ADVANCED BEARING TECHNOLOGY

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PREFACE

THIS BOOK is an outgrowth of a set of lecture notes originally published for an advanced course on bearing technology at the University of California at Los Angeles. Its objectives are twofold:

(1) To present an exposition of the fundamentals of (a) friction and wear, (b) fluid film bearings, and (c) rolling-element bearings

(2) To demonstrate, through discussion of selected research results, how fundamental principles can be applied to the solution of unique and advanced bearing problems involving environmental factors such as extreme temperature, radiation, high vacuum, and corrosive fluids

The book is devoted primarily, in the examples and the discussion of research results, to advanced bearing problems; for example, the current and anticipated bearing problems in aircraft, in missiles, and in spacecraft are covered in some detail. The principles established and enunciated herein are, however, not limited in their application to advanced bearing problems. On the contrary, these principles apply equally well to mundane and ordinary bearing problems.

Many of the research investigations described herein were a part of the exploratory research program being conducted at the laboratories of the NASA Lewis Research Center by the authors and their colleagues. This research program was designed to explore the fundamentals in advanced problem areas and to establish basic principles, where possible, in these advanced areas. Application of these basic principles is possible not only within the advanced areas but under ordinary conditions as well.

The two chapters of this book that were written by guest authors are natural outgrowths of the lectures that they originally gave as part of the advanced course on bearing technology.

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CHAPTER 1

Introduction and Definition of Newer Problem Areas

By EDMOND E. BISSON

IT IS THE PURPOSE OF THIS BOOK to discuss some of the fundamentals of bearing technology and to examine closely current and anticipated problems in the field of bearings. After a general examination of problem areas, there will be some discourse on the possible approaches to these various problems.

Many of the subjects considered are not new. There are, however, many new applications in which the state of the art is not well defined, and further information is required before successful operation under extremely severe conditions is possible. Therefore, this book is divided generally into two principal parts: (1) a discussion of fundamentals, and (2) a review of current and anticipated bearing problems. The discussion of fundamentals should be applicable to many of the applications provided that the conditions can be well defined.

Some applications that impose extremely severe operating conditions on bearings and other surfaces to be lubricated include three general types, aircraft, missiles, and spacecraft. Each one of these applications will be discussed in turn—very generally at this point and in more detail later on. There are, of course, many other sources of bearing problems. These other bearing problems may be equally as severe as those discussed; the particular situations discussed in this book are for illustration only.

In aircraft applications, the operating conditions as applied to bearings and other lubricated surfaces have become quite severe, particularly with the advent of large, high-speed aircraft. Supersonic speeds, as well as high subsonic speeds, result in high operating temperatures over the entire aircraft but particularly within the engine. The stagnation temperature at high speeds is such as to cause a very high compressor-inlet temperature in the standard turbojet engine;

further compression of the air within the compressor (even though this may be a low-pressure-ratio compressor) results in a considerable temperature increase. Temperatures, as a function of Mach number, are shown in figure 1–1. The proposed Mach 3 transport would have a compressor-inlet temperature higher than 600° F and an estimated compressor-discharge temperature higher than 1200° F. As a general rule, the entire temperature level of the bearings within the turbojet engine for supersonic speeds (as well as for high subsonic speeds) is quite elevated. At the same time, many of the design features of the engine such as high rotative speeds and large size (resulting in large bearing sizes) further impose severe operating conditions on the bearings. The control surface bearings will also be required to operate at high ambient temperatures, since at supersonic speeds the entire aircraft structure will be exposed to high stagnation temperatures.

In missiles, the principal bearing problems occur in the turbopump. For high-performance missiles, the rocket engine usually incorporates a turbopump in order that high pressures may be available to the combustion chamber. Also, for high-performance missiles, high-energy propellants (e.g., liquid hydrogen and liquid oxygen) are utilized. Because most missiles are weight limited and must show a high degree of reliability, turbopump weight and complexity must be minimum. Thus, a complex lubrication system incorporating a separate lubricant may not be tolerated. Hence, for high-performance engines utilizing high-energy propellants, one thinks in terms of cooling and lubricating the bearings with the fluid being pumped, that is, with liquid hydrogen or liquid oxygen.

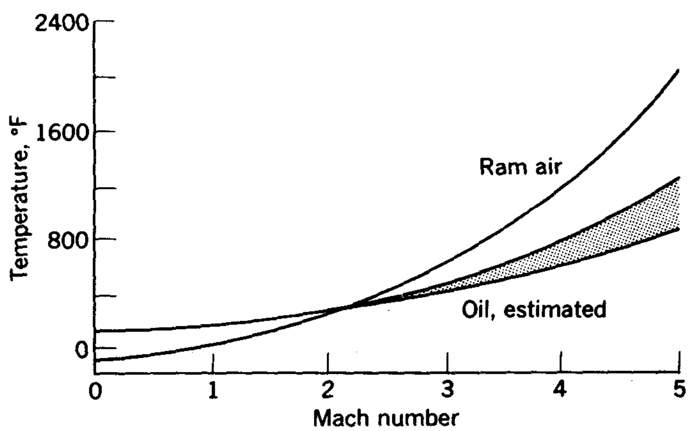

FIGURE 1–1.—Effect of Mach number on operating temperatures. (From ref. 3.)

Some of the properties of liquid hydrogen and liquid oxygen and other cryogenic liquids are shown in table 1–I. These fluids are not noted for their ability to lubricate effectively, particularly under boundary lubrication conditions; for example, liquid hydrogen is a poor lubricant for two significant reasons. First, it is a reducing medium; that is, it tends to reduce the surface oxide layers, which help appreciably in lubrication of surfaces under boundary conditions. Second, liquid hydrogen has an extremely low viscosity, and hence the possibility of building a hydrodynamic film is extremely remote. For example, the viscosity of liquid hydrogen at its boiling point (−423° F) is 2×10^{-9} reyn. This value is approximately equal to the viscosity of air at room temperature. (For comparison, the viscosity of SAE 30 oil at 100° F is 10^{-5} reyn.) Hydrogen is, however, an excellent coolant provided that the lubrication function can be supplied in some other manner. Similarly with the other fluids, such as oxygen and fluorine, problems occur because of chemical reactivity. This is particularly so with fluorine but is also true with liquid oxygen. Since both of these fluids are strong oxidizers, one can conceive of operating conditions within a bearing (particularly at the surfaces in pure sliding) under which the amount of heat generated at the sliding surface is great enough that chemical reaction occurs between the oxygen, or fluorine, and the bearing surface. Of particular importance is the fact that the reaction rate can reach disastrous levels; in other words, the surfaces can "burn." Under such conditions, one does not anticipate long life for such bearings.

TABLE 1–I.—PROPERTIES OF CRYOGENIC LIQUIDS

Liquid	Freezing point, °F	Boiling point, °F	Liquid density, lb/cu ft, at—		Liquid viscosity,[a] reyn, at—	
			Boiling point	−320° F	Boiling point	−320° F
Helium	[b]−458	−452	7.6	----	7×10^{-10}	---------
Hydrogen	−434	−423	4.4	----	19	---------
Nitrogen	−346	−320	50.1	50.1	230	230×10^{-10}
Fluorine	−360	−306	94.0	96.5	372	489
Argon	−309	−303	87.4	----	----------	---------
Oxygen	−361	−297	71.2	75.5	274	333
Methane	−299	−258	25.8	----	----------	---------

[a] Viscosity of SAE 30 oil at 100° F is approximately 10^{-5} reyn.
[b] At a pressure of 26 atm.

In spacecraft, the problem with bearings lies particularly in the pumps required to handle the working fluids. Again, if there are rocket engines, the turbopump for these engines will of necessity incorporate bearings cooled and lubricated by the fluid being pumped. Also, for spacecraft that are propelled by electric propulsion (ion propulsion, plasma propulsion, etc.), electric power for such propulsion may be generated by a turbine utilizing, as the working fluid, liquid metals such as mercury, rubidium, potassium, and sodium. As was the case for the bearings operating in turbopumps handling high-energy propellants, here again the fluids being pumped are not noted for their lubricating ability. Some of the properties of these materials are shown in table 1-II. These fluids are not only corrosive, but they have a strong reducing effect on surfaces. Thus, oxides on the bearing surfaces, which might normally help in the lubrication process, are quickly removed by the reducing action of the liquid metals. Also, at the very high temperatures under which the systems will be forced to operate in order to generate electric power in the megawatt range, the viscosity of these liquid metals will be quite low. Hence, we have a problem of using a fluid for lubrication which has low viscosity and is very corrosive.

Other problems in spacecraft involve the operation of mechanisms in a vacuum, for example, such components as horizon seekers, sun or star finders, or radar antennas. These components must normally operate in the vacuum of outer space, unless an attempt is made to solve the problem by using hermetically sealed systems, which are very complex and heavy. Since minimizing weight and complexity

TABLE 1-II.—PROPERTIES OF LIQUID METALS

Metal	Melting point, °F	Boiling point, °F	Liquid density, lb/cu ft at—		Liquid viscosity,[a] reyn, at—		Vapor pressure at 2200° R, lb/sq in. abs
			Boiling point	1200° F	Boiling point	1200° F	
Mercury	−38	674	794	752	13×10^{-8}	[b] 10×10^{-8}	3044
Rubidium	102	1295	81. 9	82. 7	2. 2	2. 2	91
Potassium	146	1395	41. 4	43	1. 9	2. 0	64
Sodium	208	1630	46. 3	49. 3	2. 2	2. 9	25
Lithium	357	2430	26. 2	29. 2	[b] 2. 0	[b] 2. 7	0. 5
NaK-78	12	1456	42. 6	44. 7	2. 0	2. 16	51

[a] Viscosity of SAE 30 oil at 100° F is approximately 10^{-5} reyn.
[b] Extrapolated.

is desirable, finding solutions for design and lubrication of bearings to be operated in vacuum is necessary. Figure 1–2 shows pressure as a function of altitude. Outside the Earth's atmosphere, the pressures involved are in the order of 10^{-13} millimeter of mercury in the solar system and in the order of 10^{-16} millimeter of mercury in interstellar space.

As can be seen from the quick description of some of the applications, which will be discussed later in more detail, there are many unique problems that will face the bearings of the immediate or distant future. Hence, of necessity, the fundamental principles that may be applied to bearing designs and lubrication techniques must be discussed in this book.

At this point, the mechanism of bearing failures under the severe conditions of operation previously described should be examined with some care. The examination should be concerned particularly with a search for some distinguishing feature common to all failures. If there *is* some distinguishing feature common to failures in most bearing types, the solution to prevention of these failures becomes appreciably simpler. Therefore, the failure modes of the three types of bearings are discussed individually.

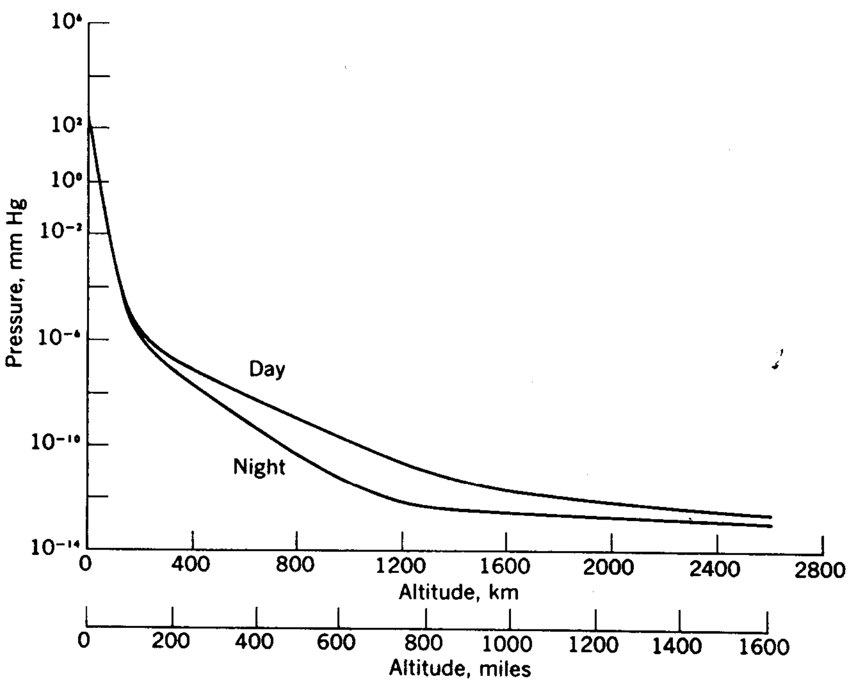

FIGURE 1–2.—Pressure as a function of altitude. (From ref. 4.)

In the rolling-element bearing, the most common type of failure involves a lubrication failure of the cage, usually at the cage locating surface. Figure 1–3 shows the various components of a rolling-element bearing. The cage is essentially a free-floating body and hence must be located at some rubbing surface, usually the inner or outer race. In figure 1–3, the cage is located by the inner race, as shown by the small clearance between cage and inner race. Thus, the cage-locating surface becomes essentially a plain bearing (i.e., a sleeve or hydrodynamic bearing) of small length-to-diameter ratio. Such a hydrodynamic bearing possesses very low load-carrying capacity, because it is difficult for pressure to build up between the surfaces since the end leakage is very high. Hence, boundary or thin-film lubrication exists at the cage-locating surface, and severe wear and metal transfer can occur because of the metal-to-metal contact.

By way of definition, figure 1–4 illustrates the regions of boundary lubrication and fluid lubrication. The curves are for a plain journal

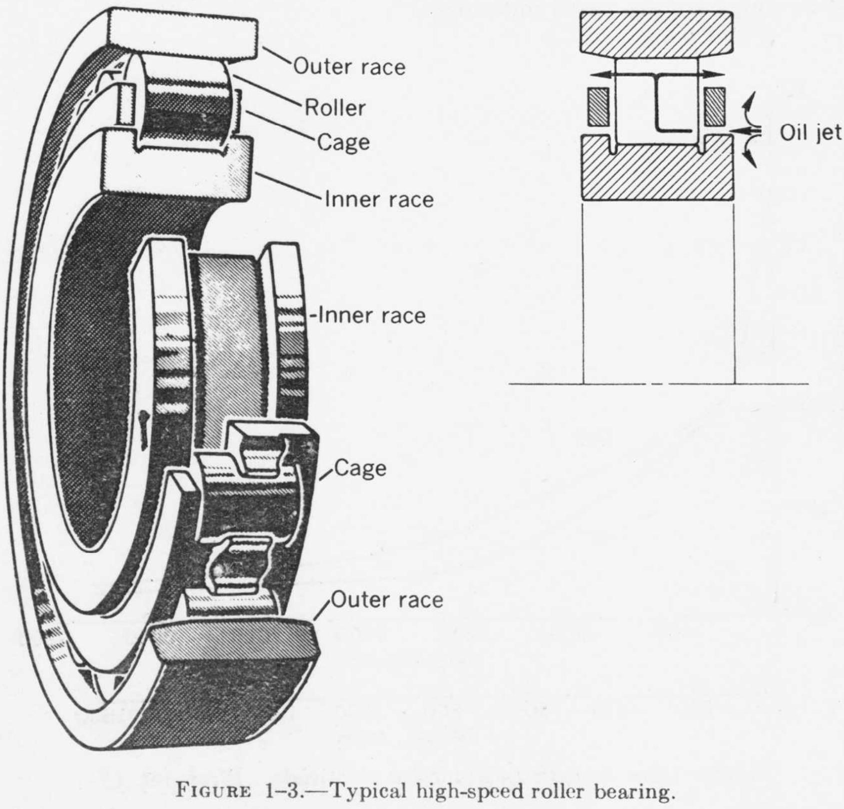

FIGURE 1–3.—Typical high-speed roller bearing.

bearing and show friction coefficient and film thickness plotted against the well-known parameter ZN/P, where Z is viscosity, N is rotational speed, and P is load per unit projected area or bearing pressure. To the right of the dashed vertical line is the region of fluid or thick-film lubrication where the surface asperities are completely separated by an oil film of such thickness that no metal-to-metal contact can occur. To the left of the dashed vertical line is the region of boundary or thin-film lubrication. As noted in the upper right sketch, the film thickness in boundary lubrication is so small that asperities can, and do, contact through the oil film (fig. 1–4).

In the case of fluid or thick-film lubrication, only the properties of the lubricant are of importance since the asperities do not contact. In the case of boundary or thin-film lubrication, the properties of the metals are of primary importance since there is true metal-to-metal contact at the asperities. While the properties of the lubricant under these conditions are of secondary importance, they are not to be

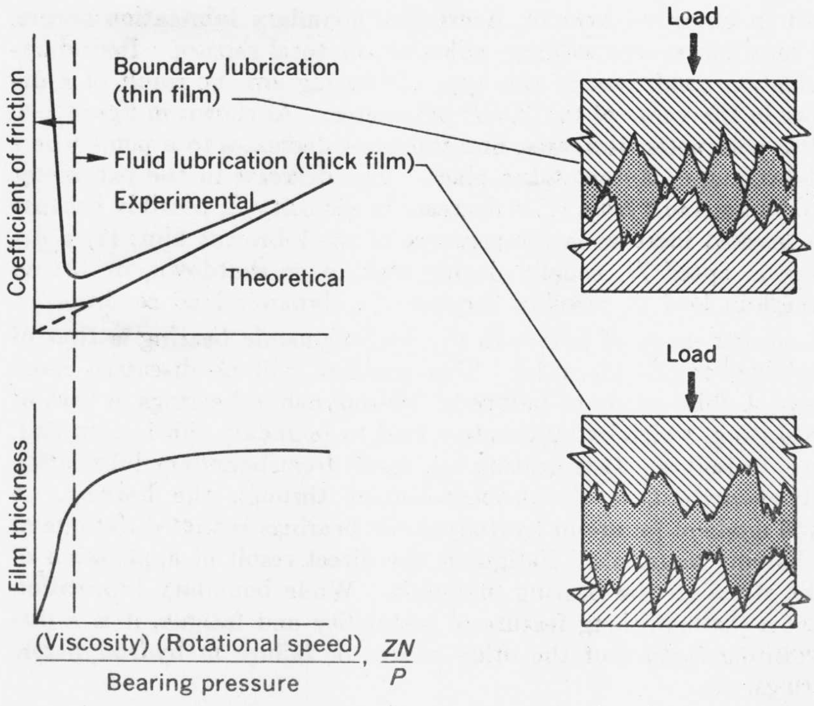

FIGURE 1–4.—Boundary and fluid lubrication.

neglected because they can strongly influence the type of damage that will occur. The lubricant in this case is serving as a contaminant. This contaminating function of the lubricant is discussed in more detail herein.

A second mode of failure in rolling-element bearings is that of wear; this failure is again a result of the existence of boundary lubrication permitting metal-to-metal contact.

A third mode of failure involves overheating and possible lockup. Overheating usually results from a combination of (1) boundary lubrication, (2) inadequate flow of the coolant-lubricant through the bearing, and (3) excessive heat generation in the bearing.

A fourth mode of failure involves fatigue under rolling-contact conditions. If the bearing has been properly designed to eliminate other failure modes (cage failure, wear, and overheating), the failure is expected to be caused by fatigue. Fatigue is one failure mode which is not dependent on boundary lubrication.

In hydrodynamic bearings, one of the common modes of failure is that of wear and/or seizure. This failure is usually caused by the existence of boundary lubrication or thin-film conditions at the bearing. The metal-to-metal contact under these conditions can result in excessive wear or, if extreme boundary lubrication occurs, can result in severe welding, adhesion, or total seizure. Boundary-lubrication conditions in this type of bearing are the result of a decrease in the value of the ZN/P parameter. As shown in figure 1–4, as this parameter decreases, film thickness decreases to a point where metal-to-metal contact takes place. The decrease in the parameter ZN/P may result from (1) a decrease in viscosity Z, possibly because of a marked increase in temperature of the lubricant film; (2) a decrease in speed N, usually during startup or shutdown, or (3) an increase in load P, possibly because of a dynamic load condition.

A second mode of failure in the hydrodynamic bearing is that of instability or oil-film whirl. This problem will be discussed more fully. A third mode of failure in hydrodynamic bearings is that of overheating, which can ultimately lead to boundary lubrication and, hence, to failure. Overheating can result from boundary lubrication or inadequate flow of lubricant-coolant through the bearing. A fourth mode of failure in hydrodynamic bearings is that of fatigue of the bearing materials. Fatigue is the direct result of application of cyclic stress to the bearing materials. While boundary lubrication is not a distinguishing feature of instability and fatigue, it is a distinguishing feature of the other modes of failure in hydrodynamic bearings.

In hydrostatic bearings, the chief mode of failure is that of instability, which may permit metal-to-metal contact and thus excessive wear and seizure.

From a discussion of the different failure modes of all bearing types, it is noted that a distinguishing feature common to many of these failure modes is the existence of boundary-lubrication conditions. Hence, it becomes important to know the mechanism involved when two surfaces slide together in the absence of enough lubricant to permit establishment of fluid or thick-film lubrication. When the mechanism of failure under these conditions of metal-to-metal contact is known, solutions can be devised to prevent severe adhesion and often complete seizure of the surfaces to each other.

Discussed herein are the principles of boundary lubrication and, in particular, the adhesion theory of friction. The strong adhesion and welding of surface to surface under adverse conditions are explored in detail and the principles involved in reducing friction, surface welding, and wear are explained.

The principles of hydrodynamic theory are also described. Since this discussion of hydrodynamic theory is concerned with the formation of thick films in order to achieve hydrodynamic lubrication, the discussions will cover the development of the Reynolds equation and show how such a film is produced and the pressure pattern within this film. The solutions for journal bearings and for slider bearings under these conditions will be discussed as well as solutions for some of the hydrodynamic bearing failure modes previously mentioned.

Also discussed are the principles of operation of hydrostatic bearings. Since the very low viscosities of some of the working fluids mentioned earlier may not permit development of a hydrodynamic or thick film, it may be necessary to design the bearings to operate under externally pressurized conditions. These are the so-called "hydrostatic bearings."

One chapter of this book is devoted to discussion of gas-lubricated bearings. The very high temperature levels expected in many applications may preclude the use of conventional liquid lubricants; under these conditions, gases may be used as the lubricant either in hydrodynamic or hydrostatic (externally pressurized) bearings.

The fundamentals of rolling-element bearings are described, and such items as bearing types and designs, the kinematics involved, the contact stresses, and the resulting fatigue problem as well as special problems of materials are explored.

Another chapter is devoted to the subject of modern developments in liquid lubricants. Liquid lubricants are still of considerable interest because of their anticipated use for many years and their versatility. One problem with the liquids is that of fluidity range;

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this problem is illustrated very roughly in figure 1–5, which is a plot of viscosity against temperature for four different liquid lubricants. Also shown in figure 1–5 are the Mil–L–7808 specification limits. These specifications are for the lubricants presently used in many turbojet engines. The four different curves are representative of different classes. The polyglycols would have curves roughly between the extremes shown, while the fluorocarbons (which are quite stable fluids) generally have a steeper viscosity-temperature curve than does the petroleum. All the curves of figure 1–5, however, illustrate the fluidity problem to a certain degree, particularly as applied to high-temperature lubrication of bearings. Liquid lubricants, in general, show a very marked decrease in viscosity as temperature increases. At the low end of the temperature range, one quickly approaches the freezing point of most liquids. This fact (as well as high-temperature stability problems to be discussed later) places rather stringent requirements on the lubrication system designer, since it makes it mandatory for him to keep the lubricant temperature within certain well-defined limits.

A major problem with present liquid lubricants lies in their degradation at high temperatures. The degradation takes the form primarily

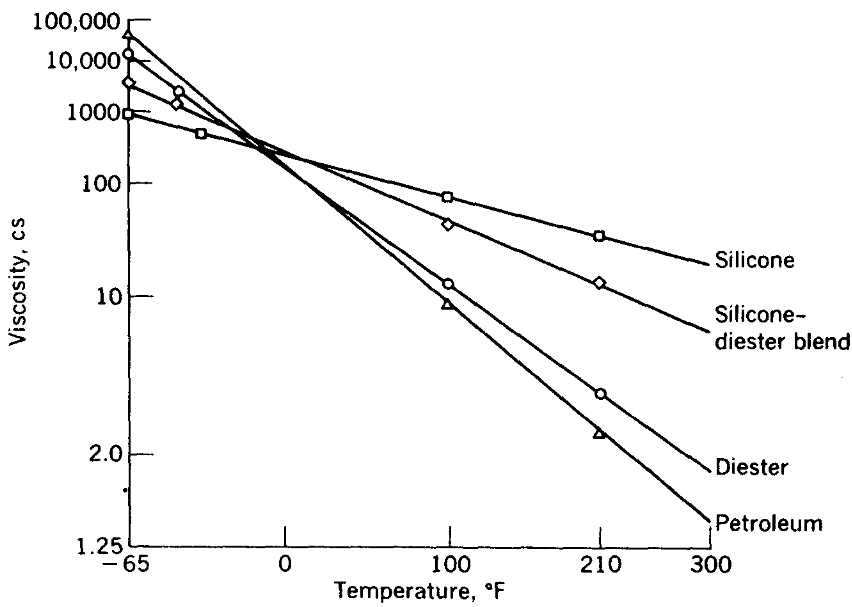

FIGURE 1–5.—Viscosity-temperature properties of various liquids. Mil–L–7808 specification limits: Maximum viscosity at −65° F, 13,000 centistokes; minimum viscosity at 210° F, 3.0 centistokes. (From ref. 5.)

of oxidation and also of decomposition because of thermal instability. Both of these mechanisms usually result in deposits on bearings and other parts from insolubles formed in the oil. Since the temperature limitation with liquids is established primarily by oxidation, one technique used to increase the temperature limitation involves the exclusion of oxygen. This exclusion can be achieved by use of a "closed" lubrication system or by use of an inert-gas blanket in the lubricating system. The closed lubrication system excludes oxygen by preventing the continual venting ("breathing") of the lubrication system. Experiments reported in reference 1 indicate that, with mineral oils, use of nitrogen as a blanketing medium increased the allowable bearing operating temperature as much as 150° F.

The next step beyond the present mineral oil and synthetic diester lubricants involves new classes of lubricants. These include such lubricants as polyphenyl ethers, hydrogenated petroleum fractions, or organometallics. Reference 2 shows that the hydrogenated petroleum fractions have the advantage at high temperature of showing clean "burn-off." That is, the oxidation products at high temperature are volatiles rather than insolubles. Since there is a relatively small amount of insolubles, the problem of deposition of the insolubles within the bearings during operation at high temperature is considerably reduced.

Because liquid lubricants are in many instances temperature limited to relatively low levels, it is necessary to consider the use of nonconventional lubricants such as solids and reactive gases. The solids include materials such as molybdenum disulfide and graphite as well as some newer materials (such as lead monoxide, calcium fluoride, and others). These solids may be utilized as loose powders to lubricate bearings or the bearing surfaces may be precoated with a thin film of lubricant. Reactive gases, that is, gases containing active atoms in the molecule, are discussed as possible lubricants under boundary-lubrication conditions. Here a distinction is made between the activity of the gases for this use and that of those used for externally pressurized bearings. In general, the gases for externally pressurized (hydrostatic) bearings would be relatively inert compared with the "reactive gases."

The commentary on liquid-metal-lubricated bearings is divided into two parts: First, a general discussion of the properties of the liquid metals, the general type of cycle, and the power-generation equipment which will use the liquid metals, and finally a discussion of the problems (such as high vapor pressure, corrosion, containment, low viscosity, etc.) to be expected with these materials at high temperature. Next

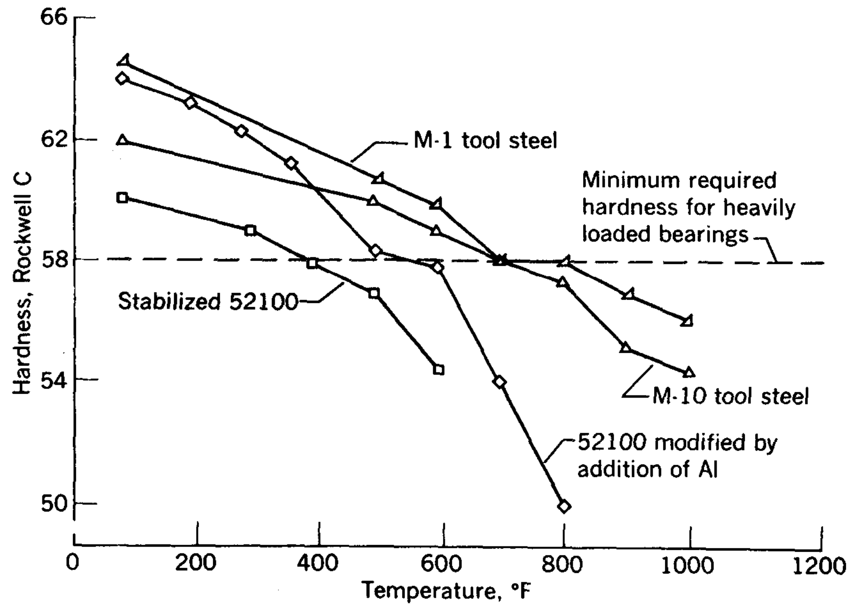

FIGURE 1–6.—Hardness of bearing materials at various temperatures. (From ref. 5.)

the hydrodynamics of bearings utilizing liquid metals as the working fluids will be covered.

The first part of the review of extreme-temperature bearing problems is concerned with the temperature limitation of conventional bearing materials and indicates the possible classes of materials for use at higher temperatures. As an example, figure 1–6 shows that the conventional material SAE 52100 for rolling-element bearings is limited by loss of hardness to temperatures lower than about 350° F. Other materials do, however, have promise of maintaining adequate hardness at high temperatures (fig. 1–6). The second part is devoted to the use of special lubrication techniques that permit bearing operation at very high temperatures. This includes discussion of such techniques as the "once-through" technique, which uses liquid lubricants at an extremely low flow rate. The discussion will also cover the operation of completely dry bearings.

Fatigue in rolling-element bearings is explored since it may become one of the very serious limitations on use of rolling-element bearings in mechanisms which have an *absolute* requirement of high reliability. This material will cover the effects of processing variables (such as material hardness, inclusions, classes of materials, etc.) as well as the influence of operating variables (such as lubricant viscosity, viscosity-pressure coefficient of the lubricant, load, speed, etc.).

The problems of operation of bearings and other surfaces to be lubricated (such as shaft seals) under extremely low temperature conditions are examined. Here reference is to the operation of bearings and seals in the presence of cryogenic liquids, such as liquid hydrogen, liquid oxygen, etc. Results from fundamental friction studies in the presence of cryogenic liquids such as liquid hydrogen, liquid oxygen, and liquid nitrogen are presented. These results are used in a selection of materials for bearings to be operated in cryogenic liquids. There is also a discussion of studies of full-scale rolling element bearings in liquid hydrogen.

The effects of vacuum and radiation on operation of bearings or other lubricated surfaces are described. Since some of the applications involve spacecraft and particularly operation of components in the vacuum of outer space, it is necessary to understand the mechanisms by which surfaces can fail in vacuum. For example, we know that under pressures in the order of 10^{-6} to 10^{-16} millimeter of mercury, contaminating films on the surfaces will gradually disappear if these films are organic in nature. If they are inorganic in nature, the films may disappear only if the temperature of the surface is relatively high. The surfaces may, therefore, be denuded of their protective films and may thus fail from a lubrication standpoint. The use of a nuclear reactor as a source of heat for an electric-power-generation system to operate in space imposes a radiation hazard on all mechanisms operating on the spacecraft. Shielding will, of course, be utilized to some extent; however, it is possible that some mechanisms will be exposed to fairly high radiation dosages of gamma rays and neutrons. These mechanisms must operate over long periods of time with a high degree of reliability; hence the effects of radiation on lubricants and on surface films are important.

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