FIELD INVESTIGATION OF BEARING HOUSING OIL CLEANLINESS

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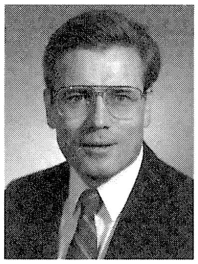

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ABSTRACT

The service life of rolling element bearings in centrifugal chemical process pumps is an issue of increasing concern. A key factor influencing bearing service life is the condition of the bearing lubricant. Several industrial users of process pumps participated in a survey of centrifugal pumps to determine the levels of water and particulate contamination in the bearing housing lubricating oil. More than 150 samples were analyzed, including new oil along with oil from operating and stand-by pumps. High levels of debris contamination were found in all size ranges of particulates. Water contamination was a much smaller problem than previously assumed. An overall conclusion is that current contamination control methods for non-recirculating oil bath rolling bearing element lubrication systems are not effective.

INTRODUCTION

A literature search revealed that little information has been published [1,2,3,4] concerning the contamination levels of lubricants in the bearing housings of industrial pumps, Figure 1. The focus of this research effort was to investigate the cleanliness of rolling element bearing lubricating oil in the bearing housings of operating and standby centrifugal chemical process pumps. This information provides an indication of current contamination levels and permits decisions to be made concerning the need for, and effective methods of, improving lubrication conditions.

The pump industry is concerned about rolling element bearing lubrication, even though bearing failure is not what limits the life of most pumps today. There are two main reasons for the pump industry to be concerned. First, bearing failure often leads to the most devastating type of pump failure, loss of shaft control. Second, as mechanical seal life continues to improve, bearing life will increasingly limit pump life.

The control of oil contamination and degradation is considered a requirement for long bearing and pump life. Contaminants are

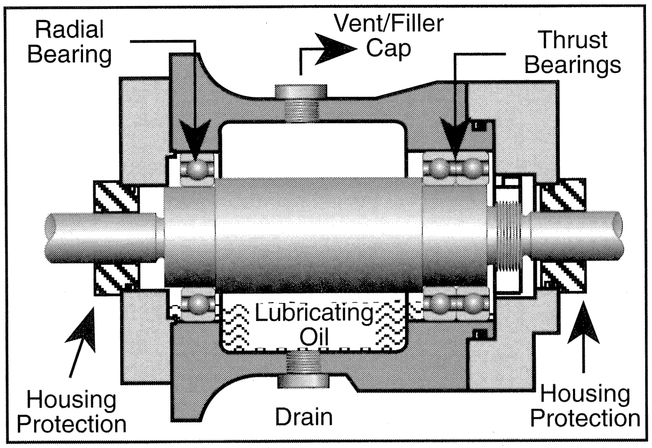


Figure 1. Typical Bearing Housing.

present in new oil, storage drums, funnels, and in the bearing housing. They can enter the bearing housing from outside and can be generated by operating bearings. The increased use of labyrinth [5] and magnetic bearing housing seals is evidence that users believe contamination from outside the bearing housing is an issue.

It is estimated that the average pump mean time between planned maintenance (MTBPM) in chemical process plants is less than 18 months. The average cost to repair a failed process pump is approximately $3,500, not including costs due to process upsets, plant shutdowns, or lost production costs. These costs include the direct labor and materials along with the associated burden and disposal costs. With a typical 20 year installation life, pump maintenance costs can exceed $45,000. In most cases, this is far greater than the initial acquisition and installation cost. Because of the failure frequency, many plants install backup pumps; doubling installation costs, consuming valuable floor space, and often compromising suction piping.

A high percentage of pump failures in the chemical process industry are attributed to the mechanical seal. However, with current improvements in seal design and materials, seal chamber design, and maintenance practices, the average seal life will soon exceed three years. As seal technology continues to improve, bearing failures will become the predominant cause for maintenance. Bearings for process pumps are designed for a minimum life of two years, with the theoretical bearing life estimated at greater than five years in the vast majority of applications. However, pump bearings will limit pump life unless bearing housing conditions improve.

Although corrosion, erosion, or seal problems can limit pump life, there are pump types that allow replacement of the process wetted parts without disassembly of the bearing frame. For many pump types, there is no reason why bearing replacement can not be extended to five years, even if the remainder of the pump does not last that long. Yet, it is common practice to replace bearings and lubricating oil when a mechanical seal is replaced. Many users replace the bearings during any pump maintenance, because of the lack of confidence that contamination is under control.

Moreover, in existing installations that incorporate older seal technology, users will benefit if the bearings, in fact, do not require replacement during routine maintenance. Usually, such bearing replacement is performed as an insurance step, in case the lubricant becomes contaminated during maintenance. This practice increases the maintenance costs as a result of the direct time and materials involved. It also increases the amount of used oil that must be disposed of or recycled. In addition to the direct cost of maintenance, unnecessary routine bearing replacement introduces the risk of future failures. A pump which has been operating successfully for six months has proven that it is not subject to startup failure. However, the act of replacing bearings involves many operations, all of which involve the possibility of error. Some of these include:

- Introducing grit into the bearing housing.
- Introducing grit into the bearings.
- Using the wrong lubricant.
- Mechanical damage to the shaft when removing the old bearings.
- Excessive heating of the bearings upon installation.
- Improper location of the bearings.
- Damaging bearing fits.
- Damaging closure seals.

A fault analysis of these areas indicates that there is a 20 percent chance that bearing life will be reduced to half its normal value through unnecessary maintenance.

It is very desirable, therefore, to develop a technology that will eliminate the need to repair or replace bearings, by providing assurance that the bearings have the optimum environment in which to operate.

LUBRICANT CLEANLINESS LEVELS

Rolling Element Bearing Fatigue

Rolling element bearing contact fatigue is caused by two processes:

- Subsurface-initiated spalling
- Surface-initiated spalling

For the past 50 years of investigation into bearing fatigue, emphasis was placed on the subsurface mechanism. This was because spalling usually started within the bearing steel at slag inclusions left over from the steel refining process. These inclusions were often oxides. As steel refining methods improved, the number of slag inclusions and the significance of subsurface-initiated spalling have been greatly reduced.

The other mechanism, surface-initiated spalling, is caused by denting of the bearing surface. Dents produce stress risers in the steel that, on subsequent repeated contact, may eventually generate a crack that propagates through the steel, producing a spalling pit. Rolling element bearings are designed so that an elastohydrodynamic lubricant film separates the two opposing surfaces to prevent denting. Within the "contact zone" this film is typically 0.2 to 1.0 μm thick.

There are two ways a bearing surface becomes dented. One is when the asperities of one surface break through this thin lubricant film and dent the opposing surface as shown in Figure 2. Asperity contact is prevented in most applications by designing the bearing and lubricant to support the load without asperity breakthrough.

The second mechanism is for a particle to enter the contact zone and make simultaneous contact with both bearing surfaces, Figure 3.

This is also known as three-body contact. The particle size must be equal to, or larger than, the thickness of the lubricant film for denting to occur by this mechanism. The amount and severity of surface denting is directly proportional to the number, size distribution, hardness, and shape of the suspended contaminant particles. Hard particles, such as metals, metal oxides, and grits, are the most damaging. However, Ioannides, et al. [6], have shown that even hardened bearing surfaces can be dented by softer particulates trapped between two rolling surfaces. Surface stresses in the contact zone can rise significantly above the yield stress of the softer material due to extrusion as the soft material is crushed. It was found that the hardness, aspect ratio, and ductility of the particulate determined its ability to dent a harder surface.

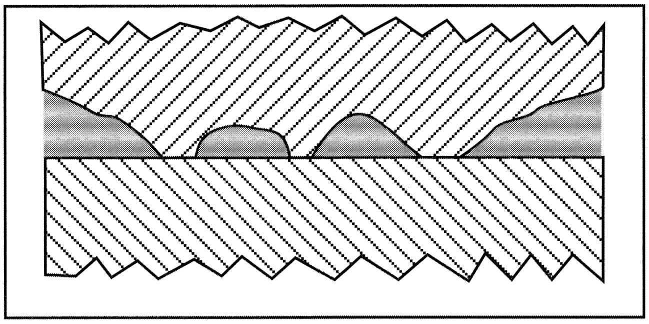


Figure 2. Asperity Penetrating Lubrication Film.

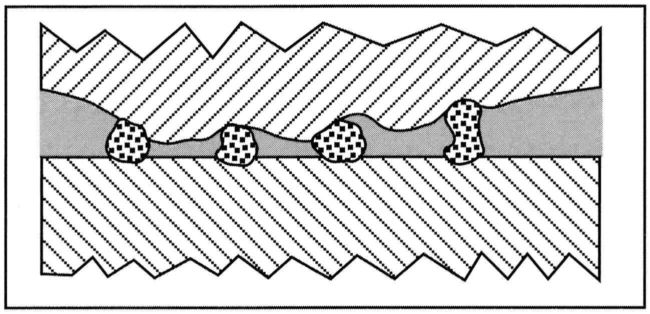


Figure 3. Particles Penetrating Lubricant Film.

Lubricant Contamination and Lubricant Life

Oil degradation leads to lubrication problems similar to contamination as the lubricant film deteriorates and fails to separate the wearing components. Increasing use of synthetic oils is evidence that users believe oil degradation is a serious issue. Oil degradation is accelerated by contamination and includes factors such as organic acids, metallic catalysts, and water.

Organic acids, as measured by the total acid number (TAN), significantly foster oil oxidation. Also, other residues, such as varnishes and gums, may occlude oil flow passages and coat heat exchange surfaces. Some of these residues may also act as oil thickeners, restricting the flow of lubricant into bearing contact zones.

Lubricant oxidation forms reactive chemical species known as "free-radicals." These initiate a chain reaction that can produce thousands of breakdown products, Figure 4.

Such chain reactions can rapidly degrade an oil. To prevent this rapid deterioration, lubricants are formulated with antioxidant additives. These additives function by reacting with free-radicals to form stable molecules, thus breaking the chain reaction before too much damage is done.

Free-radicals are constantly being produced during service and are neutralized by the anti-oxidants. However, the additive level is continuously depleted with service, until a threshold is reached, at which point the free-radical chains become unchecked, Figure 5.

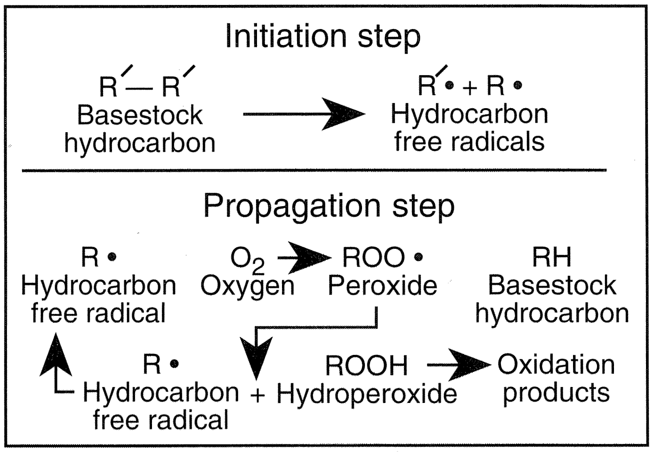


Figure 4. Free Radical Indicates Chain Reaction.

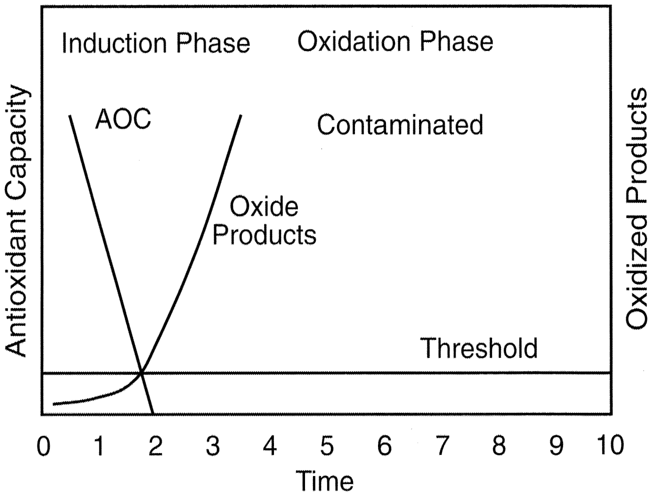


Figure 5. Additive Level is Continuously Depleted.

At this point, the oil degrades rapidly. Useful oil life can be considered as the interval of service until the antioxidant threshold is reached. The rate of depletion depends of several factors. One is temperature. It is estimated that service life is halved for every 18°F (10°C) increase in operating temperature.

Fresh metallic surfaces have also been found to accelerate the formation of free-radicals, and hence, shorten lubricant life. Oil stability tests, such as ASTM Tests D-943 and D-2272, intentionally include an acid etched metal coupon to accelerate the oxidation process. In a classic study, Figure 6, clean dry oil was found

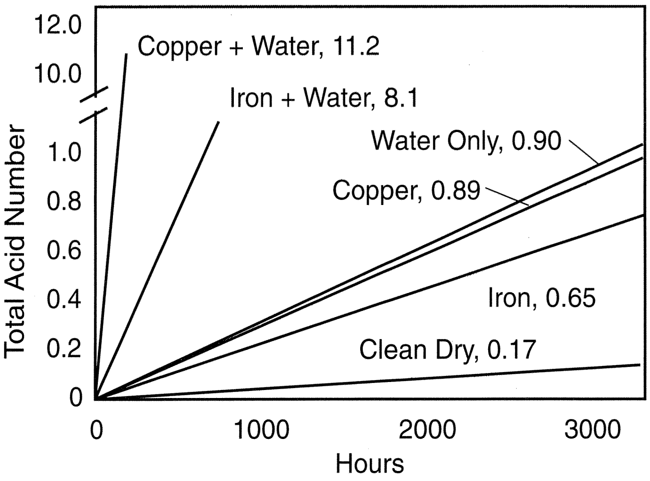


Figure 6. Metal and Water Contamination Affect on Oil Break Down.

to have insignificant degradation over the course of a 3500 hr test. The presence of a metal alone, or water alone, increased degradation by a factor of about five. The presence of a metal and water together caused total oil breakdown within the first 100 hr of the 3500 hr test.

Although etched-metal coupons are not inserted into machinery, a source of fresh metal surfaces comes from component wear debris. Surfaces on fresh wear debris, and the freshly worn component surfaces, accelerate oil oxidation. However, fine filtration has been found to inhibit the pro-oxidation effects of wearing metal surfaces, and, thereby, increase lubricant service life. It is believed this benefit accrues by four mechanisms:

- Filtration reduces the overall wear rate of component surfaces so that much less fresh metal is generated.
- Filtration reduces the number of particles available to dent wear surfaces, thereby limiting the initiation of fatigue cracks, resulting spalls, and the generation of new debris.
- Filtration reduces the number of particles available to enter hotter zones of the system where the oxidation rate is much higher.
- Filtration reduces the overall wear rate of close clearance components which, if allowed to wear significantly, would lead to misalignment, increased heat generation, higher lubricant temperature, and accelerated oil oxidation.

The effect that filtration can have on oil life is shown in Figure 7. A field study of city transit buses operating with transmissions maintained with 35 micron filter media revealed severe oil breakdown within 25,000 miles of operation. In contrast, another bus operating with the same model transmission but maintained by a 6.0 micron filter showed only moderate oil breakdown after 125,000 miles.

MacPherson, et al. [7], found that operating with a cleaner lubricant, by improving filter efficiency, increased bearing life by a factor of six, Figure 8.

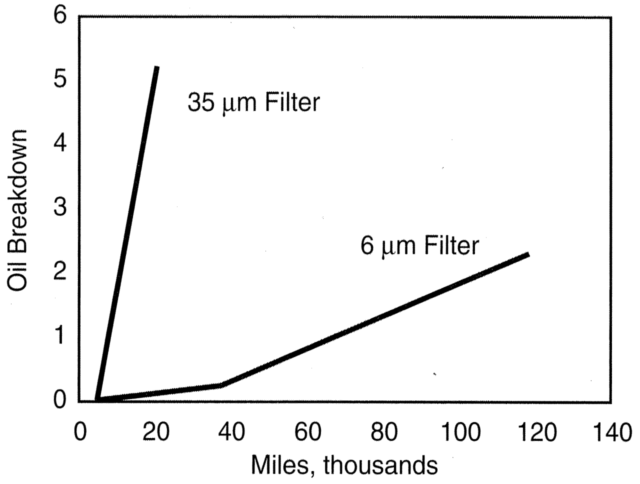


Figure 7. Effect of Filter Rating on Oil Breakdown.

Analysis of this and other studies by Zaretsky [8] led to an empirical bearing life adjustment empirical factor based on filter rating, as illustrated in Figure 9.

Similar considerations have led several bearing manufacturers to include lubricant contamination factors when calculating the fatigue life of their products.

Water has also been found to promote fatigue spalling. Free water has long been known to weaken steel surfaces via corrosion. It has also been demonstrated that dissolved water, in concentrations well below the saturation level, accelerate the spalling process.

It is believed that water dissolved in the oil penetrates deep into a crack and then accelerates crack propagation by attacking the tip of the crack, reducing overall fatigue life. One study found that by reducing water concentrations well below saturation, bearing life increased by a factor of five, Figure 10.

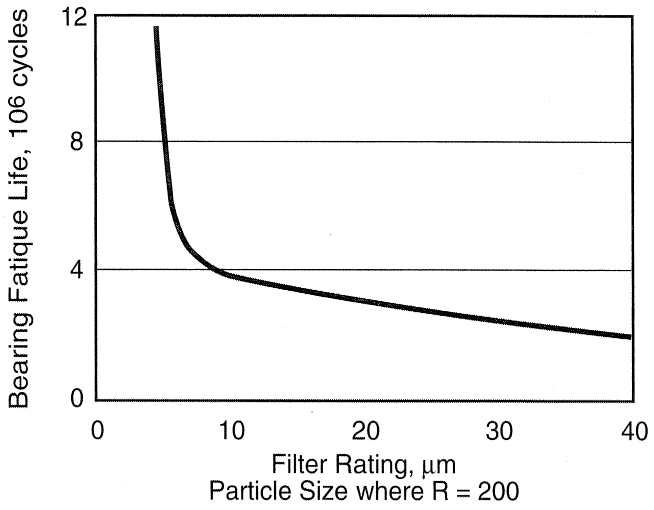


Figure 8. Bearing Life vs *Level of Filtration.*

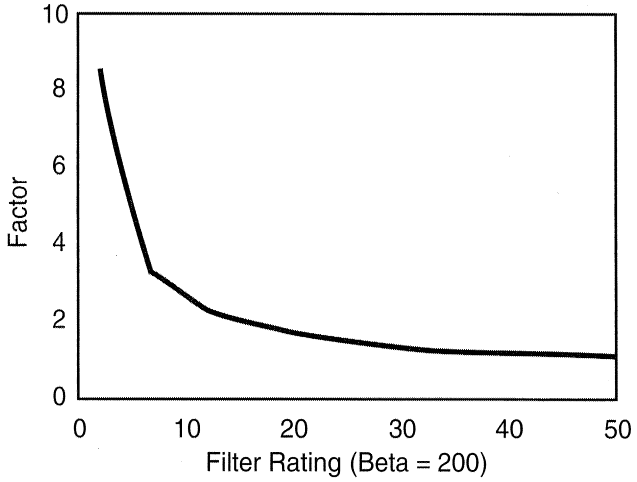


Figure 9. Bearing Life Factor vs *Filter Rating.*

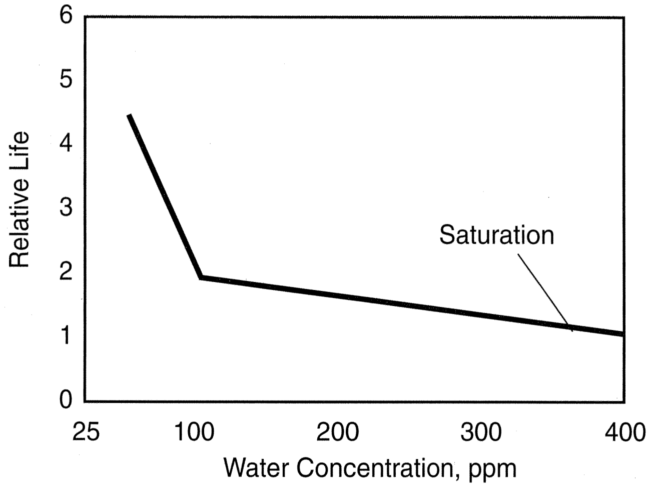


Figure 10. Relative Bearing Life vs *Water Concentration.*

Recommended Oil Cleanliness Levels

As discussed, both particulate and water contamination reduce the life of rolling element bearings along with the life of the lubricant protecting them. It is evident that the relationship between contamination and service life is very complex. Most operators of industrial equipment prefer clearly defined road maps to guide them through the murky territory of contamination control. In a set of guidelines for a wide range of machinery, Needelman [9] suggests maximum contamination limits for rolling element bearings as shown in Table 1. Others [10, 11] advise similar limits for small and medium size gearboxes, also listed in Table 1.

Table 1. Contamination Limits for Rolling Element Bearing Lubrication Oil.

Reference	Max. Particles per milliliter µm	no.	Maximum Contamination Level
STLE/CRC Lubrication Handbook	2	160	ISO 14/12/10
	>5	40	
	>15	10	
SKF	>2	n/a	ISO 13/10
	>5	80	
	>15	10	
FAG/Losche, et. al.	>2	n/a	ISO 12/9
	>5	40	
	>15	5	

However, neither of these suggestions are specific to industrial pump rolling element bearing systems. After considering both the benefits to bearing operation and oil life, and the technologies available for achieving these cleanliness levels, this current study endorses oil cleanliness levels as indicated in Table 2. Note that these recommendations are consistent with those provided for related machinery shown in Table 1.

Table 2. Recommended Maximum Contamination Levels.

Particle Size, µm	Particles per milliliter	Contamination Code, ISO
>2	160	4/12/10

Maximum water concentration: 100 ppm

FIELD SURVEY METHODOLOGY

To obtain a measure of the current cleanliness levels, a field survey plan was formulated specifically for centrifugal process pumps with oil lubricated rolling element bearings. Sites included pumps located both indoors and outdoors, with a variety of bearing housing closure seals, and high and low humidity environments.

Seven plant sites agreed to cooperate in the lubricant sampling program. The sampling site characteristics are summarized in Table 3.

Five of these plants were in the Houston area, one on the Northeast coast of the United States, and one in the Ohio River Valley area. Of the plants evaluated, one was a pharmaceutical company and six were petrochemical plants using primarily ASME B73 pumps. Only wet sump splash lubricated rolling element bearings were sampled. While oil mist systems were found at some plant sites, meaningful data were not obtained, because there were no known equivalent methods of determining particulate and moisture contamination in the bearing cavity.

Table 3. Sample Sites.

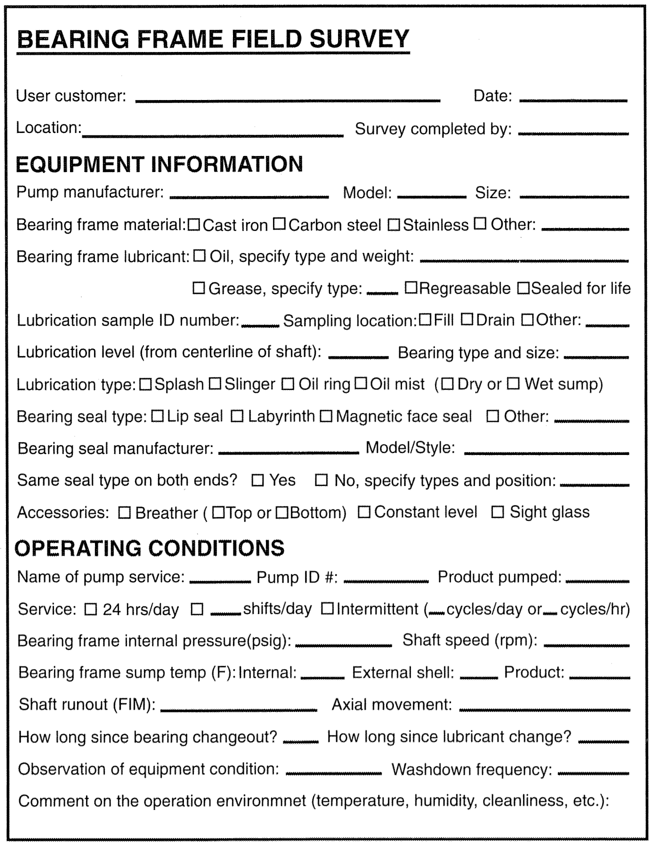
	Site	No. of Tests	Date	Pump Loc.	Oil Change, mos.	Closure Seals
1	Gulf Coast	33	July	out	4	lip & laby.
2	Gulf Coast	11	July	out	—	lip & laby.
3	NE Coast	26	Jan/ Feb	in	—	lip & laby.
4	Ohio River Valley	14	June	in & out	12	lip & laby.
5	Gulf Coast	20	July	out	>12	laby.
6	Gulf Coast	10	July	out	3	laby.
7	Gulf Coast	20	July	out	>12	lip

SAMPLING AND ANALYSIS PROCEDURES

Fluid samples were extracted from the bearing housings into precleaned glass sample bottles. A length of freshly cleaned flexible tubing was inserted through the bearing housing filler cap and extended approximately half way between the surface of the oil and the bottom of the sump, Figure 1. The other end of the tubing was attached to the sample bottle. A partial vacuum was then applied to draw oil through the flexible tubing from the bearing housing into the sample bottle. Precautions were taken during each sampling event to minimize background contamination of the fluid sample by minimizing exposure of the glass bottle interior to the environment. A sample data sheet, Figure 11, was used to record the pertinent parameters for each sample. Samples of unused oil were also taken from bulk storage containers and transfer containers at most locations.

Data were analyzed in two categories, by water content and by particle count.

Water concentrations were measured by use of an electrometric titration and reported as parts of water per million parts of the sample (ppm). Particle counts were divided into size categories of greater than two, five, and 15 µm. Particle counts for the majority of samples were performed using an automatic particle counter calibrated to AC fine test dust according to ISO 4402. A portion of the fluid sample was processed through an automatic particle counter equipped with a specific sensor. In some cases, such as when excessive water prevented using automatic counters, the samples were optically counted per SAE ARP 598. For this analysis, a portion of the sample fluid was drawn through a 0.8 µm laboratory patch, where particles isolated on the surface of the patch were then counted manually with a binocular microscope. Photomicrographs were taken of the contaminant materials isolated on the 0.8 µm laboratory patches using a similar binocular microscope equipped with a Polaroid™ camera.



BEARING FRAME FIELD SURVEY

User customer: ____ Date: ____

Location: ____ Survey completed by: ____

EQUIPMENT INFORMATION

Pump manufacturer: ____ Model: ____ Size: ____

Bearing frame material: ☐ Cast iron ☐ Carbon steel ☐ Stainless ☐ Other: ____

Bearing frame lubricant: ☐ Oil, specify type and weight: ____

☐ Grease, specify type: ____ ☐ Regreasable ☐ Sealed for life

Lubrication sample ID number: ____ Sampling location: ☐ Fill ☐ Drain ☐ Other: ____

Lubrication level (from centerline of shaft): ____ Bearing type and size: ____

Lubrication type: ☐ Splash ☐ Slinger ☐ Oil ring ☐ Oil mist (☐ Dry or ☐ Wet sump)

Bearing seal type: ☐ Lip seal ☐ Labyrinth ☐ Magnetic face seal ☐ Other: ____

Bearing seal manufacturer: ____ Model/Style: ____

Same seal type on both ends? ☐ Yes ☐ No, specify types and position: ____

Accessories: ☐ Breather (☐ Top or ☐ Bottom) ☐ Constant level ☐ Sight glass

OPERATING CONDITIONS

Name of pump service: ____ Pump ID #: ____ Product pumped: ____

Service: ☐ 24 hrs/day ☐ ____ shifts/day ☐ Intermittent (____ cycles/day or ____ cycles/hr)

Bearing frame internal pressure(psig): ____ Shaft speed (rpm): ____

Bearing frame sump temp (F): Internal: ____ External shell: ____ Product: ____

Shaft runout (FIM): ____ Axial movement: ____

How long since bearing changeout? ____ How long since lubricant change? ____

Observation of equipment condition: ____ Washdown frequency: ____

Comment on the operation environmnet (temperature, humidity, cleanliness, etc.):

Figure 11. Bearing Frame Field Survey

RESULTS

Water Contamination

Minimum, maximum, and median values of water contamination were tabulated for all categories. The median is used for comparisons rather than the mean or average because, in many cases, one or two samples had high levels of contamination that would distort the analysis. The median, maximum, and minimum concentrations of water and particulate counts are shown by oil sample type in Table 4.

The water concentrations found in the unused oil samples taken from each location are shown in Table 5.

These tests show that there were unused oil samples from every site that had excessive levels of water contamination as measured against guidelines proposed in this study.

Unexpectedly, the typical bearing frame had little water contamination, well below the recommended maximum value of 100 ppm, except for Site 3. The study further indicated that the rolling bearing element lubricating oil in 24 percent of the pumps surveyed contained moisture content greater than the recommended 100 ppm. Nine percent of the samples contained moisture content greater than 200 ppm and five percent contained moisture content greater than the saturation level of 400 ppm. When excessive water was found, it was usually as free water, indicating a severe failure or abuse.

Eleven percent of the pumps using lip seals contained oil with a moisture content greater than 100 ppm with a population median of 53 ppm, Figure 12.

Table 4. Particulate and Water Contamination by Characteristic.

	Water	Particulate Count/mil		
	ppm	>2 μm	>5 μm	>15 μm
Synthetic Oil				
Max.	309	1,000,000	200,000	30,000
Median	65	39,080	6,743	678
Min.	9	4,814	1,170	126
Mineral Oil				
Max.	5,837	1,693,000	179,600	12,160
Median	69	17,605	3,775	450
Min.	14	946	304	34
Covered Pump				
Max.	5,837	1,194,700	159,430	12,160
Median	81	27,735	4,481	550
Min.	9	2,021	410	68
Uncovered Pump				
Max.	3,166	451,000	77,030	2,740
Median	105	15,440	2,075	425
Min.	32	1764	389	57
Oil Change ,< 6 months				
Max.	5,837	1,194,700	200,000	12,160
Median	76	32,953	5,445	858
Min.	30	2,362	410	68
Oil Change, 6-12 months				
Max.	137	88,645	12,805	1,340
Median	90	9,355	2,075	372
Min.	21	1,764	510	78
Oil Change, >12 months				
Max.	266	451,000	77,030	5,250
Median	66	50,420	9,540	780
Min.	30	2,175	990	140
Lip Seal Closure				
Max.	1000			
Median	53			
Min.	14			
Labyrinth Seal Closure				
Max.	309			
Median	63			
Min.	9			

This study also shows that 21 percent of the pumps using labyrinth seals contained oil with a moisture content greater than 100 ppm, with a median of 63 ppm. This difference in moisture content between labyrinth and lip seals is not viewed as significant since sampling errors can account for such differences. Neither the labyrinth or lip seals reported on in this study do an adequate job of excluding moisture from the bearing housing. There is insufficient data concerning magnetic seals to allow any conclusions to be drawn.

During the field survey, a strong interest was expressed regarding the use of synthetic lubricants. Water content as analyzed by oil type is shown in Figure 13.

Again, there is no significant difference in the amount of water present in synthetic *vs* mineral base oils.

Data were also sorted by the type of environment to which the pumps were exposed. The moisture content data indicates that there is little difference between pumps that were covered and those that were uncovered, Figure 14. Pump wash downs were not frequently performed at any of the sites.

The frequency of oil change does not appear to influence the degree of contamination, Figure 15.

Table 5. Water Content of Unused Oil Samples.

	Water	Particulate Count/ml		
	ppm	>2 µm	>5 µm	>15 µm
Site 1				
Max.	266	2,234	636	216
Median	91	1,045	338	79
Min.	46	664	248	26
Site 2				
Max.	1,864	299,400	50,310	1,470
Median	72	2 samples counted		
Min.	9	2156	528	39
Site 3				
Max.	>1000	852	292	69
Median	49	2 samples counted		
Min.	30	404	113	30
Site 4				
Max.	149	2,369	649	139
Median	53	2 samples counted		
Min.	21	1,363	455	91
Site 5				
Max.	5837			
Median	113			
Min.	48			
Site 6				
Max.	95			
Median	40			
Min.	14			
Site 7				
Max.	231			
Median	55			
Min.	36			
New Oil				
Max.	311			
Median	57			
Min.	27			

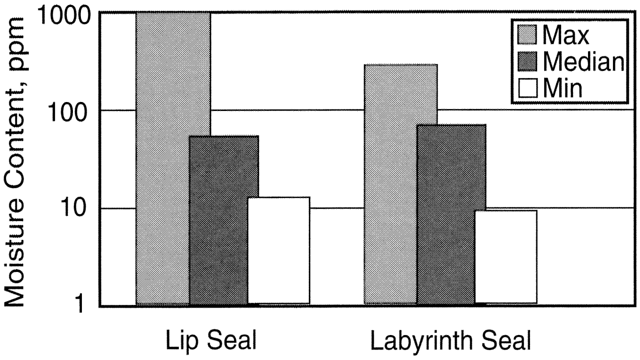


Figure 12. Contamination vs *Bearing Housing Closure Seal Type.*

Debris Contamination

The size and number of particulates are also important contamination parameters. Counts of particulates greater than two microns are shown in Table 4 according to sample site. It was recommended earlier that the lubricant contain, in particulant sizes larger than

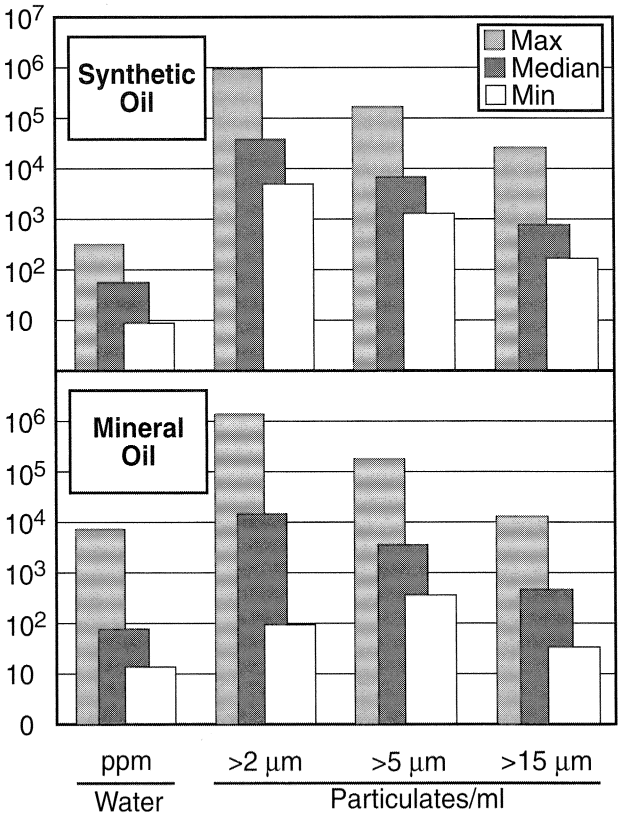


Figure 13. Contamination in Synthetic vs *Mineral Oil.*

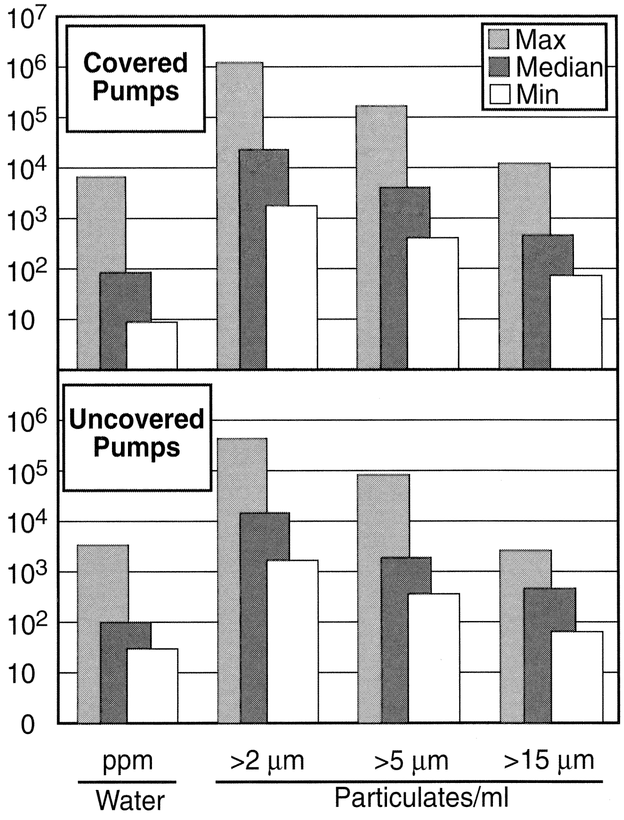


Figure 14. Contamination vs *Pump Location.*

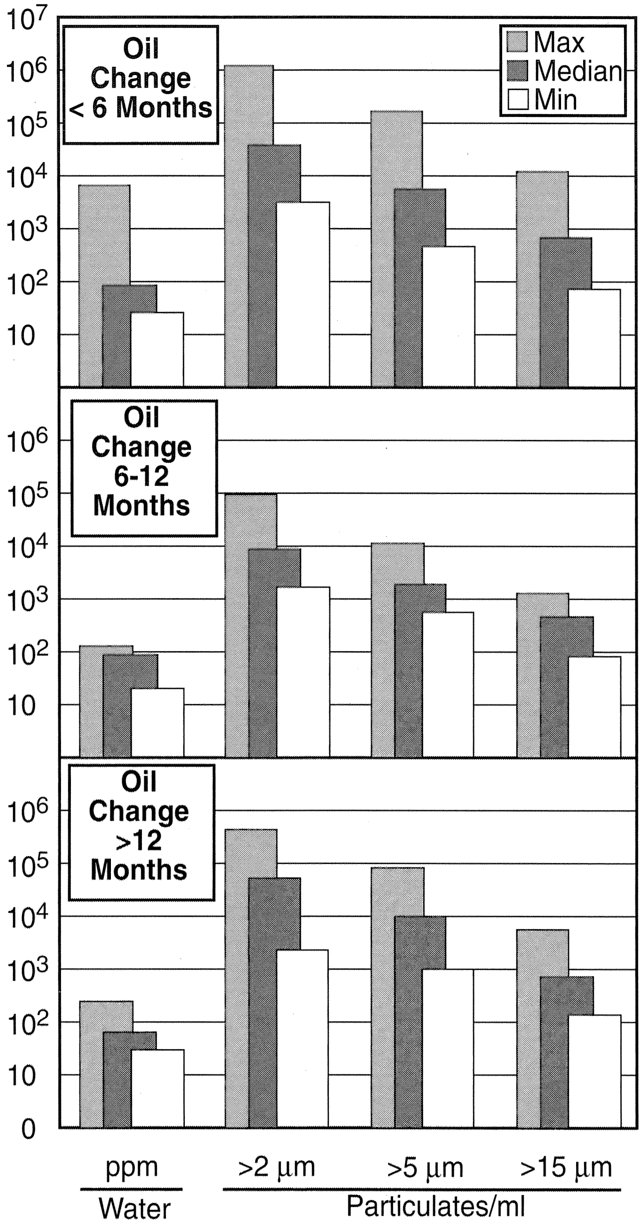


Figure 15. Contamination vs *Oil Change Fequency.*

two microns, no more than 160 particles per ml. Note that the minimum value of any sample was five times this recommended level. Of the bearing housings studied, 54 percent contained oil with particle contamination 100 times greater than the recommended maximum. The medians were 100 to 300 times the recommended level, indicating extreme levels of particulate contamination. No one site stood out as better or worse than the others.

Particulate counts are presented in Figures 12, 13, and 14 in three size ranges, correlated with bearing housing closure seal type, lubricant type, pump location, and oil change frequency. There was no correlation between any of these parameters and the contamination level.

Dirt and debris were also noted in some unused oil samples. Storage drums are typically steel that rust when water contamination occurs due to condensation. It may be necessary to pay more attention to the cleanliness of funnels, oil cans, and storage drums. Drums should be kept closed to reduce atmospheric condensation.

CONCLUSIONS

This survey identifies a heretofore unrecognized problem in process pump bearing housing lubricating oil. There is an extremely high level of oil contamination in all size ranges of particulates that is unrelated to any of the existing contamination control methods. This survey also reveals that water contamination in the lubricant is significant, but is a much smaller problem than previously assumed. In those few instances where excessive water was found, it was in the free state. The overall conclusion of this study is that contamination control methods in use today for non-recirculating oil bath roller bearing element lubrication systems are not effective. When these results are compared with bearing manufacturer's recommendations for oil cleanliness, it is evident that a great potential exists to improve the life of bearings in typical process pumps. Specific conclusions are:

- Apparently, very little is done to prevent contamination of unused oil in storage.
- Lubricant oils in pump rolling element bearing housings in this field study have particle contamination levels at least 10 times greater than recommended levels, 54 percent were more than 100 times greater. No samples were analyzed that contained less than the recommended maximum particulate contamination
- This survey finds that 24 percent of the pump bearing housings have moisture levels greater than the maximum recommended level of 100 ppm, nine percent are greater than 200 ppm, and five percent of the pumps have levels indicating the presence of free water (greater than 400 ppm).
- The type of bearing housing closure device (labyrinth, lip, or magnetic seal) shows no significant correlation with either particulate or water contamination levels.
- The type of oil (synthetic *vs* mineral) appears to have no significant effect on the moisture and particulate content of the oil.
- The frequency of oil change out (from one month to indefinite) shows no significant effect on the moisture or particulate content of the oil.
- There is no significant difference in levels of contamination in lubricating oils in pumps operated outside or under covered conditions.

RECOMMENDATIONS

Based on this study the following are recommended:

- The mechanisms by which contamination (moisture and particulate) enter unused and in-use bearing lubricants should be investigated.
- This study should be expanded to include other industries.
- The contamination levels (moisture and particulate) of oil mist systems should be investigated.
- The composition of the particulates should be identified and their effect on bearing life quantified.

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