AFRL-ML-WP-TP-2002-405

ADVANCED LUBRICANTS FOR AIRCRAFT TURBINE ENGINES

Work Unit Directive (WUD) 51

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OCTOBER 1985

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MATERIALS AND MANUFACTURING DIRECTORATE
AIR FORCE RESEARCH LABORATORY
AIR FORCE MATERIEL COMMAND
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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE ***(DD-MM-YY)*** October 1985	**2. REPORT TYPE** Reprint	**3. DATES COVERED** ***(From - To)***

4. TITLE AND SUBTITLE ADVANCED LUBRICANTS FOR AIRCRAFT TURBINE ENGINES Work Unit Directive (WUD) 51	**5a. CONTRACT NUMBER** IN-HOUSE **5b. GRANT NUMBER** **5c. PROGRAM ELEMENT NUMBER** 62102F
6. AUTHOR(S) G. A. Beane, IV (Aero Propulsion Laboratory) Lois J. Gschwender (Materials Laboratory) Carl E. Snyder, Jr. (Materials Laboratory)	**5d. PROJECT NUMBER** 2421 **5e. TASK NUMBER** 02 **5f. WORK UNIT NUMBER** 13
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Nonstructural Materials Branch (AFRL/MLBT) Nonmetallic Materials Division Materials and Manufacturing Directorate Air Force Research Laboratory, Air Force Materiel Command Wright-Patterson Air Force Base, OH 45433-7750	**8. PERFORMING ORGANIZATION REPORT NUMBER** AFRL-ML-WP-TP-2002-405
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Materials and Manufacturing Directorate Air Force Research Laboratory Air Force Materiel Command Wright-Patterson Air Force Base, OH 45433-7750	**10. SPONSORING/MONITORING AGENCY ACRONYM(S)** AFRL/MLBT **11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S)** AFRL-ML-WP-TP-2002-405

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
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Presented at Aerospace Technology Conference & Exposition, Long Beach, California, October 14-17, 1985.

14. ABSTRACT ***(Maximum 200 Words)***

An assessment of the performance of oils in Air Force turbine engines and helicopter gearboxes is presented along with predicted performance of current and upgraded military specification oils in advanced and growth engine designs. Data is presented on advanced ester base oils evolving from current research efforts. Future high temperature candidate oils representing the ultimate stability for turbine engines are also discussed. Their use, in most cases, entails engine design considerations to accommodate their unique properties. The advantages and disadvantages of the various classes of synthetic oils for turbine engines are discussed, and deficiencies are identified where additional research programs are needed.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT:**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** (Monitor)
a. REPORT Unclassified	**b. ABSTRACT** Unclassified	**c. THIS PAGE** Unclassified	SAR	26	Jeff Zabinski **19b. TELEPHONE NUMBER** *(Include Area Code)* (937) 255-4860

Standard Form 298 (Rev. 8-98)
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Reprinted from SP-633—
Aviation Gas Turbine Lubricants—Military and
Civil Aspects, Aviation Fuel and Lubricants—
Performance Testing

Aerospace Technology Conference
& Exposition
Long Beach, California
October 14—17, 1985

ISSN 0148-7191

12 page booklet. Printed in U.S.A.

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ABSTRACT

An assessment of the performance of oils in Air Force turbine engines and helicopter gear boxes is presented along with predicted performance of current and upgraded military specification oils in advanced and "growth" engine designs. Data is presented on advanced ester base oils evolving from current research efforts. Future high temperature candidate oils representing the ultimate stability for turbine engines are also discussed. Their use, in most cases, entails engine design considerations to accommodate their unique properties. The advantages and disadvantages of the various classes of synthetic oils for turbine engines are discussed, and deficiencies are identified where additional research programs are needed.

DUE TO DIFFERENT ENVIRONMENTS AND MISSIONS, the U.S. military services use different aircraft propulsion lubricating oils. For example, the U.S. Air Force has a low temperature operational requirement of -51°C (-60°F) while that of the U.S. Navy for gas turbine engine lubricants is -40°C (-40°F). This paper describes current aircraft turbine engine oils, several developmental turbine engine oils, and anticipated future U.S. Air Force advanced oil development programs.

CURRENT OPERATIONAL ESTER BASED OILS

The present status of the lubricants used in U.S. military aviation gas turbine engines indicates that MIL-L-7808J (1)* and MIL-L-23699C (2) oils are fulfilling service requirements. Visits to engine overhaul facilities generally reveal satisfactory cleanliness in lube system components and laboratory analysis of stressed oils obtained through service sampling on state-of-the-art aircraft indicate very low levels of lubricant degradation. It is therefore concluded that these current lubricant formulations are providing adequate protection against the thermal and oxidative degradation mechanisms existing in today's engines. However, it is anticipated that, as will be described, certain future U.S. Air Force aircraft will require an advanced performance oil possessing oxidative and thermal stability even greater than that of MIL-L-7808J.

MIL-L-7808J UPGRADING

The U.S. Air Force went through an upgrading process with the issuance of MIL-L-7808J in May 1982 whereby the minimum oxidative stability test duration requirement was doubled at 200°C (392°F) from 48 hours to 96 hours. This level of performance is expected to be adequate for U.S. Air Force aircraft for the next several years. However, it is anticipated that future aircraft engine systems, such as the Joint Advanced Fighter Engine (JAFE), could benefit significantly by the development of an improved high temperature ester lubricant. This oil would also need to satisfy the U.S. Air Force world-wide operational low temperature extreme design criteria of -51°C (-60°F) defined by MIL-STD-210B (3). In other words, the goal is to develop the highest temperature ester lubricant achievable which has -51°C

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*Numbers in parentheses designate references at end of paper.

(-60°F) pumpability. Thus an exploratory development program was initiated by the U.S. Air Force in 1984 to develop an aircraft turbine engine oil that would have better high temperature performance capability than current MIL-L-7808J ester based oils. This developmental engine oil will be referred to as the 4 cSt oil. Also described is an earlier program which led to the development of a MIL-L-27502 oil (4).

MIL-L-27502 OIL DEVELOPMENT

In the early 1970's, Air Force Materials Laboratory sponsored research at Monsanto Research Corporation and successfully developed a high temperature engine oil which through laboratory tests has shown potential capability for use over a -40°C to 240°C (-40°F to 464°F) temperature range. However, its capability has only been demonstrated in an engine test at 220°C (428°F). Before its use at 240°C (464°F) can be endorsed, higher temperature engine validation testing would need to be conducted. This work has been previously unpublished except in U.S. Air Force technical reports (5). This oil would have great improvement over MIL-L-7808 at the expense of some compromise in the low temperature performance. The specification values of MIL-L-27502 (slightly modified from the original fluid development program target requirements) are presented in Table I.

The selected candidate base oil was a blend of commercially available neopentyl polyol esters. It was selected based on three critical properties: 1) oxidation-corrosion resistance, 2) viscosity-temperature properties, and 3) storage stability. See Table II. Commercially available base stocks were screened for oxidation stability by formulating with an optimized additive package and subsequently evaluated in the corrosiveness and oxidation stability test. The 260°C (500°F) viscosity was set at 1.0 cSt minimum and the -40°C (-40°F) viscosity was set at 17,000 cSt maximum which ruled out many of the base stocks. Blending of lower viscosity esters with thicker esters, however, was also an approach used to increase ester viscosity, and was in fact used for the final selected candidate. Storage tests of formulated esters were also critical base oil screening tests.

Considerable effort under this contract was in selecting the right balance of additives. The final formulation which underwent turbine engine validation consisted of:

1. a neopentyl polyol ester blend
2. a deposit inhibitor (6)
3. a heterocyclic amine oxidation inhibitor
4. dioctyldiphenyl amine, oxidation inhibitor
5. triphenylphosphine oxide, metal deactivator and synergistic antioxidant
6. dimethyl silicone, 350 cSt, anti-foam additive

This formulation met the laboratory bench scale specification requirements as shown in Table I, with several exceptions which are small differences and are noted as follows: 1) low temperature viscosity: 17,643 cSt vs 17,000 cSt (15,000 cSt initially) maximum target goal at -40°C; 2) FS rubber compatibility: 4.2% swell vs 5 to 25% target range; and 3) foam test: sequence II foam volume 30 ml vs 25 ml target foam volume. The original foam test performed at Monsanto met the requirement, but after transport to Wright-Patterson Air Force Base, the value of the second sequence was over the limit. In light of the excellent results, especially oxidation corrosion, bearing deposition and gear load carrying results, this candidate was tested (7) by the Aero Propulsion Laboratory for 100 hours in a full-scale J57-P29W engine test conducted in accordance with MIL-L-27502.

The MIL-L-27502 engine test procedure is similar to that required by MIL-L-7808J except that the number 6 sump cover temperature is controlled at 300°C (572°F) and the bulk oil temperature is maintained at 220°C (428°F). Due to the high oil consumption attributable to the high bulk oil temperature, the oil normally lost through the overboard breather is collected and returned to the engine oil tank. The post test visual inspection of the completely disassembled engine indicated no evidence of corrosion or abnormal wear. Carbon deposits were rated medium which is considered relatively clean for such high operating temperatures.

Results of the 100 hour used oil analysis are presented in Table I. Overall the results are considered favorable. The largest change was in viscosity which increased 16% at 260°C (500°F) and 84% at -40°C (-40°F). Such a viscosity increase under the conditions of this engine test is not considered prohibitively excessive. The 100 hour used oil still met the new oil specification requirements of the corrosiveness and oxidation stability test at 220°C (428°F) and also at 240°C (464°F) except for bronze corrosion. Both the gear load carrying capacity and the bearing deposition test indicated very little difference between the 100 hour used oil and the new oil.

In summary, although the Air Force has not adopted the use of MIL-L-27502 because of its low temperature limitations, this 100-hour MIL-L-27502 engine test indicates that this oil formulation has excellent potential for high temperature turbine engine applications not requiring -51°C(-60°F) low temperature start-up capability.

4 cSt OIL DEVELOPMENT

The target property requirements selected for this engine oil development program are shown in Table III. The program objectives were believed attainable through a careful selection of the highest stability ester base stock combined with a critical balance of performance improving additives. The basis for this belief was the successful development of the MIL-L-27502 engine oil and earlier ester studies performed by the Air Force Materials Laboratory. In light of the base oil and additive package proven for the MIL-L-27502 gas turbine oil, advancement to the target requirements shown in Table III, was considered evolutionary in nature to the highest stability of an ester based oil possible while still meeting the -51°C (-60°F) low temperature performance criteria.

The viscosity-temperature requirements shown in Table III reflect usability at the low temperature, less than 20,000 cSt at -51°C (-60°F), and adequate hydrodynamic film strength at the high temperature, greater than 4 cSt at 100°C (212°F). Figure 1 displays the approximate maximum transient bulk oil temperature range capability of currently used military specification turbine engine oils compared to that of the 4 cSt oil. The other requirements in the Table III reflect expected performance from an ester based fluid based on MIL-L-7808 and/or MIL-L-27502 performance. The most difficult to achieve are the oxidation-corrosion test requirements and the deposit formation requirement, which are often related. The additives used must be effective in inhibiting oxidation, but must not promote deposit formation. It should be noted that the target properties are to an extent flexible and could be revised during the program if deemed necessary by the U.S. Air Force.

A letter was sent to industry requesting samples of base oils, additives and fully formulated fluids targeted to meet the requirements. Response has been highly encouraging. Material samples have been received from industry and many other companies are reportedly performing internal research from which we have not yet received samples. The comments from potential material suppliers has ranged from pessimistic i.e., the program goals are unattainable, to optimistic i.e., the program goals are challenging but attainable.

The ester base stock viscosity-temperature properties required to meet the target properties of the formulated product are achievable by appropriate ester blends. Such a base stock sample has been received from industry and properties are in Table IV. Formulation with additives thickened the final formulation, as demonstrated by the preliminary data shown in Table III on a formulation containing one of the more attractive additive packages. This formulation is continuing to be improved on a reiterative basis. Total target property compliance is believed to be highly probable or close enough to require only minor changes in the targets.

Based on this work, engine simulation evaluation is expected to begin in 1985 and actual engine testing is planned for 1986. Successful completion of these phases will then lead to transition for aircraft demonstration. Assuming successful progress, we expect to begin converting all MIL-L-7808J applications to the 4 cSt oil in 1988.

One of the advantages of this new oil is that it will be totally compatible and acceptable for use with all existing hardware now using MIL-L-7808 as well as the growth versions of these engines which will need or at least benefit from its improved high-temperature performance. Also when the 4 cSt oil becomes available with proven performance advantages, new engines can be designed to operate at higher temperatures for more efficient performance with less concern about hot spot coking and other oil degradation.

CORROSION INHIBITED MIL-L-7808 OIL DEVELOPMENT

A corrosion inhibited operational gas turbine engine oil was needed for the Air Launched Cruise Missile because of the unique application of the engine oil in this system. The missiles are required to operate satisfactorily after thirty months of storage. A storage oil is available, MIL-C-8188C (8), but it is not an operational lubricant. It was designed to be drained and replaced with MIL-L-7808 at the time the system is to become operational. MIL-C-8188C contains an additive package for storage which causes the deposit forming tendencies, corrosion-oxidation properties and foaming characteristics to be unacceptable compared to current MIL-L-7808 operational fluid. The goal of this program was to develop an oil with corrosion protection equal to or better than MIL-C-8188C storage oil and with other properties equal to or better than those of MIL-L-7808H operational oils.

This program was Air Force sponsored at Pratt and Whitney Aircraft Group, Engineering Division and has been previously reported in the literature (9,10). The approach of the program was to develop an appropriate additive package for corrosion inhibition, blended into existing MIL-L-7808H engine oil. Over one hundred additives were screened both alone and in combinations with another additive. Initial screening of soluble additives consisted of anticorrosion protection, followed by acid number and flash point determinations. Many of these formulations exhibited excessive foaming characteristics, which was unacceptable. The sludge formation of candidates in the corrosion oxidation tests was another eliminating factor. A reiterative process was employed on marginal formulations.

A final candidate formulation was selected which contained 0.75% basic barium dinonylnaphthalene sulfonate and 0.25% alkenyl succinic acid as the corrosion preventive additive package. The properties of this fluid are presented in Table V, compared to the MIL-L-7808H specification requirements. The corrosion protection of this candidate was equal to or better than that of MIL-C-8188C as determined by the Humidity Cabinet Test. While the total acid number of this candidate is 0.92 mg KOH/g, compared to the MIL-L-7808H requirement of 0.30 mg KOH/g, this was considered acceptable to continue with the more involved bearing deposition test. The post-test corrosion oxidation total acid number change of only +1.37 mg KOH/g, compared to the requirement of 4.0 mg KOH/g maximum, served to reassure that the original 0.92 mg KOH/g total acid number was not a major issue.

The bearing deposition test showed no adverse effects from the additive package. The deposit rating, viscosity change and acid number change were all equal to or less than the oil without the additive package. This was further demonstrated in a 100 hr J57 engine simulator test where the deposition and oil degradation characteristics of the candidate oil were again equal to or better than the oil without the corrosion inhibitor package. The only penalty attributable to the corrosion inhibitor additive package is a slight reduction (10%) in gear load carrying capacity. This is not considered disadvantageous since the gears and bearings in the intended Air Launch Cruise Missile engine application are not highly loaded.

The cruise missile has recently undergone design changes which have improved storage environment for the oil and have precluded the need for the oil described above. The technology gained, however, is expected to be applicable in other engine oil applications plagued with corrosion problems and is under consideration where such problems exist.

NON-ESTER BASED ADVANCED OIL DEVELOPMENT

While ester based lubricants are satisfactory for the existing and next generation of engines, lubricant manufacturers indicate that the best of ester basestock and additive technology can only provide a modest improvement in the overall high temperature capability of this class of oil. Yet trends for the long term engine designs (circa 1995 and beyond) indicate that these engines will operate at significantly hotter internal temperatures in order to obtain the operational performance desired. The higher bearing compartment temperatures projected for these future engines will thermally stress ester based oils past their breaking point resulting in severely degraded oil and "dirty" compartments. It is, therefore, apparent that in order to develop these engine designs improved non-ester based lubricants are required.

If, in the continued quest for improved performance in aerospace turbine engines, the operating temperatures of future engines continue to increase, as the trends appear to be, these temperatures will likely eventually exceed the maximum temperatures for liquid lubricants. Indeed, if we are limited to the ester based fluid technology, we are nearly to the maximum oxidative/thermal stability, as described in earlier parts of this paper. However, if we can consider significantly different chemical classes of basestocks, it is likely that the upper temperature limit of liquid lubricants can be extended by approximately 125°C (225°F) to the range of 350°C (662°F) to 370°C (698°F) bulk fluid operational temperature. The maximum operational temperatures as discussed in this section of the paper, refer to their maximum stability for extended periods of time in an oxidative environment. If future engines could be designed such that oxygen could be completely excluded from the lubricant, other chemical classes of fluids could be considered than will be discussed here. The temperature capability of the various classes of fluids to be discussed herein does not factor in the viscosity limitations as might influence load carrying ability. Because these fluids are so far away from realization as fully formulated candidate gas turbine engine oils, incorporation of factors other than low temperature viscosity and high temperature oxidative stability is not considered appropriate.

A non-ester based high temperature gas turbine engine oil was developed several years ago and its properties are described in Military Specification MIL-L-87100 (USAF) (11). This lubricant is based on the polyphenylether class of fluids. This fluid is capable of use at temperatures up to 300°C (572°F), but has one major limitation, low temperature fluidity. The fluid as described in the military specification has a pour point of approximately +5°C (41°F) which represents a significant disadvantage if an engine using this lubricant were to be designed for worldwide deployment for which the extreme low temperature requirement for land based operations is -51°C (-60°F). Extensive attempts to improve the low temperature fluidity of the polyphenylethers both by formulation and by chemical modification of the molecular structure have been unsuccessful. While some improvement in the low temperature properties of the fluids may have been achieved, this improvement has not been achieved without significantly reducing their upper temperature thermal and oxidative stability. Therefore, unless some new, innovative way is found for improving the low temperature fluidity of the polyphenylethers without adversely affecting their upper temperature stability, they do not represent a very encouraging approach to the high temperature gas turbine engine lubricants required for the future.

The most promising chemical class of fluids for future high temperature gas turbine engine oils is the perfluoropolyalkylethers (PFAE). They possess inherent oxidative stability, thermal stability, good liquid range and they are nonflammable (12,13). Typical properties for both the branched and non-branched PFAE fluids are shown in Table VI. One of the early deficiencies that was found with these fluids was their tendency to be corrosive toward ferrous alloys at elevated temperatures in oxidative atmospheres. This tendency was reduced by the development of compatible, soluble additives which at very low concentrations (0.5-1.0%) stabilized the PFAE fluids by approximately 40°C (72°F) (14). This stabilization is shown in Table VII. As can be seen from the data, these fluids do show great promise for use at high temperatures. However, we should not be lulled into a false feeling of security that these fluids are nearly available and ready for use. There are still a significant number of factors that must be addressed and they are very basic problems. Many of the bench tests that are used in the assessment of a candidate fluid's potential as a gas turbine engine oil were developed using hydrocarbon based fluids and formulations. Based on our experience in a research program to develop a nonflammable hydraulic fluid, for which the primary candidate fluid is a chlorotrifluoroethylene (CTFE) based fluid, the chemistry of base fluids is not always adequately assessed in the standard tests (15,16,17). For example, the lubricity of a CTFE formulation has been found to be superior to standard hydraulic fluids, MIL-H-5606 and MIL-H-83282, using the four-ball wear tests required by these military specifications. However, when this superior lubricity was assessed in standard aerospace hydraulic pumps, the hydrocarbon based fluids were found to be far superior. Another example found with the CTFE fluid, which is also totally halogenated like the PFAE fluids, was the need for a rust inhibitor which again was only found during component tests, although the standard stability tests including the presence of water would have been expected to reveal this potential problem based on our experience with hydrocarbon based hydraulic fluids. It is anticipated that similar deficiencies may be found with the PFAE based turbine engine lubricants as they progress from laboratory bench tests to component and hardware tests. Another major difficulty when dealing with the PFAE fluids is their poor solvency for and response to conventional performance enhancing additives. It has been our experience that when an additive is needed to improve some deficiency of the PFAE fluids, a research program is required to: 1) determine a class of additives that will provide the required improvement, and 2) synthesize a molecular structure that is soluble in the PFAE fluids. This is not meant to indicate that the task ahead to develop the PFAE fluids into high performance, high temperature gas turbine engine oils to meet the ever-increasing requirement imposed by future engines is impossible. But it is a significant challenge and the research should be initiated on a multi-disciplinary basis as soon as possible.

SUMMARY

The U.S. Air Force gas turbine engine oil developments for current, near-term future and long-term future requirements have been discussed. Although satisfactory for most current turbine engine applications, the anticipated potential limitations of MIL-L-7808J oils has led to the initiation of research and development programs to develop advanced ester based gas turbine engine oils for improved performance in both current and near-term future gas turbine engines. The lubricants resulting from these research and development programs are: (1) a -40°C (-40°F) to 240°C (464°F) gas turbine oil (the highest stability ester based oil). (2) a 4 cSt replacement oil for MIL-L-7808J which offers significantly improved performance at 204°C (400°F), while maintaining low temperature pumpability at -51°C (-60°F) and (3) a lubricant with long-term dormant rust corrosion protection superior to MIL-C-8188 which is also capable of acceptable cruise missile operational performance. Once the temperature operational capabilities of ester-based gas turbine oils are exceeded by long-term future engines, new classes of liquid lubricants will be required. Candidate classes of base fluids and pertinent data on their physical and chemical properties have been discussed.

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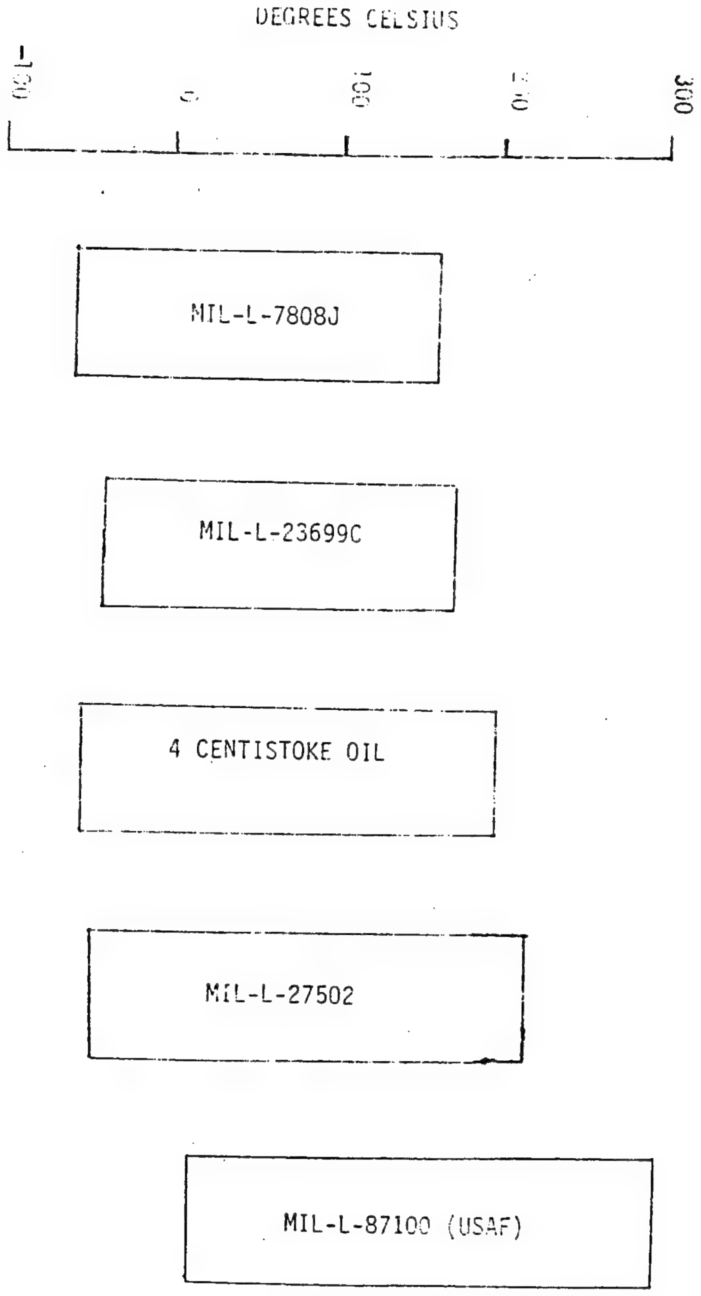

FIGURE 1. APPROXIMATE MAXIMUM TRANSIENT BULK OIL TEMPERATURE RANGE CAPABILITY FOR TURBINE ENGINES

Table I

MIL-L-27502 Laboratory and Bench Qualification Test Results

	REQUIREMENTS OF MIL-L-27502		USED OIL DATA FROM 100 HOUR ENGINE TEST OF 0-77-20			
SPECIFICATION TEST		NEW OIL	25 Hrs	50 Hrs	75 Hrs	100 Hrs
Water Content - ppm	500 Max	4.2*				
Trace Sediment - ml/200 ml of oil	0.005 Max	.001				.001
Neutralization Number - mgKOH/gm	0.50 Max	.08				1.96
Specific Gravity - 15.6°C/15.6°C	Report	0.994*				
Viscosity at 260°C - cSt	1.0 Min	1.03				1.19
Viscosity at 98.9°C - cSt	Report	7.00				
Viscosity at 37.8°C - cSt	Report	40.1				52.6
Viscosity at -40°C - cSt 35 min	15,000 Max	17,643	21544	27264	36219	32910
3 hours	15,900 Max	--				
72 hours	17,000 Max	--				33240
Pour Point - °C	-54 Max	-54				-51
Shear Stability - % viscosity loss	4.0 Max	0*				
Flash Point - °C	246 Min	271				271
Autoignition Temp. - °C	410 Min	427				
Evaporation loss at 204°C - %	5.0 Max	1.3				
260°C - %	50 Max	15.8				
Specific heat at 60°C	0.40 Min	0.45*				
160°C	0.44 Min	0.53*				
260°C	0.48 Min	0.64*				
Foaming Characteristics - ml foam						
Sequence 1, 25°C - 5 min/60 sec	25/0	0/0* 10/0				10/0
Sequence 2, 93°C - 5 min/60 sec	25/0	15/0* 30/0				40/0
Sequence 3, 25°C - 5 min/60 sec	25/0	0/0* 0/0				10/0
NBR-H Rubber, swell - %	12 to 35	17.9				
F-A Rubber, swell - %	5 to 25	10.6				10.6
tensile strength - % chg	± 50	14				-13
elongation - % chg	± 50	7				19
hardness - chg	± 25	-5				5
FS Rubber, swell - %	5 to 25	2.3				1.6
tensile strength - % chg	± 50	-9				-4
elongation - % chg	± 50	-13				-9
hardness - chg	± 25	0				5
QVI Rubber, swell - %	No Req.	5.4*				

*Contractor Data

Table I (Cont'd)

Laboratory and Bench Qualification Test Results

SPECIFICATION TEST	REQUIREMENTS OF MIL-L-27502	NEW OIL	USED OIL DATA FROM 100 HOUR ENGINE TEST OF 0-77-20 25 Hrs	50 Hrs	75 Hrs	100 Hrs
Corrosiveness and Oxidation Stability:						
48 Hours at 220°C (428°F)						
Viscosity Change at 37.8°C - %	25 Max	6.5				6.6
Neutralization Number Change	2.0 Max	0.8				-0.8
Metal Weight Change, Al - mg/cm^2	±.2	+.03				+.05
Ag	±.2	-.02				+.02
B_z (AMS 4616)	±.4	-.04				+.02
Fe	±.2	-.07				+.08
M-50	±.2	-.06				+.10
Mg	±.2	-.05				+.07
Ti	±.2	-.05				+.02
48 Hours at 240°C (464°F)						
Viscosity Change at 37.8°C - %	100 Max	15.2				33.3
Neutralization Number Change	8.0 Max	4.4				6.15
Metal Weight Change, Al - mg/cm^2	±0.2	-.06				+.02
Ag	±0.2	-.07				-.01
B_z (CA 674)	±0.4	-.08				-2.65
Fe	±0.2	-.05				+0.05
M-50	±0.2	-.04				+0.01
WSP	±0.2	-.05				+0.02
Ti	±0.2	-.05				+0.02
Bearing Deposition Test - 240°C/300°C						
Avg. Demerit Rating/No. of Tests	80 Max	26/2				25
Filter Deposits Wt. - gms	2.5 Max	0.36				1.8
Oil Consumption - ml	3600 Max	1700				1800
Viscosity Change at 37.8°C - %	100 Max	30				45.5
Neutralization Number Change	2.0 Max	1.02				0.7
Metal Weight Change, Al - mg/cm^2	±0.2	-.1				0.0
Ag	±0.2	-.1				0.0
B_z (CA 674)	±0.2	-.1				0.0
Fe	±0.2	-.1				0.0
M-50	±0.2	0.0				0.0
WSP	±0.2	-.1				0.0
Ti	±0.2	-.1				0.0

Table I (Cont'd)

Laboratory and Bench Qualification Test Results

SPECIFICATION TEST	REQUIREMENTS OF MIL-L-27502	NEW OIL	USED OIL DATA FROM 100 HOUR ENGINE TEST OF 0-77-20			
			25 Hrs	50 Hrs	75 Hrs	100 Hrs
LUBRICATION CHARACTERISTICS						
Gear Load Carrying Ability at 74°C	2400 Min	2825				2980
Gear Load Carrying Ability at 220°C	1000 Min	1009				

Table II

Target Goals of Initial Screening, MIL-L-27502 Base Oil*

TEST	TARGET	
Corrosiveness and Oxidation Stability (96 Hours) at	220°C	240°C
Viscosity change at 37.8°C - %	15 Max	25 Max
Neutralization Number Change - mg KOH/g	2.0 Max	4.0 Max
Metal Weight Change - mg/cm^2		
Al	±.2 Max	±.2 Max
Ag	±.2 Max	±.2 Max
Br**	±.4 Max	±.4 Max
Fe	±.2 Max	±.2 Max
M-50	±.2 Max	±.2 Max
Mg	±.2 Max	±.2 Max
Ti	±.2 Max	±.2 Max
Viscosity at 260°C - cSt	1.0 Min	
-40°C - cSt	17,000 Max	
Storage at 100°C - Days, No Precipitate	27 Min	
65°C - Days, No Precipitate	100 Min	

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*Clark, F. S., Morris, G. J. and Reid, S. L, "New 465°F Turbine Oils," Unpublished Paper, 1976.

**Silicon Bronze (AMS 4616) at 220°C, Bronze Alloy (SAE-CA674) at 240°C

Table III

Target and Candidate Properties For -51°C to 205°C
4 cSt Gas Turbine Engine Oil

PROPERTY	TARGET REQUIREMENT	CANDIDATE	TEST METHOD
Kinematic Viscosity (cSt)			
at 205°C	Report	--	ASTM D 445
100°C	4.0 Min	3.96	
40°C	Report	17.14	
-51°C	20,000 Max	16,000	
Total Acid Number (mg KOH/g)	0.5 Max	0.39	ASTM D 664
Pour Point (°C)	-55 Max	-65	ASTM D 97
Flash Point (°C)	210 Min	255	ASTM D 92
Foaming Tendency (ml foam/ml foam after 60 second settling period)	100/0 Max	5/0	FTM 791b Method 3213
Autogeneous Ignition Temperature (°C)	350 Min	402	ASTM E 659
Evaporation Loss, %, 6.5 hr at 205°C	10 Max	3.1	ASTM D 972
Elastomer Compatibility, % Swell			ASTM D 3604
NBR -H	12-35	15.4	
FA	5-25	7.0	
FS	5-25	1.6	
QVI	5-30	13.0	
Vapor Pressure at 200°C (mm Hg)	10 Max	5.4	ASTM D 2879
Four Ball Wear Scar, mm			ASTM D 2266
52100, 75°C, 1 hr, 40 Kg Load, 600 rpm	0.7 Max	0.66	
M-50, 200°C, 1 hr, 40 Kg Load, 600 rpm	1.0 Max	0.51	
Deposit Forming Tendencies	0.5 Max	1.6	Fed. Test Method Std No. 791b Method 5003
Viscosity Change (%)	Report	124	
Acid Number Increase	Report	8.34	
Consumption, ml	Report	90	

Table III (Cont'd)

Target and Candidate Properties For -51°C to 205°C
4 cSt Gas Turbine Engine Oil

PROPERTY	TARGET REQUIREMENT				CANDIDATE	TEST METHOD
Corrosiveness and Oxidation Stability						FTM - 791b Method 5307.1
220°C, 48 hr,						
Viscosity Change (%)	25 Max				8.7	
Acid Number Increase	4.0 Max				1.13	
Metal Weight Change (mg/cm^2)						
Al	±0.2 Max				-0.1	
Ag	±0.2 Max				0.0	
Bz (AMS 4616)	±0.4 Max				+0.1	
Fe	±0.2 Max				0.0	
M-50	±0.2 Max				+0.1	
Mg	±0.4 Max				0.0	
Ti	±0.2 Max				0.0	
Shear Stability (% Viscosity loss)	4.0 Max				--	ASTM D 2603
	Goal	Max Accept.	Goal	Max Accept.		
Bearing Deposition Test						
Deposit Rating	20	40	30	80	--	
Test Conditions Per MIL-L-	7808J		27502		--	MIL-L-7808J/27502
Neutralization Number Change	1.0 Max		2.0 Max		--	
Viscosity at 40°C, % Change	-5 to +15		-5 to +100		--	
Filter Deposits, g	1.0 Max		2.5 Max		--	
Oil Consumption, ml	1440 Max		3600 Max		--	
Aluminum Wt. Change, mg/cm^2	±0.2		±0.2		--	
Silver Wt. Change, mg/cm^2	±0.2		±0.2		--	
Bronze Wt. Change, mg/cm^2	±0.2		±0.2		--	
Iron Wt. Change, mg/cm^2	±0.2		±0.2		--	
M-50 Steel Wt. Change, mg/cm^2	±0.2		±0.2		--	
Waspaloy Wt. Change, mg/cm^2	±0.2		±0.2		--	
Titanium Wt. Change, mg/cm^2	±0.2		±0.2		--	
	Goal			Min Accept.		
Gear Load Carrying Capacity						ASTM D-1947
Capacity, KN/m (ppi)	2550			2320	--	
Number of Determinations	4			4		

Table IV

4 cSt Engine Oil Base Stock Properties

PROPERTY	CANDIDATE
Kinematic Viscosity - cSt	
at 100°C	3.83
40°C	15.81
-51°C	12,500
Total Acid Number - mg KOH/g	0.13
Pour Point - °C	-55
Flash Point - °C	232
Autoignition Temperature - °C	392
Evaporation Loss, 6.5 hr at 200°C - %	8.0

Table V

Comparison of MIL-L-7808H Requirements and Best Candidate Corrosion-Inhibiting Formulation

PROPERTY	MIL-L-7808H REQUIREMENTS	BEST CANDIDATE FORMULATION	TEST METHODS ASTM	TEST METHODS FED STD 791b
Kinematic Viscosity, cSt				
a. 98.9°C (210°F)	3.0 Min	3.54	D445	
b. -53.9°C (-65°F)			D2532	
@ 35 Minutes	17,000 Max	15,000		
3 Hour	17,000 Max	15,000		
72 Hour	17,000 Max	15,000		
Flash Point, °C (°F)	204 (400) Min	222	D92	
Neutralization Number (TAN)	0.30 Max	0.92	D664 (Modified)	
Foaming Characteristics				3213
a. Foam volume, ml	100 Max	15		
b. Foam collapse time, s	60 Max	5		
Evaporation loss @ 204°C (400°F), %	30 Max	10.4	D972	
Corrosiveness and Oxidation Stability @ 200°C (392°F) for 48 hours				5307.1
a. Change in Viscosity, %	-5 to 25 Max	+8.2	D445	
b. Change in TAN, mg KOH/g	4.0 Max	+1.37	D664 (Modified)	
c. Sludge, Volume %	Report	0.0		
Oil Deposit Rating	1.5 Max	0.2		5003.1
Bearing Deposition				
a. Overall deposit demerit rating	60 Max	34.6		
b. Change in Viscosity, %	25 Max	4.1	D445	
c. Change in TAN, mg KOH/g	25 Max	0.11	D664 (Modified)	
d. Filter Deposits, g	2.0 Max	0.49		
e. Oil Consumption, ml	1440 Max	400		

Table V (Cont'd)

Comparison of MIL-L-7808H Requirements and Best Candidate Corrosion-Inhibiting Formulation

PROPERTY	MIL-L-7808H REQUIREMENTS	BEST CANDIDATE FORMULATION	TEST METHODS ASTM	TEST METHODS FED STD 791b
Humidity Cabinet Test			D1748	
Hours till failure	Not Required	5 Panels 480 1 Panel = 320		
Engine (J57) Simulator Test, 100 Hrs				
a. Deposit Rating	Not Required	14.5		
b. Change in Viscosity, %	Not Required	10		
c. Change in TAN, mg KOH/g	Not Required	1.24		
Load Carrying Capacity			D1947	
a. Four Determinations, kN/m(lbf/in)	406 (2320)	370 (2110)		

Table VI

Typical Properties of Branched and Non-Branched PFAE Fluids

FLUID	KINEMATIC VISCOSITY (cSt) -53.9°C -65°F	-40°C -40°F	37.8°C 100°F	98.9C 210°F	POUR POINT (°C)	(°F)	EVAPORATION, % WT. LOSS AFTER 6 1/2 HRS AT 204°C 400°F	260°C 500°F	288°C 550°F	316°C 600°F
LINEAR PFAE										
Fraction A	872	330	18	6.0	-54	(-65)				
Fraction B	7940	2875	132	42	-54	(-65)		0.32		55.6
Fraction C	24105	8675	376	113	-54	(-65)		0.32		100
BRANCHED PFAE										
Fraction AB	46000a	6900	85	0.2	-43	(-45)	5.0	27		
Fraction AC	b	42000c	280	25	-34	(-30)			12	34.8

a - at -18°C (O°F)

b - too viscous to measure

c - at -32°C (-25°F)

Table VII

Corrosion and Oxidation Stability of Branched and Non-Branched PFAE Unformulated and Formulated Fluids

Temperature °C (F)	% Visc Change at 37.8°C (100F)	Fluid Loss Wt%	Weight Change (mg/cm^2) 4140	52100	410	M-50	440C	Formulation
Unbranched PFAE								
288 (550)	a	84	0.02	+0.48	5.57	-2.37	-3.10	None
288 (550)	+0.22	0.31	+0.04	+0.03	+0.05	+0.01	0.00	1% P-3
316 (600)	+0.10	0.25	+1.43	+0.41	-0.35	+0.44	-0.02	1% P-3
Branched PFAE								
316 (600)	+3.4	5.2	+3.11	+1.17	+0.72	+1.80	+0.46	None
316 (600)	+3.0	0.14	+0.13	+0.01	+0.01	+0.10	0.00	1% P-3
329 (625)	+4.8	0.22	+0.13	0.00	-0.02	+0.07	0.00	1% P-3
343 (650)	+2.3	0.50	+0.05	+0.12	+0.01	+0.31	+0.06	1% P-3

a - Insufficient Sample to Determine