Copy 7
RM 51D20

NACA RM 51D20

NACA

RESEARCH MEMORANDUM

REVIEW OF CURRENT AND ANTICIPATED LUBRICANT PROBLEMS IN TURBOJET ENGINES

By NACA Subcommittee on Lubrication and Wear

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON
April 20, 1951

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

REVIEW OF CURRENT AND ANTICIPATED LUBRICANT PROBLEMS IN TURBOJET ENGINES

By NACA Subcommittee on Lubrication and Wear

SUMMARY

A review of the current and anticipated lubricant problems as related to aircraft turbojet engines (employing rolling contact bearings) has indicated that the current and anticipated bearing operating temperature ranges to be met by the lubricant are as follows: (1) -65° to 350° F (current), (2) -65° to 500° F (future), and (3) -65° to 750° F (future). The latter two temperature ranges are future goals predicated on future availability of suitable materials. The Subcommittee agrees that these goals are desirable to permit important advancements in aircraft turbojet engines.

For the current bearing operating temperature range of -65° to 350° F, maximum oil reservoir temperature is approximately 260° F. On shutdown following operation in some of the present aircraft turbojet engines, outer race bearing temperatures of 500° F are encountered, making it essential that the lubricant be sufficiently heat stable and high boiling to endure that temperature for about an hour. The upper bearing operating temperatures of 500° and 750° F result in corresponding bearing outer race shutdown temperatures of 700° and 1000° F.

Present and future lubricants must therefore meet operating requirements of fluidity, lubricity, volatility, and stability over bearing operating temperature ranges of: (1) -65° to 350° F (current), (2) -65° to 500° F, and (3) -65° to 750° F.

For the three bearing operating temperature ranges of interest, several approaches to the general problem of providing adequate lubricants have been discussed by the Subcommittee. The most promising approaches for the three temperature ranges are as follows: (1) synthetic lubricants in whole or in major part for the bearing operating temperature range of -65° to 350° F; and (2) synthetics for the bearing operating temperature range of -65° to 500° F. It is too early to state

which approaches for the bearing operating temperature range of -65° to 750° F are best; however, the following should be considered: high-temperature greases, composite lubricants (solids dispersed in fluid carriers), and solid lubricants.

Because aliphatic diesters are particularly promising in the first two temperature ranges, availability of these materials was reviewed. It was concluded sufficient supplies made from native materials could be produced commercially without difficulty within 1 or 2 years to satisfy anticipated requirements.

It is recommended immediate and extensive aircraft turbojet engine research be carried out on the synthetics to determine their suitability in the bearing operating temperature range of -65° to 350° F.

INTRODUCTION

Service experience with some of the present lubricants (specification MIL-O-6081, grades 1015 and 1010, and AF specification 3519, grade 1005) for lubrication of aircraft turbojet engines has indicated that these lubricants are not entirely satisfactory, either because they are too viscous for engine starting (without dilution or preheating) at low temperatures (grades 1015 and 1010) or because they provide marginal lubrication and/or are excessively volatile at high temperatures (grade 1005). Consideration of the lubrication problems that may arise in future aircraft turbojet engines reveals that the demands on the lubricants will be difficult (if not impossible) to meet. In accordance, the NACA Subcommittee on Lubrication and Wear at two of its regular meetings (June and October 1950) reviewed the problems involved in providing adequate lubricants to meet the stringent requirements of aircraft turbojet engines for current and projected use. Several papers were presented by members of the Subcommittee which established the general requirements and several possible solutions were discussed. The primary objectives of this report are to present (based on these papers and the accompanying discussion): (1) an analysis of the current and anticipated lubricant problems in aircraft turbojet engines including presentation of the requirements for lubricants for both current and future use; (2) the most promising approaches to the problem of obtaining lubricants for operation over the wide temperature ranges anticipated.

This report includes the papers (Appendices A through E) which were presented before the NACA Subcommittee on Lubrication and Wear. Because they were written independently, there is some repetition, particularly in the discussion of requirements.

REQUIREMENTS

The primary requirement for aircraft turbojet engine lubricants is that they must be suitable for operation over the required temperature range. The current temperature range of aircraft turbojet engines using rolling contact bearings is shown as item 1 of table I. The temperature ranges of items 2 and 3 are future goals predicted on future availability of suitable materials. The Subcommittee agrees that these goals are desirable to permit important advancements in aircraft turbojet engines. In the current temperature range of -65° to 350° F (item 1, table I), the maximum temperature is for the outer race, of the turbine bearing. Under these conditions, the temperature of the bearing outer race, after engine shutdown is approximately 500° F. The corresponding maximum oil reservoir temperature is 260° F. The temperature range of item 2, table I involves a minimum temperature of -65° and a maximum bearing outer race temperature of 500° F. The corresponding bearing outer race temperature after shutdown would be approximately 700° F. The temperature range of item 3, table I involves a minimum temperature of -65° F and a maximum bearing outer race temperature of 750° F. The corresponding outer race temperature after shutdown would be approximately 1000° F. As shown in the footnote to the table, temperatures as low as -100° F have been encountered in service but this minimum temperature is not now a requirement of the military services.

Temperatures such as indicated in item 2 of table I are already being encountered in guided missiles.

It has been generally established in the papers presented in this report (Appendices A and B) that the present aircraft turbojet engine lubrication system requires lubricants with a maximum viscosity of approximately 10,000 centistokes at the minimum temperature of operation. This maximum viscosity is based on the pumpability of the lubricant in present engine designs.

In the current temperature range, the 2.5 centistoke specification of grade 1010 oil at 210° F appears to be entirely adequate, from a lubrication standpoint. As indicated in Appendix A it is apparent that a desirable turbojet engine lubricant for the current temperature range should have the high-temperature viscometric properties of grade 1010 oil, the low-temperature viscometric properties of grade 1005 oil, and the lowest volatility (and highest flash and fire point) possible. Since, as discussed in Appendix A, no petroleum fraction known has properties approaching such a turbojet engine lubricant, it is apparent that a completely synthetic material will be required to meet this specification. A possible compromise specification was written which differed from this specification only in that the maximum viscosity at -65° F is 7000 centistokes instead of 3000 centistokes. The requirements are still so severe, however, that it is not believed they can be met by petroleum oils. A variety of synthetics are, however, available to meet these properties. The specifications for grades 1010 and 1005, the specifications combining the best features of these two lubricants, and the compromise specifications are listed in table I of Appendix A. The compromise specification is as follows:

Viscosity at 210° F	2.5 centistokes (min.)
at 100° F	9.2
at 0° F	135
at -20° F	330
-40° F	1040
-65° F	7000 (max.)
Viscosity index	108
Low-temperature stability	-75° F (max.)
Flash point	250° F (min.)

It appears from the papers and their discussions that the lubricating effectiveness of grade 1010 oil is satisfactory under the present operating temperatures and loads of aircraft turbojet engines. This lubricant is, however, unsatisfactory under the conditions where high temperatures are encountered at shutdown because the oil then evaporates and "cokes" or lacquers. It was concluded that grade 1005 oil is apparently marginal in its lubricating effectiveness under the operating temperature range, some users reporting no difficulties and others reporting difficulties. Grade 1005 oil is less satisfactory than grade 1010 oil with respect to evaporation from the bearing after shutdown.

It should be noted here that this discussion pertains to lubrication of turbojet engines only and does not apply to lubrication of the reduction gear of an aircraft turbopropeller engine. For this latter service, a lubricant with a load-carrying capacity equal to that of AN-O-3M or grade 1120 and with the viscometric properties of the compromise specifications is needed. There are numerous other properties of importance including: oxidation and thermal stability, low volatility, flammability, etc., (see Appendices).

APPROACHES TO THE PROBLEM

Several approaches to the general problem of providing adequate lubricants for the temperature ranges listed in table I have been discussed by the Subcommittee and are presented in the following sections.

Bearing Operating Temperature Range of -65° to 350° F

Petroleum lubricants have the two advantages of availability and of considerable service experience. They have disadvantages such as high viscosity at low temperatures, high volatility at high temperatures, and low flash point (Appendices A and B). Improvements in grade 1010 oil with respect to lower viscosity at low temperatures without sacrifice in high-temperature viscosity and volatility properties are desirable. It is not believed that such improvements are obtainable without resorting to entirely new methods of petroleum refining.

For the bearing operating temperature range of -65° to 350° F the aliphatic diesters appear to show considerable promise. As shown in Appendix A, the diesters can be synthesized with low pour points and excellent VI's. The diesters are compatible with and responsive to the inhibitors used in petroleum oils and their lubricating ability is equivalent to that of similar viscosity petroleum oils. Diesters meeting the compromise specifications previously listed can be made from adipic, azelaic, and sebacic acids. As a general rule the diesters are much less volatile than similar viscosity petroleum lubricants. Other advantages of the diesters are that, being pure chemical compounds, they do not foam or show changes in viscosity or pour point with vaporization of some of the fluid. Although there is considerable experience with these materials in reciprocating engines, there is very little turbojet engine experience available on these materials.

Polyalkylene glycol ethers have very desirable viscometric properties although very little is known of their lubricating effectiveness under aircraft turbojet engine conditions. Those having viscosities below 10,000 C.S. at -65° F are intermediate in volatility between the diesters and the petroleums.

Of the available nonpetroleum fluids, the methyl silicones have the best viscometric properties. A disadvantage of the methyl silicones lies in oxidation stability. Although oxidation stability of the methyl silicones is much superior to that of petroleum oils and most other organic compounds up to 400° F, they gel rapidly when subjected to temperatures above 400° F under oxidizing conditions (Appendix A).

Since the bearing outer race shutdown temperature is 500° F, it is quite likely the methyl silicones would deposit gels in the bearings and oil passages. The greatest limitation to the use of the silicones is that they have poor boundary lubricating properties for steel sliding on steel.

The diesters (and polyethers) are the most promising available lubricants for the bearing operating temperature range of -65° to 350° F.

The availability of synthetic fluids is a very important consideration regarding their possible use. A synthetic fluid must be available in large quantities (1,000,000 to 5,000,000 gallons per year) and the raw materials obtained domestically. Basic ingredients for the manufacture of many adipic diesters are already derived from petrochemicals. The supply of the polyethers can be expected to meet any likely demand. No serious barrier exists for large scale production of these two types of fluids. A number of suitable oxidation inhibitors are available to stabilize both the diesters and the polyethers. Wear preventatives will be necessary in both of these fluids if the fluids are used to lubricate reduction gear systems of turbopropeller engines.

Bearing Operating Temperature Range of -65° to 500° F

In the bearing operating temperature range of -65° to 500° F (item 2, table I), the synthetics again show the most promise. For the diesters and polyethers, more effective high temperature antioxidants are required. For the silicones, the problem of "gelling" becomes increasingly severe as the temperature increases because of the rapid increase in gelling rate.

Bearing Operating Temperature Range of -65° F to 750° F

The bearing operating temperature range of -65° to 750° F (item 3, table I), is not an immediate requirement for aircraft turbojet engines, however, applications of this nature already exist in guided missiles because of the high ambient temperatures encountered at supersonic flight speeds. It is expected that similar operating conditions will be encountered in the future with piloted aircraft.

It is possible that greases and rolling contact bearings may be developed which are suitable for application at high temperatures. While no data were obtained at high dn values (diameter in millimeters multiplied by speed in rpm) the data of Appendix D indicate that, at 600° F, 17-millimeter bore bearings operated with a finite life with silicone greases. Some greases which are available for temperatures much higher than those obtainable with ordinary petroleums are reported in NRL report 3672 entitled "Phthalocyanine Lubricating Greases" by C. G. Fitzsimmons, R. L. Merker, and C. R. Singleterry, dated May 25, 1950, Naval Research Laboratory, Washington, D. C. This report indicates that adequate lubrication was obtained in ball bearings with a copper phthalocyanine-silicone grease at temperatures to 225° C (437° F). There is a need for further research on high-temperature greases, since very little information is now available on such greases or their performance at elevated temperatures.

Composite lubricants consisting of a fluid carrier plus an additive of either the soluble or of the suspended solid type may possibly be used for the bearing operating temperature range of -65° to 750° F. Preliminary experiments at the NACA Lewis Flight Propulsion Research Laboratory have indicated: (1) low friction can be obtained with lubricants such as MoS_2 in a liquid carrier, (2) composite lubricants (MoS_2 in air) will lubricate rolling contact bearings successfully at temperatures as high as 1000° F for periods of time as long as $2\frac{1}{2}$ hours. The results of the preliminary research on rolling contact bearings (in process of publication) also indicated that the bearings operated successfully for $10\frac{1}{2}$ hours at elevated temperature ($2\frac{1}{2}$ hours at each of four temperature levels: 400° F, 600° F, 800° F, and 1000° F.)

CONCLUDING REMARKS

The most promising approaches for items 1 and 2, table I are as follows: (1) synthetic lubricants in whole or in major part for the current bearing operating temperature range of -65° to 350° F; and (2) synthetics for the bearing operating temperature range of -65° to 500° F. It is too early to state which approaches for item 3 are best; however, the following should be considered: high-temperature greases, composite lubricants (solids dispersed in fluid carriers), and solid lubricants.

RECOMMENDATIONS

Analysis of the current and anticipated lubricant problems as related to aircraft turbojet engines has indicated that petroleum lubricants may not be entirely adequate in the future. In accordance the following recommendations are made:

1. Immediate and extensive aircraft turbojet engine research and development are required on diesters and other synthetics meeting the compromise specification (of Appendix A). This research is required to determine suitability of these synthetics in the bearing operating temperature range of -65° to 350° F.

2. Research should be carried out on improving the oxidation resistance and wear properties of the synthetic lubricants for the temperature range of -65° to 500° F before initiating extensive engine research.

3. Extensive research is required on high-temperature greases, composite lubricants, and solid lubricants to determine their suitability in the bearing operating temperature range of -65° to 750° F.

APPENDIX A

THE DEVELOPMENT OF LUBRICANTS FOR EXTREME TEMPERATURE OPERATIONS FOR CURRENT AND PROJECTED TURBINE-POWERED AIRCRAFT ENGINES

By C. M. Murphy and W. A. Zisman
Naval Research Laboratory

3270-160-50/hl June 5, 1950

Subj: The Development of Lubricants for Extreme Temperature Operation for Current and Projected Turbine-Powered Aircraft Engines. NRL Problem No. 32C02-06D (BuAer Problem No. TED NRL 0405) Interim Report on

A. REQUIREMENTS

1. Lubricants for turbojet and turbo-prop engines are required to be operable over a wide range of temperature. Combat military aircraft must be able to start without preheaters and operate at ambient temperatures as low as -65° F (1), carrier based planes seldom encounter such low temperatures. The maximum turbine bearing operating temperatures in flight are about 285° F (2). Therefore, low pour point oils with high V.I.'s are required in order that the lubricant be sufficiently fluid at low temperature and have sufficient viscosity at high temperatures to support the bearing loads. Bearing temperatures from 400° to over 500° F are observed after the grounding of turbojet aircraft (7). These high temperatures are due to radiation and conduction of heat from the gas turbine to the bearings when there is no dissipation of heat by the air blast or heat transfer by the circulating lubricant. This necessitates an oil which is unusually stable to heat and thermal oxidation. It is also advantageous to have it as nonvolatile as possible since the evaporation of the less viscous and more volatile components will cause an increase in the viscosity and pour point of the residual oil. Clearly, these turbine-powered aircraft engines demand a combination of properties which are difficult (if not impossible) to obtain in conventional lubricants.

2. The current specification, AN-O-9 (3) for turbojet lubricating oil was adopted in May 1947. This specification covers two viscosity grade petroleum oils (table 1 spec. I and IIO grades 1010 and 1015); the last two digits referring to their viscosity in centistokes at 100° F. The former grade has a minimum pour point of -70° F with a maximum viscosity of 3000 cs. at -40° F and the latter grade a pour point of -50° F with

maximum viscosity of 700 cs. at 0° F. As grade 1015 has a pour point above -67° F it is not suitable for combat military aircraft. The viscosity of a typical grade 1010 oil was reported by CRC (4) as being 49,000 centistokes at -65° F. Somewhat lower viscosity values are obtained by extrapolating the viscosity data on other grade 1010 oils; therefore, 40,000 centistokes at -67° F was taken as a reasonable approximation of grade 1010 viscosities at this temperature.

3. Tests at the Naval Aeronautical Engine Laboratory at Philadelphia (2) on the low temperature lubricant requirements for the J-34 turbojet engine indicate that 20,000 centistokes is the upper viscosity limit for the pumpability of the lubricant in this engine. Since grade 1010 oil has a viscosity of 20,000 centistokes at approximately -57° F (see table 1) it will not operate satisfactorily in a J-34 engine at lower temperatures. Exhaustive tests on the pumpability of oils in a simulated turbojet lubricating system have been made by the Coordinating Research Council (4). It was found that the flow of oil could be related to the viscosity. Their data indicate that the limiting viscosity for pumpability may be somewhat less than 20,000 centistokes. However, under starting conditions, a small oil flow (0.1 gpm) is obtained at temperatures well below the condition for zero flow obtained by extrapolation from oil flows at higher temperatures. In some cases this minimum flow continues below the pour point of the oil. No effect of altitude was observed up to 35,000 feet with a one-inch inlet line. There is, however, a critical altitude at which flow starts to fall off; with grade 1010 oil at -57° F and a pump speed of 900 rpm this altitude is 42,000 feet. The work of both NAEL and CRC led to the conclusion that grade 1010 oil will not be satisfactory for operation at altitudes above 42,000 feet and temperatures below -50° to -57° F in the J-34 turbojet and presumably other turbojet engines with similar lubricating systems.

4. Grade 1010 oil has given fairly satisfactory operation as the lubricant for J-33, J-34 and J-35 turbojet engines at the higher temperatures encountered in flight (5). However, difficulties have been experienced with the carbonization and lacquering of the oil on the bearings due to the high temperatures attained after grounding of the aircraft. More effective high temperature antioxidants should alleviate the difficulty with deposits due to oxidation. Rapid evaporation of the oil film is probably a contributing factor. Volatility of the lower boiling components of the petroleum results in increasing the viscosity and pour point of the remaining oil. This would have the effect of reducing the temperature and altitude range of operation.

5. In the J-47 engine the lubricant is also used as the hydraulic fluid. Grade 1010 oil has been found to be so viscous at low temperatures as to cause sluggish operation of the hydraulic controls. An investigation of the limiting viscosity for adequate response of the hydraulic controls set this figure at approximately 3000 cx. (6). To

meet this viscosity requirement a grade 1005 oil was proposed (7). Some pertinent properties of this oil are shown in table 1, specification II. It is evident that the low viscosity, (3000 cs.) at -67° F, was attained by making a corresponding reduction in the high temperature viscosity. The reduction in viscosity of the oil is also reflected by its lower flash point and higher volatility as compared to grade 1010. This oil is therefore more flammable and sensitive to evaporation changes than is the latter. Tests on this proposed grade 1005 oil indicate that satisfactory operation can be attained with it in a J-47 engine at low temperatures (5). Its low viscosity at operating temperatures makes it undesirable for normal operation from the standpoint of lubrication and evaporation.

6. It has been evident for almost two years that the most desirable turbojet oil should have the high temperature viscometric properties of grade 1010 oil, the low temperature properties of grade 1005 oil, and the lowest volatility (and highest flash and fire points) possible. Such a specification is given in table 1 as specification IV. No petroleum fraction known has properties even approaching those required by this specification, therefore a completely synthetic material will probably be required. A possible compromise (specification V) differs only in that the maximum viscosity at -67° F is 7000 cs. instead of 3000 cs. It is not believed that these requirements can be met by a petroleum oil but a greater variety of synthetics with these properties are available than for specification IV. It is possible that petroleum-synthetic oil blends can be made to conform to specification V but will require a major proportion of the synthetic.

7. Only one turbo-prop engine is operational in the Navy, the Allison T-40. In this the same oil is used to lubricate the gas turbine and the high speed gear reduction system. The lubricant used has been AN-O3, grade M with a viscosity of 60-82 centistokes at 100° F, a pour point of -20° F and a sulfurized fatty oil to give a pressure-wear index of 15. Starting torque requirements at low temperatures are not yet available. Foaming of the gear oil is a potential problem that must be considered. A difficult problem has been to determine E.P. agent referred to decrease gear tooth wear without causing excessive corrosion of the plain bearings in the planetary gear system. It is obviously desirable to lubricate the gas turbine bearing system with the same oil as the gear reduction system. In any case the lubricating oil for the turbine bearing system of the turbo-prop engine has the same requirements as that of the turbojet lubricant. Therefore, the viscosity, pour point, volatility and stability requirements can be expected to approach those of the turbojet lubricant.

B. SYNTHETIC OILS OF PROMISE

8. Of the available non-petroleum fluids the methyl silicones have the lowest temperature coefficients of viscosity. These fluids also have the desired low pour points. For example, a methyl silicone having a viscosity of 6 cs. at 210° F will have a viscosity of only 200 cs. at -67° F and a pour point of -75° F. Though the oxidation stability of the methyl silicones is much superior to petroleum oils and most other organic compounds up to 400° F, they gel rapidly when subjected to temperatures above 400° F under oxidizing conditions (8). As the bearings attain temperatures approaching 500° F after shut down, it is quite likely that the methyl silicones will deposit gels in the bearings and oil supply lines. Their inferior lubricating properties (9) (10) (11) for steel on steel make them unsuitable for this application. The methylphenyl silicones, though more thermally and oxidation stable than the methyl silicones, have much lower V.I.'s and no better lubricating characteristics.

9. Aliphatic diesters can be synthesized with low pour points and excellent V.I.'s (12) (13). In general they are compatible with and responsive to the inhibitors used in petroleum oils (13) (14). Their lubricating ability is equivalent to that of similar viscosity petroleum oils, as has been proven by both laboratory and field tests (14) (17). The properties of some aliphatic diesters having viscosities of approximately 10 cs. at 100° F are shown in table 2.

10. Of the diesters shown in table 2 (2-ethylhexyl) adipate (column II) is the least viscous, having viscosities below the requirements of grade 1010 at 100° F and of specification V at 210° F. Its -67° F viscosity of 6000 cs. is, however, even lower than required by specification V. Its flash point, 380° F, is 100° F higher than the minimum required by grade 1010. The higher flash point of this diester reflects its lower volatility. At 210° F in the C.R.C. L-25-745 test, the weight loss of the ester was only 0.5 percent as compared to 6 to 10 percent for similar viscosity petroleum oils. The diester being a pure chemical compound will not change in viscosity or pour point regardless of the amount vaporized. This is a valuable property in lubricant applications where some critical viscosity must not be exceeded.

11. Two other adipic acid diesters are shown in table 2, Plexol 244 (column IV) and B-24 adipate (column III). The former is the diester of a commercial isooctyl alcohol, (probably a mixture of several isomers) and the latter a diester of monyl alcohol predominantly 3, 5, 5, trimethyl hexanol -1. Plexol 244 has the better viscometric characteristics, having a viscosity of only 8000 cs. at -67° F as compared to approximately 17,000 cs. for the other ester. Their freezing points, flash points and volatilities are not greatly different from those of di(2-ethyl-hexyl) adipate.

12. The properties of the di(2-ethylhexyl) esters of azelaic and sebacic acids are also given in table 2. As would be expected, increasing the molecular weight by lengthening the principal chain results in increased viscosities, higher V.I.'s, higher flash points and lower volatilities. Both of these diesters slightly exceed the viscosity requirements of grade 1010 at 100° F and specification V requirement at 210° F; however, their viscosities at -67° F of 8000 and 9000 cs. respectively are above the limit of 7000 centistokes but they are much less viscous at this temperature than conventional petroleum oils conforming to grade 1010. Blends of these esters with di(2-ethylhexyl) adipate were prepared to meet the requirements of specification V. The properties of a typical blend containing 75 percent by weight of the adipate is shown in table 2, column 7. This blend conforms to the viscosity requirements and is much superior to grade 1010 as regards volatility and flash point. Such a blend was recommended by this laboratory to the Bureau of Aeronautics (15) in 1948 for turbojet engine tests and have been under test by the Naval Aeronautical Engine Laboratory.

13. A commercial grade of di(1-ethylpropyl) sebacate was found to conform to the viscometric requirement of proposed grade 1005 at -67° F and is nearly half again as viscous as the minimum requirement at 100° F. This oil is the diester of a commercial grade of diethyl carbinol and sebacic acid, the small amounts of other isometric amyl alcohols accounting for its low freezing point. Its flash point is higher and it is less volatile than is even the grade 1010 petroleum oils. According to these criteria it is much superior to petroleum oil for this application.

14. In the course of a previous investigation on the 1-ethylpropyl esters it was observed that dehydration occurs on contact with certain absorbents or drying agents with the formation of amylenes and free acid. When used with an antioxidant in the crankcase of an internal combustion engine there was large increase in acidity and an insoluble material precipitated. This material was identified as sebacic acid. As the secondary esters are less stable than esters of primary alcohols it was considered advisable to concentrate on the latter.

15. None of the diesters of primary alcohols in the viscosity range of grade 1005 (12) had sufficiently low freezing points for this application. The freezing point of a compound, as is well known, can be depressed by the addition of another component. An examination of the properties of likely diesters revealed that the di(3-methyl-butyl) and di(2-ethylbutyl) esters of azelaic acid were in the approximate viscosity range and had low freezing points, -50° F. A 50-50 blend of these esters showed no indication of crystallization after 168 hours of storage at -80° F. The viscometric properties of this blend, shown

in table 3, column 5 are considerably better than the requirements of grade 1005 and it is also much superior as regards flash point and nonvolatility. Therefore, this laboratory recommended the blend to the Bureau of Aeronautics for engine tests (20). Due to the inability to obtain, at that time, an adequate supply of the di(3-methylbutyl) azelate component, other blends were investigated. The properties of 50-50 blends of di(3-methylbutyl) adipate with di(2-ethylhexyl) adipate and "Plexol 244" conform to the viscometric requirements of grade 1005 and some of their pertinent properties are given in table 3, columns 2 and 3. The last two blends are slightly more volatile and have lower flash points than did the azelate blend but they are much superior in this respect to petroleum fractions conforming to grade 1005. The Rohm and Haas Company agreed to prepare experimental quantities of the blend with "Plexol 244" which was then recommended to the Bureau of Aeronautics for engine tests (21).

16. An investigation of the relation of the structure of organic compounds to V.I. and freezing points (17) revealed that aliphatic ethers have lower freezing points and viscosities than do the analogous hydrocarbons. The viscosity-temperature characteristics of the ethers are comparable to those of the hydrocarbons of the same reference viscosity. By analogy the polyethers should have even more desirable viscometric properties. The polyalkylene glycols have very low V.I.'s (18). These polymers are polar liquids containing two unreacted hydroxyl groups and are associated in the liquid state. If one of the hydroxyl groups is reacted to form an ether linkage, i.e., chain stoppered with an alkyl group, association is greatly decreased and fluids such as the Ucon LB fluids with much higher V.I.'s result. When no hydroxyl end groups are present, fluids with even higher V.I.'s can be obtained.

17. Examples of the doubly chain-stoppered polyalkylene glycols are the "Ucon DLB" fluids (19). The properties of one of these fluids, Ucon DLB-50BX, in the turbojet lubricant range is shown in table 2, column 8. It has a viscosity of 2.5 cs. at 210° F and 8000 cs. at -67° F which exceeds the 7000 cs. limit proposed in specification V but is much less than a typical grade 1010 oil and below the critical viscosity requirement. The flash point of this liquid is slightly higher than required. It is believed that a narrower molecular weight fraction would have a higher flash point and lower volatility.

18. Another recently available fluid of the same chemical type is "Ucon DLB-47-E" (see table 3, column 6). This conforms to the requirements of grade 1005. Though less viscous than DLB-50BX this fluid has a higher flash point and would be expected to be less volatile. It is probably a narrower molecular weight fraction than the latter.

C. ADDITIVES

19. It is evidently necessary to stabilize turbojet and turbo-prop lubricants against oxidation at high temperatures. A number of anti-oxidants were investigated using di(2-ethylhexyl) sebacate as the reference fluid. The results of this investigation (16) revealed that phenolic, alkyl sulfide and phosphite inhibitors lose their effectiveness at temperatures above 250° F. Above 300° F, most of the aromatic amine inhibitors become ineffective, the exception being phenyl alpha naphthylamine. At 325° F, only phenothiazine, dilaurylselenide and phenyl alpha naphtylamine were able to stabilize the ester to oxidation for 168 hours in the presence of metal catalysts, the latter being required in larger concentrations. Inhibition can be obtained for shorter periods at higher temperatures. None of these inhibitors was able to prevent the formation of a slight amount of lacquer or other insoluble material at temperatures above 300° F. Of these inhibitors, dilauryl selenide is insoluble at sub-zero temperatures and phenyl alpha naphtylamine being required in larger concentrations, has a more adverse effect on the low temperature viscosity; hence phenothiazine was selected as the antioxidant for the experimental diester lubricant (16). Another desirable feature of diester oils is that they can undergo considerable oxidation with only minor changes in viscometric properties as compared to hydrocarbon or petroleum oils. Since the above mentioned investigation, selenide antioxidants have been made available with much better low temperature solubilities and comparably high temperature antioxidant activity (22).

20. High temperature oxidation inhibitors will be required to stabilize the polyether fluids also. No extensive tests have been made on the high temperature oxidation characteristics of the DLB fluids and their response to inhibitors by this laboratory but further information can be expected to be obtainable from commercial suppliers. The polyethers, like the diesters, do not tend to increase in viscosity with oxidation as rapidly as petroleum and hydrocarbon oils. The potentialities of the polyethers for turbojet engines deserve further consideration.

21. Rust inhibiting additives have not been employed recently in turbojet and turbo-prop engine oils. These may be necessary for protection during prolonged storage in humid regions. As such additives usually increase foaming tendencies of oils and decrease the high temperature oxidation stability, their use should be minimized. The foaming of oils is a well known problem in high altitude flying and in the operation of turbo-prop gear reduction systems. Pure diester oils foam little, but the presence of additives and impurities can make them foam as much as petroleum oils. However, the familiar methyl silicone defoamer additive is very effective in both synthetic fluids and petroleum oils. Wear preventives for ordinary loads and extreme pressure

additives for turbo-prop gear reduction systems must be used with the synthetic fluids just as with petroleum products. Fortunately, many types of widely used petroleum addition agents are satisfactory for use in the diesters. It is concluded that although the need for addition agents is evident, except for the gear reduction systems of turbo-prop engines, there are no new problems and no drawbacks to the development of improved lubricants for turbine powered aircraft.

AVAILABILITY OF IMPROVED LUBRICANTS

22. Present supplies of synthetic lubricants such as diesters and polyethers are not sufficient to care for large-scale use in turbine power-driven aircraft, but with any reasonable assurance of a market such as by an active specification, commercial production could care for the need in peacetime within two years. There should be no great difficulty at the end of this period of producing at the rate of at least 1,000,000 gallons per year. What is most important is the wartime supply of such lubricants. This was of concern to the Navy in 1945, but ample supplies from domestic raw materials are rapidly becoming available. The facts deserve a brief discussion here.

23. The polyethers are derived from cracked petroleum fractions. Hence the supply is limited in time of war only by competitive American users, and the supply can be expanded to care for any likely demand. The diesters of interest are branched aliphatic in structure and are either (a) dicarboxylic acid diesters or (b) glycol diesters of carboxylic acids. Type (a) are derived from adipic, azelaic or sebacic acids and branched-chain alcohols, at present. Type (b) are derived from glycol ethers and branched-chain acids. Both types of diesters are used as plasticizers, while the chemicals from which they are derived are widely used as starting materials for synthesis as solvents, coupling agents, perfumes and antifreeze materials. In 1945 the main source of dibasic acids was sebacic acid which is made from the oxidation of castor oil - an imported material. Within a few years large supplies of a competitive material, azelaic acid, were made available from oleic acid produced by the oxidation of animal fats. However, in time of war oleic acid is always in short supply. In the past three years the supply of adipic acid, one of the main ingredients of Nylon, has increased greatly. This is a petro chemical being derived through the oxidation of cyclohexene, the supply therefore is readily expanded and maintained in wartime. Branched-chain alcohols and acids from petrochemicals are rapidly increasing in variety and quantity. In short, basic ingredients for the manufacture of many adipic acid diesters are already derived from petrochemicals.

24. As an illustration, an increase of 1,000,000 gallons per year in the supply of diesters for turbojet and turbo-prop engines can be made from

adipic acid diesters by diverting only five percent of the present domestic production of adipic acid for Nylon. Clearly, this poses no plant expansion problem. The supply of alcohols to be esterified with the adipic acid is more of an immediate problem, but industrial petro-chemical activity is such as to resolve this rapidly on creation of an assured market.

CONCLUSIONS

25. For cold starts at temperatures down to at least -40° F and for operation in flight, the present grade 1010 petroleum oil appears to be satisfactory for turbojet engines, and with modification by the addition of suitable additives it may prove satisfactory for turbo-prop engines. For cold starts at temperatures down to -65° F an essentially synthetic oil such as certain aliphatic diesters or certain polyethers appear durable. No additive problems are involved which are insurmountable. Such synthetic oils can be produced commerically within several years at the rate of at least 1,000,000 gallons per year. Their production from domestic materials is important because of the critical nature of the equipment in which they are used. No serious barrier exists today for producing such lubricants in reponse to a demand of from 1,000,000 to 5,000,000 gallons per year, and there is no doubt that eventually the supply will be based entirely on petro-chemical materials.

BIBLIOGRAPHY

(1) Specification MIL-E-5007 and 5009 (Restricted), Turbojet Engine Oil Specification AN-E-20 (Restricted) Feb. 19, 1947, p. 8.

(2) AEL Restricted Report - 1110 "Lubricating Oil Requirements of J-34 Turbojet Engines under Low Temperature Conditions", 31 Jan. 1950.

(3) Army-Navy Aeronautical Specification AN-O-9 Oil; Low Temperature Lubricating.

(4) Coordinating Fuel and Equipment Research Committee of CRC Report "Pumping Tests of Oils at Low Temperatures in a Simulated Turbojet System." Sept. 27, 1949.

(5) Air Materiel Command Progress Report of Feb. 16, 1949 by Edgar Wolfe, to NACA Subcommittee on Lubrication and Wear.

(6) NACA restricted memo: "High Fluidity Oils for Turbojets" of 14 June 1948.

(7) Fourth Progress Report of Work Conducted by CRC under Navy Contract No. NOa (S) 9440.

(8) Atkins, D. C., Murphy, C. M., Saunders, C. E., Ind. Eng. Chem. 39 1395 (1947)

(9) Brophy, J. E., Militz, R. O., and Zisman, W. A., Trans. ASME 68, 355 (1946).

(10) Fitzsimmons, V. G., Pickett, D. C., Militz, R. O., and Zisman, W. A., Trans. ASME 68, 361 (1946).

(11) Brophy, J. E., Larson, J., and Militz, R. O., Trans. ASME 70, 929 (1948).

(12) Bried, E. M., Kidder, H. F., Murphy, C. M., and Zisman, W. A., Ind. Eng. Chem. 39, 484 (1947).

(13) Atkins, D. C., Baker, H. R., Murphy, C. M., and Zisman, W. A., Ind. Eng. Chem. 39, 491 (1947).

(14) Glovis, F. J. and Stringer, H. R., American Society for Testing Materials - Special Technical Publication No. 77, pp. 16 (1947).

(15) NRL. ltr. report 3270-220-48/af of 10 Aug. 1948, "Lubricants for Bearings of Turbojet Engines" to BuAer.

(16) NRL ltr. report 3270-206-49/hl of 3 Aug. 1949 "Investigation of Oxidation Inhibitors for Turbojet Engines and Other High Temperature Lubricant Applications".

(17) NRL Report 3667 "Structural Guides for Synthetic Lubricant Development" being printed, given at symposium on Synthetic Lubricating Oils sponsored by Petroleum Division, ACS Houston, Texas, March 26-30, 1950.

(18) Murphy, C. M., Romans, J. B., and Zisman, W. A., "The Viscosities and Densities of Lubricating Fluids from -40 to 700° F" Trans. A.S.M.E., July, 1949, p. 561.

(19) "Ucon-Brand Fluids and Lubricants", pamphlet of Carbide and Carbon Chemical Corporation, April 1, 1949.

(20) NRL letter report 3270-290-48/af of 11 Oct. 1948 "Lubricants for Bearings of Turbojet Engines" to BuAer.

(21) NRL ltr report 3270-178-49/hl of 10 June 1949 "Lubricants for Bearings of Turbojet Engines" to BuAer.

(22) NRL ltr report 3270-121-50/hl of 17 May 1940 "Antioxidant Action of Dialkyl Selenides in a Diester Fluid" to BuAer.

TABLE I

TURBOJET LUBRICANT REQUIREMENTS

PROPERTY	ARMY - NAVY AERONAUTICAL SPECIFICATION AN-0-9			Best features of grades 1010 and 1005	Compromise
	Grade 1015	Grade 1010	Proposed grade 1005		
	Specification I	Specification II	Specification III	Specification IV	Specification V
Viscosity, centistokes at 210° F	2.9[1]	2.53	1.63	2.5 (min)	2.5 (min)
100° F	15 min	10.3 (10 min)	5.0 (5 min)	8.4[1]	9.2[1]
0° F	700 max	220	52	90[1]	135[1]
-20° F	3000[1]	685	115	200[1]	330[1]
-40° F	20000[1]	2600 (3000 max)	315 (400 max)	550[1]	1040[1]
-67° F	----------	40000 Ca	2000 (3000 max)	3000 (max)	7000 (max)
Viscosity index	12	70	83	139	108
Pour point	-50 max	< -70 (-70 max)	< -75	-75	------------
Low temperature stability	-50 max	----------------	-75 (-75 max)	-75 (max)	-75 (max)
Flash point, °F	285 min	300 (275 min)	215 (225 max)	300 (min)	250 (min)
Fire point, °F	----------	----------------	----------------	------------	------------
Evaporation loss 210° F, WF, percent	----------	8 Ca	20 Ca	5 max	------------

[1]Interpolated or extrapolated value.

TABLE II

PROPERTIES OF PROMISING SYNTHETIC OILS FOR COMPARISON WITH

SPECIFICATIONS II AND V OF TABLE I

PROPERTY	DIESTER OILS					75-25 blend Di(2-ethyl-hexyl) adipate and sebacate	POLYETHER OILS
	Di(2-ethyl-hexyl) adipate	D-24 adipate	Plexol 244	Di(2-ethyl-hexyl) azelate	Di(2-ethyl-hexyl) sebacate		Ucon DLB-50 HX
Viscosity, centistokes at 210° F	2.35	2.6	2.8	3.1	3.3	2.5	2.5
100° F	8.3	9.9	10.0	11.4	12.6	9	8.6
0° F	109	155	135	156	187	120	110
-20° F	275	440	330	380	445	310	280
-40° F	850	1600	1040	1190	1410	940	900
-67° F	6000	17000	8000	8200	9000[1]	6600	8000
Viscosity index	121	138	141	146	154	116	139
Pour point, °F	<-75	-90	<-75	<-75	-67	<-75	<-75
Low temperature stability	<-75	<-75	<-75	<-75	-67	<-75	<-75
Flash point, °F	380	385	370	445	450	>380	270
Fire point, °F	430	410	430	470	490	>430	335
Evaporation loss 210° F, WF, percent	0.5	0.7	1	0.2	0.1	0.5	------

[1]Interpolated or extrapolated.

TABLE III

PROPERTIES OF PROMISING SYNTHETIC OILS FOR COMPARISON WITH

SPECIFICATIONS III AND IV OF TABLE I

PROPERTY	DIESTER OILS				POLYETHER OILS
	50-50 blend Di(3-methylbutyl) Di(2-ethylbutyl) adipate	50-50 blend Di(3-methylbutyl) plexol 244 adipate	Di(1-ethylpropyl) sebacate	50-50 blend Di(2-ethylbutyl) Di(3-methylbutyl) adipate	Ucon DLB-47E
Viscosity, centistokes at 210° F	2.0	2.2	2.28	2.4	2.3
100° F	6.2	6.9	7.38	7.6	6.6
0° F	59	68	80	71	60
-20° F	142	150	182	148	140
-40° F	354	404	504	393	340
-67° F	1870	2260	3000	2010	2500
Viscosity index	124	142	125	150	173
Pour point, °F	<-75	<-75	-90	<-75	-80
Low temperature stability	<-75	<-75	<-75	<-75	<-75
Flash point, °F	>350	>350	380	350	330
Fire point, °F	>390	>390	410	395	340
Evaporation loss 210° F, WF, percent	3	3	3	2	------

APPENDIX B

AIRCRAFT TURBINE LUBRICANTS FOR MILITARY USE

By C. C. Singleterry
Bureau of Aeronautics

The information presented herein is a coordinated presentation of Navy and Air Force background on an experience with turbine lubricants. Mr. Seidl from the Air Materiel Command has furnished the specific information relating to Air Force problems and has concurred in the general conclusions relating to specification trends.

When jet engine development started in this country a variety of lubricants was used. The Services soon recognized the necessity for establishing some sort of standard lubricant even though the requirements of the engines were not clear. The Navy at that time had rather large excess stocks of a general purpose light oil, Specification AN-O-6, which had a viscosity of approximately 15 centistokes at 100° F. Since this oil had reasonably good low temperature properties and was readily available it was adopted as a temporary standard. The Air Force did not have the same oil in stock but did have a background of experience in using a more recent specification oil, AN-O-6a, in many types of airframe accessories and considered it to be a logical starting point for investigating turbine oils. The AN-O-6a oil had a viscosity of 10 centistokes at 100° F and was rust inhibited.

It soon became apparent that the rust inhibitor requirement was a serious limitation on the availability of the oil so a new specification, AF 3606, was written which retained the characteristics of the AN-9-6a oil minus the rust inhibitor requirement. Later a joint specification, AB-O-9, was adopted by the services. This specification listed two grades, 1010 and 1015. The 1015 grade corresponded to the higher viscosity oil the Navy had been using. Although the Navy recognized the advantage of the lighter grade 1010 oil it was necessary to include the 1015 grade in the specification until engines which had been developed on this grade were cleared for use with the 1010 oil.

At present there is no use for the 1015 grade oil and it will probably be dropped from the specification at the time of the next revision.

The grade 1010 oil now in use in all turbojet engines is a straight petroleum oil with oxidation inhibitor and pour point depressant. It has a minimum viscosity of 10 centistokes at 100° F and a maximum viscosity of 3000 centistokes at -40° F. The pour point is below -70° F and the flash point is above 265° F.

Service experience with grade 1010 oil indicates that the high temperature characteristics of the oil are adequate for present service engines where maximum bearing operating temperatures are between 250° and 300° F. There has been considerable concern over the temperature rise in the bearing at the turbine end of the shaft on engine shutdown but there is little evidence to date that this is a service problem; however, it is recognized that engine designers would prefer to utilize higher bearing temperatures in future designs and this will be taken into consideration in further development or turbojet oils.

The lubricating ability of the grade 1010 oil appears to be adequate for present turbojet engines.

From the standpoint of low temperatures (-65° F) starting the grade 1010 oil is not entirely satisfactory. At -65° F it has a viscosity of approximately 40,000 centistokes. At this viscosity it will add considerably to the starting torque and is difficult or impossible to pump. It is considered that a viscosity below 10,000 centistokes is desirable from the standpoint of pumpability. Recent tests on a J-34 engine at the Naval Aeronautical Engine Laboratory have shown, however, that sufficient oil flows can be maintained when pumping a 20,000 centistokes oil at altitudes as high as 37,000 feet. Mechanical characteristics of other engines place more severe limitations on the viscosity of the oil. The J-35 engine had rubber nozzles for controlling the oil flow which blew out when the viscosity went as high as 1000 centistokes. The J-47 engine uses the oil as a hydraulic fluid in actuating the control system and control becomes too sluggish as the viscosity increases above approximately 1000 centistokes. On earlier model engines the cranking capacity of the starter was not sufficient to bring the engine up to idling speed with viscous oil in the bearings and gears; however, the cranking capacity of starters has increased greatly on newer engines so that it is not anticipated that engine starting torque considerations will limit the viscosity to below that required for pumpability.

As a result of difficulties with the J-47 engine control system the Air Force undertook an extensive investigation of a grade 1005 oil which had a minimum viscosity of 5 centistokes at 100° F and a maximum viscosity of 400 centistokes at -40° F. When the viscosity-temperature curve for this oil is extrapolated it appears that its viscosity at -65° F will be approximately 2500 centistokes. This oil is now approved for use in the J-47 engine below -30° F and has been considered for other engines below -40° F or -50° F. This grade may possibly be added to specification AN-O-9 at the time of the next revision but is procured at present under Air Force specification 3619. Requirements of the 1005 grade are similar to the 1010 grade except for the viscosity limits indicated above, a pour point limit below -75° F and a maximum flash point of 225° F.

The lubricating ability of the 1005 does not appear from tests to date to be entirely adequate for unlimited use in turbojet engines at all temperatures. There has been no operational use of the 1005 oil.

Present low temperature requirements for jet engines specify starting at -65° F. Recently there has been serious consideration by the Air Force of the necessity for extending this requirement to -100° F in view of the altitude starting requirements for B-36 jet engines. Temperature records indicate that ambient temperatures below -100° F are often encountered at the altitudes at which the B-36 may operate. The Air Force is at present making temperature recordings at various stations in the B-36 for the purpose of establishing the actual temperature conditions existent at altitude and will presumably take further action to modify the low temperature starting requirements of their engines if warranted by the results of the investigation. Any changes in the high temperature requirements of turbojet lubricants will be the result of new engine designs rather than changes in operational requirements.

Turbo prop engine lubricant requirements will closely parallel the requirements for turbojet engines except for the added lubricating ability required by the speed reduction gears. Although progress in developing turbo prop engine lubricants has been greatly hindered by the lack of knowledge as to the requirements of the gears in this respect it is possible to indicate generally the direction in which development should be channeled. Since the low temperature starting requirements for the turbo prop engine are -65° F it follows that the viscosity at -65° F should be as low as feasible - preferably not over 10,000 centistokes. Gear lubrication is more sensitive to viscosity variations than antifriction bearing lubrication and therefore it will be important to maintain as high a viscosity as possible at normal engine operating temperatures. In other words, there will be great advantage in using very high VI oils. Engine manufacturers have reported inadequate lubrication of turbo prop gears with grade 1010 oil. In view of the previously indicated limit on viscosity at low temperature the most promising method of obtaining adequate gear lubrication appears to be through the use of extreme pressure additives. Mr. Ryder presented data at the last meeting of the subcommittee which indicated that an additive 1010 oil was able to prevent scuffing of test gears at higher loads than 1120 oil. Similar results were reported by Socony Vacuum in a CRC report under Navy Contract NOa(s)9440.

In summation, it is probable that grade 1010 oil will be used for turbojet engine oils in the future. Emphasis in improvement of the oil will be in obtaining lower viscosities at -65° F. A grade 1005 oil may be used in a limited way for certain engines required to start at extreme low temperatures but will probably be eliminated if improvements in 1010 oil as indicated above can be accomplished. A separate grade of oil will be established for turbo prop engines as soon as requirements of the engines are defined. It appears that this may be a high VI additive type oil.

APPENDIX C

BEARING PROBLEMS IN CURRENT AND PROJECTED TURBO POWER PLANT

By C. J. McDowall
Allison Division - General Motors Corp.

The major bearing problems encountered in turbo power plants which differ from those previously encountered in reciprocating engines are concerned with the support of the compressor and turbine rotors in the power plant proper. In turbo prop power plants a new bearing problen has been introduced by the high speed of the power input shaft.

The compressor rotor is usually supported on a ball bearing at the rear which is the normal location point and at the front end by a roller bearing to permit the differential expansion between the case and the rotor. The front bearing offers no particular problems except the speeds encountered. Except for gyroscopic conditions the loads are light and surrounding temperatures are moderate. The rear compressor bearing presents more of a problem in that it is normally surrounded with air at compressor outlet temperatures which may vary from approximately 400° F at moderate compression ratios and flight speeds up to 800° F at high compression ratios and high flight speeds. Because of the high surrounding temperatures it is usually necessary to provide cooling air between the bearing and the surrounding diffuser. This requirement results in numerous complicated passages in the diffuser section of the engine. Since the rear compressor bearing is normally the locating bearing, it is also subjected to severe axial loads unless proper pressure balancing means are employed. The speeds encountered will vary from approximately 18,000 rpm in the smaller units to 6,000 rpm in the larger units. These rpm result in dn (d = bearing bore in millimeters n = rpm) values in the order of 700,000 to 1,000,000. These high dn values are so far in excess of catalog ratings that interpolation becomes doubtful. The only high loads encountered in a radial direction are the gyroscopic and G loads. Since they are normally of very short duration these are considered satisfactory if below the Brinelling load of the bearing used. Operating temperatures of the rear compressor bearings measured in the bearing cage are normally in the order of 300° F to 325° F with maximum allowables of 350° F to 400° F. Because of the high operating temperatures encountered, the use of phenolic composition cages usually recommended for high-speed applications becomes doubtful.

The bearings used to support the turbine rotor operate under the most severe temperature conditions encountered in the engine in that they are surrounded by gases of from 1700° to 900° F. This of course requires even more attention to be paid to cooling than the rear compressor bearings. These bearings may have to operate under temperatures of as high as 375° F again measured in the surrounding cage. One of the most severe conditions encountered by the turbine bearings is the high temperatures encountered after shut down. Even though adequate cooling may be furnished while running the high temperature of the surrounding parts causes a temperature rise after shut down which may exceed 400°F under severe conditions. This after shut down baking introduces a particularly severe lubrication problem. The dn values encountered in the normal turbine installation are of approximately the same values 700,000 to 1,000,000 encountered in the compressor bearings. However, in the case of some multistage turbines it would be possible to eliminate the rear support bearing, thus considerably simplifying the structure, if dn values up to approximately 2,500,000 could be used. Such bearings would present a difficult cage problem in that to avoid excess weight they would have to be considerably lighter than even the present extra light series bearing. If such bearings could be made available to the design engineer with adequate information in regard to their loading capacity, expected life and lubrication requirements, they would result in simpler and lighter multistage turbine constructions.

The input pinion of the turbo prop reduction gear introduces unusual problems both in the speeds encountered, which again may vary from 6,000 to 18,000 rpm, being accompanied in the case of spur gearing by loads varying from 3,000 pounds at the high speed to as high as 15,000 pounds at the lower speeds. The accompanying dn values may be as high as 1,500,000.

Another problem caused by the use of highly stressed reduction gearing is that of selecting a proper lubricant for both the reduction gear and the turbo power plant. The turbo power plant operates best using a thin oil that is adapted to an extreme range of temperatures, whereas the reduction gear requires a heavier oil, perhaps with an EP additive, to carry the high crushing loads of the gear teeth.

The starting requirements of the turbo prop and turbojet engines differ radically from previous reciprocating engine practice in that no warm up is employed. It was customary in reciprocating engine practice to start the engine at low speed and run it until oil pressures had been established and lubrication to all points was adequate. The speed was then gradually increased until the minimum operating oil temperature was reached. In jet engine practice it is customary to start the engine and go to maximum speed and power in as short a time as possible. This latter requirement has necessitated the use of very light oil inadequate for lubricating highly stressed gearing.

The use of high-speed extension shafting in lengths sufficient to necessitate intermediate support bearings to prevent the exceeding of the whipping speed of the shafting has resulted in a severe lubrication problem in that dn values in the order of 1,000,000 are used. Although oil is recommended for such high dn values, the space and weight requirement of the bearing supporting structure are such that grease lubrication becomes practically mandatory. Since these bearings are very lightly loaded such lubrication has proven satisfactory.

Other severe conditions encountered in turbo engine service are concerned with bearing mounting conditions. Because most of the shafting employed is hollow to decrease weight and because the bearing mounting structures are made as light as possible for the same reason, the bearings are usually supported in a fashion which bearing engineers are prone to call inadequate. Because of these flimsy supporting structures, the galling problems between the inner race and the shaft and the outer race and the cage are quite severe. Another problem encountered is that of misalignment due to deflections at high loading conditions. At times these deflections may be severe enough to require the use of crowned rollers. Because of assembly problems it is sometimes necessary to control the roller drop to quite close limits which results in complications in the cage design.

In spite of all the above adverse conditions, ball and roller bearings are performing exceptionally well in present-day turbo power plants.

APPENDIX D

INVESTIGATIONS OF ROLLING BEARINGS AT SKF INDUSTRIES, INC.

By H. Styri

ENDURANCE TESTS

Ball and roller bearings of design roughly approaching present-day design were in use 150 years ago, but a thorough investigation of the engineering properties of bearings was not made until 50 years ago.

Stribeck in Germany studied the carrying capacity of ball bearings based on Hertz equation for bodies in contact. As long as the contacting bodies did not take measurable permanent set, the axis of the contact ellipse would be proportional to $\sqrt[3]{p}$. Stribeck also found that when permanent deformation was observed for different sizes of balls, the load p on the ball would be proportional to d^2 or $K = \frac{p}{d^2}$ where K is called the specific ball load. He assumed that permanent deformation in balls and races could be noticed for $K = 10\ kg/(1/8")^2$.

Stribeck calculated the approximate relative radial capacity of ball bearings with N number of balls to be $P = \frac{N}{5} Kd^2$.

The maximum permissible value of K would depend on the shape of the races because permanent deformation would be less for races with better conformity to the ball or roller. It was therefore natural that the design of ball bearings and roller bearings soon took a shape that deviates from present design only in minor geometrical details, which, however, are of considerable importance.

About the same time Goodman in England also verified the validity of the Hertz equations for bearings, and made an intensive investigation of the load-carrying capacity for bearings that would last 1 million revolutions without surface pitting of the balls. He set up equations for loads that showed dependency of ball size and number, and these have been found reasonably good.

In the early 1910's the Swedish SKF company tested self-aligning ball bearings up to about 6 million revolutions at $K = 20\ kg/(1/8")^2$. and cumulative data gave about 50 percent failure at this life. They found in course of testing that the bearings would last much longer under lighter loads, and, in fact, thought that the life would be inversely proportional to about the cube of the load. When A. Palmgren came to SKF in 1917 and started thorough testing and calculations of the life-load relationship, this assumption had been generally accepted, but Palmgren, like many other investigators, felt that there should be an endurance limit at some low load as well as an upper load limit that should not be exceeded without damage to the bearing. A correction factor for speed was at that time also introduced in the life formula.

More comprehensive life-load studies were started in Philadelphia in 1920. Larger groups of bearings of the same manufacture were tested, each group under definite load and speed that differed from conditions of the other groups. The tests on the 6408 bearings are shown in graph 1, and gave as result that the number of revolutions before failure was independent of speed and various lubricants used; that the relative dispersion in life at the different loads was about the same; and that the average life L varied inversely as about the cube of the load, or more nearly the 3.3 power

$$\frac{L_1}{L_2} = \left(\frac{P_2}{P_1}\right)^{3.3}$$

This means simply that by reducing the load to 1/2, the life would increase ten times.

Later on a number of tests were made on groups of 25 - 35 bearings under two or three loads, verifying the general relationship, and just recently an extensive test has been made on 6207 bearings shown in graph II, where also the power of 3.3 well satisfies the load life relation. Additional tests have been run abroad, and particularly in Sweden, and when all significant tests are plotted it seems that a power of 3 covers the data somewhat better than 3.3. This power of 3 is also preferable because other factors, such as lubrication and wear, may influence the life at light loads. It will be seen that the life-load relationship of the averages for the two bearing sizes have practically the same slope, although the lives for the more recently manufactured 6207 are about 10 times higher than for the older 6408. This fact is also brought out, and perhaps better, in graph III where the lives in millions of revolutions are plotted against mean unit pressure on the contact ellipse against the inner race for the most loaded ball. There is not much difference in the conformity for the two types of bearings, and although some advantage must be given the smaller ball, it is obvious that the more recent manufacture is of high quality. If higher contact stress can be permitted by improvement in quality of steel, the lives can be greatly improved.

TESTS AT HIGHER TEMPERATURES

We have run endurance tests on spherical roller bearings under loads up to 35,000 pounds and speeds 1000 rpm at temperatures up to 150° C, without difficulties, but not in sufficient number to state whether such higher temperatures have any effect on the life. We believe that the endurance is but little influenced by such high temperatures, as long as there is no change in the hardness of the parts. Hardness of stabilized 52100 held at 240° C for over 200 hours remains at about 60 Rc, and for a steel with 1 percent Cr, 1 percent Mn, 0.5 SI held at 270° C for over 100 hours stays at 59 Rc.

High-speed steel will maintain its hardness for prolonged times at up to 450° C, but we have run no endurance tests at such temperature. Other alloys are also available that will maintain high hardness at elevated temperatures, but some reduction in endurance in life at high temperatures, compared with room temperature, must be expected.

Tests on grease lubricated bearings operated at 25,000 and 13,000 rpm at temperatures 200°, 250°, 300° C have previously been reported, and a supplement is shown in graph V. Tests on oil lubricated bearings 6203 run at 25,000 rpm, and 320° - 350° C have also been reported, with running time up to 100 hours on some synthetic lubricants.

At lower temperatures tests have been successfully run on 6304 at 40,000 rpm for 1500 hours; on 7203 with fog lubrication at 50,000 rpm for up to 1000 hours; and on 7007 bearings successfully at 32,000 rpm, but not so good at 40,000.

Larger angular contact bearings of 100-mm bore have been operated at 10,000 rpm under combined loads, and cylindrical bearings under radial loads at temperatures up to 120° C, and for a short time to 150° C, without difficulty.

In operating bearings at very high speeds it is of greatest importance to introduce lubricant between the sliding parts. If there occurs direct local contact of the solid members, particularly separator and races, high local heat develops that may smear or melt the local contact spot and by repetition rapidly destroy the bearing. It is therefore obviously necessary to have a nonseizing film present to prevent solid metallic contact, and a lubricant to carry off the heat developed by friction, so that the temperature is kept at a balance; but the quantity of lubricant may be kept at minimum, depending on conditions of operation, graph VI. When occasional solid contact is unavoidable it is equally obvious that the best material should be selected for the cages, to avoid smearing. Some compounds like Synthane are excellent at high speeds, but carbonize and get brittle at high temperatures. Nonferrous

Tests on bearings made of steels with different analysis have, however, shown little difference in life, provided they had the same hardness and structure.

In connection with graph III it may be of interest to compare some endurance tests of other types made on heat treated hard bearing steel, shown in graph IV. Here the lower straight line represents the average endurance of torsion specimens for different loads, and the slope of this line is -10. The upper straight line is drawn through the average lives of ring-type specimens for different maximum tension stresses on the inside surface of the ring, and has a slope of -12.

The most recent theory, developed by Dr. A. Palmgren and Professor Lundberg of Gothenburg, is based on the probability of failure or survival in an element of the volume of material subjected to stress, and has been widely accepted by the bearing industry. This theory has the great advantage that capacity of various types of bearings can be calculated with the same accuracy, and gives the basic dynamic capacity "C" of bearings that will permit 90 percent of the bearings to survive 1 million revolutions.

The life is expressed by $L = \left(\frac{C}{P}\right)^3$ and C is proportional to $N^{2/3}d^{1.8}$ where P is load on bearing, C is basic dynamic capacity, N is number of balls (rollers), and d is ball diameter.

For roller bearings a product $d^{1.07}l^{0.78}$ is introduced instead of $d^{1.8}$.

We have known for over 25 years that the majority of flakings start at some point below the contacting surface from some weak point in the structure. This week point may be a slag inclusion or a microscopic void between grains or a weak slipplane in an unfavorable direction, situated near the region of heavy shear stresses at a depth equal to about one-third of the short axis of the contact ellipse, and which may amount to about one-half the mean contact stress. We have found many times in outer races of self-aligning bearings that flakings may start away from the maximum load point at points where lower stresses occur, which explains the high dispersion in life of bearings and other hardened steel parts.

The surface finish of the contacting parts, as found in standard manufacturing, does not seem to influence the life under heavy test loads, but a relatively rough surface may cause early fatigue failure under light bearing loads, because in fact we may have a high contact stress at the irregular high points in the surface.

alloys have a coefficient of expansion almost twice that of iron and may bind the bearing at elevated temperatures if not properly designed or dimensioned for a great enough range of operating temperatures. The best nonferrous alloys are not satisfactory for high rubbing speeds and loads, and ferrous alloys are even less satisfactory. It is possible that some surface coating may be applied on rubbing surfaces of cages and races, that will prevent or delay metallic transfer or smearing.

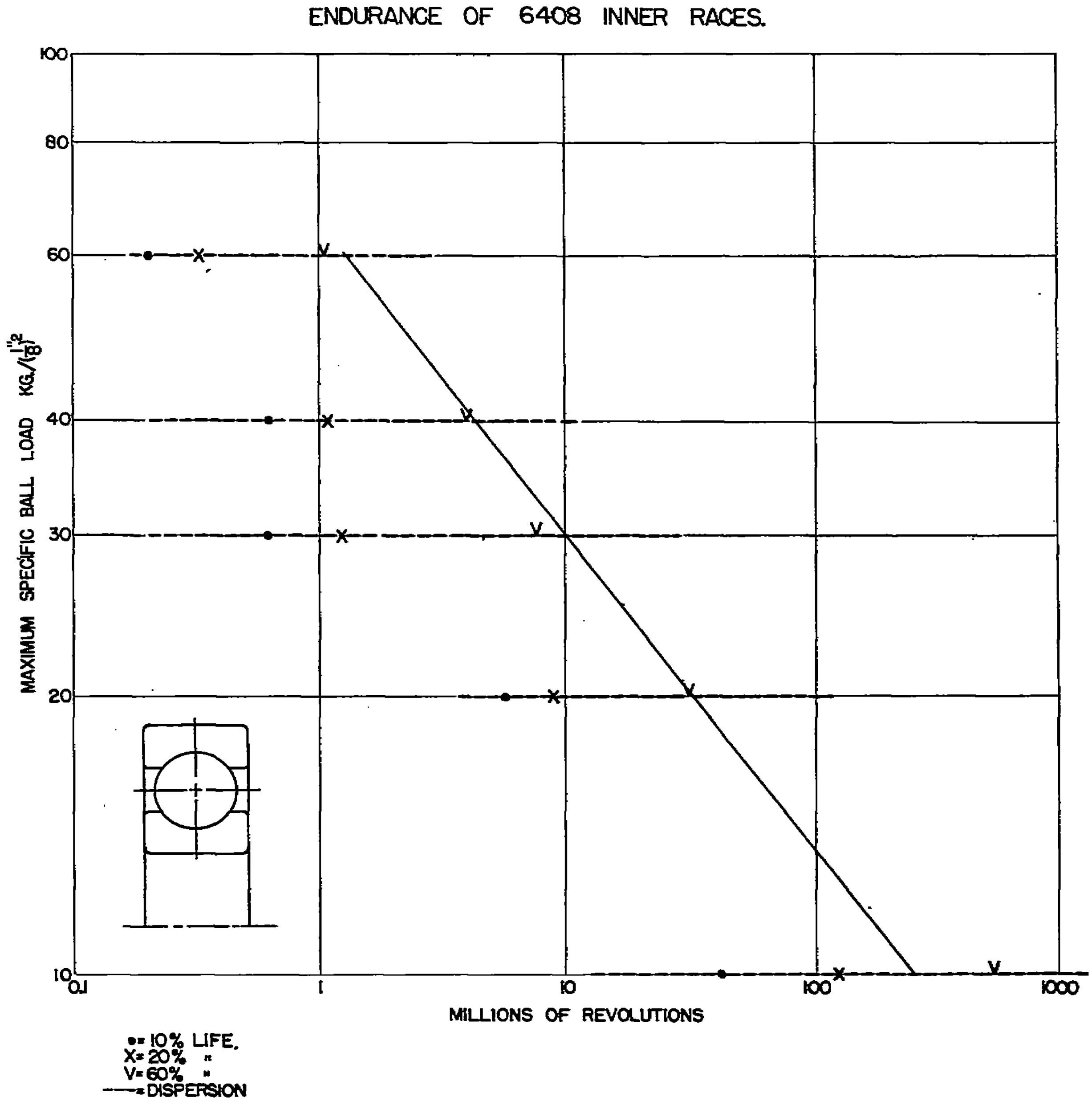

ENDURANCE OF 6408 INNER RACES.
MAXIMUM SPECIFIC BALL LOAD KG./(1/8")²
100
80
60
40
30
20
10
0.1
1
10
100
1000
MILLIONS OF REVOLUTIONS
• = 10% LIFE.
X = 20% "
V = 60% "
—— = DISPERSION

Figure 1.

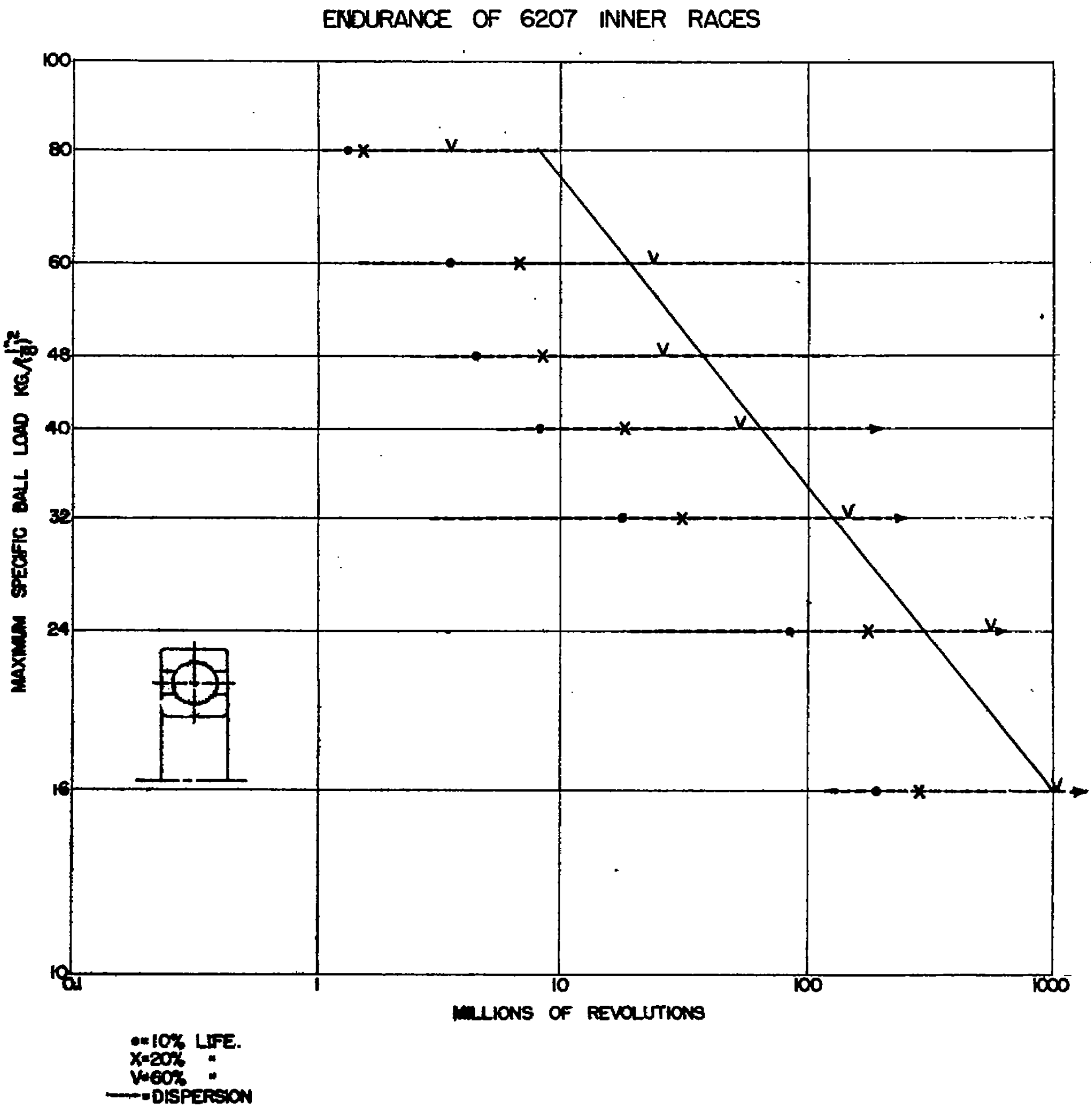

ENDURANCE OF 6207 INNER RACES
MAXIMUM SPECIFIC BALL LOAD KG./(1/8)²
100
80
60
48
40
32
24
16
10
0.1
1
10
100
1000
MILLIONS OF REVOLUTIONS
•=10% LIFE.
X=20% "
V=60% "
——=DISPERSION

Figure 2.

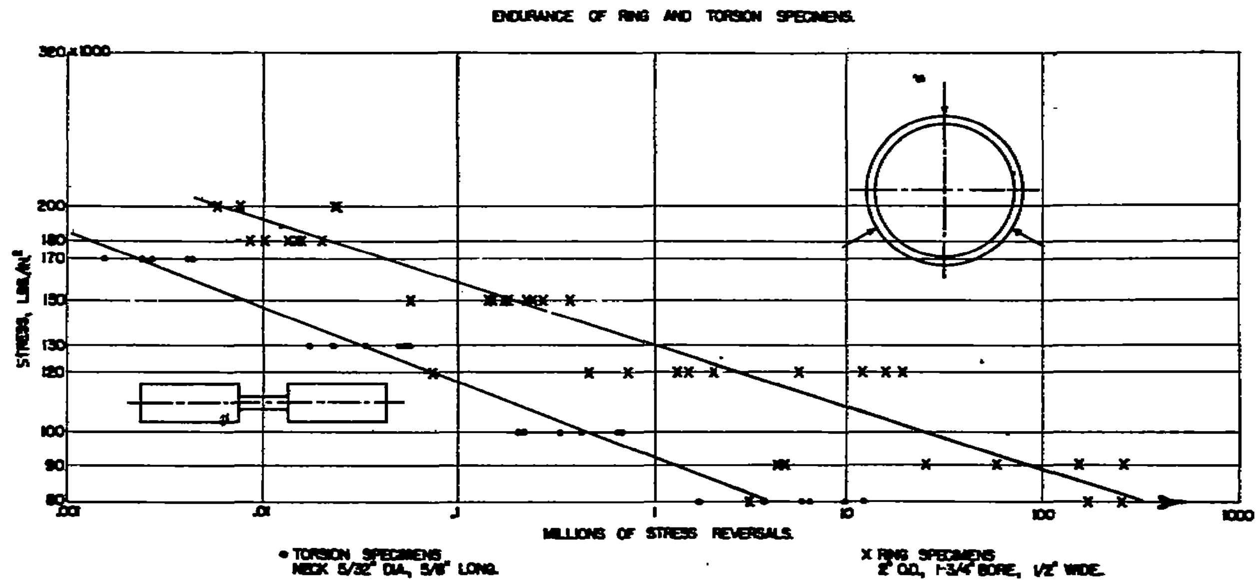


Figure 3.

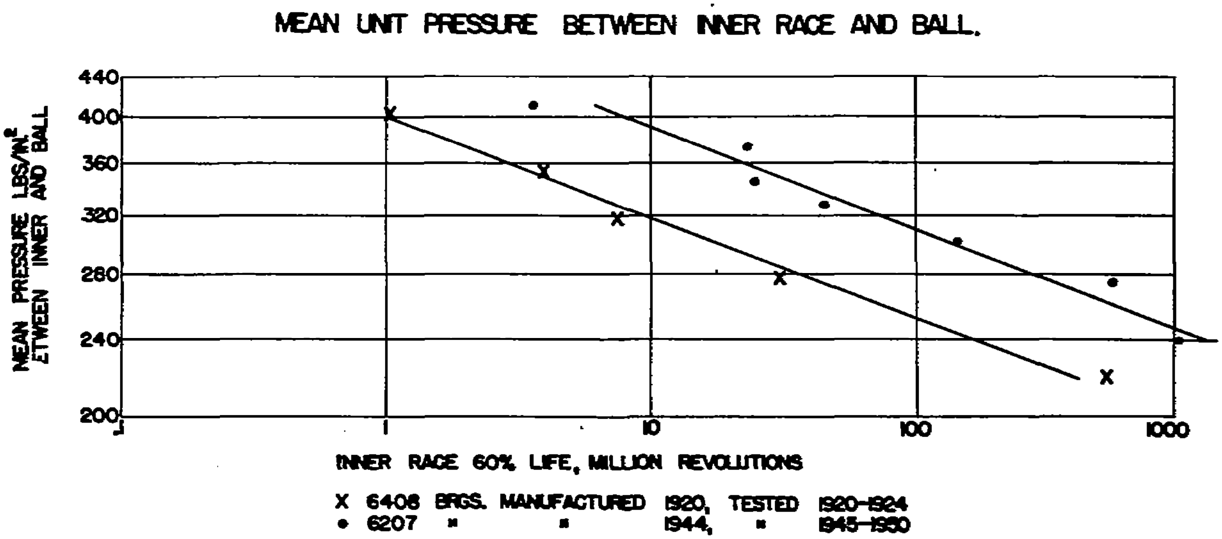
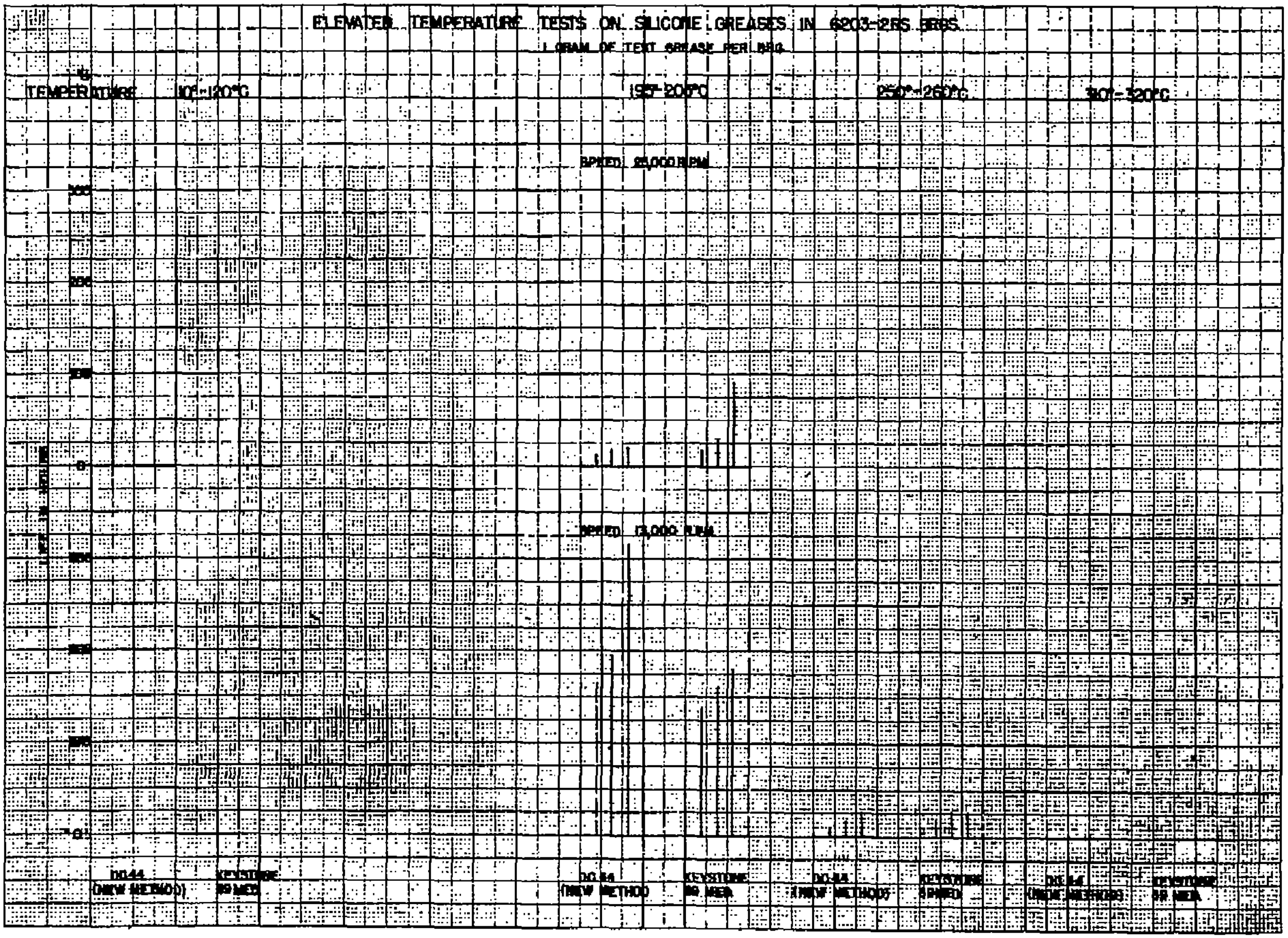


Figure 4.



ELEVATED TEMPERATURE TESTS ON SILICONE GREASES IN 6203-2RS BRGS.
TEMPERATURE
SPEED 25,000 RPM
0
DC 44 (NEW METHOD)
KEYSTONE

Figure 5.

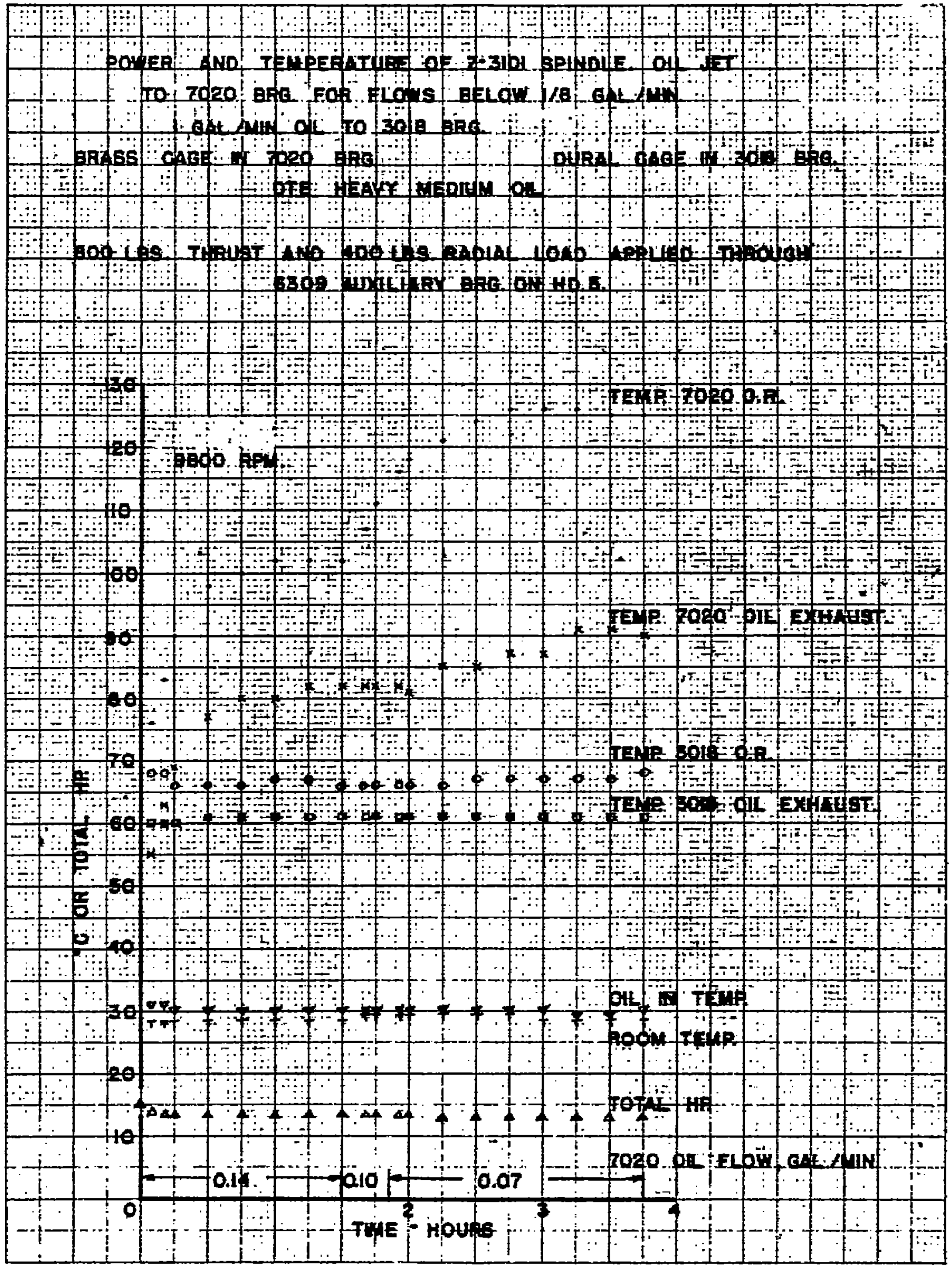

POWER AND TEMPERATURE OF Z-3101 SPINDLE. OIL JET
TO 7020 BRG. FOR FLOWS BELOW 1/8 GAL./MIN.
1 GAL./MIN. OIL TO 3018 BRG.
BRASS CAGE IN 7020 BRG.
DURAL CAGE IN 3018 BRG.
DTE HEAVY MEDIUM OIL
800 LBS. THRUST AND 400 LBS. RADIAL LOAD APPLIED THROUGH
6309 AUXILIARY BRG. ON HD. S.
9800 RPM
TEMP. 7020 O.R.
TEMP. 7020 OIL EXHAUST
TEMP. 3018 O.R.
TEMP. 3018 OIL EXHAUST
OIL IN TEMP.
ROOM TEMP.
TOTAL HP.
7020 OIL FLOW, GAL./MIN.
0.14
0.10
0.07
°C OR TOTAL HP.
TIME - HOURS

Figure 6.

APPENDIX E

LUBRICANTS FOR OPERATION OF AIRCRAFT GAS TURBINE ENGINES OVER WIDE TEMPERATURE RANGES

By NACA Lewis Flight Propulsion Laboratory Staff

(Presented at meeting of Subcommittee on Lubrication and Wear October 17, 1950)

Previous discussions of the problem of providing lubricants for operation of aircraft gas turbine engines by Dr. Zisman (Appendix A) and Mr. Singleterry (Appendix B) have indicated both the general lubricant requirements and possible solutions to these requirements for a limited temperature range. The general requirements presented included those of fluidity, adequate lubrication characteristics, and temperature stability. To these requirements could be added two additional requirements: (1) good heat transfer properties; and (2) nonflammability. These two additional requirements are each highly desirable and the flammability requirement may become even more important if many aircraft fires are traced to the lubricant as the initial combustible. The generally promising solutions involve the use of synthetic fluids (diesters and polyethers), Appendix A, or improvement in the present Grade 1010 lubricant, Appendix B. Both of these solutions may provide lubricants which are adequate for the temperature (bearing operating temperature) range of -65° to 350° F.

There has been some discussion of lowering the current specified low temperature of -65° F to -100° F because temperatures in the range of -100° F have been encountered in service. This low temperature may, however, impose unwarranted limitations on lubricating fluids. If possible, therefore, the difficulties introduced by the -100° F temperature limit should be solved by mechanical design changes. While this method of solution may be difficult, finding a lubricant to meet the requirements of the broad temperature range may be even more difficult.

The temperature range will undoubtedly be broadened in the other direction, however. Engine designers have indicated that it would be desirable for many reasons to increase the upper limit of bearing temperature to values of: (1) 500°, (2) 750°, and (3) even as high as 1000° F. These increases in bearing temperatures will result in corresponding increases in lubricant temperature limits. Broadening of the temperature range to include temperatures from -65° to 1000° F makes the problem of providing lubricants more difficult. Relatively few fluids are available at present which have viscosity indexes high enough to meet the requirements of the current viscosity specifications or the compromise viscosity specifications of Appendix A. In consequence, the specifications must be made less severe with respect to viscosity (and consequently viscosity index) in order to encompass a greater number of fluids.

In order to establish practical and realistic goals in the development of lubricants the following temperature (bearing operating temperature) ranges have been established: (1) -65° to 350° F (current temperature range); (2) -65° to 500° F; (3) -65° to 750° F; and (4) -65° to 1000° F. As previously stated, the solutions suggested in Appendices A and B cover, generally, only the temperature range from -65° to 350° F.

Since a fluid to meet the requirements of the broadened temperature range can be obtained only if the current and compromise viscosity specifications are made less severe, the requirements were studied to determine where changes might be made. It is obvious that no increase in viscosity can be tolerated at low temperatures, unless engine designs are changed to provide adequate pumpability of the fluid at viscosity greater than 10,000 centistokes. The specifications can, however, be changed at high temperatures if the condition is met wherein lubrication can adequately be supplied by an additive (i.e., if the fluid is not required to be a lubricant). Such a condition involves the use of a composite lubricant consisting of a fluid carrier plus an additive. The carrier meets the requirements of fluidity, stability, heat transfer properties, and nonflammability, but does not necessarily meet the lubrication requirement; the additive meets the lubrication requirement. This general approach to the problem is not new except perhaps in degree since the additive in the composite lubricant may be required to fulfill the entire lubrication function, whereas in the past additives have been used as a means of providing supplemental lubrication to fluids which inherently possess some lubricating ability. It is possible that a great number and variety of fluids may then come into consideration in using the composite lubricant because of the fact that the fluid carrier is not necessarily a lubricant.

Before the use of composite lubricants as a possible solution to the problem of operation over extreme temperature ranges can be considered, it must be established that adequate boundary lubricating effectiveness can be provided by additives, that is, it must be established that adequate lubrication can be provided by the addition of additives to a fluid that in itself has extremely poor boundary lubricating characteristics. Boundary lubrication data presented herein were obtained with a kinetic friction apparatus (described in reference 1) consisting of a hardened steel ball sliding on a lubricated rotating steel disk. The load produced an initial Hertz stress of 126,000 psi and runs were made at the sliding velocities (75 to 18,000 feet per minute) currently encountered in rolling contact bearings of aircraft turbine engines. The data of figure 1 show that the addition of a chemically reactive additive (free sulfur) to cetane (which is a very poor boundary lubricant) provided lubricating qualities that were effective enough to prevent welding and to decrease friction markedly at low sliding velocities. With cetane, as shown in Figure 1, the friction coefficient is exceptionally high and welding occurred at all sliding velocities. The addition of free sulfur showed a marked decrease in friction coefficient and, what is more important, prevented welding from occurring over some of the velocity range (75 to 1000 feet per minute). Above 1000 feet per minute (the approximate critical sliding velocity) welding occurred even for the solutions of sulfur in cetane. The data of reference 2 confirm these findings (i.e., that friction can be decreased and welding prevented at velocities less than the critical) and also show that increasing the reactivity of the additive will increase the critical sliding velocity.

Results of a preliminary investigation (fig. 2) indicated the ability of an additive of the suspended solid type to provide the lubrication function for a carrier fluid having extremely poor boundary lubricating properties. These data show that mixtures of molybdenum disulfide, MoS_2, and a silicone are quite effective as boundary lubricants. With the silicone fluid alone, the friction coefficient was relatively high and welding occurred at all sliding velocities. The addition of MoS_2 in all percentages investigated markedly decreased the friction coefficient and prevented welding from taking place at all sliding velocities. These data show that MoS_2 concentrations as low as 5 percent by weight are effective in preventing welding and in reducing friction. The investigation included higher percentages of MoS_2 in order to determine the limit of effectiveness of the MoS_2. The two higher percentages, 18 percent and 50 percent, show that an extremely low friction coefficient can be obtained. It should be emphasized that the mixtures of MoS_2 in silicone used in this investigation were not colloidal suspensions but were simple mixtures.

Another preliminary research investigation has indicated that MoS_2 suspended in air can lubricate rolling contact bearings at temperatures as high as 1000° F for periods of time of $2\frac{1}{2}$ hours.

In summary, the friction data of figures 1 and 2 show that the concept of fulfilling the entire lubrication function by the use of a lubricant additive and a carrier, which by itself is a poor lubricant, is worthy of further consideration. The difficulties inherent in obtaining a composite lubricant are not to be minimized. The types of additives for composite lubricants include those which have been in general use for many years (soluble or suspended solid types).

Because of the extremes in operating conditions, it may be very difficult to obtain stable solutions or suspensions of the additives in the carrier fluid. In view of the difficulties involved in the use of a composite lubricant, it is probable that this solution to the lubricant problem will be limited in application. Where it becomes impossible to find a single fluid that is adequate to meet the requirements, however, it is believed the composite lubricant type may be necessary.

REFERENCES

1. Johnson, Robert L., Swikert, Max A., and Bisson, Edmond E.: Friction at High Sliding Velocities. NACA TN 1442, 1947.

2. Bisson, Edmond E., Swikert, Max A., and Johnson, Robert L.: Effect of Chemical Reactivity of Lubricant Additives on Friction and Surface Welding at High Sliding Velocities. NACA TN 2144, 1950.

TABLE I

OPERATING TEMPERATURE RANGES IN AIRCRAFT TURBOJET

ENGINES USING ROLLING CONTACT BEARINGS

Item	Status	Temperature range		Approximate bearing outer race shutdown temperature	Maximum oil reservoir temperature
		Minimum	Maximum bearing outer race temperature		
1	Current	[a]-65° F	350° F	500° F	260° F
2	Future	[a]-65	500	700	------
3	Future	[a]-65	750	1000	------

[a]Temperatures as low as -100° F have been encountered in service, but this temperature is not now a requirement of the military services.

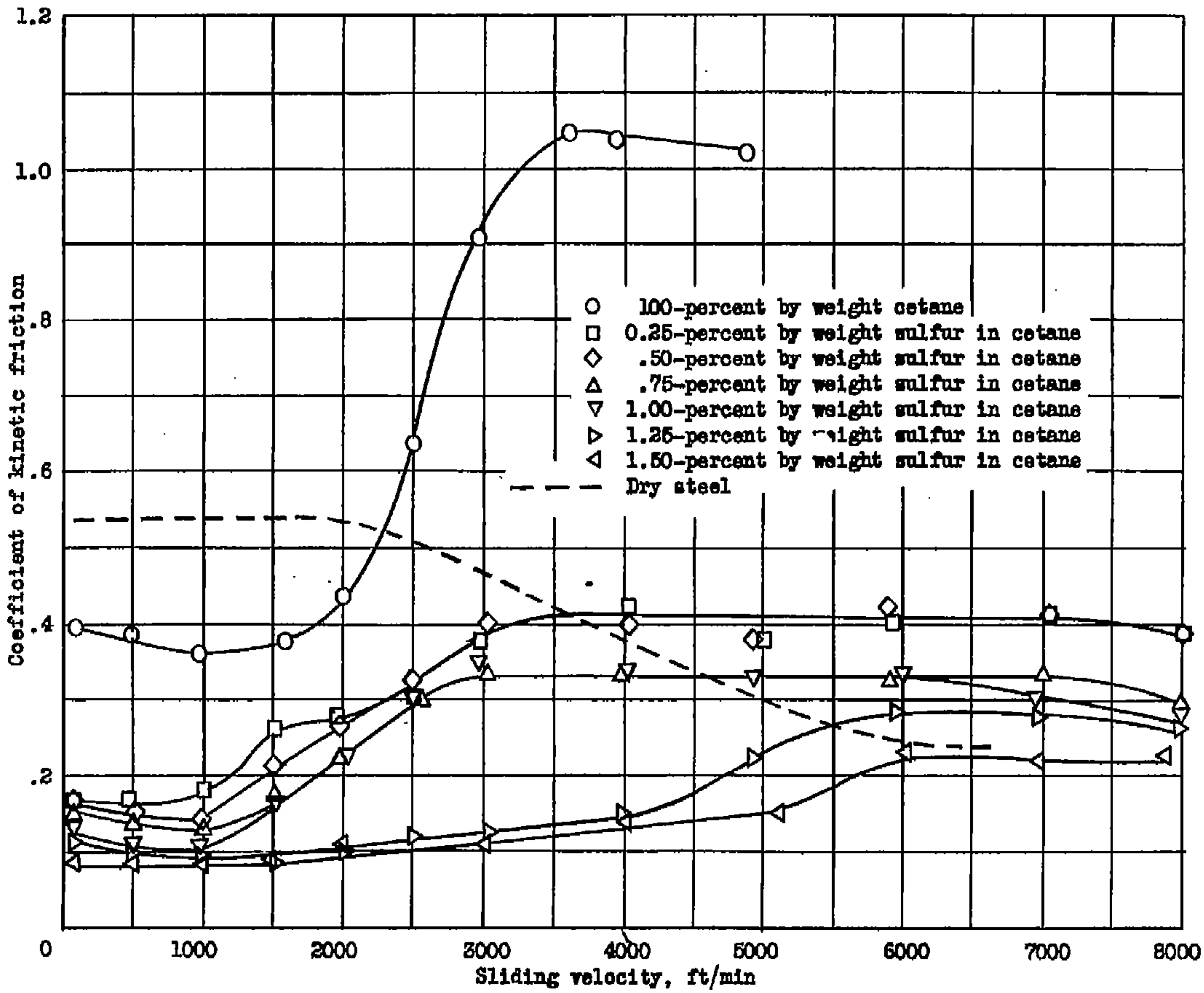


Figure 1.- Effect on friction and surface welding of addition of a lubricant additive (free sulfur) of extreme pressure type to a carrier (cetane) of very poor boundary lubricating qualities. Load, 269 grams (Initial Hertz surface stress, 126,000 psi).

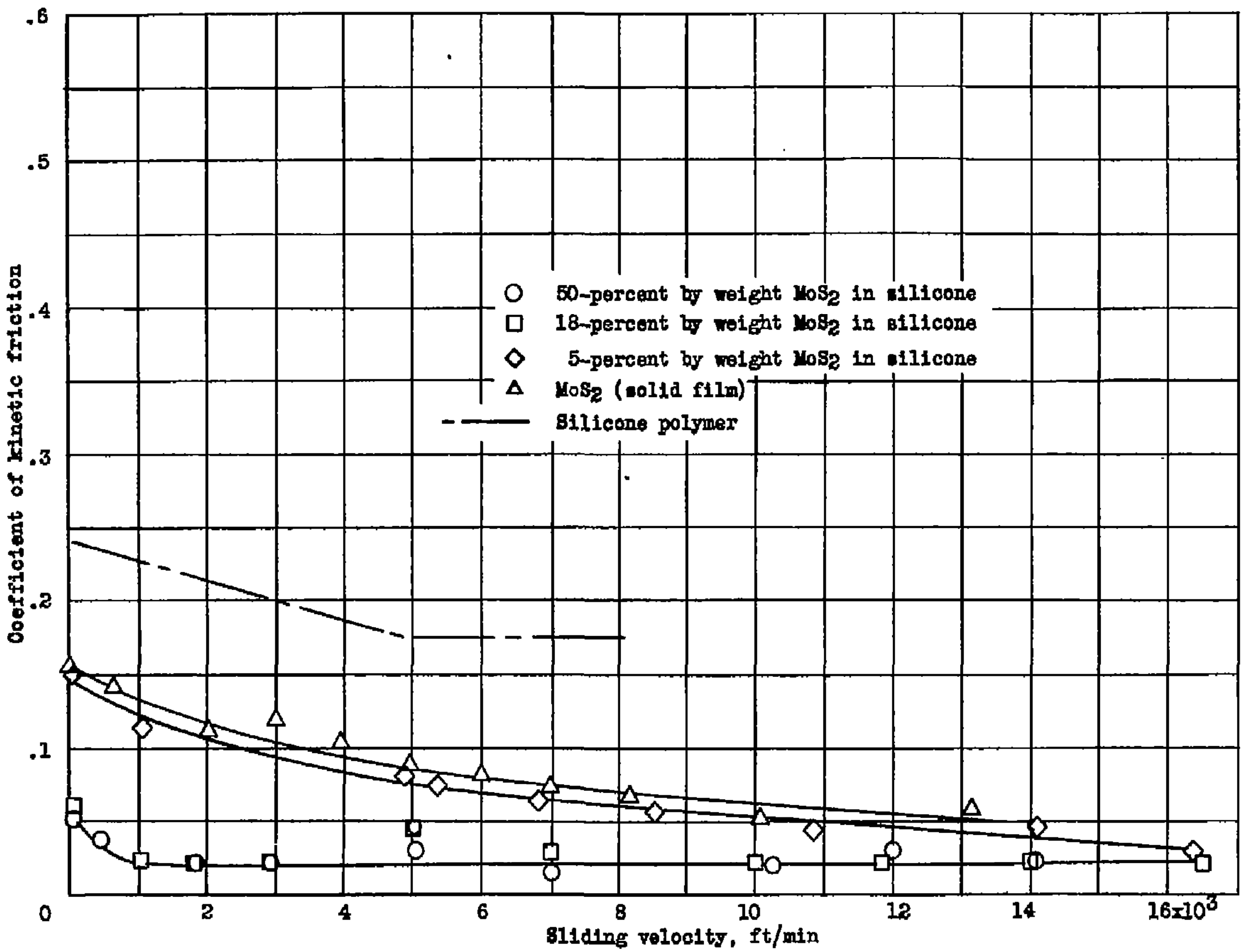


Figure 2.- Effect on friction and surface welding of addition of a lubricant additive (MoS_2) of the suspended-solid type to carrier (silicone of 50 centistoke viscosity at 25° C) of very poor boundary lubricating qualities. Load, 269 grams (Initial Hertz surface stress, 126,000 psi).

NACA-Langley - 4-20-51 - 400