Chapter 10
Bearings

10-1. General

Bearings can be divided into two subgroups: plain bearings and rolling-contact bearings. Both have their place in the world of machines. Each type has some obvious advantages and disadvantages, but there are subtle properties as well that are often ignored. Each type of bearing can be found in a multiplicity of places, and each can be lubricated with either oil or grease. Some bearings are lubricated by water, and some are lubricated by air (as in the case of a dentist's drill).

10-2. Plain Bearings

Plain bearings consist of two surfaces, one moving in relation to the other. Plain bearings can be the journal type, where both wear surfaces are cylindrical; thrust type, where there are two planar surfaces, one rotating upon the other; and various types of sliding bearings where one surface slides in relation to the other. All depend upon a lubricating film to reduce friction. Unless an oil pump is provided to generate the oil film, these bearings rely on shaft motion to generate a hydrodynamic oil wedge.

a. Advantages of plain bearings.

(1) They have a very low coefficient of friction if properly designed and lubricated.

(2) They have very high load-carrying capabilities.

(3) Their resistance to shock and vibration is greater than rolling-contact bearings.

(4) The hydrodynamic oil film produced by plain bearings damps vibration, so less noise is transmitted.

(5) They are less sensitive to lubricant contamination than rolling-contact bearings.

b. Types of plain bearings.

(1) Journal (sleeve bearings). These are cylindrical with oil-distributing grooves. The inner surface can be babbitt-lined, bronze-lined, or lined with other materials generally softer than the rotating journal. On horizontal shafts on motors and pumps, oil rings carry oil from the oil reservoir up to the bearing. In the case of very slow-moving shafts, the bearings may be called bushings.

(2) Segmented journal. These are similar to the journal except that the stationary bearing consists of segments or bearing shoes. Each shoe is individually adjustable. This type of bearing is commonly found in vertical hydrogenerators and large vertical pumping units. This bearing is usually partially immersed in an oil tub.

(3) Thrust bearings. These bearings support axial loading and consist of a shaft collar supported by the thrust bearing, many times in segments called thrust shoes. The thrust shoes are sometimes allowed to pivot to accommodate the formation of the supporting oil wedges. There are many different configurations

of the thrust bearing aimed at equalizing loading and oil wedges. The bearing is immersed in a tub of oil. On large hydrogenerators and pumps an oil pump is sometimes used to provide an oil film at start-up.

(4) Self-lubricated bearings. These are journal (sleeve) bearings in which the bearing surface contains a lubricant, usually solid, that is liberated or activated by friction in the bearing. This type of bearing is gaining popularity as a wicket gate bearing or wicket gate linkage bushing.

c. Plain bearing lubrication selection.

(1) The most common lubricants for plain bearings are mineral and synthetic oils, and greases. Mineral oils are generally used except in extreme hot and cold temperature applications where synthetics provide superior performance. Oil is used for faster rotational speeds where the hydrodynamic oil wedge can be formed and maintained. It also is used in high-temperature conditions where grease may melt or degrade. Grease is used for slower rotational speeds or oscillating movements where the hydrodynamic oil wedge cannot form. It is also used in cases of extreme loading where the bearing operates in boundary conditions. Table 10-1 shows some of the important considerations regarding lubricant selection.

Table 10-1
Choice of Lubricant

Lubricant	Operating Range	Remarks
Mineral oils	All conditions of load and speed	Wide range of viscosities available. Potential corrosion problems with certain additive oils (e.g., extreme pressure) (see Table 7.1).
Synthetic oils	All conditions if suitable viscosity available	Good high- and low-temperature properties. Costly.
Greases	Use restricted to operating speeds below 1 to 2 m/s (3.28 to 6.56 fps)	Good where sealing against dirt and moisture is necessary and where motion is intermittent.
Process fluids	Depends on properties of fluid	May be necessary to avoid contamination of food products, chemicals, etc. Special attention to design and selection of bearing materials.

Reference: Neale, M. J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd., Oxford, England.

(2) The lubricating properties of greases are significantly affected by the base oil and type of thickeners used. Table 10-2 provides general guidelines for selecting the type of grease for bearing lubrications. In Table 10-2, speed factor (also referred to as speed index) is determined by multiplying the pitch diameter of the bearing by the bearing speed as follows;

$$d_n = n \frac{D + d}{2} \tag{10-1}$$

where D is the bearing diameter (mm), d is the bore diameter (mm), and n is the rev/min. Speed factors above 200,000 are usually indicative of fluid film lubrication applications. The load column provides indications of the degree of loading on a bearing and is defined as the ratio of rated bearing load to the actual bearing load.

Table 10-2
Bearing Lubrication Considering Speed Factor

Load, Rated Applied	Temperature, C° (°F)	Base Oil	Thickener	Additives
		Speed Factor Less than 100,000		
<10	-56.6-17.7 (-70-0)	Mineral oil, synthetic, ester	Lithium	Graphite or MoS_2, rust oxidation
<10	-17.7-176.6 (0-350)	Mineral oil	Lithium, calcium, barium, aluminum sodium	Graphite or MoS_2, rust oxidation
<10	176.6+ (350+)	Synthetic, ester	Sodium, clay, calcium, lithium, polyurea	Graphite or MoS_2, rust, oxidation
		Speed Factor 100,000 to 500,000		
<10	-17.7-176.6 (0-350)	Mineral oil, synthetic, PAG, ester	Lithium, calcium, aluminum, barium, polyurea	Graphite or Mos_2, rust, oxidation
<10 (high) >30 (low)	-17.7-176.6 (0-350)	Mineral oil, synthetic, PAG, ester	Lithium, calcium, aluminum, barium, polyurea	EP, rust, oxidation
>30	17-7-176.6 (0-350)	Mineral oil, synthetic, PAG, ester	Lithium, clay, polyurea, aluminum, barium, calcium	Antiwear, rust, oxidation
		Speed Factor Greater than 500,000		
>30	-17.7-93.3 (0-200)	Mineral oil, synthetic, ester	Lithium, calcium, barium	Rust, oxidation

(3) Viscosity is the most critical lubricant property for insuring adequate lubrication of plain bearings. If the viscosity is too high, the bearings will tend to overheat. If the viscosity is too low the load-carrying capacity will be reduced. Figure 10-1 is a guide to selection of viscosity for a given operating speed. For plain journal bearings the surface speed u is given by:

$$u = \pi dn, \quad \text{m/sec} \tag{10-1}$$

and the mean pressure p_m is given by

$$P_m = \frac{W}{ld}, \; kN/m^2 \tag{10-2}$$

where

n = shaft speed, rev/s

l = bearing width, m

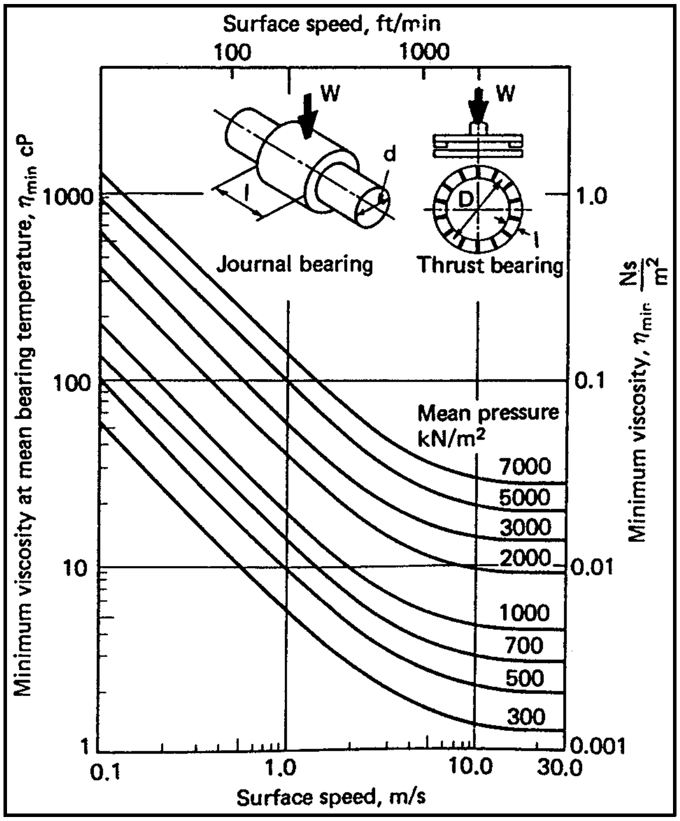

Figure 10-1. Lubricant viscosity for plain bearings (Reference: Neale, M. J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd., Oxford England)

d = shaft diameter, m

W = thrust load, kN

For thrust bearings, the surface speed u is given by Equation 10-1. The mean pressure is given by

$$p_m = \frac{0.4W}{lD}, \quad kN/m^2 \qquad (10\text{-}3)$$

where p_m, and l are as previously defined, W = thrust load, kN, and D = mean pad diameter, m. Equations 10-1 through 10-3 are intended to provide a means for understanding Figures 10-1 and 10-2. Refer to Machinerys Handbook, 24th edition, for a detailed discussion and analysis of bearing loads and lubrication.) Figure 10-2 shows the relationship between temperature and viscosity for mineral oils.

(4) Table 10-3 identifies some of the methods used to supply lubricants to bearings. The lubricant should be supplied at a rate that will limit the temperature rise of the bearing to 20°C (68 °F).

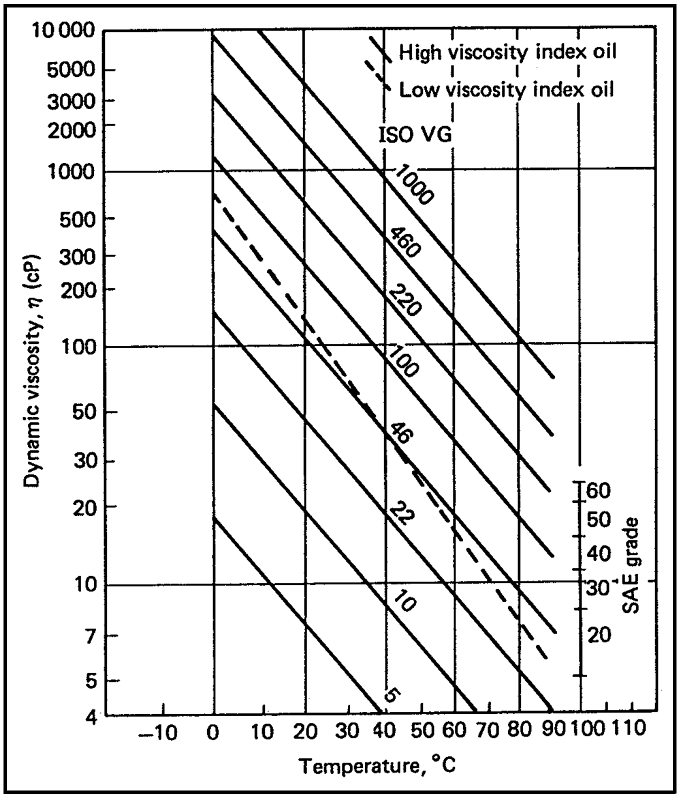

Figure 10-2. Typical viscosity/temperature characteristics of mineral oils (Reference: Neale, M. J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd, Oxford, England)

Table 10-3
Methods of Liquid Lubricant Supply

Method of Supply	Main Characteristics	Examples
Hand oiling	Nonautomatic, irregular. Low initial cost. High maintenance cost.	Low-speed, cheap journal bearings
Drip and wick feed	Nonautomatic, adjustable. Moderately efficient. Cheap	Journals in some machine tools, axles
Ring and collar feed	Automatic, reliable. Efficient, fairly cheap. Mainly horizontal bearings	Journals in pumps, blowers, large electric motors
Bath and splash lubrication	Automatic, reliable, efficient. Oiltight housing required. High initial cost.	Thrust bearings, bath only. Engines, process machinery, general
Pressure feed	Automatic. Positive and adjustable. Reliable and efficient. High initial cost.	High-speed and heavily loaded journal and thrust bearings in machine tools, engines, and compressors

Notes:
Pressure oil feed: This is usually necessary when the heat dissipation of the bearing housing and its surroundings are not sufficient to restrict its temperature rise to 20 °C (68 °F) or less.
Journal bearings: Oil must be introduced by means of oil grooves in the bearing housing.
Thrust bearings: These must be lubricated by oil bath or by pressure feed from the center of the bearing.
Cleanliness: Cleanliness of the oil supply is essential for satisfactory performance and long life.
(Reference: Neale, M. J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd, Oxford, England)

(5) Generally, oil additives such as those noted in Table 7-1 are not required in plain bearing applications. Some additives and contaminants may cause corrosion, so caution should be exercised when using bearing lubricants containing additives or when contaminants may be present. Table 10-4 identifies some of the most common bearing materials used, and their resistance to corrosion when subjected to the additives noted.

Table 10-4
Resistance to Corrosion of Bearing Metals

	Maximum Operating Temperature, °C (F°)	Additive or Contaminant				
		Extreme-Pressure Additive	Antioxidant	Weak Organic Acids	Strong Mineral Acids	Synthetic Oil
Lead-base white metal	130 (266)	Good	Good	Moderate/poor	Fair	Good
Tin-base white metal	130 (266)	Good	Good	Excellent	Very good	Good
Copper-lead (without overlay)	170 (338)	Good	Good	Poor	Fair	Good
Lead-bronze (without overlay)	180 (356)	Good with good quality bronze	Good	Poor	Moderate	Good
Aluminum-tin alloy	170 (338)	Good	Good	Good	Fair	Good
Silver	180 (356)	Sulfur-containing additives must not be used	Good	Good - except for sulfur	Moderate	Good
Phosphor-bronze	220 (428)	Depends on quality of bronze. Sulfurized additives can intensify corrosion.	Good	Fair	Fair	Good
Copper-lead or lead-bronze with suitable overlay	170 (338)	Good	Good	Good	Moderate	Good

Note:
Corrosion of bearing metals is a complex subject. The above offers a general guide. Special care is required with extreme-pressure lubricants; if in doubt refer to bearing or lubricants supplier.
(Reference: Neale, M. J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd, Oxford, England)

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10-3. Rolling-Contact Bearings

In rolling-contact bearings, the lubricant film is replaced by several small rolling elements between an inner and outer ring. In most cases the rolling elements are separated from each other by cages. Basic varieties of rolling-contact bearings include ball, roller, and thrust.

a. Advantages of rolling-contact bearings.

(1) At low speeds, ball and roller bearings produce much less friction than plain bearings.

(2) Certain types of rolling-contact bearings can support both radial and thrust loading simultaneously.

(3) Rolling bearings can operate with small amounts of lubricant.

(4) Rolling-contact bearings are relatively insensitive to lubricant viscosity.

(5) Rolling-contact bearings have low wear rates and require little maintenance.

b. Types of rolling-contact bearings.

(1) Ball bearing. This bearing has spherical rolling elements in a variety of configurations. It is able to carry both radial and moderate axial loads. A special type, called maximum-type ball bearings, can take an extra 30 percent radial load but cannot support axial loads.

(2) Roller bearing. The roller bearing has cylindrical rolling elements and can take much higher radial loads than ball bearings but can carry no axial loads.

(3) Tapered roller bearing. This type has truncated-cone shaped rolling elements and is used for very high radial and thrust loads.

(4) Double-row spherical. The bearing has a double row of keg-shaped elements. The inner surface of the outer race describes part of a sphere. This bearing can handle thrust in both directions and very high radial loads.

(5) Ball thrust. This type has ball elements between grooved top and bottom races.

(6) Straight roller thrust. This bearing has short segments of cylindrical rollers between upper and lower races. The rollers are short to minimize skidding.

(7) Spherical thrust. This type is also called a tapered roller thrust bearing. The lower race describes part of a sphere. The rolling elements are barrel-shaped and the outside has a larger diameter than the inside.

(8) Needle bearing. These bearings have rollers whose lengths are at least four times their diameter. They are used where space is a factor and are available with or without an inner race.

c. Rolling-contact conditions. The loads carried by the rolling elements actually cause elastic deformation of the element and race as rotation occurs. The compressive contact between curved bodies results in maximum stresses (called Hertzian contact stresses) occurring inside the metal under the surfaces involved. The repeated stress cycling causes fatigue in the most highly stressed metal. As a result, normal wear of rolling contact bearings appears as flaking of the surfaces. Lubrication carries away the excessive heat generated by the repeated stress cycles. While lubrication is necessary, too much lubrication--especially with grease lubrication--results in churning action and heating due to fluid friction.

d. Rolling bearing lubricant selection. In most cases, the lubricant type--oil or grease--is dictated by the bearing or equipment manufacturer. In practice, there can be significant overlap in applying these two types of lubricant to the same bearing. Often the operating environment dictates the choice of lubricant. For example, a roller bearing on an output shaft of a gearbox will probably be oil-lubricated because it is contained in an oil environment. However, the same bearing with the same rotational speed and loading would be grease-lubricated in a pillow block arrangement.

(1) Selection of lubricant. Table 10-5 provides general guidance for choosing the proper lubricant.

Table 10-5
General Guide for Choosing Between Grease and Oil Lubrication

Factor Affecting the Choice	Use Grease	Use Oil
Temperature	Up to 120 °C (248 °F) - with special greases or short relubrication intervals up to 200/220 °C (392/428 °F)	Up to bulk oil temperature of 90 °C or bearing temperature of 200 °C (428 °F) - These temperatures may be exceeded with special oils.
Speed factor*	Up to *dn* factors of 300,000/350,000 (depending on design)	Up to *dn* factors of 450,000/500,000 (depending on type of bearing)
Load	Low to moderate	All loads up to maximum
Bearing design	Not for asymmetrical spherical roller thrust bearings	All types
Housing design	Relatively simple	More complex seals and feeding devices necessary
Long periods without attention	Yes, depending on operating conditions, especially temperature	No
Central oil supply for other machine elements	No - cannot transfer heat efficiently or operate hydraulic systems	Yes
Lowest torque	When properly packed can be lower than oil on which the grease is based	For lowest torques use a circulating system with scavenge pumps or oil mist
Dirty conditions	Yes - proper design prevents entry of contaminants	Yes, if circulating system with filtration

* *dn* factor (bearing bore (mm) x speed (rev/min)).
Note: For large bearings (0.65-mm bore) and nd_m (d_m is the arithmetic mean of outer diameter and bore (mm)).
(Reference: Neale, M. J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd, Oxford, England)

(2) Grease.

(a) Grease is used for slower rotational speeds, lower temperatures, and low to medium loads. Grease is used in situations where maintenance is more difficult or irregularly scheduled. It can be used in dirty environments if seals are provided. Tables 10-6 and 10-7 provide guidance on method of application and environmental considerations when using grease.

Table 10-6
Effect of Method of Application on Choice of a Suitable Grade of Grease

System	NLGI Grade No.
Air pressure	0 to 2 depending on type
Pressure-guns or mechanical lubricators	Up to 3
Compression cups	Up to 5
Centralized lubrication	2 or below
(a) Systems with separate metering values	Normally 1 or 2
(b) Spring return systems	1
(c) Systems with multidelivery pumps	3

Reference: Neale, M. J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd, Oxford, England.

Table 10-7
Effect of Environmental Conditions on Choice of a Suitable Type of Grease

Type of Grease	NLGI Grade No.	Speed Maximum (percentage recommended maximum for grease)	Environment	Typical Service Temperature Maximum °C	Maximum °F	Minimum °C	Minimum °F	Base Oil Viscosity (approximate values)	Comments
Lithium	2	100 75	Wet or dry	100 135	210 275	-25	-13	Up to 140 cSt at 37.7 °C (100 °F)	Multipurpose, not advised at max. speed or max. temperatures for bearings above 65-mm (2.5-in.) bore or on vertical shafts
Lithium	3	100 75	Wet or dry	100 135	210 275	-25	-13		
Lithium EP	1	75	Wet or dry	90	195	-15	5		Recommended for roll-neck bearings and heavily-loaded taper-roller bearings
Lithium EP	2	100 75	Wet or dry	70 90	160 195	 -15	 5	14.5 cSt at 98.8 °C (210 °F)	
Calcium (conventional)	1, 2, and 3	50	Wet or dry	60	140	-10	14	140 cSt at 37.7 °C (100 °F)	
Calcium EP	1 and 2	50	Wet or dry	60	140	-5	25	14.5 cSt at 98.8 °C (210 °F)	
Sodium (conventional)	3	75/100	Dry	80	175	-30	-22	30 cSt at 37.7 °C (100 °F)	Sometimes contains 20% calcium
Clay		50	Wet or dry	200	390	10	50	550 cSt at 37.7 °C (100 °F)	
Clay		100	Wet or dry	135	275	-30	-22	Up to 140 cSt at 37.7 °C (100 °F)	
Clay		100	Wet or dry	120	248	-55	-67	12 cSt at 37.7 °C (100 °F)	Based on synthetic esters
Silicone/ lithium		75	Wet or dry	200	390	-40	-40	150 cSt at 25 °C (77 °F)	Not advised for conditions where sliding occurs at high speed or load

Reference: Neale, M. J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd, Oxford, England

(b) Figure 10-3 shows approximate maximum bearing speeds for grease-lubricated bearings based on the bore diameter and series of grease. Figure 10-4 provides guidance on grease life expectancy for various operating speeds (given in percent) as a function of temperature. Correction factors for use with Figure 10-3 are shown in Table 10-8.

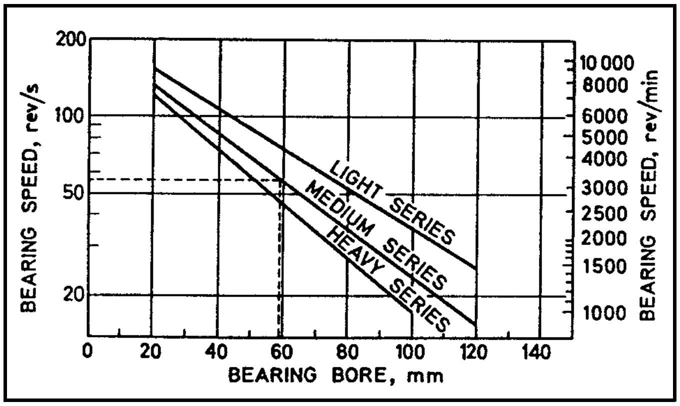

Figure 10-3. Approximate maximum speeds for grease-lubricated bearings ((Reference: Neale, M. J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd, Oxford, England)

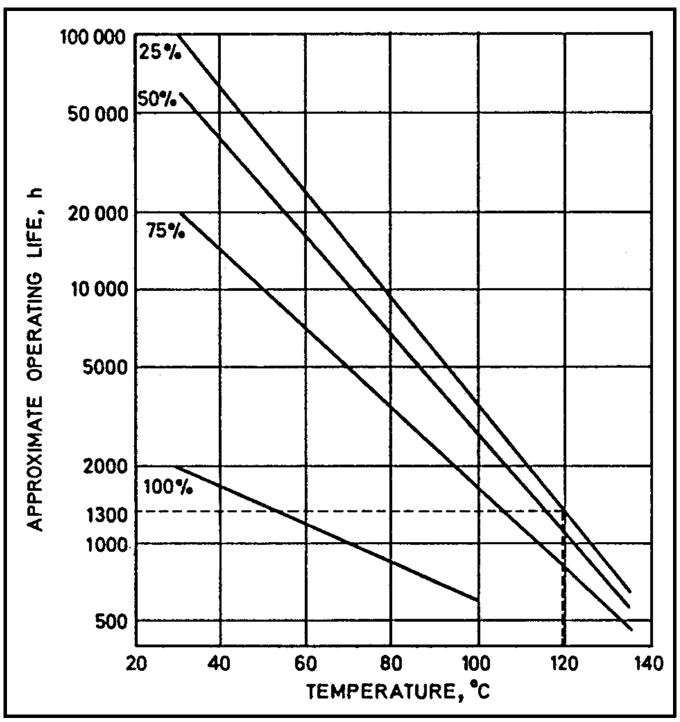

Figure 10-4. Variation of operating life of Grade 3 lithium hydroxystearate grease with speed and temperature (Reference: Neale, M. J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd, Oxford, England)

Table 10-8
Correction Factors for Figure 10-3

Bearing Type		Multiply Bearing Speed from Figure 10-1 by This Factor to Get the Maximum Speed for Each Type of Bearing
Ball bearings and cylindrical roller bearings	Cage centered on inner race	As Figure 10-1
	Pressed cages centered on rolling elements	1.5-1.75
	Machined cages centered on rolling elements	1.75-2.0
	Machined cages centered on outer race	1.25-2.0
Taper- and spherical-roller bearings		0.5
Bearings mounted in adjacent pairs		0.75
Bearings on vertical shafts		0.75
Bearings with rotating outer races and fixed inner races		0.5

Reference: Neale, M. J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd, Oxford, England

(3) Oil.

(a) Oil is used for higher rotational speeds and higher operating temperatures. It is used in maximum loading situations and for bearing configurations where a high amount of heat generated in the bearing can be carried away by the oil. It is used in dirty conditions when the oil is circulated and filtered. For moderate speeds, the following viscosities are recommended:

Ball and cylindrical-roller bearings	12 cSt
Spherical-roller bearings	20 cSt
Spherical-roller thrust bearings	32 cSt

(b) In general, oils will be the medium to high viscosity index type with rust and oxidation inhibitors. Extreme pressure (EP) oils are required for taper-roller or spherical-roller bearings when operating under heavy loads or shock conditions. Occasionally EP oils may be required by other equipment or system components.

(c) Figure 10-5 provides a means for selecting bearing oil lubricant viscosity based on the bearing operating temperature, bore diameter, and speed. The following example shows how to use this figure. Assume a bearing bore diameter of 60 mm (2.3 in.), speed of 5000 rev/min and an operating temperature of 65 °C. To select the viscosity, locate the bore diameter then move vertically to the required speed. At this intersection move left to intersect the operating temperature. Since the required viscosity falls between an S8 and S14 oil, select the oil with the higher viscosity (S14). The correct oil selection has a viscosity of 14 cSt at 50 °C. Table 10-9 provides guidance on applying oil to roller bearings.

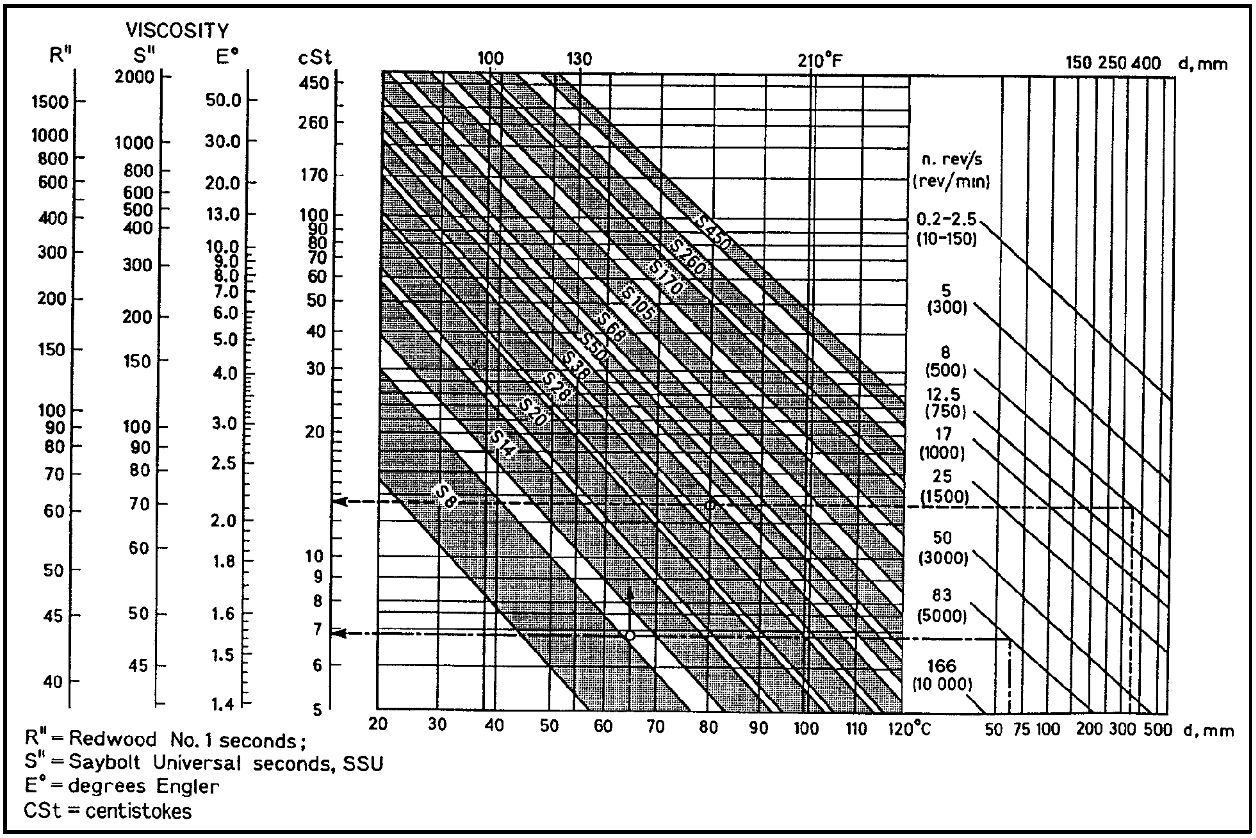

Figure 10-5. Roller bearing oil selection (Reference: Neale, M. J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd, Oxford, England)

10-4 Calculation of Bearing Lubrication Interval

The following procedure for calculating lubrication intervals is extracted from Neale, “Lubrication: A Tribology Handbook” (see Appendix A for complete reference). The required interval is calculated using the data from Figures 10-3 and 10-4. The following example illustrates the procedure:

1. Given:

Bearing type:	Medium series with 60-mm bore diameter
Cage:	Pressed cage centered on balls
Speed:	950 rev/min
Temperature:	120 °C (bearing temperature)
Position:	Vertical shaft
Grease:	Lithium grade 3
Duty:	Continuous

2. Determine the lubrication interval.

3. Procedure:

Table 10-9
Application of Oil to Roller Bearings

System	Conditions	Oil Levels/Oil Flow Rates	Comments
Bath/splash	Generally used where speeds are low A limit in *dn* value of 100,000 is sometimes quoted, but higher values can be accommodated if churning is not a problem.	Bearings on horizontal and vertical shafts, immerse half lowest rolling element Multirow bearings on vertical shafts, fully immerse bottom row of elements	
Oil flingers, drip-feed lubricators, etc.	Normally as for bath/splash	Flow rate dictated by particular application; ensure flow is sufficient to allow operation of bearing below desired or recommended maximum temperature - generally between 70 °C and 90 °C (158 °F and 194 °F)	Allows use of lower oil level if temperature rise is too high with bath/splash
Pressure circulating	No real limit to *dn* value Use oil mist where speeds are very high	As a guide, use: *0.6 cm^3/min cm^2 of projected area of bearing (o.d. x width)	The oil flow rate has generally to be decided by consideration of the operating temperature
Oil mist	No real limit to *dn* value Almost invariably used for small-bore bearings above 50,000 rev/min, but also used at lower speeds	As a guide use: * 0.1 to 0.3 x bearing bore (cm/2.54) x no. of rows - cm^3/hour Larger amounts are required for pre-loaded units, up to 0.6 x bearing bore (cm/2.54) x no. of rows - cm^3/hour	In some cases oil-mist lubrication may be combined with an oil bath, the latter acting as a reserve supply which is particularly valuable when high-speed bearings start to run

* It must be emphasized that values obtained will be approximate and that the manufacturer's advice should be sought on the performance of equipment of a particular type.
Reference: Neale, M. J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd, Oxford, England.

a. From Figure 10-3, determine the speed for a 60-mm bore medium series bearing (3100 rev/min).

b. Maximum speed correction factor for cage centered bearing from Table 10.8. (1.5).

c. Maximum speed = 1.5 x 3100 = 4650 rev/min.

d. Obtain correction factor for vertical shaft mounting from Table 10.8 (0.75).

e. Corrected speed = 0.75 x 4650 rev/min = 3,488 rev/min (this is the maximum speed rating, i.e., 100 %).

f. Percent of actual speed to maximum speed = 100 x [950/ 3488] = 27 %.

g. Refer to Figure 10-4. Using 120 °C and the 25 % line, obtain the estimated operating life = 1300 hours.