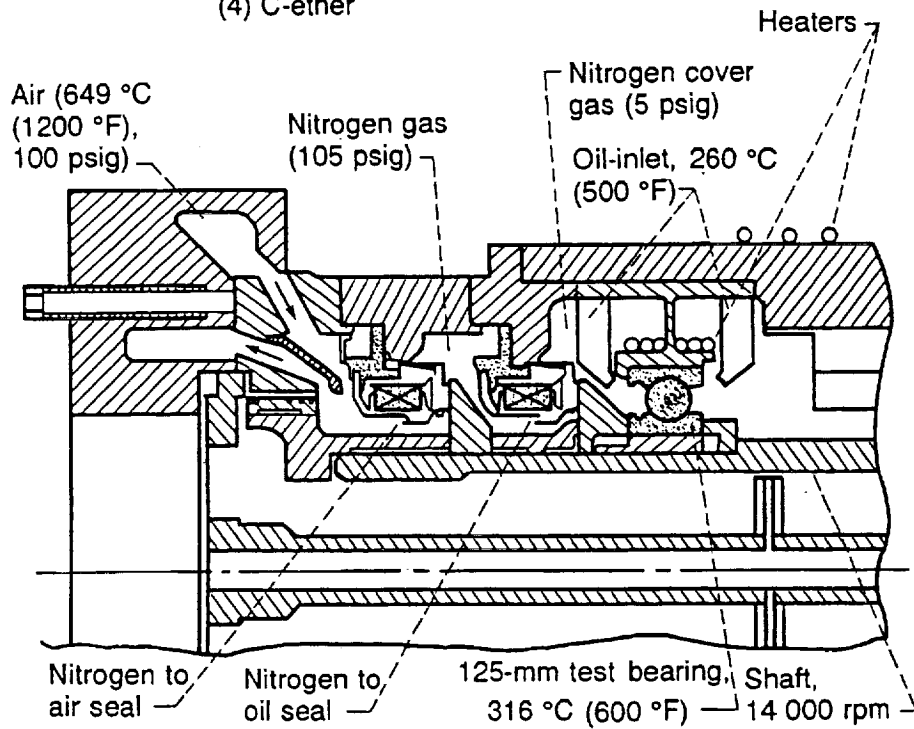


Figure 7. - Inerted lubrication system in simulated engine sump.

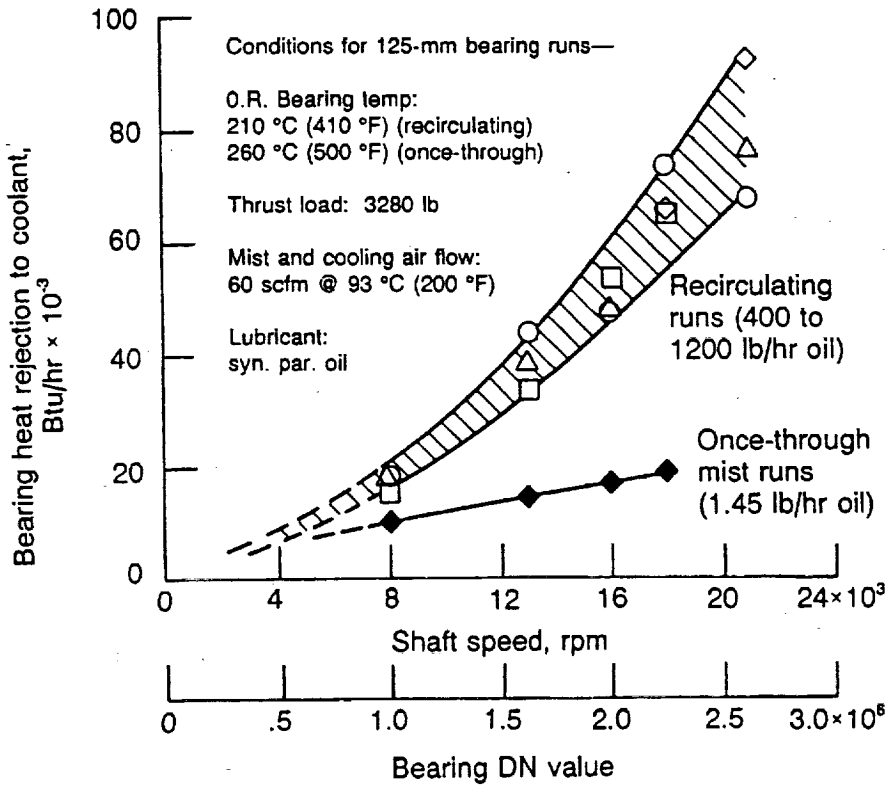


Figure 8. - Bearing heat rejection to coolant for recirculating and once-through lubrication systems

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13. ABSTRACT (Maximum 200 words) A overview of liquid lubricants for use in current and projected high performance turbojet engines is discussed. Chemical and physical properties are reviewed with special emphasis 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 eleven 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.				
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