TROUBLESHOOTING BEARING AND LUBE OIL SYSTEM PROBLEMS

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ABSTRACT

Information and an approach intended to help engineering and other plant personnel troubleshoot bearing problems and diagnose the mode of bearing failures are presented. Six leading modes of bearing failure (abrasion, corrosion, electrical pitting, fatigue, overheating, and wiping) are covered in some detail. Each mode is defined and mechanisms of occurrence are described. Also, for each mode, the visual appearance of failed bearings is discussed and possible causes of failure are reviewed. An illustrative example is provided: symptoms on a bearing surface are described and the mode of failure is identified, as is the root cause of failure and possible remedial actions. Because lubrication system problems are a leading cause of bearing failures, effective means of monitoring oil condition are also discussed.

INTRODUCTION

Turbine generator bearing failures are a leading cause of power plant unavailability and can cause serious damage not only to bearing systems but also to rotors, stators, and nearby equipment. In addition to failures in turbine generators, bearing failures in other rotating equipment, including pumps, fans, and auxiliary gas turbines and motors, can also lead to plant outages. Given the serious consequences of such breakdowns, determination of the causes of bearing failure and methods of effective repair are of paramount importance.

The electric utility industry, in conjunction with users, original equipment manufacturers and bearing vendors, has diagnosed various modes of thrust and journal bearing failures, linked the failure modes to potential causes and, for each failure-inducing root cause, developed a guideline manual for remedial actions and bearing refurbishment [1]. The manual classified 16 separate modes of bearing failure that are likely to occur in hydrodynamic bearings on power plant rotating equipment (Table 1). In the following six sections, symptoms, mechanisms and characteristics of six fairly common modes of failure-abrasion, corrosion, electrical pitting, fatigue, overheating, and wiping are described and ways of visually identifying and diagnosing bearing failures in each of the six modes are treated. Then the root-cause analysis and remedy of an actual power plant bearing failure is outlined.

Table 1. Modes of Bearing Failure.

Mode	Other Names
Abrasion	Gouging; scoring;scratching
Bond failure	Spalling
Cavitation erosion	Cavitation
Corrosion	Chemical attack
Electrical pitting	Frosting
Erosion	Worm tracks
Fatigue	
Fretting	Fretting corrosion
High chromium damage	Wire-wool; black scab
Non-homogeneity	Blistering; porosity
Overheating	Mottling; anisotropy; ratcheting; sweating
Seizure	
Structural damage	
Surface wear	Black scale
Tin oxide damage	Wear
Wiping	Smearing; polishing

Familiarity with and recognition of visual and laboratory symptoms that may be considered representative of a particular mode of failure can be instrumental in identifying the failure mode when a bearing is damaged and a number of failure modes are possible. Therefore, the following sections include several photographs of damaged bearing surfaces; these and similar visual aids can be important tools for persons attempting to diagnose the mode of bearing failure involved in a particular incident.

A number of possible underlying causes are listed for each of the six modes of failure under consideration. One should keep in mind the distinction between direct and indirect causes. Thus, while wiping is classified as a distinct mode, it is often a consequence of other mechanisms such as fatigue or overheating; the root cause, therefore, would not be a condition likely to cause wiping, but one leading to either fatigue or overheating. The troubleshooter's ultimate goal is to determine from a number of possible mechanisms the one distinct cause of the problem. This is often specific to local situations and involves the particular power plant, its history, and practices. Whenever pertinent, therefore, the troubleshooter will consider these elements too, to facilitate identification of the specific condition that led to a bearing failure.

Finally, because one third of turbine bearing failures, including most failures due to abrasion, involve contaminated lubricants or malfunctioning lubricant supply system components, some aspects of maintaining a turbine lubrication system are also discussed.

ABRASION

Abrasion is a mode of bearing failure due to the erosive action of a large number of solid particles that are harder than the bearing surface. Under certain conditions both the bearing and the shaft may be damaged by the abrasive action of the particles.

Mechanisms

When the lubricant carries few particles, they eventually become embedded harmlessly in the bearing surface. When there is a large number of particles, they recirculate through the clearance, causing wear and scoring (Figure 1). The particles may be metallic or nonmetallic, large or small. When they are large they may become partially embedded in the babbitt. They will then protrude against the journal and function as a cutting tool.

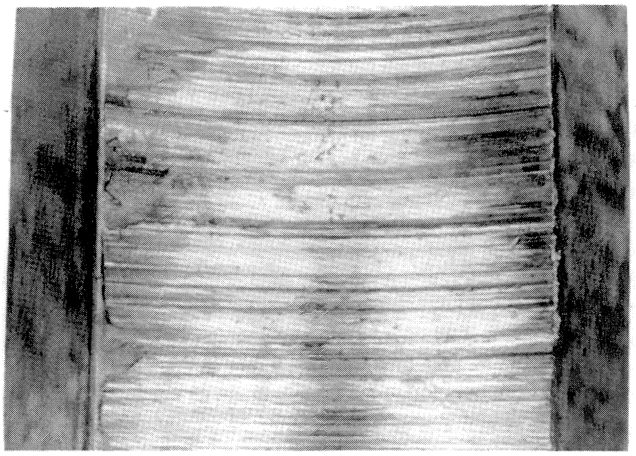


Figure 1. Abrasion of a 12 in (30 cm) Turbine Journal Bearing.

Occasionally, embedded particles are lifted out of their seats and deposited elsewhere, leaving gouged out indentations, as well as tracks in the bearing surface. Because they are deeper than the clearance, such tracks become channels for the drainage of oil; likewise, any embedded large particle offers a barrier to the flow of oil, forming a starved pocket nearby. The presence of a channel or starved pocket creates a hot spot in the bearing. When the bearing structure is penetrated by foreign material, the babbitt is brought past its thermal yield point and undergoes recrystallization accompanied by strong local heating. Contaminant particles too large to be drawn into the oil film will be battered around in the oil groove, generating many smaller pieces which will then enter the clearance.

Contaminants

Many different types of particulate, varying in size and properties and in potential for causing damage, may enter the lubrication system. The most important characteristics of these particles are size, hardness, and shape. Additional properties of importance are compressive strength and crushability; a material that is hard but brittle may be less harmful than a softer material. Particles below 10 micrometers (0.4 mil) in diameter can usually be considered too small to cause grooving in bearings for large power plant rotating machinery.

The more common particulates found in lubrication systems and their possible origins are as follows:

- *Quartz or Sand.* Sand is a very hard material that will scratch the hardest steel as well as chromium.
- *Grit Blasting Substances.* Grit is not only damaging when it enters the clearance space but it often lodges behind the bearing shell causing high spots in the bearing. This is particularly hazardous in thin shell bearings.
- *Metal Chips.* These are usually leftovers from manufacturing. Although they are too soft to scratch hard shafts, they often undergo undesirable changes. In the presence of water they will rust and may form hematite (Fe_2O_3), which is a very strong abrasive.
- *Weld Spatter.* These, too, are leftovers from the construction period and are usually egg shaped.
- *Fly Ash.* These are relatively small combusted and noncombusted coal particles, ranging from 25 micrometers (1.0 mil) down to less than 1.0 micrometer (0.04 mil) in diameter.
- *Silicon Carbide.* These are synthetic abrasives close to 25 micrometers (1.0 mil) in size with many sharp jagged edges.
- *Cast Iron Chips.* These may come from the bearing housing, which on occasion is made of cast iron.

The appearance of typical oil contaminants as seen under a microscope is shown in Figure 2.

Appearance of Abraded Bearings

The main visual characteristic of abrasion is the presence of parallel, circumferential, tracks running over most of the loaded part of the bearing. Small particles may bounce between shaft and bearing, causing intermittent scratches. Frequently, the pits have smooth bottoms; but ordinarily they do not have the melted appearance of electrical pitting. Often a series of pits of identical shape will be spaced at regular intervals circumferentially over a portion of the bearing; this is unmistakable evidence of pitting due to foreign particles. Naturally the most frequent location of scoring is near the minimum film thickness, h_{min} (Figure 3). As illustrated in Figure 4, scoring at low speed or startup produces a more irregular pattern than scoring at high speed. The embedment of particles is, of course, indicated by the termination of a particular groove, as documented in Figure 5, for the case of a tin babbitt matrix magnified 15 times.

While scratches and tracks are the most common features of abrasion, two additional characteristics are often present with this kind of damage:

- When the particles are small, there are grooved tracks, but the surface has a dull matte finish; this is easier to detect on the steel shaft than on the gray babbitt. Although individual grooves are not visible to the eye, the surface will be rough and gritty to the touch.
- When the particles are large and hard, they may form "halos." The particles generate rings of elevated babbitt that are then polished by contact with the shaft into shiny halos.

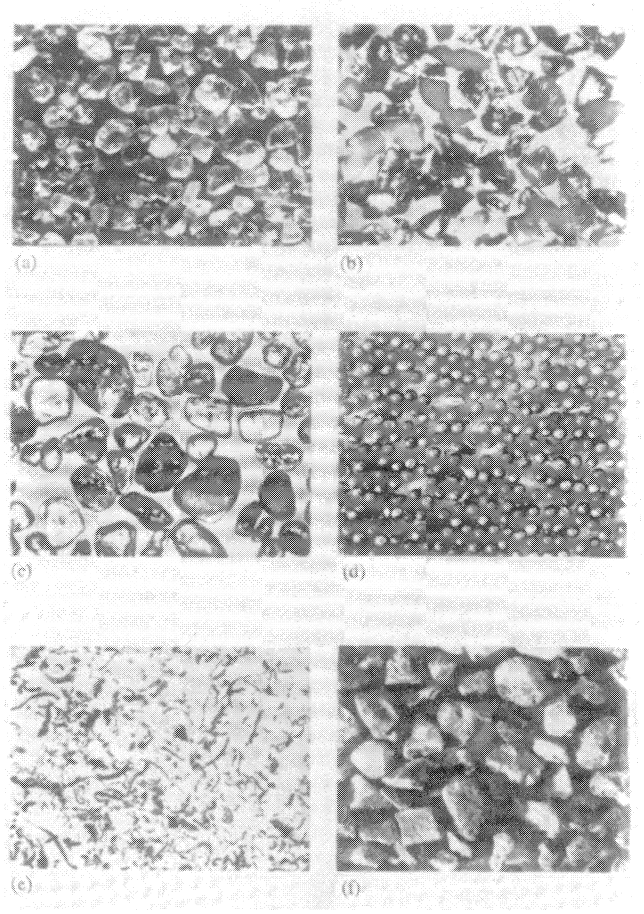


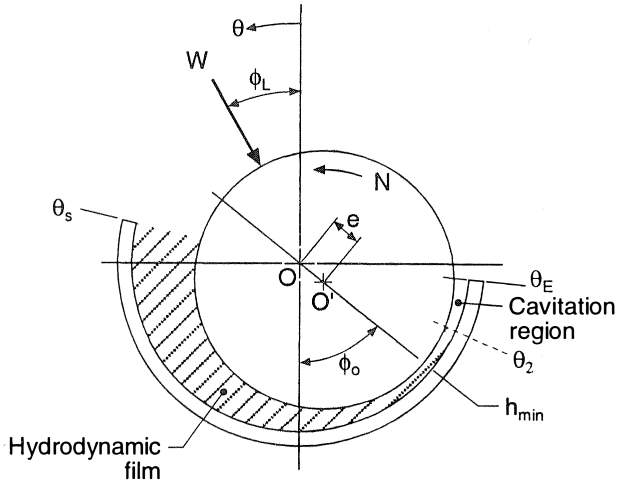
Figure 2. The Appearance under the Microscope of Various Forms of Contaminants. (a) Common sand, 20×. (b) Silicon carbide grinding compound, 70×. (c) Garnet spark plug abrasive cleaner, 40×. (d) Steel grit-blasting material, 10×. (e) Steel grinding chips from tool grinder, 20×. (f) Granulated nut shells used for blast cleaning of engine parts, 10×.

Scratches and grooving are caused by particles riding the surface; plowing is caused when particles become embedded under the surface. Both grooving and plowing raise the babbitt edges on either side of the track. In an abraded surface the asperities are an order of magnitude higher than the machined surface roughness. During the grooving, the babbitt is plastically deformed, and the raised edges are polished by the journal, giving them a flattened shiny appearance. This, in combination with the raised banks of the groove, produces canyons of the form shown in Figure 6; in this figure the vertical has a magnification 10 times the horizontal. Both the flat roof on the right and the sharp protrusions toward the journal on the left are clearly visible on the sides of the track.

The shape of the embedment most often reveals whether the particles are hard or soft. If the embedment is due to a hard particle, the shape of the depression corresponds to that of the particle; if due to a soft particle, a wide shallow indentation results and the particle is often absent.

Appearance of the Journal

If the journal is damaged, that is usually the result of the presence of large, hard particles or of embedded and work-hardened soft particles. Abrasions by very small particles may be more easily noticed on the journal than on the bearing.



e — Eccentricity

ϕ_L — Load angle

ϕ_O — Line of centers

h_{min} — Minimum film thickness

θ_2 — End of hydrodynamic film

Figure 3. Nomenclature in Journal Bearings.

Appearance of Contaminants

In a qualitative way, it can be said that:

- Metal chips are relatively large and rectangular or curled in shape.
- Weld spatter particles are large, egg-shaped, and dull in appearance.
- Fly ash particles are small and spherical in shape.

Possible Causes of Abrasion

The following are operating conditions that may lead either directly or indirectly to abrasion:

- Contaminated lubricant
- Polluted environment
- Inadequate seals
- In-plant formation of fly ash, coal dust, and other contaminants
- Too thin a minimum film thickness
- Rough journal or runner surface

Contaminated Lubricant

The oil storage tanks in electric utilities are large and located underneath the turbogenerator stand in an environment likely to collect all kinds of dust and debris. In addition, they are likely to contain detritus from the plant as a whole, including chips and weld spatter going back to the time of plant installation. Typical plots of the state of turbine oils in terms of quantity and size of solid contaminants are shown in Figure 7, including exceptionally clean and exceptionally dirty oils.

Damage is caused mostly by hard particles of a size larger than the minimum oil film thickness during normal operation or turning gear operation. In most cases that have been examined,

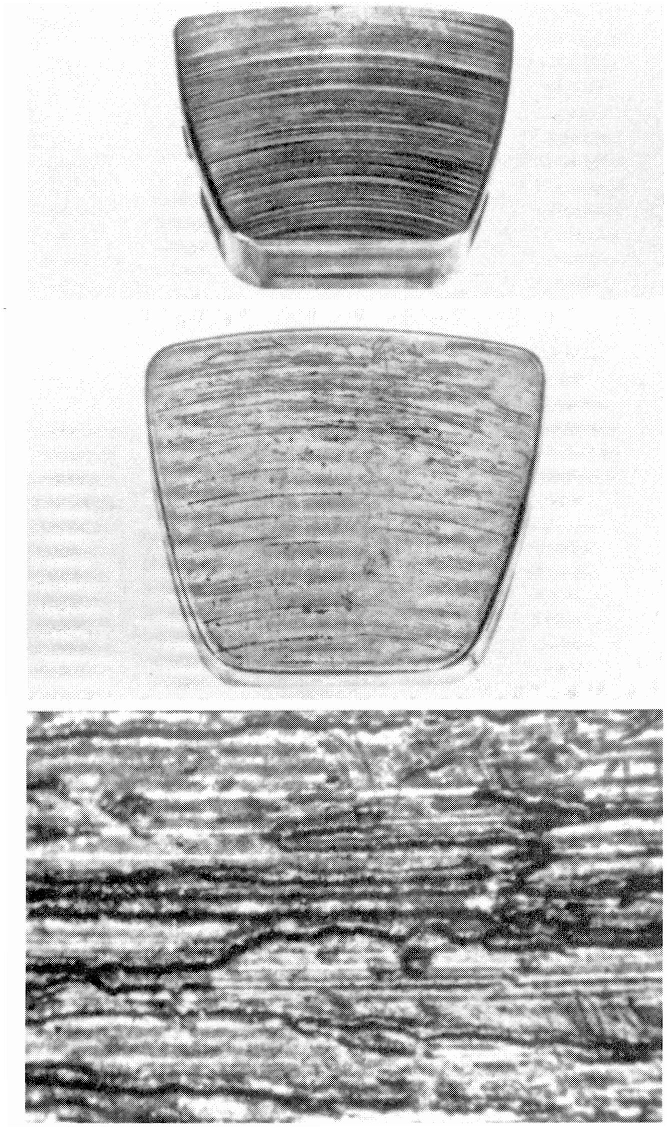


Figure 4. Abrasion of Thrust Bearing Tilting Pads. (a) Concentric score marks at high speed. (b) Ragged score marks produced at startup. (c) Magnification of surface of part (b)

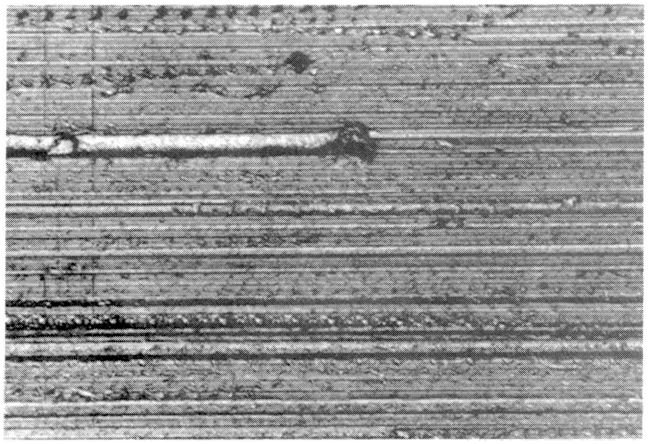


Figure 5. Scoring of a 3.0 in (7.6 cm) Diameter Tin Base Babbitt Journal Bearing with Embedment of Particle at the End of the Path.

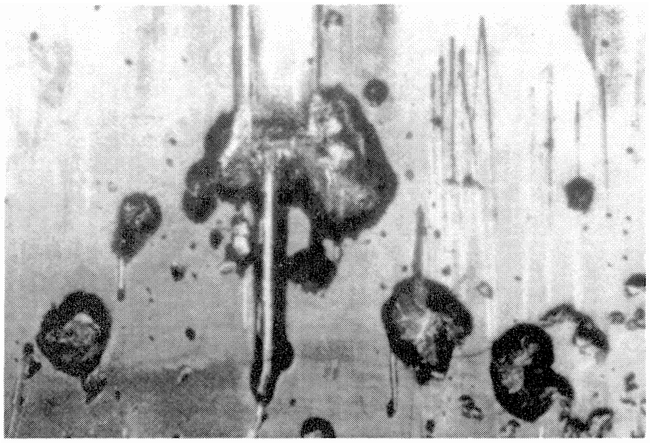


Figure 6. Profile Section of a Scratch in a Babbitt Surface, Showing Built up Edges Adjacent to the Scratch: horizontal, 200×; vertical, 2000×.

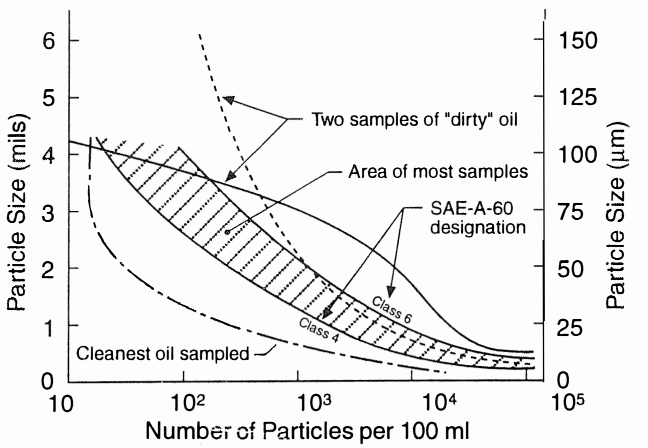


Figure 7. Typical Contamination Levels of Turbine Oils in Electric Utilities.

this dirt has been found to be of foreign origin; weld bead, machining chips, or other particles of considerable hardness. A warning sign of scored journals has been found to be a spike in the babbitt metal temperature occurring during coastdown at a speed somewhat below the rated rev/min. In other cases, the damage is found only during bearing inspection.

Polluted Environment

Another source of contaminants can be the environment of the power plant. Fly ash, dusty air, desert conditions, proximity of quarries, or other industrial pollutants will provide a steady supply of contaminants that often find their way into the lubrication system and directly into the bearing housing. Water is also a likely contaminant, originating either from cooler leaks or atmospheric condensation.

Inadequate Seals

In order for the environmental or locally generated contaminants to be able to reach the bearings, it must penetrate the seals. Thus, inadequate sealing of the bearing drain areas are often responsible for the damage resulting from the presence of external (as opposed to oil-carried) contaminants. For operation in harsh environments proper sealing is therefore particularly important.

In-plant Formation of Contaminants

Sometimes the facility itself generates foreign particles on a sustained basis. These may come from continuous wear of machine parts—gears, couplings, or the bearings themselves. Also, they may be generated by coking and chemical action in the hot parts of the machine. Thus, the formation of carbonaceous deposits near seals and baffles may provide a stream of large hard particles known to cause considerable damage by scoring and cutting both bearings and runners.

Too Thin a Minimum Film Thickness

While the presence of contaminants is the primary cause, operating bearings at too low an h_{min} may cause abrasions that would not have occurred with a larger film. The causes of a too small film thickness, for a given bearing geometry, are: too high a load, too low a viscosity, misalignment, excessive shaft deflection, and vibration. An inadequate film thickness may also be caused by the operation of bearings with too low an rpm at turning-gear and under start-stop conditions.

Rough Journal or Runner Surface

A common cause of bearing abrasion is the installation of a new bearing running against a rough journal or runner surface. While this roughness may occasionally be due to poor machining, most often it is a consequence of previous abrasions. A new bearing run against an abraded journal surface will soon itself become abraded.

CORROSION

As used here, and as differentiated from such processes as erosion and cavitation, corrosion damage is due to chemical attack on metal surfaces by reactive agents. The damage can be to both the bearings and the shaft. This damage results from chemical attack on some bearing constituent by a substance originating in the lubricant or the environment. Corrosion may produce either removal of bearing material or buildup of a deposit on the bearing surface. The two main groups of corrosive agents that affect bearings are electrolytes and organic acids.

Mechanisms

The process of corrosion converts metal to metallic compounds. In order to cause problems, the products of corrosion must be soluble or porous, or must be continually removed, so as to expose fresh metal to attack. Corrosion is often selective in that it attacks some constituents more than others, as in the case with the removal of lead from copper-lead bearings. Corrosion of lead-based babbitts may be caused by acidic oil oxidation products formed in service, by decomposition of certain oil additives, or by ingress of water or coolant into the oil. The ability of a turbine oil to absorb water under equilibrium conditions is given in Figure 8 as a function of temperature. Should the water present in the oil exceed the curve at some given temperature, it would appear as free water. The onset of corrosion can be sudden or gradual. A special set of conditions, perhaps a combination of pressure, temperature, and shear stress in the bearing is required to produce corrosion.

Corrosion by Electrolytes

Attack of metal surfaces by electrolytes results either in the pitting of the surface (Figure 9) or in the oxidation of the alloy. Lead corrosion is the most common form of attack in lead-base babbitts and leaded bronze-bearing metals. Fuel sulfur is one of the agents likely to react with lead babbitt, forming in the process lead sulfides that are likely to be deposited on bearing surfaces. Sulfur compounds are added to many oils to provide extreme-pressure properties and as antiwear agents, detergents, rust inhibitors and antioxidants. These properties are generated by an essentially corrosive action of the sulfur compounds whereby a low-shear-strength surface layer is formed over the bearing material to prevent destructive contact with the journal material. Corrosive contaminants in the surrounding atmosphere, such as chlorine and sulfur acids, may also cause corrosion, particularly when moisture is present.

When combined with soot, sulfides can also clog oil passages and bearing grooves, thus interfering with adequate lubrication

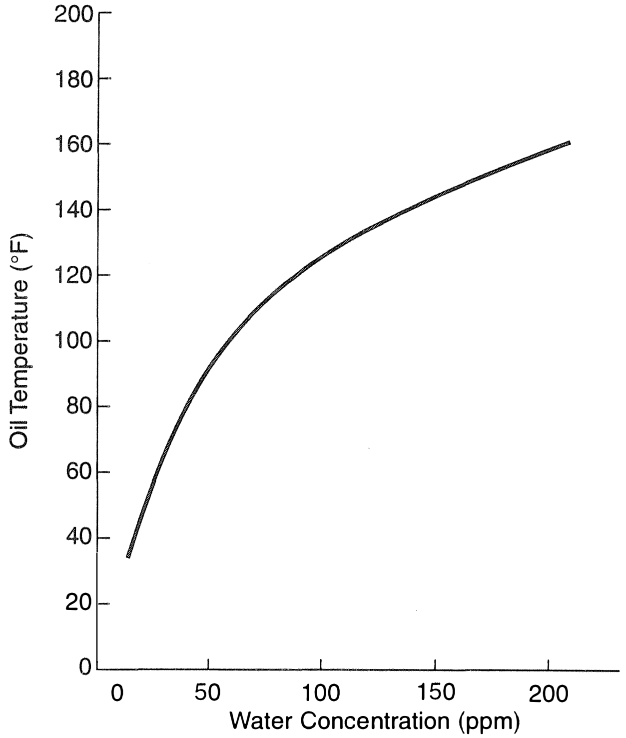


Figure 8. Equilibrium Water Content in a Turbine Oil at 40 Percent Humidity.

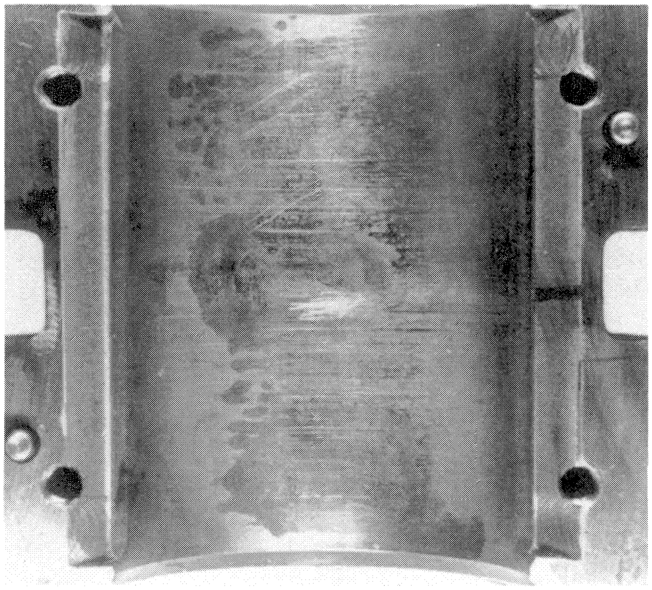


Figure 9. Corrosion of a 5.0 in (12.7 cm) Diameter Lead-base Babbitt Journal Bearing.

and in extreme cases can cause starvation and seizure. Water, particularly brackish water, is another damaging agent. It may lead to the oxidation of the tin in tin-base babbitts, a problem often referred to as tin oxide damage.

Corrosion by Organic Acids

Corrosion of lead-bearing materials by organic acids has been troublesome, both because lead is used extensively in babbitts and copper-lead bearings and because lead reacts relatively rapidly with the organic acids and peroxides present in oil oxidation products. Such acids and peroxides are formed in the oil under conditions of aeration, high temperature, prolonged usage and catalysis by the metal surfaces. The rate of oil oxidation doubles for each 10°C (18°F) temperature rise; any copper or cadmium in the bearing or lubrication system will catalyze this reaction. Although lubricating oils contain additives to retard oxidation and to protect bearing surfaces against corrosive contaminants, prolonged usage of these oils depletes the additives, exposing the alloys to oxidation and corrosion.

In corrosion of lead babbitts, peroxides first oxidize the lead surface, and the lead surface oxides are then converted by the organic acids to lead soaps. These soaps may dissolve in the oil or become dispersed in the form of a sludge. The tin and antimony present in lead babbitts tend to mitigate this corrosive tendency while water in the oil accelerates corrosion. Tin babbitts are usually free of this type of corrosion.

Visually Identifying Corrosion

Selective removal of the microconstituents of a bearing by corrosion will generally embrittle the structure so that it finally fails by cracking. Cracking from these causes cannot always be distinguished from cracking caused by fatigue. However, with corrosion, the typical fatigue crack networks are usually absent and the portions of removed metal are shallower than those removed by fatigue.

Of the two main babbitt families, lead babbitts are much more prone to corrosion. In fact, any bearing material having a lead constituent is liable to corrode given the proper environment. Tin (as well as antimony) is usually added to forestall corrosion, but tin babbitts themselves are occasionally corroded by electrochemical effects, oxidation, or sulfur attack. Corrosion usually proceeds from the surface inward, eating away the lead components and leaving a rough and weakened babbitt layer. The result —empty pockets left by the corroded element—can be seen under the microscope, though they give no indication as to whether the damage was caused by oxidation or acidic attack. An enlargement of the corroded area of a 5.0 in (127 mm) diameter lead-base babbitt bearing in which lead has been removed by corrosive attack is shown in Figure 10.

In a less common type of corrosion, the copper phase of the tin-rich babbitt is attacked. The result is the formation of copper sulfates, from the copper in the babbitt and sulfur present in the oil or atmosphere. The damage results in the eating away of the tin matrix leaving tin-antimony cuboids on the surface. This occurs more readily in the high-pressure zone. Thus, the deposit of copper sulfates is uneven over the bearing surface, often leading to pad crowning.

The appearance of the babbitt surface of a thrust bearing pad (an ASTM alloy B23, Grade 2) before and after attack by environmental sulfur is shown in Figures 11 and 12, respectively. The dark voids left by the corroded parts can be seen clearly in the latter photograph.

Possible Causes of Corrosion

To recapitulate, several contaminants may contribute to corrosion damage. These include:

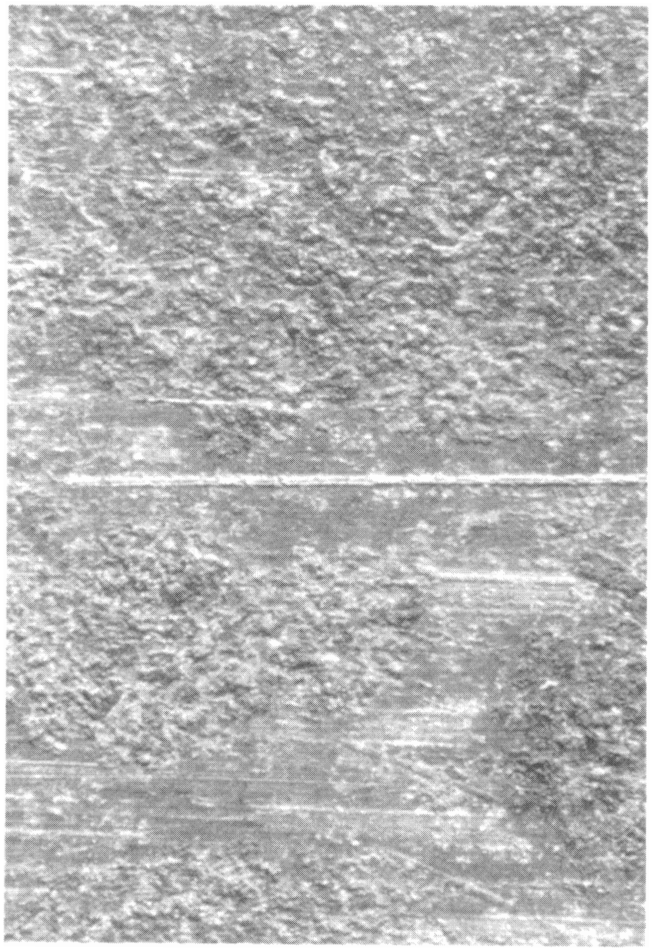


Figure 10. Corroded 5.0 in (127 mm) Lead Babbitt Journal Bearing, 15× Magnification of Bearing Surface.

- Sulfur compounds, originating from inadvertent contamination or from some oil additives.
- Organic acids, the presence of which is due to the oxidation of light hydrocarbons in the fuel.
- Water in the oil.

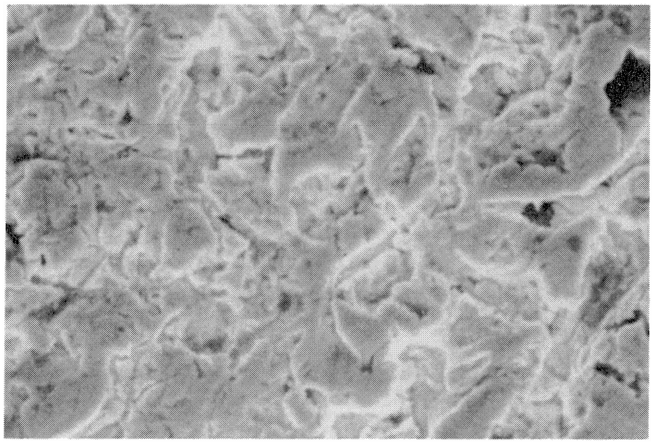


Figure 11. Normal Appearance of Thrust Bearing Pad Using an ASTM B23, Grade 2, Babbitt.

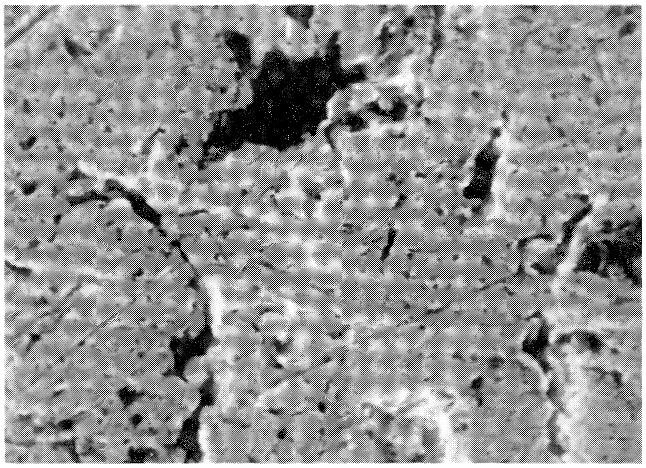


Figure 12. Pad Surface Attacked by Environmental Sulfur.

- External corrosive substances, which may flow into the system

Operating practices may also contribute to corrosion damage. Operating conditions that favor and accelerate corrosive attack are: high temperatures; high humidity; foaming and aeration of oil; and prolonged usage of the same oil.

ELECTRICAL PITTING

Electrical pitting consists of damage caused to bearings (and sometimes also to runners) by the intermittent arcing of electrical current as a result of voltage discharge across the oil film. The source of the buildup in potential may be chronic to the generator or incidental, such as an electrically-charged lubricant.

Mechanisms

The wear that occurs in electrical pitting is caused by the intermittent passage of current between the bearing and runner. High voltages are not necessary for arcing, and damage can occur at potentials well below one volt. The consequence of arcing is the removal of metal fused in the arc, followed by mechanical wear. All this is aggravated by the formation of rough surfaces. An additional penalty is contamination of the oil and the lubrication system by the resulting debris. The damage may set in soon after startup or it may take months to become apparent.

It is important to realize that a continuous flow of current is not necessarily harmful; it is the intermittent discharge due to a buildup of a potential which is relieved in the form of sparking that causes the damage. Consequently, when the film thickness is very small and there is near contact between the asperities of runner and bearing, there may be no wear because any potential will produce a continuous current. On the other hand, if the film thickness is very large, the resistance across the film is too high to permit discharge and there will be no arcing. In between these two extremes there will be, as shown in Figure 13, a point of maximum wear. A three-dimensional plot of the effect of voltage and film thickness on wear rate, Wear = f(E, h), will then look like the mountain of Figure 14, where a particular combination of E and h yields maximum wear. Thus, in Figure 14, taking ABD, along which E is constant, notice that near D, where h is small, there is no wear; at some h corresponding to point B there will be maximum wear; and when the film thickness has increased to an h corresponding to point A, wear again will have dropped to zero.

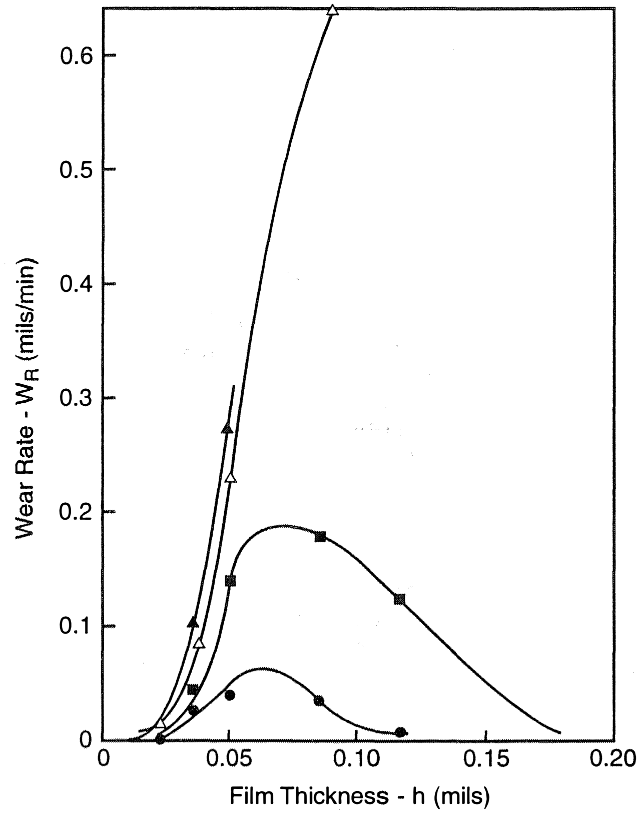


Figure 13. Wear Rate Vs *Film Thickness for Different Voltages.*

Levels of Damage

Electric arcing produces four effects. The most damaging are pitting and wear. Often, too, a thin layer of babbitt on the surface becomes overheated. Finally, metallic particles are set free in the oil, thus commencing an abrasive process.

Although both are often affected, in general the journal surface is less seriously damaged by pitting than is the babbitt. This is as expected, considering the greater area and the higher melting point of the journal material. A more serious effect is the roughening produced by built up debris, which greatly increases mechanical wear.

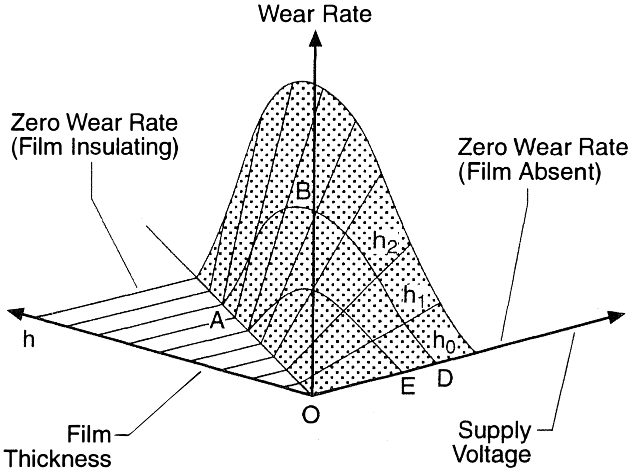


Figure 14. Effect of Film-Thickness and Voltage on the Wear Rate Due to Electrical Pitting.

Visually Identifying Electrical Pitting

In early stages, damage caused by electrical pitting consists of minute pits in the area of minimum film thickness and gives the bearing a frosted surface. These pits are characterized by a crater-like appearance. The backs of the bearing shells may also be pitted where currents have passed through the pedestal. With restricted lubricant circulation, electrical trouble often shows up as a gradual rise in bearing temperature and a darkening of the oil. When the oil is changed, temperatures return to normal for a while before starting to climb again. Each electrical discharge releases a cloud of fine babbitt particles and causes carbonization of the oil. Both of these reactions serve to further lower oil film resistance, allow the passage of higher currents, and accelerate the damage. As the process continues, the pits begin to overlap, masking much of the evidence of the origin of the damage. Still, if the surface appears frosted, it is possible to identify electrical pitting by scrutinizing the periphery of the frosted area where isolated pits with a crater-like appearance can be found. Also, with the proper beaming of a light source onto the frosted area, electrical pits can usually be detected by the reflection from their characteristic smooth, melted bottoms. As with the cycling of the high temperatures in the oil exposed to electrical arcing, there may also occur a cycling in the formation of an adequate fluid film. When the bearing surface becomes incapable of accommodating an oil film, the bearing may wipe. But as this cleans away the pits, the bearing may recover an oil film and continue to operate, and pitting will again begin. This process may occur several times until little babbitt is left and failure follows. Even then it is possible to pinpoint the cause by the telltale pits left on the shell and other adjacent parts of the bearing. On the journal, which is generally hard, the pits are usually smaller and not as easily homogenized as on the bearing. In Figure 15, the appearance of electrical pitting damage on a lead babbitt bearing and its steel journal is shown.

The severity of electrical pitting, expressed in extent of damaged area along with the size of the pits, depends on voltage, current, film thickness, circuit resistance, and several other factors. Although individual pits vary in size depending on these factors, the pits all have the form of more or less hemispheric depressions with smooth shiny surfaces, giving the appearance associated with a melted metal, as shown in Figure 16. A slight ridge of melted metal is usually found around the periphery of the pit at the bearing surface, unless it has been worn away by the operation of the journal. Higher levels of both voltage and current aggravate the extent of damage. Larger pits are formed with positive rather than with negative polarity.

Possible Causes of Electrical Pitting

Electrical pitting is induced by two types of currents—electrostatic and electromagnetic. Although both types result in pitting damage, their nature and destructive capabilities are different. Electrostatic shaft current (or direct current) is the milder of the two. This is generated by either impinging particles or condensed water droplets in the condensing stages of a steam turbine. Pitting damage progresses slowly and always occurs at the location of lowest resistance to ground. Thrust bearings are especially prone to electrostatic shaft currents.

Electromagnetic shaft currents (alternating current) are stronger and more severe than electrostatic currents. They are produced by the magnetization of rotating and/or stationary components. This type of current will not always "jump" the gap with lowest electrical resistance. Bearing damage is often accompanied by journal, collar, or runner damage.

The principal sources of electromagnetic current are shown in Figure 17. The path of the current is indicated by the short dashed line and is designated by the letter I.

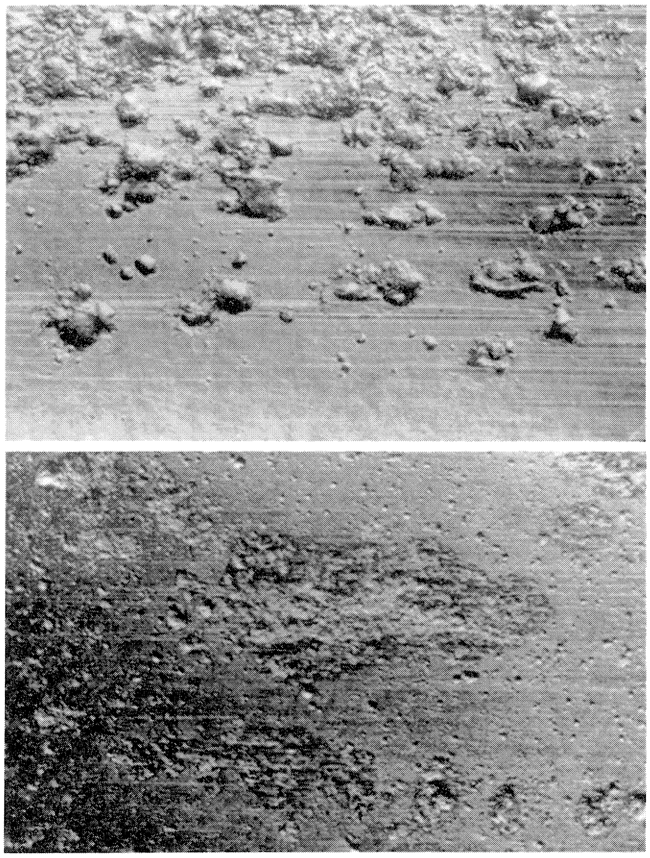


Figure 15. Electrical Pitting on a Lead Babbitt Bearing and Its Journal. (a) Pitting on lead-base babbitt, 15×. (b) Pitting on steel journal, 15×.

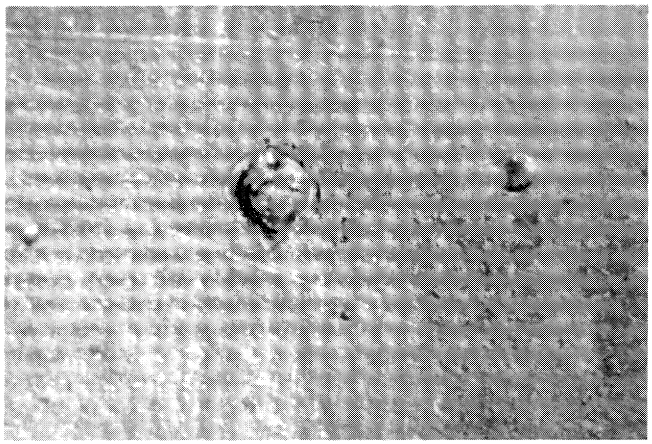


Figure 16. Typical Appearance of a Single Electrical Pit in a Tin-Base Babbitt, 45×.

FATIGUE

Fatigue failure is the cracking and fracture of metals due to an excessive number of cycling stresses when the stress level is above a threshold limit characteristic for a given material at a given temperature.

Mechanisms

Forces that tend to flex, reverse stress direction, or produce thermal cycling in a bearing are conducive to fatigue. However,

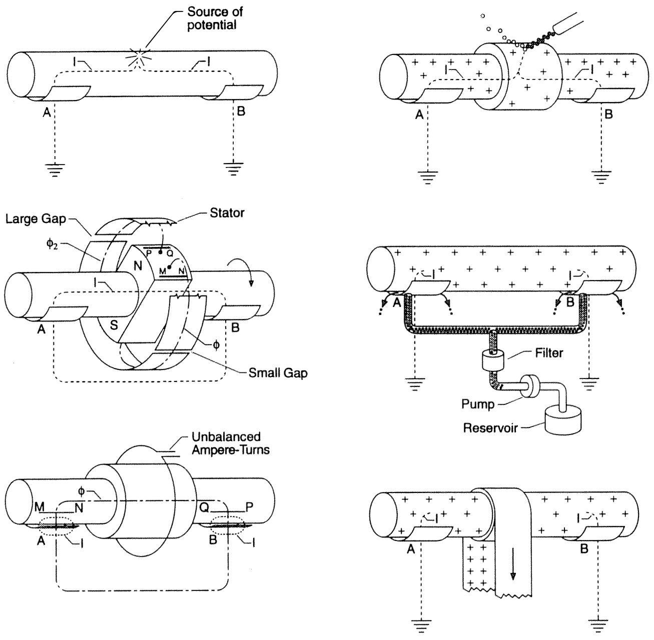


Figure 17. Principal Sources of Bearing Current. (a) Potential applied to shaft. (b) Dissymmetry effect. (c) Shaft magnetization effect. (d-1) Electrostatic effect-potential developed by impinging particles. (d-2) Electrostatic effect-potential developed by charged lubricant. (d-3) Electrostatic effect-potential developed by charged belt.

to initiate damage the intensity of these forces must exceed a certain threshold. The greater the stress, mechanical or thermal, the sooner damage occurs. In its early stages, fatigue failure is manifested in isolated cracks. At a more advanced stage of fatigue failure, the cracks, having reached the vicinity of the bond, travel parallel to it, eventually lifting out small pieces of babbitt. This process will ultimately cause the bearing to seize or overheat as a result of the drainage of oil from high-pressure areas of the film. There is evidence that the rate of application of load is of some importance in this process. Some bearing alloys that withstand heavy loads seem to fail when subjected to similar loads rapidly applied.

Three exposures of fatigue caused by edge loading with the bulk of the damage caused to the end of the bearing are shown in Figure 18. The severity of the cracks that penetrated nearly to the bond are shown in the close-up in Figure 18(b); loose chunks of babbitt protruding above the bearing surface are shown in a side view of a fatigue crack in Figure 18(c).

A frequent cause of fatigue failure in thin-walled sleeve bearings is flexure, when part of the bearing is alternately forced away from the shaft and returned to the original position. This flexing movement is a particular hazard where contact between the bearing shell and its housing is faulty. Bearings that are not in close contact with the housing also have poor heat dissipation, resulting in flexing at comparatively high temperatures. Fatigue failure always commences in the vicinity of these poorly fitting areas.

Factors in Fatigue Failure

Several parameters influence the likelihood of fatigue failure. These are:

- *Load and speed.* The onset of fatigue failure becomes more likely as the difference between maximum and minimum stresses on the bearing increases and as the frequency of the stress cycle rises.

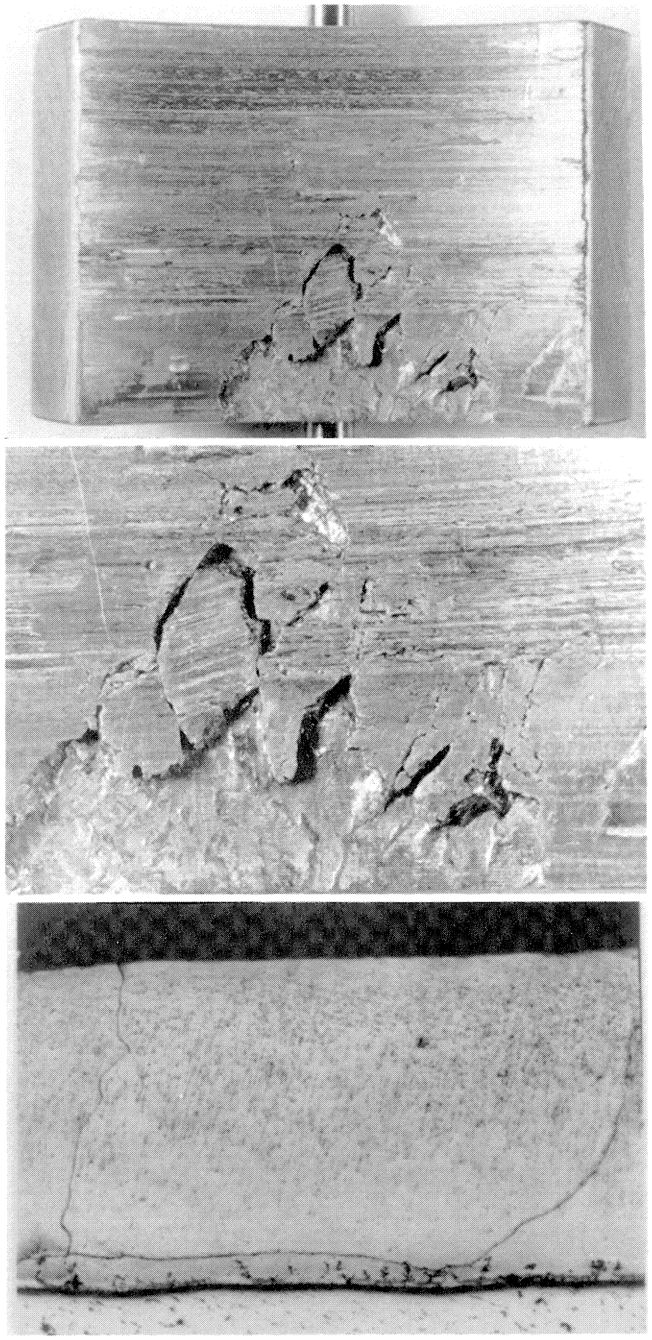


Figure 18. Fatigue Caused by Edge Loading on a Steam Turbine 4-7/8 × 1-7/8 in (12 × 4.76 cm) journal bearing. (a) Top view. (b) Close up of lower edge. (c) Side view of (a).

- *Temperature.* With increasing surface temperature, the physical properties of babbitts deteriorate and fatigue failures therefore increase.

- *Hardness and thickness.* Susceptibility to fatigue failure varies inversely with hardness, and directly with thickness of the babbitt.

- *Superimposed tensile stresses.* While the main stresses acting on a bearing are compressive, fatigue cracking of bearings is accelerated by the superimposition of a tensile stress on a pulsating compressive stress. Tensile stresses set up by casting a bearing alloy on a backing material of different thermal expansion as well as stresses set up by the anisotropy of thermal expansion in the grains of an alloy can be significant.

- *Thermal cycling.* Thermal stresses, such as those imposed during repeated heating and cooling, can, in themselves, lead to cracking of the bearing alloy. After a relatively small number of cycles, cracks are formed in the babbitt in the vicinity of the bond and become more pronounced as the number of thermal cycles increases. This type of cracking depends on: relative values of the coefficients of thermal expansion of bearing alloy and backing; operating temperature of the bearing; and the frequency with which the bearing is heated and cooled.

In addition to field data, a number of special studies have yielded information on the effects of mode of loading, bending stresses, and geometry on fatigue failure in bearings. In one study, three kinds of loading were imposed on a bearing (Figure 19). The results in terms of number of cycles and the four different modes of loading are given in Figure 20. As seen, the rotating load was the most damaging mode of loading, followed by that of a stationary reversing load. These loading modes are unfavorable because of the alternate imposition of positive and negative stresses in the bearing, that is of compressive and tensile forces. A series of fatigue tests conducted by the same investigator [2] revealed that in the early stages axial cracks started to form, followed by a tessellated pattern with breakouts of pieces of babbitt. The theoretical studies indicated that the axial cracks were due to the presence of tangential stresses. The nature of fatigue cracking was found to differ markedly, depending on whether the load is unidirectional (even if alternating) or rotating. A unidirectional load produces cracks normal to the surface, whereas a rotating load produces cracks at an angle of about 60 degrees It was also found that fatigue life under rotating load is inferior to that under a unidirectional load.

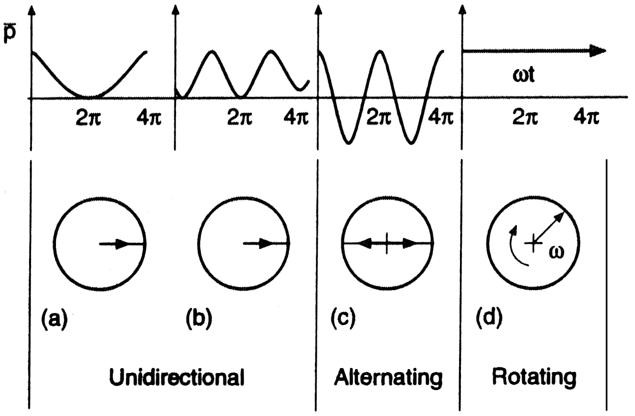


Figure 19. Modes of Loading in Fatigue Tests. (a) and (b) Unidirectional. (c) Alternating. (d) Rotating.

Fatigue failures can also occur at sites usually assumed to be safe, such as, for example, the unloaded top pads of tilting-pad bearings. In such pads (if not preloaded), there is usually enough radial play in the pivot to allow the pads radial motion, with cyclic loading of the edges of the pad. The result can be upper pad fatigue failure, as illustrated in Figure 21. The mechanism of this failure is as follows: when the radial play in the pivot is larger than the concentric clearance, a self-excited subsynchronous pad vibration is likely to occur. The base frequency of this vibration will be less than half the rev/min. The self-excited motion results from the absence of a stable static equilibrium position for the pad which, at each instant, seeks an instantaneous pressure distribution such as to produce a zero force and zero moment.

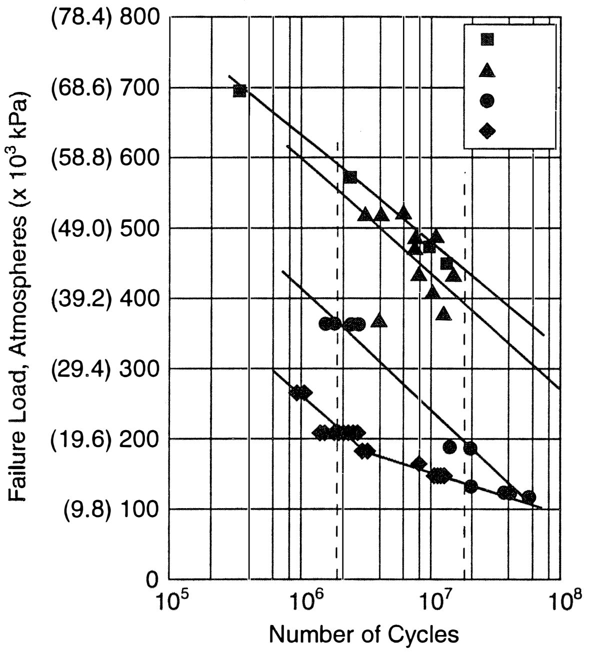


Figure 20. Failure Diagrams for the Four Modes of Loading.

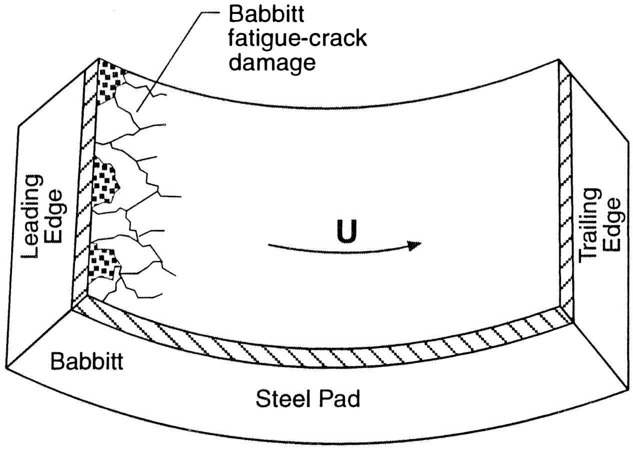


Figure 21. Example of Damage to a Large Journal Bearing Tilting-Pad Due to Self-Excited Vibration under Statically Unloaded Conditions.

Visually Identifying Fatigue

Although the cycling loading that is required to produce fatigue is not a very common condition of operation in electric utility rotating equipment, such failures do occur, because of the presence of unbalance loads and because babbitts are particularly low in strength. Fatigue usually starts at the surface, at the point of maximum pressure, and is first visible as fine surface cracks that penetrate the babbitt at an angle of about 45 to 90 degrees to the surface, depending on the mode of loading. Microscopically, fatigue appears on the surface in the form of a cobbled pattern and the cracks appear to grow, or open up, in the direction of rotation, as shown in Figure 22. In the case of bonded babbitt, the cracks propagate from the surface toward the bond, turn and continue parallel to, but above, the bond, as shown in Figures 23 and 24. Continued stress extends the cracks horizontally, undermining wide areas until large segments of bearing alloy are loosened and dislodged, thus reducing the area supporting the load. Loose babbitt particles eventually work their way into the clearance space and cause additional damage.

Tests with different layer thicknesses showed that the size of loosened babbitt pieces increases with increasing layer thickness, provided the other parameters remain unchanged. The loss of metal by fatigue breakout has the additional effect of disrupting the lubricating film, and causing loss of lubricant from the pressurized zones, which frequently leads to severe damage.

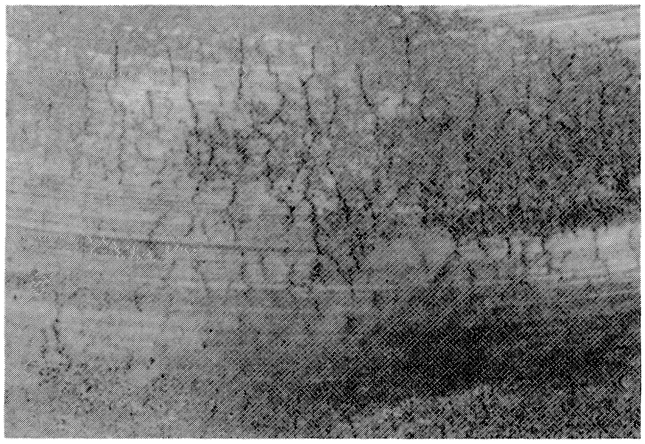


Figure 22. First Indication of Fatigue Failure-Fine Surface Cracks.

By comparing damaged bearings with photographs, inspectors may detect telltale traces of fatigue caused by load concentration and in relatively lightly-loaded bearings, where fatigue may appear in the upper unloaded half in the presence of an unbalance load, and in the loaded zone, where fatigue may result from cutting grooves, thereby raising the levels of maximum pressures (for a given load) and thus the proneness to fatigue.

Fatigue can also occur due to thermal cycling, particularly in tin-based babbitts that do not crystallize uniformly. Here the fissure could penetrate the babbitt normal to the surface, usually not in the center but at the edges of the bearing.

Possible Causes of Fatigue

To summarize, fatigue can be caused by a wide variety of operating conditions and flaws in bearing construction. The most frequent causes are as follows:

- *High stress concentration.* Electric utility bearings are not usually highly loaded, but this does not exclude the existence of local regions where stress concentration is sufficiently high to initiate fatigue cracks. High stress concentration, of course, would cause fatigue only if it were accompanied by cycling loading, discussed next.
- *Cycling loading.* Any of the following conditions can produce cyclic loading: shaft unbalance, which introduces a synchronously rotating load; instability (oil whip, etc.); intrusion of some external high-frequency load (from gears, etc.); and journal noncircularity.
- *Flexing of bearing shell.* A bearing shell can undergo flexing leading to fatigue, if the shell is too thin, the seating of the bearing in its housing is loose, or there is pinching at the joints due to improper clamping of the two bearing halves.

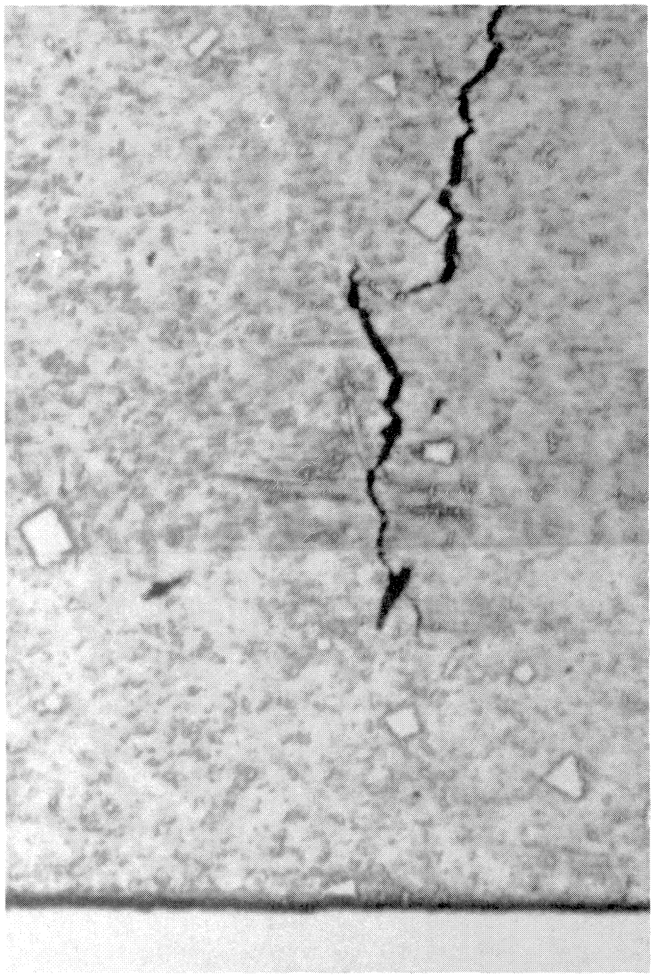


Figure 23. Fatigue Crack Extending from Surface toward Babbitt Bond.

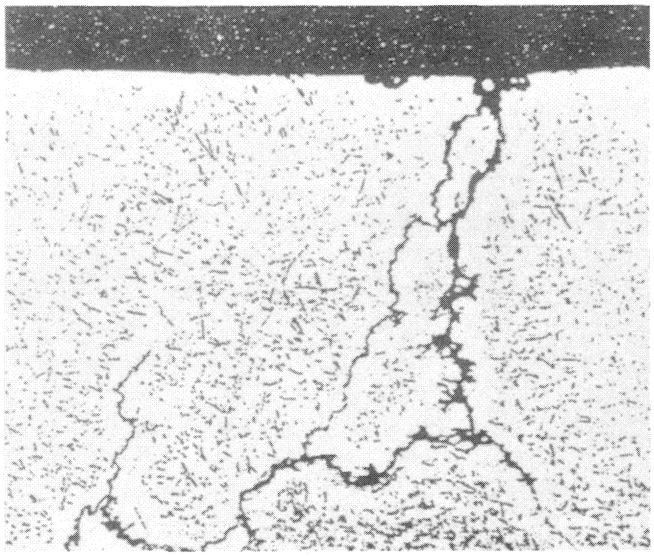


Figure 24. Fatigue Crack Starting to Extend along and above the Babbitt Bond.

- *Poor Babbitt-shell bonding.* Defective bonding accelerates fatigue and can often trigger it. Where poor bonding has assisted failure, the bare base metal is revealed when failure occurs.

- *Unloaded tilting-pad bearings.* In tilting-pad bearings without preload, the unloaded shoes are free to translate radially, and, in search for an equilibrium position, they are prone to slide into a vibratory mode conducive to fatigue failure.

- *Bearing replacement by new design.* Sometimes the replacement of a bearing by one of a different design will cause stress concentration or other difficulties when the replacement bearing runs against a journal that had worn so as to accommodate itself to the previous bearing.

- *Thermal cycling.* High temperatures in the babbitt, subject to a cyclic variation in maximum and minimum levels, may lead to a fatigue failure of the bearing.

OVERHEATING

Overheating includes both damage caused to bearings by exposure to temperatures above the softening point of one of the babbitt constituents and damage due to excessive thermal gradients causing the babbitt to crack.

Mechanisms

Bearing damage due to high temperatures can be direct or indirect. In the first category are those difficulties that result from the reduced-strength properties of babbitts. At elevated temperatures, babbitt undergoes creep with rippling of the surface and possible wiping. When the temperatures are sufficiently high, portions of the bearing will simply melt. When one constituent of the alloy melts and oozes out of the structure, the bearing is said to have undergone "sweating."

An indirect form of damage, which may be called thermal fatigue, is due to material anisotropy. Anisotropic materials, including some tin-base babbitts, have different coefficients of thermal expansion along each crystal axis. Such anisotropy can result in grain distortion when thermal stresses are imposed. Repeated thermal exposure causes mottling of the bearing surface, which is usually not detrimental to bearing performance. However, when grain distortion is severe, cracks will occur in the babbitt surface along the grain boundaries. This form of thermal cracking—a form of thermal fatigue—is called "ratcheting" (Figure 25).

Visually Identifying Overheating

A bearing failure due to excessive temperatures can be visually identified by the blackened, coked, or burnished appearance of the damaged surface and its surrounding areas. Two such surfaces are shown in Figures 26 and 27. In more severe cases, the babbitt will have been sufficiently softened during operation as to be displaced and lodged in areas of large clearances.

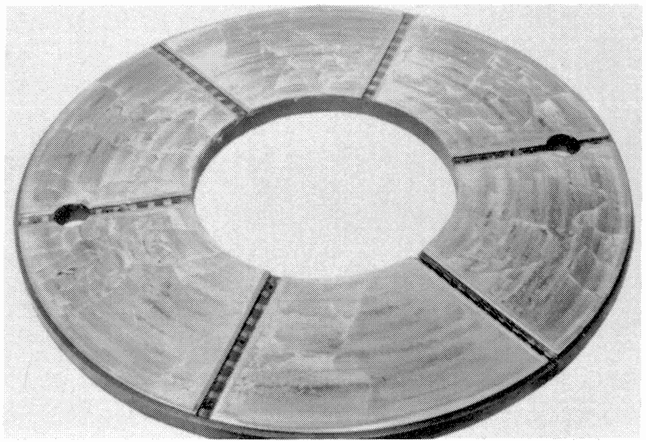


Figure 25. Ratcheting of a Thrust Bearing Due to Overheating.

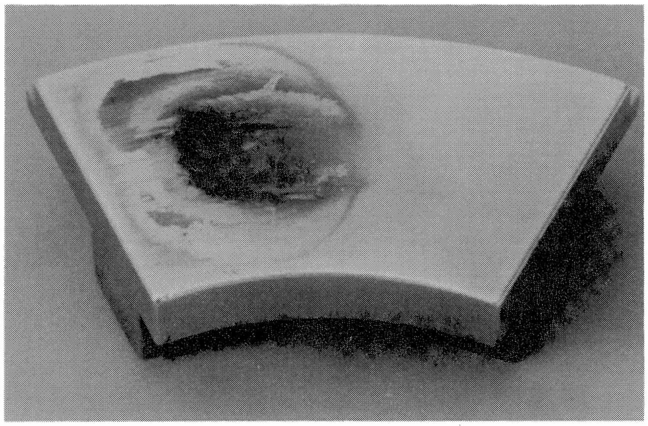


Figure 26. Overheating in an 8.0 in (20 cm) OD Thrust Pad.

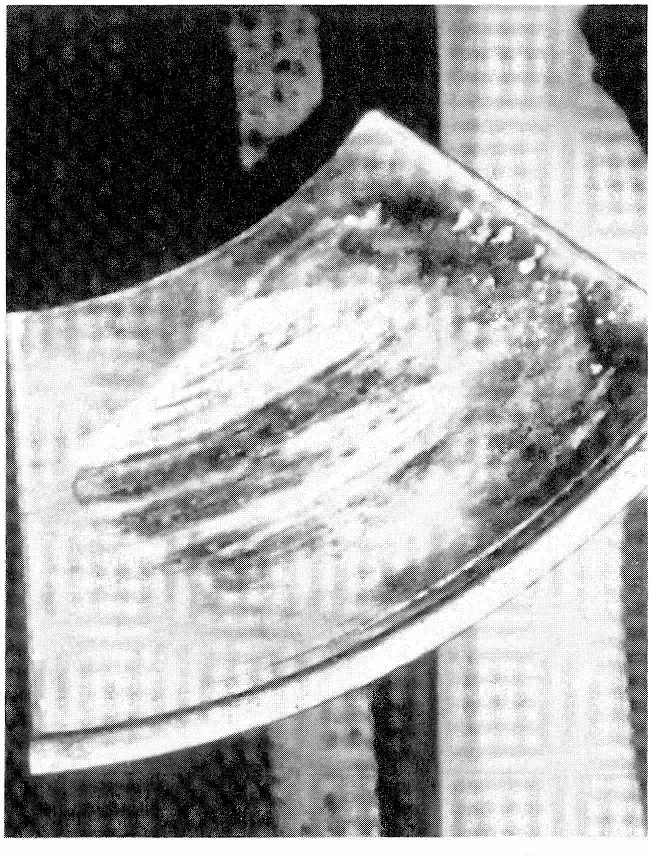


Figure 27. Overheating of Thrust Pad Due to Small h_{min}.

When the temperatures are high enough, portions of the bearing will actually melt. As noted, when only one constituent of the alloy melts and oozes out of the structure, the bearing is said to have sweated. Presence of globules of babbitt along the periphery of the low-pressure areas is evidence of sweating. These areas usually have a rippled and "flowed" appearance. Sometimes beads of sweat may be observed along oil grooves and pockets.

Still another category of telltale surface appearance is ratcheting-cracking or mottling of the babbitt due to the prevailing high thermal gradients. Viewed in cross section, a ratcheted surface would appear wavy rather than flat. When the temperature gradients are sufficiently high, the surface cracking can lead to dislodging of chunks of babbitt. The dislodging is caused by overheating with consequent reduction in strength, so that the babbitt yields and cracks due to the normal and shear forces transmitted through the oil films. These processes usually occur in the loaded areas. The extruded chunks are carried away and redeposited in the unloaded portions of the bearing. Wiping does not necessarily occur under such conditions.

Often the high temperatures are caused by insufficient lubricant and thus the bearing, in addition to having a damaged surface, is covered with a varnish deposited by the deteriorating oil. When the babbitt has been brought near its softening point, i.e., close to melting, a recrystallization of the babbitt alloy occurs. In the region of high pressure, the bond between the constituents may be severely distorted or destroyed.

Possible Causes of Overheating

A wide spectrum of conditions may generate excessive temperatures, many of them achieving this in an indirect way. Also, an excessive temperature in even a small local area is sufficient to bring about failure, although the general temperature level, the familiar temperature rise $T_{out} - T_{in}$, may not be high. Thus, a full description of the conditions and mechanism leading to an excessive T_{max} in journal or thrust bearings far exceeds the confines herein. However, some of the major causal pathways involve: insufficient lubrication or oil starvation, anisotropy, warping, faulty bearing geometry, excessively thin minimum film thickness, flooded lubrication, overheated or over-viscous supply oil, transfer of heat into the bearings from external sources, and misalignment.

WIPING

Wiping damage occurs whenever a substantial amount of babbitt is displaced or removed by direct contact with the journal or runner. Often, this material is redeposited at another bearing location.

Mechanisms

Wiping, full or partial, is probably the most familiar kind of damage encountered in babbitted bearings. The general appearance of a wiping in a thrust bearing is presented in Figure 28. Three mechanisms can be visualized as the direct cause of wiping. In one of these, melting of the babbitt occurs as a consequence of direct contact between the surfaces. In the second mechanism, the bearing metal is fractured in shear during contact; the sheared material is plastically deformed by mechanical cold working by the journal. In the third mechanism, excessive pressures developed near h_{min} cause localized plastic deformation of the babbitt once the babbitt yield strength is exceeded. The deformed material then protrudes into the clearance and contacts the runner, so that wiping occurs.

Classification and Possible Causes

Wiping is a generic term, since it is usually a result of underlying causes that can be divided into primary and secondary categories. The first category consists of wipings due to causes such as deprivation of lubricant, contact due to impact or excessive loading, and thermal and elastic distortions of the bearing. The second category consists of wipings that are a consequence of other damaging mechanisms.

A list of primary causes for the physical displacement of babbitt would include:

Figure 28. A Wiped 21.75 in (55 cm) Thrust Bearing Pad Due to Overload.

- Misalignment
- Tight clearances
- Starting problems
- Elastic and thermal distortions
- Excessive bearing load
- Instability or excessive vibration
- Shock loading
- Improper assembly
- Wrong load angle
- Oil starvation

Several failure modes, when not remedied, eventually lead to secondary wiping of the bearing. Some of these are:

- *Fatigue wiping.* As illustrated in Figure 29, when a fatigued bearing is permitted to continue in service, dislodged fragments will contact the shaft leading to a direct removal of babbitt material.
- *Gas diffusion.* Wiping sometimes is the result of blistering at the interface of babbitt bonded to steel.
- *Boundary lubrication wiping.* Wiping may be caused by excessive loading during starts and stops before a hydrodynamic film has been formed and possibly during slow speed operation on turning gear.

Visually Identifying Wiping

Since wiping is a consequence of direct contact between the runner and the bearing, this sort of damage is characterized by

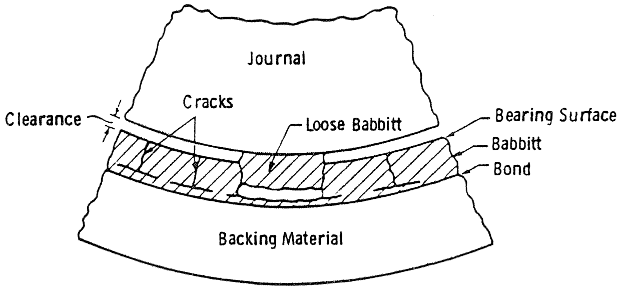


Figure 29. Sketch Showing Babbitt Fatigue Initiating Wiping Damage.

the physical displacement of babbitt material. The heaviest signs of this displacement are usually near h_{min}. This displacement extends over a fairly wide angular region, and it is characterized by irregular jagged edges at the end of the wiped area, where the displaced material has been deposited on top of the undamaged bearing surface. If the temperatures during the wipe are not high, the damaged area has a polished appearance; if high temperatures are generated in the process, parts of the wiped area may look dark and burnished.

Some specific examples of wiped bearings together with their underlying causes as diagnosed in the field are given later.

- A typical case of light to moderate wiping of a journal bearing is shown in Figure 30. A typical feature of such wiping, as already noted concerning fatigue wiping, is the presence of a layer of babbitt that has been displaced from its original location to a low-pressure region where its deposition on the previous surface can be noticed both by appearance and touch. Such a periphery is shown in enlarged scale in Figure 30b.
- A wiping concentrated is shown in Figure 31 at one end of the bearing brought about by severe misalignment.

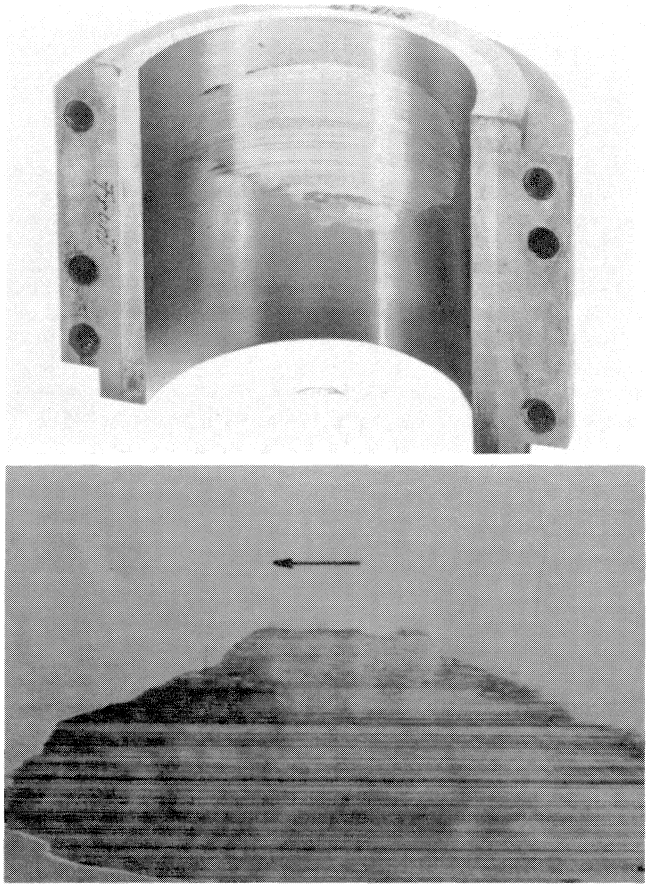


Figure 30. A Wiped 3.0 in (7.6 cm) Diameter Journal Bearing Wipe Due to Temporary Loss of Lubricant. (a) Loaded half of bearing. (b) Section of wipe.

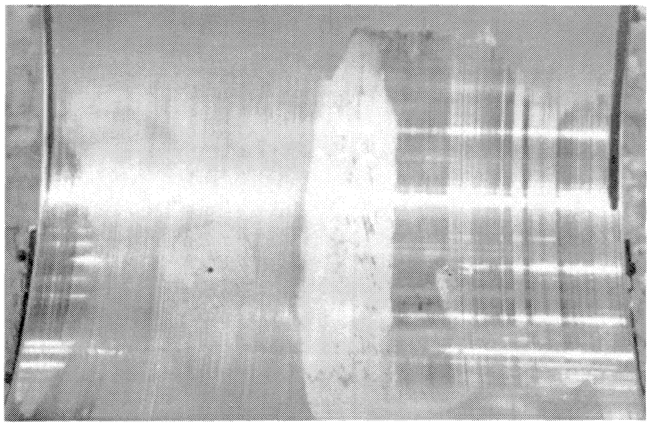


Figure 31. Steam Turbine Journal Bearing Wipe Due to Bearing Tilt.

LABORATORY TECHNIQUES FOR DIAGNOSING BEARING FAILURES

There are, essentially, two generic approaches available for identifying the specific kind of damage incurred by a failed bearing. The first, already discussed, consists of a visual, and possibly microscopic, inspection of the damaged surface and comparison of its appearance with catalogued photographs of classified modes of failure. The other consists of various laboratory techniques ranging from using a simple hand tool to highly sophisticated diagnostic procedures. These latter procedures include advanced physical and chemical techniques involving, for example, spectroscopy, lasers, and atomic scanning. One of these laboratory techniques for determining the nature of bearing damage—lube oil ferrography, a method of analyzing wear particles deposited in lubricants—is discussed below.

Ferrography

In use at dozens of utilities, ferrography is one of the more recent methods of contaminant identification. Its principle of operation (Figure 32) consists of pumping a sample of oil at a slow, steady rate between the poles of a magnet. The fluid runs down an inclined microscope slide and the net effect of the viscous and magnetic forces acting on the particles is to sort them by size. The larger particles are deposited first, and the smaller particles are carried farther downstream.

Information on the morphology of the deposited particles is obtained with the aid of a bichromatic microscope, which uses simultaneously reflected red light and transmitted green light. Metal particles as small as one micron reflect red light and block green light and thus appear red. Particles composed of compounds allow much of the green light to pass and appear green or, if they are relatively thick, yellow or green.

Particles generated by different wear mechanisms have characteristics that can be identified with each specific mechanism. Rubbing wear particles found in the lubricant of most machines have the form of platelets and indicate normal permissible wear. Cutting or abrasive wear particles take the form of miniature spirals, loops, and bent wires similar to swarf from a machining operation. A concentration of such particles is indicative of a severe, abrasive wear process. Particles consisting of compounds can result from an oxidizing or corrosive environment.

Various regimes are shown in Table 2 classified by the nature of the particles produced in sliding contact. Six regimes of rubbing wear that generate characteristic particles have been identified. Regimes 1 and 2 represent normal wear conditions corresponding to hydrodynamic and boundary lubrication. Evidence of one or more of the higher regimes (3, 4, or 5) indicates that some parameter of the system has changed unfavorably. The occurrence of regime 6 indicates impending failure. Free metal particles are produced in regimes 1, 2, 3, and 6, and these wear regimes may be identified by the particle size. With steel wear particles in regime 4, a mild form of oxidative wear dominates, and the majority of wear particles are hematite. Regime 5 generates black iron oxides which indicate a severe form of oxidative wear.

Table 2. Wear Regimes.

Regime	Particle Description and Major Dimension	Surface Description
1	Free metal particles usually less than 5 microns	Varies between polished and very rough; one surface can be polished while the opposing surface remains as generated
2	Free metal particles usually less than 15 microns	Stable, smooth, shear-mixed layer with a few grooves, depending on the number of particles in the oil
3	Free metal particles usually less than 150 microns	Ploughed with evidence of plastic flow and surface cracking
4	Red oxide particles as clusters or individually up to 150 microns	Ploughed with areas of oxide on the surface
5	Black oxide particles as clusters or individually up to 150 microns	Ploughed with areas of oxide on the surface
6	Free metal particles up to 1 mm	Severely ploughed, gross plastic flow and smearing

A CASE OF SECONDARY WIPING

In this section a diagnostic-remedial sequence, following the failure of a utility's bearing, is outlined. Failure is traced to a specific root cause, and a brief description of repair procedures is provided. The particular case, one of bearing wiping, is included because wiping represents perhaps the most generic form of bearing failure. In this particular case, bearing failure occurred in an old power plant and involved an overshot groove circular bearing (Figure 33). The failure was instantaneous and manifested itself as a near seizure of the rotor shaft, accompanied by smoke emanating from the bearing housing. The plant was immediately shut down and the housing opened for inspection. A diagrammatic picture of the diagnostic-remedial sequence is given in Figure 34.

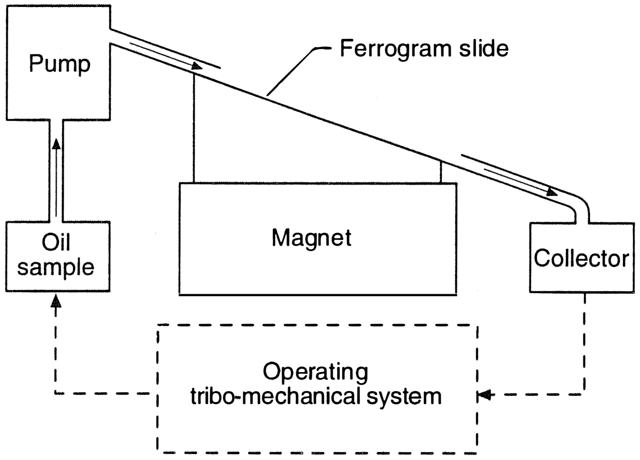


Figure 32. Schematic Representation of Ferrograph Analyzer.

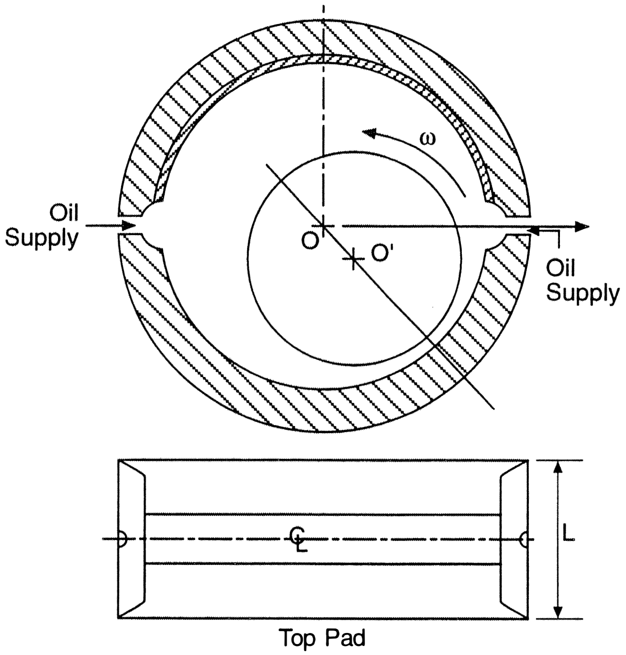


Figure 33. Common Design of an Overshot Groove Bearing. This type of bearing is a two-axial groove bearing with or without preload, in which the unloaded (top) pad is traversed by a deep circumferential channel extending across the entire arc of the pad.

Mode of Failure

The bearing surface showed the following symptoms:

- The loaded lower half showed no trace of distress.
- The upper half having the overshot groove showed severe displacement of babbitt over the downstream portions of the pad, with lumps of recongealed babbitt deposited in the overshot groove, in the downstream oil groove, and, to a lesser extent, at the leading edge of the lower half of the bearing. A diagram of the damaged upper half of the bearing is shown in Figure 35.
- No cracks were visible when the upper half of the bearing was viewed frontally because the babbitt covered any possible

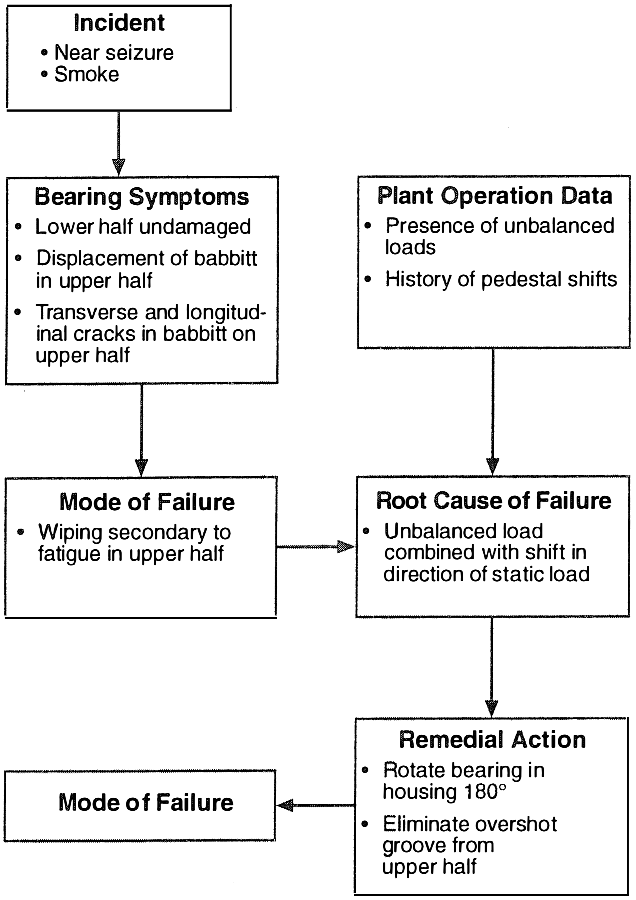


Figure 34. Illustrative Diagnostic-Remedial Procedure for Case of Secondary Wiping.

evidence. But when the upper half was viewed sideways inside the overshot groove, the babbitt layer showed small cracks both transversely across the layer and parallel to the bond line. No such cracks were visible in the lower half.

- These symptoms suggest that failure was caused by secondary wiping, triggered by a fatigued upper half of the bearing.

Root Cause of Wiping

This case represents a compound mode of failure, involving both fatigue and wiping. It is improbable that babbitt fatigue by itself would have caused immediate bearing failure. Likewise, the severe hydrodynamic conditions, while significant factors in the failure, would not alone have produced a wiping failure of this magnitude. A reasonable supposition is that the fatigued state of the babbitt aggravated the hydrodynamic conditions, resulting in a wiping. As such, fatigue constitutes the primary agent of failure.

The next diagnostic steps are to locate the root cause of bearing fatiguing, and then to determine the element that favored a wiping failure in the upper instead of the lower loaded half of the bearing.

About a dozen distinct processes can cause a fatigue or wiping failure. An element common to both failure modes is vibration of the rotor, caused by an oscillating load.

A review of the history of the power plant yielded some pertinent facts about two negative conditions surrounding the failure:

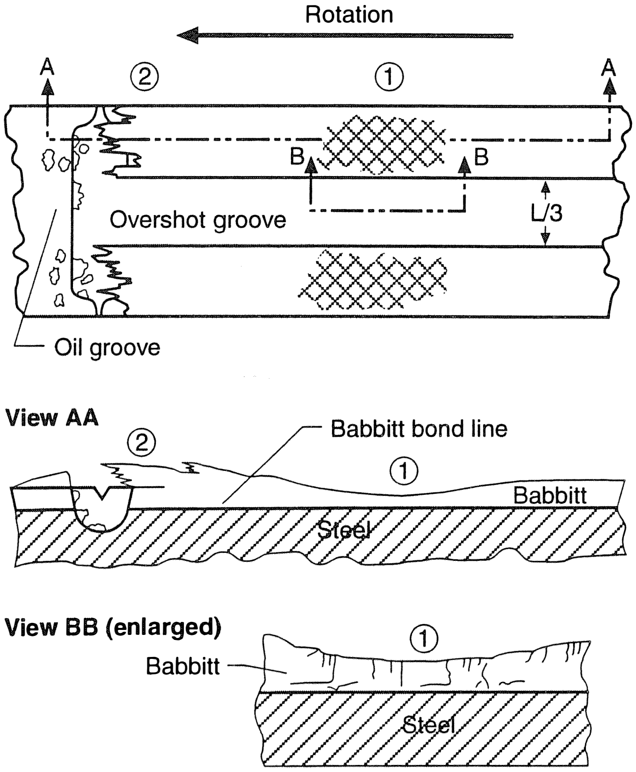


Figure 35. Topography of Damaged Upper Half of Bearing.

- The aging plant had a history of deteriorating unbalance loadings.
- The plant had problems with rotor alignment or mismatch due to shifts in the pedestals housing the bearings.

The first condition supports the supposition that an unbalance load precipitated the fatiguing process. However, the presence of an unbalance load does not resolve the question of why the upper, and not the loaded lower half suffered fatigue. The second condition, rotor mismatch, suggests some possible explanations, namely:

- The pedestal housing the failed bearing had shifted downwards, which unloaded the lower half and imposed an unknown load on the upper half.
- The unbalance load imposed a rotating force on both halves of the bearing; but with the static load diverted upwards, the upper half was loaded much more severely than the lower half.

The upper half with its overshot groove had a much lower load capacity than the lower half. Load capacity is proportional to $(L/D)^2$, where L is length, D, diameter. In this case the load capacity of the upper half relative to the lower half is given in Equation (1).

$$\text{Ratio} = (L/D)^2 \cdot 2 = (1/3)^2 \cdot 2 = 22\% \tag{1}$$

Thus, what has occurred is the introduction of a load rotating at a frequency of 60 Hz acting against the upper half of the bearing, which had only 22 percent of the load capacity originally designed into the bearing.

It is evident that the root cause of failure lies in the imposition of both oscillating and steady loads on the upper half of the overshot groove bearing.

Remedy

A fundamental remedy to this type of problem consists of eliminating the unbalance load and preventing the shift of pedestals. If feasible at all, this constitutes a major plant modification. However, from the standpoint of a bearing remedy, two options are available:

- Rotate the bearing 180 degrees so that the half with the unbroken surface is at the top. This would work if no subsequent changes in load direction occur.
- Eliminate the overshot groove entirely, yielding a design that ought to work satisfactorily regardless of the directions of the load.

MAINTAINING STEAM TURBINE LUBRICATION SYSTEMS

The lubrication system of a turbine generator supplies oil to the thrust and journal bearings under all operating conditions. After many years of trouble-free operation, these systems can suddenly fail because of degradation of the lubricant, malfunction of mechanical or electrical components, or deterioration of the emergency power source. Although lubrication system failures are rare, they cause major damage to turbine bearings and rotors. Since this can result in extended plant outages, regular inspection and maintenance of system elements are essential. Guidelines for maintaining steam turbine lubrication systems were developed for large power plant turbines by the author's organization [3]. In the following pages, discussion focuses on some key aspects of monitoring oil condition detailed in those guidelines.

Testing and Maintenance Requirements: Steam Turbine Oils

Present-day turbine oils are formulated with a highly-refined mineral oil base and a varying number of additives that enhance or impart a specific oil property. The finished oil is required to resist thermal or oxidative breakdown, inhibit rusting or corrosion, provide satisfactory lubrication and cooling of load-carrying components, resist foaming, and possess good water-separation properties. Through use, certain of these properties may deteriorate over extended periods of time. As a consequence, it is important to establish a sampling and analysis schedule that permits the turbine operator to monitor the oil condition. Information obtained from oil sample analysis not only provides a basis for judgment as to oil suitability, but also may identify system problems not otherwise detectable, such as coolant leaks, excessive wear, overheating, etc.

Specifications

Specifications for new lubricating oil are formulated by equipment manufacturers, oil suppliers, and certain technical societies active in the field of turbine lubrication. A minimum specification guide has been issued by the American Society for Testing and Materials (ASTM) and titled "Standard Specification for Mineral Lubricating Oil Used in Steam and Gas Turbines (D 4304)."

Additives

As a minimum, steam turbine oils contain an antioxidant to retard oxidative attack and a rust inhibitor to protect iron-base metals. In addition, an antifoam agent and a metal deactivator may be present. Depending on the properties of the mineral oil base, other functional additives may be used to achieve the required performance characteristics.

Over extended periods of time, some additives may be consumed through adsorption onto system materials or contaminants, deterioration by chemical reaction, thermal degradation, etc. This consumption may be wholly or partially offset by the routine addition of makeup oil. It is not unusual for turbine oils to remain in service for periods between 15 and 20 years. In turbine lubrication systems requiring relatively low makeup, oil properties should be monitored closely to make certain that any performance loss is identified. While it is possible to reinhibit an oil by mixing in an additive, this approach should be carefully considered and should only be taken after close consultation with the turbine oil supplier.

Contamination

Contaminants within the turbine oil system may be generated internally or drawn into the system from the surrounding environment through entry at seals or vents. External contamination may include airborne dust, sand, coal particulates, moisture, etc. Internally generated contaminants may consist of wear-metal particulates, which are constantly being produced in some degree; leaked coolant; oil degradation products such as sludge; and rust particles. Typical plots of the state of turbine oils in terms of quantity and size of solid contaminants were shown in Figure 7.

Excessive or uncontrolled buildup of contaminants should alert the turbine operator to identify the source, take corrective action, and determine whether oil purification equipment or system filters are properly functioning.

Analyses

In-service monitoring of the condition of a turbine oil should focus on the following properties:

- Antirust protection
- Remaining oil life (oxidation stability)
- Viscosity
- Total acid number
- Cleanliness
- Foaming tendency
- Color/appearance
- Water content
- Flash point

In the following paragraphs, the significance of the first two properties is discussed, along with recommended test procedures that have been developed, approved, and published by ASTM.

Within the turbine oil system, numerous ferrous metals require rusting protection. This protection is afforded in large part by the anti-rust additive present in the oil. New and used oils suitable for continued service must pass ASTM Method D 665-83 Procedure A, or D 3603-82. This is a dynamic test designed to evaluate the ability of steam turbine oils to prevent the rusting of ferrous components should water become mixed with the oil in service.

In this method, a cylindrical steel specimen is immersed in a glass beaker containing 300 ml of the test oil and 30 ml of distilled water at a temperature of 140°F (60°C). The mixture is stirred throughout the test, which normally lasts 24 hours. Rusting of the steel specimen is determined by visual examination after the test.

Remaining oil life is a measure of the remaining capability of oil to resist severe thermal/oxidative breakdown. Remaining useful oil life is strongly related to the remaining concentration of the antioxidant in the oil. The oxidation stability of new oils is generally measured by ASTM Method D 943-81. However, this procedure can take a relatively long time (over six weeks) and, as a consequence, is not employed for monitoring the condition of oils in service. For this purpose, ASTM Method D 2272-84, the rotating bomb oxidation test (RBOT), is preferred.

A 50 g sample of the test oil and 5.0 ml of water are placed in a small glass container containing a copper catalyst coil. The container is put into a metal oxidation bomb that is pressurized with oxygen to 90 psi (620 kPa), and then placed in a constant temperature bath at 302°F (150°C). The bomb is rotated at 100 rpm at an angle within the bath of 30 degrees from horizontal. Oxygen pressure is monitored continuously during a run, and the test is terminated when the pressure drops more than 25 psi (172 kPa) below the maximum pressure. This event generally reflects accelerated oxidation of the test oil, and the test time elapsed before accelerated oxidation is a measure of the remaining oxidation life of the oil in service when compared with the RBOT data for the new oil.

Turbine Severity Level

Each turbine generator lubrication system is unique due to exclusive conditions that arise during construction and operation of the system. These conditions set the rate at which a new charge of fresh oil will lose its oxidation resistance. A property called turbine severity (B) level has been established which can be used to take these conditions into consideration when monitoring the remaining oxidation resistance of the oil during its service life (DenHerder and Vienna). "B" is defined as the percentage of fresh oil oxidation resistance lost per year due to oil reactions in the turbine generator lubrication system. "B" takes into consideration the following three factors:

- Amount of make up oil added to the system to replenish the oil oxidation resistance
- Time that the oil has been in use
- Oxidation resistance that remains as determined by a RBOT, ASTM D 2272-84

Equation (2) determines turbine severity, B:

$$B = M\,(1-X/100)/(1-e^{-Mt/100}) \qquad (2)$$

where

M = Amount of oil added as makeup into the system per year, expressed as a percentage of the total amount of oil originally placed in the system (percentage per year)

X = Amount of oxidation resistance that remains in the oil, expressed as a percentage of the original oxidation resistance of the oil (percentage of fresh oil)

t = Amount of time the original oil has been in service in years

The effect of makeup rate, M, on oil degradation for a turbine with a severity level of 25 percent per year is shown in Figure 36.

The severity level for a particular lubrication system should be determined over a period of time beginning with initial operation or installation of a fresh oil charge. Keeping accurate records of the amount of oil makeup is essential, and RBOT should be conducted at three- to six-month intervals for one to two years. By knowing the oil makeup and degradation of the oil with time, the turbine severity for the oil can be found from Figure 37.

A lubrication system with a high severity level requires frequent makeup or completely new charges, whereas one with a low severity level may have no problems with routine makeup. Turbine generator units of recent design have higher "B" levels than units installed before 1965. Increases in lubrication system temperatures are suspected as reasons for the higher "B" levels

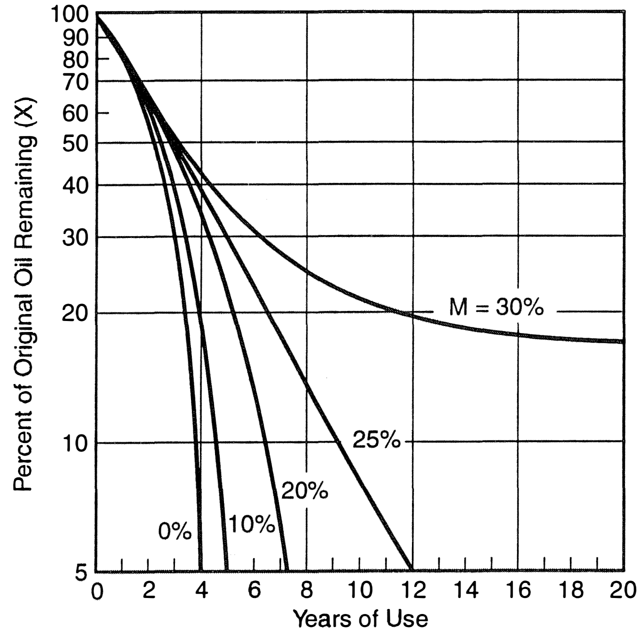


Figure 36. Effect of Makeup Rate on Oil Degradation. (Turbine severity, B = 25 percent per year.)

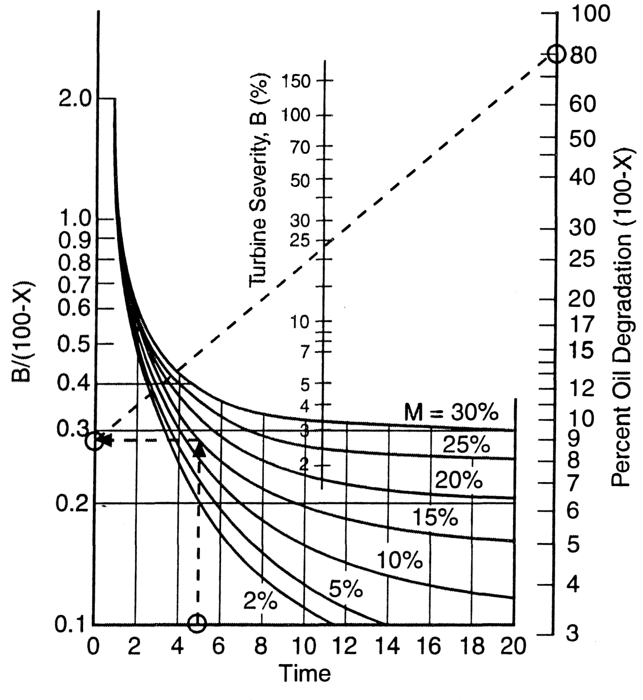


Figure 37. Effect of Turbine Severity (B) and Makeup Rate (M) on Oil Degradation. The dotted lines show the process for obtaining a value for turbine severity, B. In the example, the turbine oil has been in service for five years, and the annual makeup rate is 15 percent. The oil has degraded from a rotary bomb test life of 1700 minutes initially to only 350 minutes, a loss of 79.5 percent. Starting at five years on the time axis, a point on the 15 percent makeup curve is determined, and a line is projected left to the B/(100×) axis. A straight line between this point on the B/(100×) axis and a point at 79.5 percent on the percent oil degradation axis intersects the turbine severity scale at 22 percent per year.

obtained in new turbines. Larger shafts, turning gears, and couplings, and smaller oil reservoir volumes have increased the amount of heat each gallon of oil must transfer per hour to the oil cooler. Oil contamination by coal dust and fly ash from pressurized furnaces has also been a factor.

CONCLUDING REMARKS

The author's organization has developed a manual and software designed to help plant engineering and maintenance personnel identify specific modes of bearing damage, as well as root causes, and to respond appropriately. By identifying the mode and cause of bearing failures and often remedying associated problems on site, power plant maintenance costs can be reduced while equipment reliability is increased. Also, because lubrication deterioration is a leading cause of turbine bearing failures, including failures in several of the modes treated herein, turbine lubrication systems must be properly maintained. The author's organization has developed industry guidelines for maintaining and monitoring such systems.

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ACKNOWLEDGMENTS

The technical contributions of the following individuals and organizations for specific data and background information for this manuscript is gratefully acknowledged and sincerely appreciated: O. Pincus, Mechanical Technology Inc.; M. Adams, Case Western Reserve University; Glacier Bearings Inc.; Kingsbury Bearings Inc.; H. N. Kaufman, J. Boyd, A. Raimondi, Westinghouse Electric Corp.; E. R. Booser, J. Kure Jensen, General Electric Company; and G. Lamping, Southwest Research Institute.