# POWDERED AND GASEOUS LUBRICANTS FOR USE IN BALL BEARINGS AT TEMPERATURES FROM ROOM TEMPERATURE TO 1200°F

By D. S. Wilson
Stratos Division
Fairchild Engine and Airplane Corporation

## ABSTRACT

A method of approach to the operation of high-speed, high-temperature ball bearings is outlined. The results of bearing operation to speeds of 50,000 rpm and temperatures from room temperature to 1200°F using the methods outlined is presented.

The most successful bearing operation has been attained using powdered lubricants suspended in a gaseous carrier with titanium carbide and Stellite material bearings. Research efforts are still in progress, however, evaluations to date indicate that molybdenum disulfide in a nitrogen atmosphere and a graphite-cadmium oxide mixture in an air environment are capable of functioning as a lubricant in ball bearings of either material over the temperature range from room temperature to 1200°F. Satisfactory bearing operation has been obtained with these lubricants over the temperature range at speeds of 25,000 rpm for periods of two hours or more. Wear during these evaluations appeared to be a function of lubricant flow varying from a build-up condition at flows above 1 gram/min to a wear condition at flows below 0.2 grams/min. Longer periods of operation have also been attained at the temperature extremes of room temperature and 1200°F with both lubricants. Short periods of operation at speeds to 50,000 rpm at both room temperature and 1200°F have also been conducted.

## INTRODUCTION

The ever-increasing trend toward higher speed aircraft, missiles and space vehicles introduces a serious demand on the capabilities of secondary power equipment to operate in temperature environments beyond the limits of common usage rolling-contact bearing materials and lubricants. In recognition of this problem, a WADD-sponsored program was undertaken by Stratos to investigate and develop various unconventional lubricants and lubrication techniques as well as bearing materials and designs in order to attain operation of at 20-mm (bore size) ball bearing at the following conditions:

| | |
|---|---|
| Bearing Temperature, °F | Room to 1200 |
| Bearing Speed, rpm | To 50,000 |
| Operating Time, hr | 10 (minimum) |
| Bearing Load: | |
| Radial, lb | 50 |
| Thrust, lb | 50 |

It is quite evident that the success of operating over the performance parameters outlined is dependent upon the ability of meeting the 1200°F bearing temperature condition. At this temperature (which is above the melting temperature of most aluminum alloys and described as a cherry red color for most steels) it becomes apparent that limitations will be encountered with standard lubricants and bearing materials.

Considerable work has been devoted in recent years to developing the use of powdered solids, reactive gases and vapors as lubricants for high-temperature applications. However, the information available on the suitability of these lubricants for ball bearings operating at temperatures up to 1200°F and at very high speeds is limited, and the investigations reported herein were undertaken to achieve satisfactory operation at such temperatures and speeds for periods to ten hours. Longer bearing life in terms of hundreds of hours was considered as an ultimate objective.

Let us examine why a material such as a powdered solid might perform the function normally accomplished by liquid lubricants and greases. To do this it is first necessary to determine the function of the lubricant within a ball bearing. There exist two basically different types of contact regions in a bearing, i.e., (1) the essentially rolling contact of the balls in the raceways, and (2) the sliding contact of the balls on the ball retainer pockets and of the retainer on the retainer locating shoulders of the bearing race. The function of the lubricant, therefore, is to prevent seizure, galling and wear in the bearing at these contact surfaces.

To accomplish these ends, it is supposed that the effective lubricant is a film[3, 4] of material that separates bearing contact surfaces without transmitting such high stresses between the relatively-moving surfaces as to exceed the surface strength of the bearing material. Lubricant reaction in the two types of contact regions in a ball bearing is apt to be quite different. A considerable amount of shearing, and consequently heating, must be absorbed in the lubricant film at the sliding contacts. The lubricant must undergo this shearing without being wiped off the bearing surfaces and without decomposing from frictional heat.

At the rolling contacts, however, the film need only be sufficient to prevent welding and wear of the rolling surfaces under the load conditions imposed. With this film formation consideration in mind, materials were selected (from the general categories of reactive vapors and powdered solids) which might be capable of performing these functions. The selection of specific materials was dictated primarily by thermal stability, hardness, and film forming considerations.

One solution to the problem of insuring a film formation on bearing surfaces is to precoat the contact regions of the bearings with a film of lubricant material containing a binder. However, because the attrition rate of the film limited bearing life, this procedure was not considered desirable for operating periods of ten or more hours. The method adopted was to utilize a continuous lubricant supply, wherein the lubricant would adhere to the contact surfaces and be continually replenished during bearing operation. The important consideration in utilizing a continual flow is the adherence of the lubricant to the metal surfaces; some means must be sought to insure that film formation is accomplished. Two possible means to attain lubricant film formation are by chemical reaction of the lubricant with the surface of the bearing material, or by the physical absorption of the lubricant on the surface. From this it is evident that the bearing material is an important consideration if some type of reaction between the lubricant and the bearing material is desirable. The approach followed was to select bearing materials suitable for operation in the 1200°F temperature range, and then investigate the various powdered and gaseous materials which might react to form a protective film on the bearing contact surface.

The formation of such a film is only the first step in attaining satisfactory operation of a bearing-lubricant system. The nature and consistency of the film must also be considered. It must be strongly bonded if it is to be maintained in spite of the mechanical and thermal stresses developed by high-speed, high-temperature rolling and sliding. The rate of reaction of the filming process must be such that it insures a continual replenishment of the film during operation. If filming is too rapid, the lubricant material may build up in the bearing, resulting in a reduction of internal bearing clearance and excessive bearing loads. If, on the other hand, filming is intermittent, the uneven film on the contact surfaces may result in rough operation and high vibrational loads. Therefore, it is quite possible that some materials which might function as a lubricant will not be suitable for use with ball bearings.

Because of the important role the bearing material plays in the ability of a lubricant to function, the program was divided into four general categories and conducted in the order outlined:

(1) Bearing Material Selection
(2) Bearing Design
(3) Lubricant Selection
(4) Lubricant-Bearing Evaluations

This procedure introduces the approach of a bearing-lubricant system to obtain the program objectives. It is important to note that test evaluations are still being carried out. However, it can be stated that based on the technical data obtained to date, it is entirely feasible to operate rolling-contact bearings at high temperatures and high speeds using powdered lubricants.

## BEARING MATERIALS

Based on the results of a comprehensive survey of available high-temperature materials suitable for use in ball bearings, it was soon observed that no single material is outstanding for use in raceways and rolling elements at temperatures in the 1200°F temperature region. Materials of the cobalt alloy family and the carbide cermets appear to offer more promise in the 1200°F temperature range because of their friction, wear and physical properties at room and elevated temperatures. As a result of this survey, bearings were constructed using three different cobalt alloy materials, Stellite Star J for both raceways and balls, Haynes Alloy No. 25 for raceways and retainers, Stellite No. 3 for retainers. In addition, bearing raceways, balls and retainers were also constructed of two different grades of titanium carbide cermets, Kentanium K163A-1 and K162B. Although the nickel alloys were not used for raceways and balls because of lower hardness properties, one alloy (Rene'41) was utilized as a retainer material.

## BEARING DESIGNS

Because of the considerations of thermal gradients within the bearing and possible lube build-up problems, a bearing design was chosen containing what was considered to be sufficient internal clearance (0.0028 to 0.0030 inch) while directing the remaining geometry toward maintaining minimum stress levels. An angular contact design was selected as the suitable type bearing for high-speed operation to 50,000 rpm. A size 204 (20-mm bore) bearing, which was considered as representative of those bearings found in secondary power supply applications, was chosen for all investigations.

A solid-machined retainer design guiding on the inner race was used as the ball separator. Modifications to a straight ring type design were also fabricated in an attempt to reduce retainer weight and to provide relief for lubricant and wear debris. However, no advantage was noted from these modifications during actual bearing evaluations.

## INVESTIGATION PROCEDURE AND APPARATUS

With the selection of specific bearing materials finalized, and the general lubricant categories established, it was necessary to devise an evaluation procedure for screening lubricant materials which did not involve the long and expensive method of using complete bearings for every lubricant. Therefore, the Battelle Memorial Institute conducted a research program to thoroughly investigate and select specific potential lubricant materials. Materials selected were evaluated in a rolling disk device to determine friction and wear characteristics. This machine, as shown in Figure 1, was designed to simulate the rolling and sliding action of ball bearings. Lubricants and lubricant mixtures considered successful during these evaluations were further screened in a complete bearing using the Stratos combined load bearing test rig as shown in Figure 2. Due to the dynamic load influences induced in the bearings at high-speed conditions with this rig, a second rig was utilized for investigations of maximum lubricant-bearing capabilities.

## INITIAL LUBRICANT SCREENING EVALUATIONS

A number of materials of the sulfide family, one soft oxide and several other powdered materials such as graphite and boron nitride, comprised the selection of powdered lubricants. Three organic

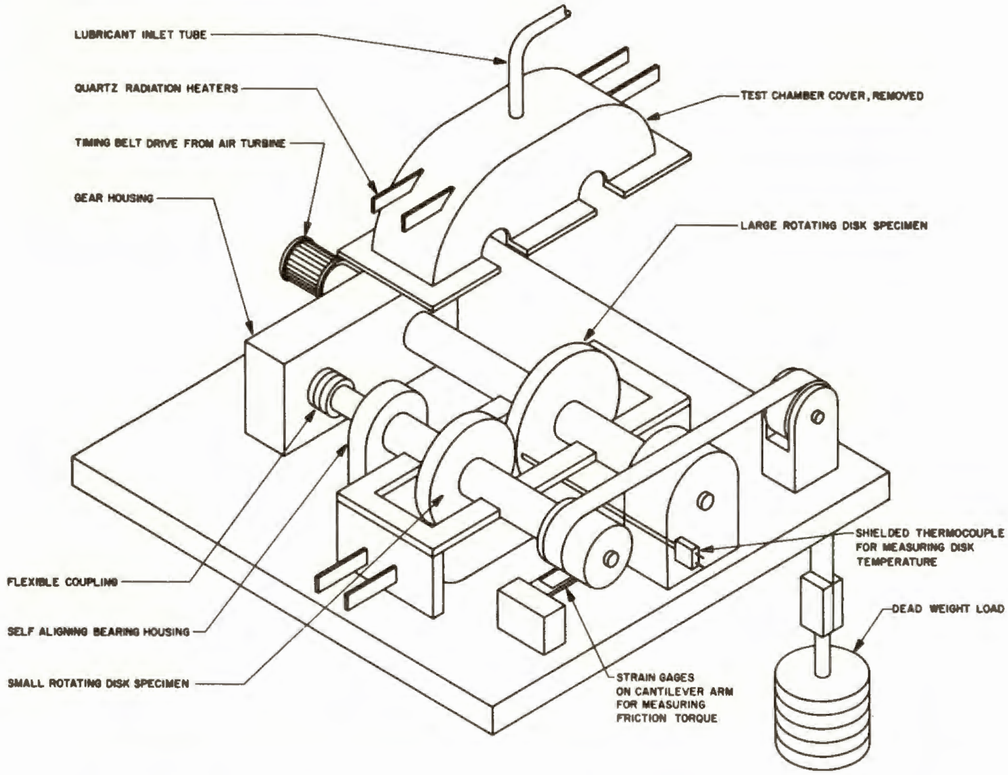



FIGURE 1. HIGH-TEMPERATURE ROLLING DISK MACHINE

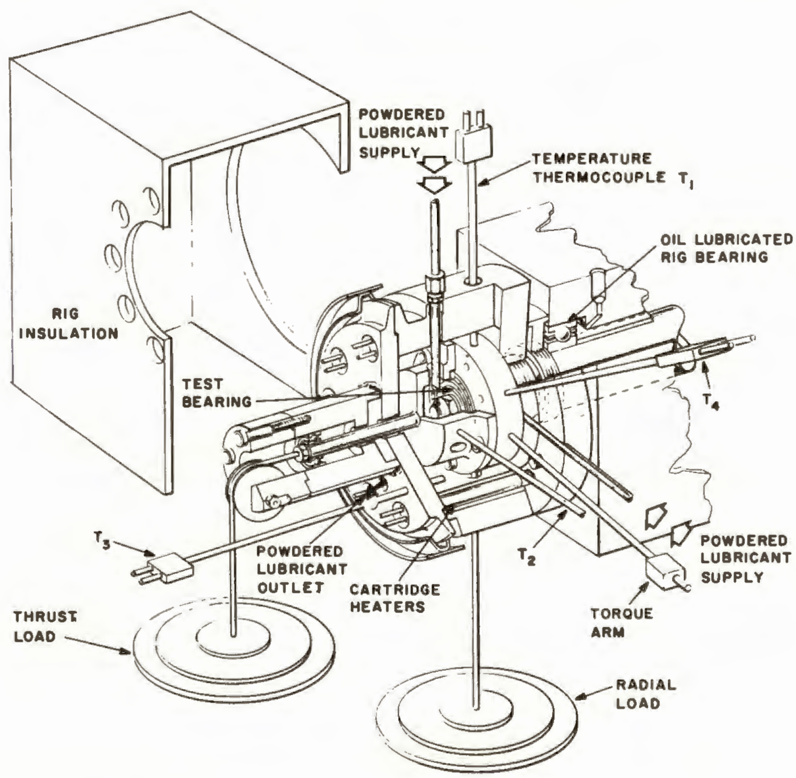


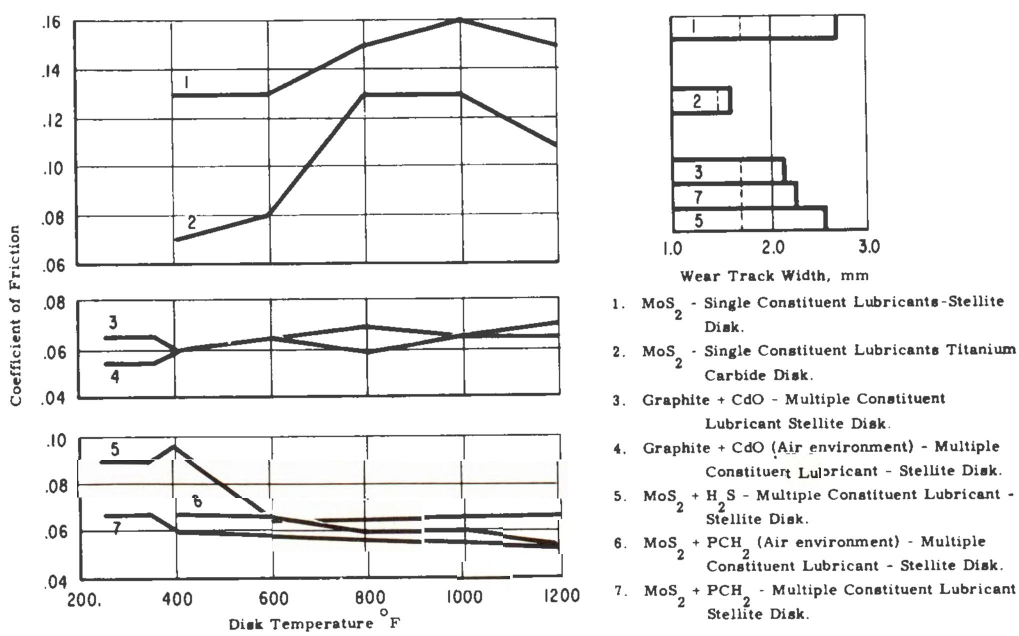

FIGURE 2. HIGH-TEMPERATURE COMBINED LOAD BEARING TEST RIG

halogen-containing vapors which might be capable of reacting with the bearing surfaces, and one sulfide-containing gas were also selected for screening evaluations in the rolling disk machine.

A total of seventeen different single-constituent lubricant materials were screened in the rolling disk machine. Of the powdered materials, those considered worthy of evaluation in a bearing at 1200°F were lead oxide, bismuth sulfide, metal-free phthalocyanine, graphite and molybdenum disulfide. (All lubricants were recommended for use in a nitrogen atmosphere.) Molybdenum disulfide was also considered capable of operations over the temperature range from room temperature to 1200°F in a nitrogen atmosphere. Generally, the single-constituent powdered lubricant materials were effective over limited temperature ranges, but not throughout the entire range. They also require an inert atmosphere to protect them against lubricant oxidation.

The halogen-containing gases did not require an inert atmosphere because they create their own environment. Although the halogen gases provided some lubrication, their friction and wear performance was not as good as molybdenum disulfide and, therefore, wear was anticipated if they were used in a bearing. The most successful of the gases for the full temperature range was tetrabromoethylene. The hydrogen-containing gas (hydrogen sulfide) resulted in a rather high corrosive wear on cobalt alloy disk specimens at 1200°F. Hydrogen sulfide is not suitable for use with nickel-containing materials such as titanium carbide and Rene '41 because of its chemical affinity for nickel. If diluted in an inert gas and combined with another potential lubricant, it was felt that this gas might offer some promise when used with the cobalt alloy materials.

The results of the single-constituent lubrication evaluations were also of value in providing a basis for selecting promising lubricant mixtures. As a result, nine mixtures were evaluated of which three were considered suitable for bearing operation over the temperature range. The first two (molybdenum disulfide plus metal-free phthalocyanine, and graphite plus cadmium oxide) were capable of operation in either an air or a nitrogen atmosphere when used with both titanium carbide and cobalt alloy materials. The third (a mixture of molybdenum disulfide and hydrogen sulfide) was recommended for use in a nitrogen atmosphere with cobalt alloy materials only. The mixtures appeared to be capable of making up for the shortcomings of each single constituent. Figure 3 presents the results of the friction and wear evidenced during evaluations with these mixtures, as well as the results for molybdenum disulfide as a single-constituent material.




NOTE: Length of run - 15 minutes; speed 12,000 rpm (resulting in a mean surface velocity of 9,400 fpm with 4% sliding); temperature 1,200°F; Hertizan contact area widths shown by dashed lines representing 96,000 psi maximum Hertz stress for stellite disks and 118,000 psi maximum Hertz stress for titanium carbide disks if no wear occurs.

FIGURE 3. AVERAGE COEFFICIENT OF FRICTION IN ROLLING DISK EXPERIMENTS

## RESULTS OF LUBRICANT EVALUATIONS IN BALL BEARINGS

All of our lubricant evaluations conducted to date have been centered around the use of powdere( lubricants, although the use of at least one mixture of a powder and a gas will be evaluated in the near future. When using the powdered-type lubricants, the bulk lubricant is stored at room temperature and preheated during its travel to the bearing. The powder is picked up by a gaseous carrier, which also provides the bearing environmental atmosphere. At a 1200°F bearing temperature the lubricant-carrier combination attains a temperature of approximately 900°F before entering the test bearing. As far as possible, each lubricant-bearing combination was screened at 1200°F in a bearing operating at a speed of 25,000 rpm and under loads of 50 pounds radial and 50 pound thrust for a period of two hours. Successful combinations were further evaluated under similar conditions at room temperature. An additional two-hour run followed the room temperature operation to screen the temperature region between room and 1200°F. Dynamic loads imposed by the test rig were found to impose higher loads in the bearing than the recorded applied loads. Therefore, the initial screening was conducted under internal bearing stress conditions equivalent to the designed stress levels in the bearing at a bearing speed of 50,000 rpm. Although this screening condition was severe, it furnished a significant performance scale for the different lubricant-bearing combinations.

### Bearing Materials

During lubricant-bearing evaluations, it was observed that the cobalt alloy bearing materials were superior to the titanium carbide materials over the temperature range from room temperature to 1200°F as far as maximum bearing load capabilities are concerned. However, disk experiments indicated that titanium carbide materials had lower friction and wear properties than the cobalt alloys. Wear in the titanium carbide material bearings normally occurred by microscopic pitting, and failure occurred by gross pitting and plucking of the surface materials. The cobalt alloy materials generally wore by a polishing action, while failure occurred by metal flow, especially in the case of the wrought alloy Haynes No. 25. Dimensional thermal stability over long periods of time at 1200°F appeared to be a shortcoming of this wrought cobalt material. A dimensional reduction with time at temperature was encountered with the wrought alloy, although this condition was not considered detrimental to bearing operation for periods of ten hours or less.

### Lubricant Films

The results of bearing operation appeared to depend on the formation and nature of a lubricant film on the bearing surfaces. Films formed in the rolling contact areas of the raceways generally appeared dull and granular, while films in the sliding contact regions of the retainer were smoother and polished. In the case of molybdenum disulfide, films were quite soft and operation was relatively smooth. A microscopic pitting type of wear was evidenced beneath the molybdenum disulfide films, although no marked degree of measureable wear was detected after operation at both room temperatur and 1200°F in a nitrogen atmosphere. A considerable build-up of powdered residue was observed throughout the test rig after a period of ten hours of operation.

Metal-free phthalocyanine, on the other hand, was a relatively clean lubricant when used at 1200°F temperatures. Unlike the other lubricants evaluated, the films were very light and in many cases could not be detected. The absence of deposits might be expected as this lubricant's decomposition rate increases with time at temperatures above 900°F. Despite the lack of visual signs of a film, this lubricant limited internal wear of titanium carbide bearings operating at 25,000 rpm and 1200°F to 0.001 inch per hour. Wear was slightly higher with cobalt alloy material bearings, although surfaces in both material bearings after operation were polished. At temperatures below 600°F this lubricant tends to clog and build up rapidly on the bearing surfaces causing rough operation, in contra to the smooth operation of the bearings at 1200°F.

Lead monoxide also has the tendency to clog the bearing by rapidly building up heavy films. Lower lubricant flows will prevent rapid build-up, but wear may be encountered if the flow is reduced too much. An optimum flow at which clogging does not occur and wear is maintained at a minimum was not achieved during 1200°F bearing evaluations with this lubricant. The films that were formed were smooth, but intermittent, with heavy local build-up areas which caused rough operation.

Hard crusty films were encountered during 1200°F evaluations with bismuth sulfide. These films caused very rough operation of the bearing. Analysis of the films revealed free bismuth metal apparently caused by bearing operation exceeding the disassociation temperature of the lubricant. Because of the high bearing temperatures (above 1265°F), the evaluations were not truly indicative of the performance of the lubricant for operation at 1200°F. However, they do furnish a good example of the importance of smooth surface films.

In addition to the relatively smooth, soft films formed during evaluations with molybdenum disulfide at both room temperature and 1200°F in a nitrogen atmosphere, a mixture of graphite and cadmium oxide in an air environment also showed the same type of film consistency at both temperature extremes. The pitting wear noted in the titanium carbide bearings with molybdenum disulfide was not as extensive when using the graphite cadmium oxide mixture.

## Bearing Performance

Bearing operations to 50,000 rpm for periods of 30 minutes have been conducted with molybdenum disulfide and with the metal free phthalocyanine molybdenum disulfide mixture with no measureable wear detected. These runs were conducted with a 100-lb bearing thrust load and no radial load. Incidentally, bearing outer-race temperatures stabilized during these runs between 200 and 225°F. The only reason for stopping this run was to inspect the bearing.

At 1200°F most of the bearing operation to date has been conducted at the 25,000 to 30,000 rpm bearing speed condition. Operations for periods of five minutes have been run at 1200°F and 50,000 rpm using the graphite/cadmium oxide mixture in a titanium carbide bearing. However, rig difficulties prevented longer operation at this speed during the run.

Because of the shorter duration of runs above 30,000 rpm, accurate bearing wear rate data are still very limited. At 30,000 rpm using the graphite cadmium oxide mixture, average wear rates (in terms of increase in internal bearing clearance) on titanium carbide bearings have been recorded in the range of 0.0001 to 0.0003 inches per hour over the temperature range. In the case of molybdenum disulfide, operations to periods in excess of 10 hours at a speed of 25,000 rpm and a temperature of 1200°F have been conducted without increase in internal bearing clearance. This same experience has been noted over shorter periods to 2 hours at room temperature and speeds from 10,000 to 50,000 rpm. Bearing wear rates with the molybdenum disulfide and the metal free phthalocyanine - molybdenum disulfide mixture appear to be a function of lube flow rate. At lubricant flows above 0.4 grams per minute, a loss in internal clearance has been encountered, while wear has occurred at flows below 0.2 grams per minute. Optimum flow rates for the entire temperature range are still being investigated.

As mentioned earlier, lubricant bearing combinations were screened first at the high temperature of 1200°F, then at room temperature and finally over the entire temperature range. Let us briefly review the results of operation over the temperature range.

The graphite-cadmium oxide mixture was evaluated in a titanium carbide bearing using an air environment wherein the temperature range from room temperature to 1200°F was scanned twice for a total running time of nine hours at a fixed bearing speed of 30,000 rpm and a 100-pound thrust load. No erratic areas of operation were evidenced during this run and a bearing wear of 0.0025 inches was measured at completion.

The metal free phthalocyanine-molybdenum in a nitrogen environment has been operated over the temperature range for a period of 4-1/2 hours in a Stellite Star J bearing and has indicated no erratic areas of operation. Internal wear of this bearing after operation was 0.0018 inches. Lubricant flow rate, however, was low at a rate of 0.125 gram per minute which, it was felt, contributed to this wear condition.

Operation with molybdenum disulfide in a nitrogen environment has consistently introduced an area of erratic operation between 800 and 1000°F in both material bearings. No additional bearing wear has been associated with this temperature region; however, higher torque levels and bearing vibrations were noted. Recently investigations indicate that this may be caused by the change in frictional characteristics of molybdenum disulfide in this region. During evaluations of this lubricant in the rolling disk machine, it was noted that an increase in friction coefficient occurred at 600°F, (from 0.08 to 0.13 at 800°F) with titanium carbide disks. A drop in friction coefficient was again evidenced at 1000°F with a coefficient of 0.11 recorded at 1200°F. What this means to the bearing while operating over this range is greater frictional heating within the bearing and reduction in internal play. If the loss in play is sufficient, erratic operation of the bearing will result. Rapid traversing of this area, however, has been possible without bearing failure.

A comparison of torque values using molybdenum disulfide and graphite-cadmium oxide mixture is presented in Figure 4.

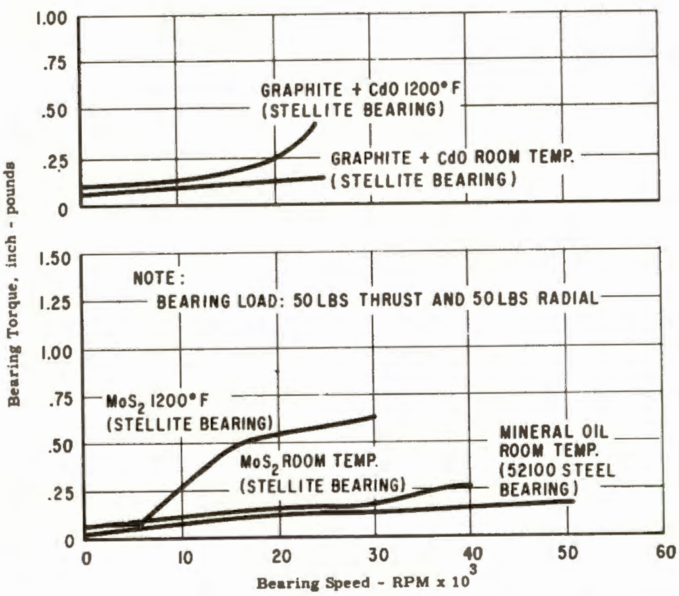



FIGURE 4. AVERAGE BEARING TORQUE OF SOME SINGLE-CONSTITUENT LUBRICANTS IN STELLITE MATERIAL 20-MM BEARINGS

Room temperature operation with both lubricants has indicated that bearing torques do not differ greatly from those encountered utilizing a mineral oil under the same operating conditions. As noted, the higher torque values have been observed with both lubricants at the 1200°F temperature condition.

## CONCLUSION

The problem of high-temperature, high-speed operation of a bearing-lubricant system is a two-fold one. When operation is desired over a broad temperature range, consideration must be given to differential expansion rates between the various materials being utilized and the thermal gradients that may occur during heating and cooling cycles. For high-speed operation, alignment, balance and precision of shaft components are essential but are adversely affected by the problems associated with high-temperature operation. Despite these obvious difficulties and other less apparent problem areas, operation has been successfully conducted with at least three lubricant-bearing systems. Bearing speeds of 50,000 rpm have been attained for short periods of five minutes at 1200°F and thirty minutes at room temperature with no apparent wear. Longer periods of operation to 11 hours have been successfully completed at 1200°F and speeds of 25,000 to 30,000 rpm with molybdenum disulfide in a nitrogen atmosphere. Successful operation over the temperature range from room temperature to 1200°F at speeds of 30,000 rpm have also been conducted for periods of nine hours with a graphite/ cadmium oxide mixture in an air environment and for periods of five hours with a $MoS_2/PCH_2$ mixture. These results have been possible with both cobalt alloy and titanium carbide material bearings, although bearing fatigue life under the conditions investigated appears superior with the cobalt alloy materials.

Evaluations have indicated the importance of approaching the problem of high-temperature ball bearing operation as a lubricant-bearing system and have shown the feasibility of bearing operation at both high speeds and high temperatures using powdered type lubricants. Investigations are continuing to more fully explore the capabilities of these systems. It is anticipated that in the near future the program objectives of speed and temperature for periods of at least ten hours will be attained and that longer periods of ball bearing operation will be possible.

## ACKNOWLEDGEMENTS

The research program discussed in this paper was conducted jointly for the Wright Air Development Division by the Stratos Division of Fairchild Engine and Aircraft Corporation, Battelle Memorial Institute and Tribo-Netics Laboratories under the auspices of the Stratos Division. The work and contributions of the Battelle Memorial Institute and Tribo-Netics Laboratories are sincerely acknowledged.

## LIST OF REFERENCES

1. Wilson, D. S., Gray, S., Sibley, L. B., et al. "The Development of Lubricants for High Speed Rolling Contact Bearings Operating at 1200°F Temperature" WADC TR 59-790, December 1959.

2. Wilson, D.S., Gray, S., Orcutt, F. K., et al. "The Development of Lubricants for High-Speed Rolling-Contact Bearings Operating Over the Temperature Range to 1200°F", Progress Report No. 1, WADD Contract AF 33(616)-6589, Supplemental Agreement No. 1 (60-717), April 1960.

3. Bowden, F. P. and Tabor, D., The Friction and Lubrication of Solids, Clarendon Press (Oxford), 1950.

4. Marshall, B., Peterson, and Johnson, R. L., "Friction of Possible Solid Lubricants with Various Crystal Structures," NACA Technical Note 3334, December 1954.