

INVESTIGATIONS INTO THE CONTAMINATION OF LUBRICATING OIL IN ROLLING ELEMENT PUMP BEARING ASSEMBLIES

by
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ABSTRACT

The use of rolling element bearings in pumps is standard practice. Of the many factors that affect their long-term performance, contamination in the bearing lubricating oil plays a major part.

Of particular concern are contamination and degradation of the lubricating oil over a short period of time. Repeated short-term contamination implies that the lubricating properties of the oil will be impaired and bearing reliability will be reduced.

This paper presents an analysis of the factors affecting the short-term contamination of oil in ring oil lubricated rolling element bearings. The bearings analyzed were those used in the author's company's standard range of centrifugal pumps where short-term oil degradation had been reported in a number of installations.

The tests conducted are reviewed and the results are discussed. Recommendations are made and details of field tests are given demonstrating the success of the modifications carried out.

INTRODUCTION

Standardized ball bearing assemblies are a feature of the majority of pumps manufactured by the author's company. Figure 1 shows a matched 40-degree contact angle ball bearing arrangement used as a thrust and radial bearing, and a single deep groove ball bearing used as a radial bearing. Both bearing arrangements use ring oil lubrication with bronze oil rings submerged into the bearing oil sump.

Figure 2 shows the bearing arrangement in a single stage overhung pump, which utilizes matched 40-degree contact angle ball bearings for the thrust and radial bearing, and either a deep groove ball bearing or a cylindrical roller bearing for the radial bearing. The bearings are mounted in a common housing and use ring oil lubrication with bronze oil rings submerged into the bearing oil sump.

Within the last few months, a number of field reports of "black oil" formation, predominately in the thrust bearing assembly, were reported. Often these reports stated that small amounts of bronze had been detected in the oil.

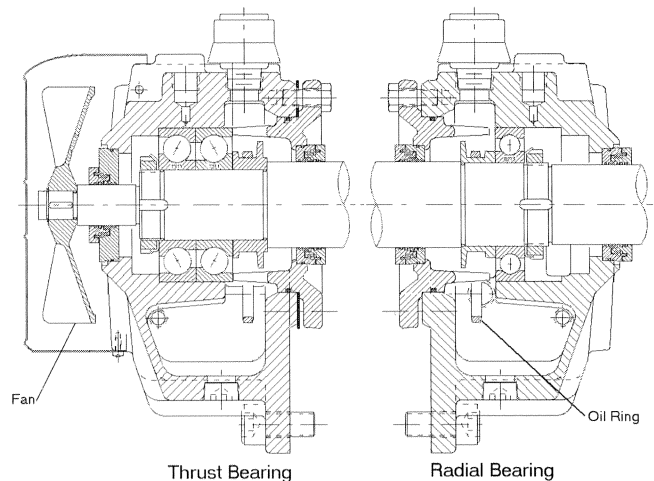


Figure 1. Standard Arrangement for Between Bearing Pumps.

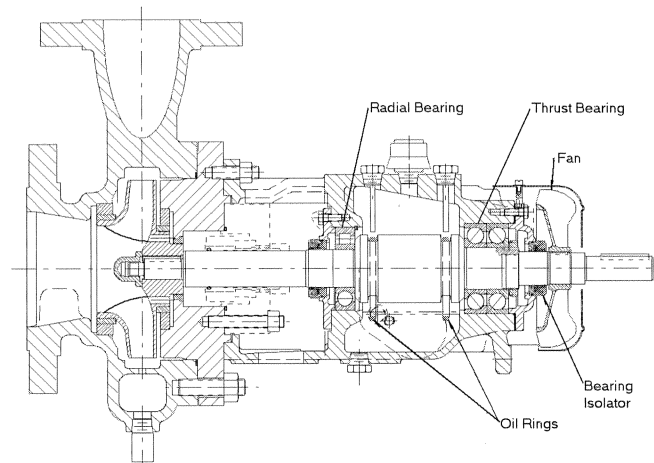


Figure 2. Standard Arrangement for Overhung Process Pumps.

This phenomenon of "black oil" is defined as the process by which the lubricating oil darkens or turns black within a time period ranging from one hour to several weeks.

In the case of the overhung process pump (Figure 2), there were reports of both "black oil" formation and significant amounts of bronze found in the bearing oil.

Analysis of oil samples taken from the field showed high concentrations of particles 3 to 5 μm in size resulting in a range of oil colors from dark brown to black. (Refer to Figure 3 for a typical oil analysis.) However, no single cause of the degradation could be isolated from the field report data.

In order to determine the causes of the phenomenon, it was decided to undertake a full investigation.

Tribo Clean		Customer: SULZER PUMPS (SULZER PMP)	
Lub Supp		PUMP (PUMP)	
Lub Type 32		CAP 8 PUMP BEARING HOUSNG (UNIT 2982)	
		RUN 1 (RUN 1)	
		Res Per: SIMON BRADSHAW	
		Tel:	
		Fax:	

Sample No.			971107-01011	RANGE
Bottle No.			1001094	
Date Y-M-D			97-11-03	
Meter Read			0	
Oil Hours			0	
Oil/Fil Chng	/	/	/	
Diagnosis			MCL	
Status			4	

Contamination

>2 um			351570	
>5 um			266294	
>15 um			35287	
>25 um			3226	
>50 um			55	
>100 um			0	
ISO 2			26	
ISO 5			25	
ISO 15			22	
Silicon			5	
Boron			0	
Sodium			1	

Additives

Magnesium			3	
Calcium			199	
Barium			3	
Phosph.			14	
Zinc			9	
Molybdenm			0	

Wear Metals

Iron			105	
Chrome			2	
Lead			47	
Copper			47	
Tin			0	
Aluminum			0	
Nickel			0	
Silver			0	
Titanium			0	

Viscosity

CST 40C			32.0	
CST 100C			5.4	
Visc Indx			103.7	

Oil Condition

Water PPM			0	
OXIDATION			.06	
NITRATION			.08	
TAN			.25	

Figure 3. Example of Typical Oil Sample.

IDENTIFICATION AND CLASSIFICATION OF THE POSSIBLE CAUSES

To help identify all possible issues that could contribute to the phenomenon, several groups within the company carried out reviews. All issues identified were then reassessed and compiled to form a problem matrix (Table 1). The matrix listed all the potential causes of the phenomenon that were felt to merit further investigation or testing. For clarity, the matrix was then subdivided into three issue groupings.

- *Wear related issues*—Those issues relating to wear mechanisms.
- *Chemistry related*—Those issues relating to chemical reactions.
- *Cleanliness related*—Those issues relating to contamination during manufacture, assembly, or operation.

It was felt that potentially several issues in combination may have been contributing to the “black oil” formation. However, by using the matrix as a guide to the investigation, the belief was that many of the possible causes could be eliminated early on. This would allow resources to be focused more on the real issues that did have an effect on the “black oil” formation. The issues listed in the matrix were therefore examined in detail to determine their significance. Some issues were reviewed using data gathered from the field such as oil samples and replaced bearings. Other issues had to be evaluated using in-house testing.

WEAR RELATED ISSUES

Five issues were identified in the matrix as possible contributors to “black oil.” These were:

Table 1. Investigation Matrix.

Investigation Issue	Overhung Process Pump	Horizontal Between Bearings	
Oil ring stability and immersion depth	3	1	WEAR RELATED
Low oil delivery to the bearings	3	2	
Bearing type	1	1	
Bearing fits	1	2	
Skidding of bearings	3	2	
Bearing misalignment	1	2	
Oil viscosity and additives	3	2	
Reaction caused by addition of Bearing Corrosion Inhibitor	1	1	CHEMISTRY RELATED
Reaction caused by addition of Bearing Housing Sealing Paint	1	1	
Lubrication oil type and additives	1	1	
Housing cleaning after manufacture	1	1	CLEANLINESS RELATED

Key	
1	Investigation concluded on this issue
2	Testing Planned
3	To be determined on conclusion of tests

- Oil ring stability and immersion depth
- Low oil delivery to the bearings
- Bearing type
- Bearing fits
- Oil viscosity and additives

In order to determine the significance of each of the issues, an in-house test program was established. An in-house test program was necessary because of the need to control the variables in a consistent way and to allow completion of the testing of all possible combinations within a reasonable period of time. This was impossible to achieve using bearings installed in the field because of the number of configuration changes required and the inability to hold constant parameters such as axial thrust and run time.

The test program consisted of 13 two-hour and seven eight-hour tests and was carried out on a custom designed test rig. The rig had the ability to apply radial and axial loads to an assembly duplicating the configuration of the between bearing pump (Figure 4). By provision of Plexiglas viewing windows mounted into the bearing housing and temperature probes, the complete behavior of the bearing being studied could be observed.

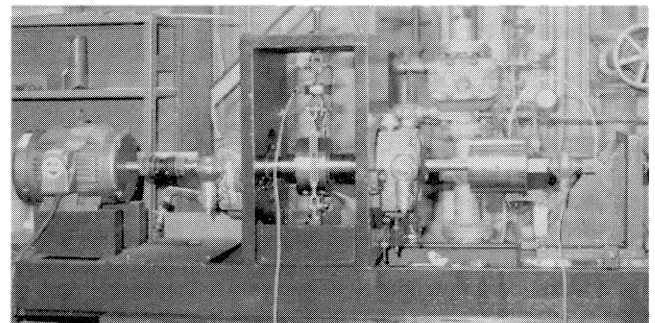
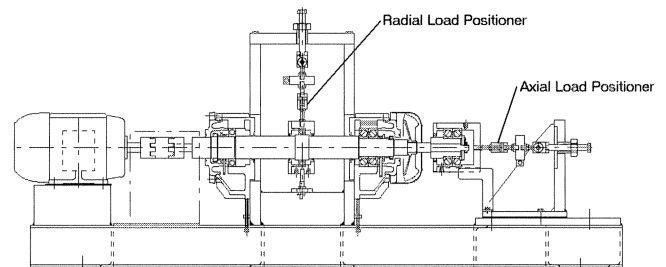


Figure 4. Bearing Test Arrangement.

Prior to each group of tests, the test rig was disassembled and new angular contact thrust bearings were fitted to the bearing housing. Clean ISO VG32 turbine oil was used for each test. After each test, within seconds of stopping, a sample of oil was taken from the radial and thrust bearing. The test rig was then disassembled and the bearings removed for inspection. At this time the bearing housings were cleaned to remove all traces of oil and contamination.

The reason for the replacement of bearings, oil replacement, and cleaning was to ensure that the results yielded by the test rig consistently reflected the configuration being tested and not the after-effects of a previous test run.

Oil degradation was determined by color change, although some conventional oil analysis was undertaken for comparison. It was found that oil color was an accurate indicator of the level of 3 to 5 μm particles within the oil. Magnetic separation and filtration of the oil sample also easily determined the quantities of ferrous and nonferrous metallic particles present in the oil.

During the testing, the parameters identified in the matrix as contributors to black oil were evaluated to determine their significance.

Oil Ring Stability and Immersion Depth

The testing showed that oil ring stability was variable and depended strongly on oil viscosity and oil ring immersion depth. Generally the bronze oil ring operated erratically once operating temperature was reached. This behavior can be characterized as:

- A pendulum motion pivoting about top dead center of the ring (where it contacts the shaft), swinging in a plane at 90 degrees to the shaft axis.
- Tracking of the ring backwards and forwards across the oil ring carrier (Figure 5).

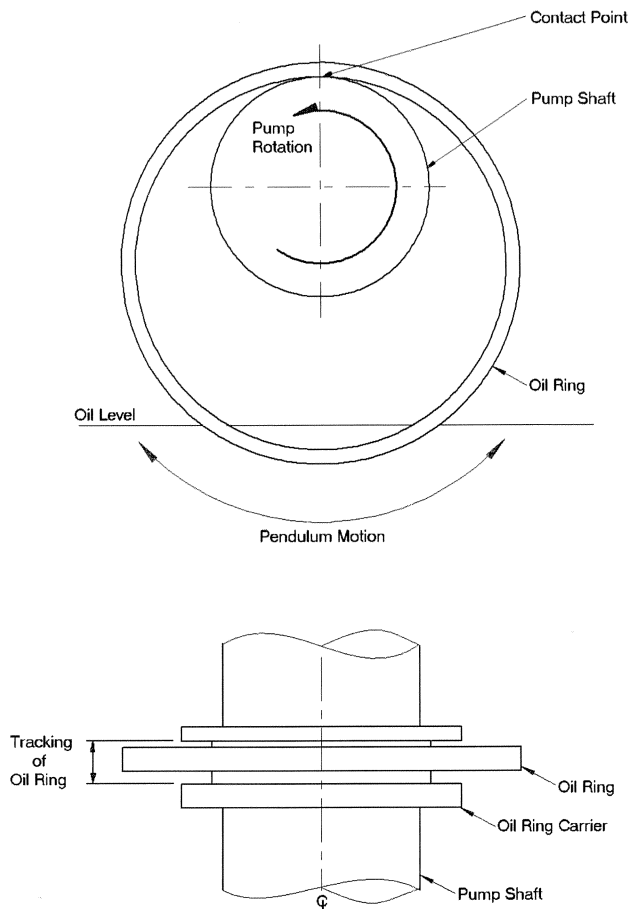


Figure 5. Oil Ring Motion.

Tests showed that the source of bronze in the oil was primarily due to the oil ring erratically hitting the bearing housing and bearing cap or wearing against the oil ring carrier. Varying the oil level did not eliminate this behavior. As the oil level was varied, the oil ring motion became erratic at a different oil temperature. It is not possible to set an oil level that will remove this behavior completely. The behavior is also very sensitive to small changes in oil viscosity.

During the testing, alternative metallic oil ring materials were tried in an attempt to prevent bronze material being deposited in the oil. Both mild steel and Nitronic 60 materials were used. The result of these tests was that the bronze particles in the oil were substituted by mild steel or Nitronic particles.

Following the unsuccessful testing with metallic oil rings, a nonmetallic oil ring was selected. The nonmetallic ring ran in a more stable fashion, eliminating the erratic tracking and pendulum behavior seen with the metallic rings, and did not exhibit any wear during testing.

It was concluded that oil viscosity exerts a greater damping influence over the low mass, nonmetallic ring than a metallic ring, thereby effectively preventing the erratic motion and tracking from occurring.

The deposition of bronze particles into the oil was concluded to be a contributing factor in black oil formation. Circulation of large metallic particles through a rolling element bearing would result in undesirable metal-to-metal contact, with removal of the rolling element bearing material and oil degradation being a consequence.

Low Oil Delivery to the Bearings

The oil delivery to the bearings was observed using Plexiglas windows mounted in the side and end of the bearing housing. It was found that oil delivery was highest at cold startup and then reduced by approximately 75 percent (but still an acceptable quantity), once operating temperature was reached.

From the test observations, the hypothesis was that oil delivery was sufficient to ensure adequate lubrication. To verify this, additional oil feed gallery was added to increase oil delivery (Figure 6). Tests were conducted using this arrangement and oil samples compared with previous tests showed no improvement in color. The only observation was that increased oil delivery resulted in increased bearing temperature due to more oil churning within the bearings.

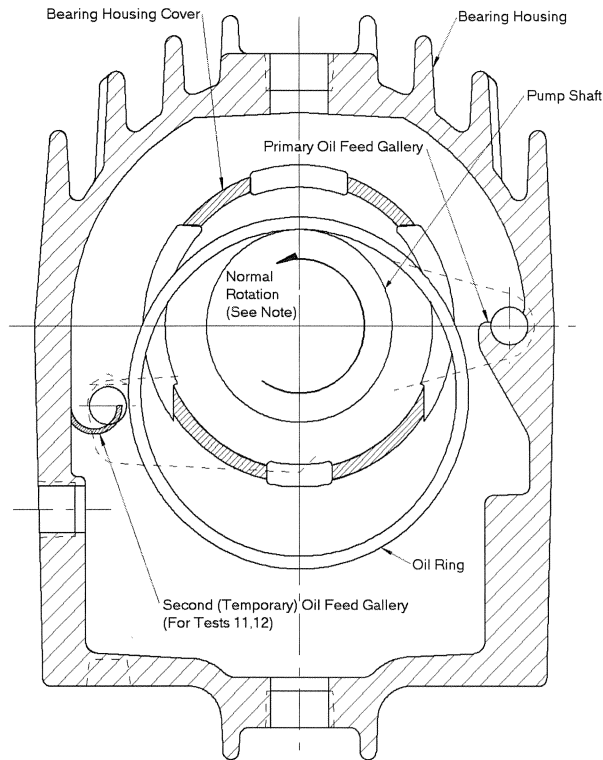
The conclusion reached was that oil delivery was not a contributing factor to black oil formation. The actual oil requirements for lubrication of a rolling element bearing are only a few drops per minute. Any additional oil only serves to help remove the heat generated by the bearing.

Bearing Type

Initial reports from the field suggested that the problem of "black oil" was more severe in the thrust bearing of the pump than in the radial bearing. Some sites reported that it occurred only in the thrust bearing. In order to investigate these reports, separate oil samples from the drive end (DE) (radial) and nondrive end (NDE) (thrust) bearings were taken during testing.

From the initial tests on the between bearing pump test rig, it was found that the oil samples from the DE (radial) bearing with the deep groove ball were considerably better than the samples from the NDE (thrust) bearing with the matched angular contact bearings. It was concluded that matched bearings were much more susceptible to this form of oil degradation/contamination, due to the geometric and functional factors inherent in a paired bearing design. These factors were:

- Less control over bearing internal clearance.
- Thrust loading that created unloaded conditions for one of the bearings, causing ball skidding.
- Higher oil operating temperatures reducing the oil viscosity and oil film thickness at point of ball contact.



Note: Normal CCW rotation at the thrust bearing end (as shown) was reversed for test 3 only

Figure 6. Bearing Housing Modifications for Increased Oil Delivery.

While it was found that matched bearings were a factor in black oil formation, it was not possible to alter the basic bearing type due to customer expectation and requirements of API 610 (1995). Instead, other bearing parameters such as bearing fit were optimized instead to compensate for the design limitations of this type of bearing.

Bearing Fit

When the matched angular contact thrust bearings were originally installed, a between bearing shim was included (Figure 7). This 0.002 inch thick shim was fitted between the inner races of the angular contact thrust bearings to increase the internal clearance, resulting in a lower operating temperature. Testing showed that the inclusion of the interbearing shim caused high levels of bearing skidding (of the unloaded bearing) and “black oil” formation. For the remainder of the tests, the interbearing shim was removed and testing was conducted using medium clearance angular contact bearings and medium preload angular contact bearings. This was done to evaluate the effect of decreasing the bearing internal clearance and its effect on black oil formation. Subsequent testing showed that two bearing fit factors affected “black oil” formation:

- **Level of bearing preload**—Testing showed that with a higher level of bearing preload, the lower the occurrence of “black oil” formation. This is believed to be due to preloaded bearings having a lower probability of skidding. The disadvantage to using preloaded bearings is that they have the tendency to run hotter than comparable clearance bearings.
- **Bearing assembly techniques**—Bearing tests L13 and L14 were made using improved assembly techniques. With this process, great care is taken to ensure that the internal clearance within the matched angular contact bearings is achieved. The testing showed that good results could be obtained using correctly assembled medium clearance angular contact bearings.

In order to assemble the bearings correctly, the bearings were heated uniformly in an oven, mounted to the shaft, and allowed to cool to *room temperature*. The shaft nut was then used to tighten the bearings together until the two bearing outer races could be counter rotated by hand against each other with reasonable resistance.

This guaranteed that the bearings had the desired internal clearance. Other assembly methods such as torquing the shaft nut rely on *estimated* variables such as friction factor and level of shaft to bearing fit. These variables can vary by 50 percent or more between geometrically identical arrangements. Thus these other methods are less accurate than the above method.

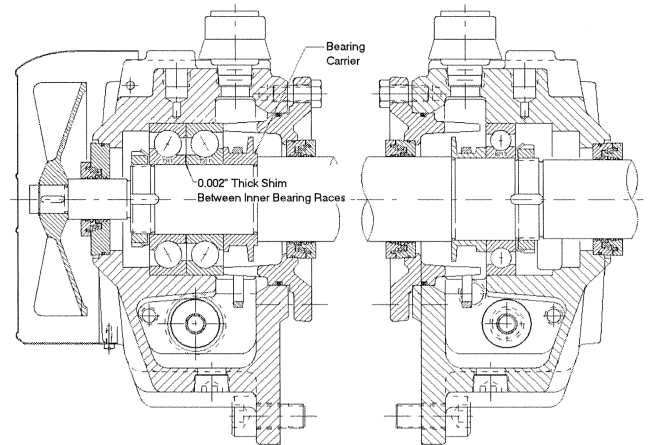


Figure 7. Original Bearing Design with Interbearing Shim.

The conclusion was that the internal clearance of matched angular contact bearings is critical to their correct operation. Provided the bearing internal clearance is held at a low design value, the bearing can be made to operate with minimum skidding and black oil formation.

Oil Viscosity and Additives

Oil viscosity was identified as a factor important in black oil formation. This is because oil viscosity affects the oil film thickness at the ball/raceway/cage interface. Under conditions of ball skidding and less than ideal conditions, this oil film acts as a barrier separating the components from metal-to-metal contact. Thus, in general terms, the thicker the oil film is, the better its separation potential. The purpose of the testing was to determine the significance of an increase in oil film thickness on black oil formation.

Oil additives were evaluated to determine whether antiwear additives had any effect on the level of black oil. Most of these additives work by cushioning metal-to-metal contact under conditions of poor lubrication. The purpose of the testing was to determine if this cushioning effect was important in the reduction of black oil formation.

The standard oil used by the author’s company for many years was turbine oil with a VG32 viscosity. To evaluate whether alternative oil viscosity and composition could help reduce the level of “black oil,” testing was performed using VG46 and VG68 turbine oils (from the same manufacturer) and antiwear VG32, VG46, and VG68 oils.

Generally the more viscous the oil, the better the oil color for a given length of test. The change from VG32 to VG46 oil seems to give the greatest improvement. Increasing the oil viscosity to VG68 did not seem to improve the oil color additionally.

With the more viscous oils, the temperature rise of the oil sump increased. The increase compared with VG32 oil was 0 to 5°F for VG46 oil, and 3 to 15°F for VG68 oil.

The antiwear VG32 and VG46 oils evaluated were found to give similar results to standard turbine VG32 and VG46 oils. The conclusion is that antiwear additives alone will not reduce the level of blackening.

CHEMISTRY RELATED ISSUES

Chemistry related causes for black oil formation were considered. This was because it is possible for oil to react with other chemicals present in the bearing housing. Known examples of this phenomenon include reactions between some oil additive packages and the rolling element bearing. The testing was then concerned with identifying if there were any such reactions occurring within the bearing housing assembly.

Three issues were identified in the matrix as possible contributors to "black oil." These were:

- Reaction of the oil to the preservative used inside the bearing housing
- Reaction of the oil to the sealing paint used inside the bearing housing
- Changes in the lubricating oil and additives

Reaction of the Oil to the Preservative Used Inside the Bearing Housing

All pump bearing housings in the author's company are treated prior to shipping to prevent corrosion. The interior of the bearing housing was treated with a proprietary corrosion inhibitor contained within an oil carrier. The concern was that the corrosion inhibitor was not being flushed out during commissioning and that it was breaking down during bearing operation due to the high temperature. To determine whether this was a factor, a number of test runs were made using bearing housings that had not been treated with the corrosion inhibitor. It was found that there was no significant difference between treated and untreated bearing housings.

Reaction of the Oil to the Sealing Paint Used Inside the Bearing Housing

The interiors of all bearing housings in the author's company are sealed using paint formulated for this purpose. It is normal practice to seal bearing housing castings in this way to stabilize the casting surface and prevent any remaining subsurface casting sand from entering the bearing oil.

The bearing housing sealant paint used was an alkyd resin-based paint with iron oxide and magnesium silicate fillers. To determine whether the paint was reacting with the oil, samples of paint from a freshly painted bearing housing and a two month old bearing housing were removed and placed in glass sample containers. These containers, together with a control container, were filled with the standard oil, then heated to 250°F for eight hours. All containers remained unchanged and showed no signs of oil color change.

Changes in the Lubricating Oil and Additives

The composition of the lubricating oil and the additive package are critical to the reliable performance of the rolling element bearing. There was concern that some compositions of oil or additives were contributing to oil degradation.

To determine whether oil or additive package degradation or reaction was a cause, a review was made of the oil type and make used on all bearings that had a reported field problem. These oil types were then reviewed to determine what common factors existed. It was found that the type of oil varied considerably. Although no correlation could be found between oil type and "black oil."

CLEANLINESS RELATED ISSUES

Cleanliness of the lubricating oil is of great concern. If the oil or the system into which it is placed is contaminated, the contamination will be circulated through the rolling element bearings. These

bearings are easily damaged by the passage of particles through them or by corrosion on contact with water in the oil.

Particles passing through a rolling element bearing can cause accelerated wear within the bearing by bridging the oil film between moving surfaces. The resultant contact between the metal of the bearing and the particle can cause wear particles from the bearing to be added to the oil, thus accelerating the oil's degradation.

The presence of water in the oil can allow the rolling element bearing surfaces to corrode. These corroded surfaces have an undesirable surface finish that prevents the formation of the normal elasto-hydrodynamic lubrication. Metal-to-metal contact and wear particle formation is a consequence of this.

Two issues were identified in the matrix as possible contributors to "black oil." These were:

- Housing cleanliness after manufacture
- Contamination during operation

Housing Cleanliness after Manufacture

In order to determine if the manufacturing process was contributing to the oil blackening, the following testing was performed. Random samples of typical bearing housings were selected after final machining and painting. These housings had their openings blanked before being filled with the standard volume of lubricating oil. The housings were then mounted in a lathe and spun for 30 minutes in each direction at 20 rpm. After spinning, the oil was drained from the housings and examined.

The tests proved that the bearing housing manufacturing process did not contribute to the oil blackening or the bronze in oil. The oil color of the samples from these tests was unchanged compared with the control sample.

Contamination During Operation

It is known that contamination of lubricating oil with silicon, water, or other foreign materials can lead to rapid degradation of the oil and rolling element bearings. In order to determine whether contamination during operation was a factor, oil samples were taken from all bearings that had been reported as affected by "black oil." These samples were then analyzed to determine what common factors existed.

In looking for external contamination, the levels of the following elements were of interest:

- Silicon: any level above 50 ppm
- Water: any level above 600 ppm

Silicon is found in dust and sand, which enter the housing from the atmosphere. The bearings are fitted with a breather/filter, which helps to prevent the ingress of dust particles. Silicon may also be introduced when the bearing is filled with contaminated oil or if the bearing is opened up for inspection.

Badly sealed bearing housing sand castings may also introduce silicon into the bearing from pores in the metal. Due to the sealant type paint used during manufacture, this type of silicon contamination was not found.

Water can be introduced into the bearing housing through the bearing breather and shaft seals, e.g., due to hosing down of equipment or extreme weather. Water can also enter the bearing housing due to temperature cycling of the bearing housing. As the bearing heats up, hot air is expelled through the bearing breather. When the pump stops and the bearing cools, air is drawn back into the bearing housing. If this air is moisture laden, condensation and contamination of the oil can result.

The oil samples taken generally had an analysis profile as referenced in Figure 3. This showed that contamination from external sources was generally very low. There were very rare occurrences of gross contamination by silicon or water that may have contributed to the oil discoloration. The conclusion made was that external contamination was not a cause of the "black oil."

CONCLUSIONS MADE FROM THE TESTING

Based on the testing described above, the following conclusions were reached:

- The bearing arrangements that gave the lowest levels of wear and oil discoloration on long-term test were:
 - Nonmetallic oil ring, VG46 oil, and a medium preloaded bearing.
 - Nonmetallic oil ring, VG46 oil, and a medium clearance bearing (with controlled assembly).
- The bearing arrangement that gave the worst levels of wear and oil discoloration on test were:
 - Bronze oil ring, VG32 oil, medium clearance bearing, and an interbearing shim.
- The primary source of bronze debris in the oil is due to the oil ring wearing against the bearing housing and oil ring carrier. A nonmetallic ring was successful in eliminating this wear.
- The viscosity of the oil affects the level of discoloration of the oil. Higher viscosity oil will reduce the discoloration (but not eliminate it if the other design problems are not addressed).
- The use of antiwear oils alone does *not* prevent the discoloration of the oil.
- Varying the amount of oil delivery to the bearing did not affect the discoloration of the oil. Oil delivery rate (beyond that required for good lubrication) is not a factor in black oil formation.
- The use of thrust bearings without an interbearing shim will reduce the blackening of the oil by eliminating ball skidding within the bearing.
- The use of preloaded thrust bearings is a method to reduce the probability of ball skidding, which is a factor in black oil formation. This type of bearing will have a tendency to run hotter (comparative tests show a 0 to 10°F increase in sump oil temperature compared with nonpreloaded bearings).
- Clearance thrust bearings can be made to give comparable oil color to preloaded bearings provided nonmetallic oil rings, VG46 oil, and controlled assembly techniques are used.
- In the cases studied, black oil formation was not caused by cleanliness or chemistry related issues.

IMPLEMENTATION OF DESIGN CHANGES

Following the testing and based on the conclusions reached, the following design changes were implemented. These changes affected all ring oil lubricated pumps made by the author's company:

- Nonmetallic oil rings were fitted in place of the bronze oil rings.
- The standard viscosity of oil used in the bearings was changed from VG32 to VG46. Bearing temperature alarm/trip settings were adjusted upward by approximately 5°F to allow for a slightly higher operating temperature.
- Medium clearance thrust bearings without an interbearing shim were made the standard thrust bearing choice.
- Assembly procedures and the installation and operating manuals for the pumps were revised to reflect the best practice identified during testing.

VALIDATION OF TEST RESULTS

Production Test Stand

As the changes were implemented, oil samples were taken from pumps being tested prior to shipment. This testing showed that

after the design changes were implemented, the number of instances of "black oil" and brass in the oil reduced by greater than 95 percent. The remaining instances were each checked thoroughly and could usually be attributed to:

- Incorrect assembly
- Component damage
- Other sources of contamination

Results from Field Changes

Reports from the field have shown that, with the design changes made to the bearing arrangement, the "black oil" phenomenon has diminished.

Field reports that refer to a problem with black oil have reduced by 90 to 95 percent since the implementation of the changes, and currently there is only one field report on this issue every six months.

Pumps in the field, which had experienced problems, were retrofitted with the updated design and reports from these installations are very encouraging. In particular:

- A major refinery in Port Arthur, Texas, has had no problems with the "black oil" in their overhung process pumps since the design changes were made.
- Another refinery in Sweeny, Texas, converted both their API Eighth Edition and their older upgraded overhung process pumps to the new design and have had no additional occurrences of "black oil."
- Two cogen plants in Lodi and Modesto, California, have had no indication of "black oil" since the conversion to the new design on their between bearings pumps.
- A major plant operator, in Texas, is investigating the possibility of applying the design changes to all oil ring lubricated pumps as a preventive measure.

The issue of bearing life improvement has been difficult to isolate from field reports. This is because operator reporting of bearing failures is not consistent. There are also variations in the maintenance procedures of different operators. Some operators may change out bearings during routine maintenance as a precautionary measure, and others may not. When these variations are coupled with the myriad possible operating regimes for the bearings, it becomes very hard to establish whether a bearing failed prematurely and by how much.

Although the appearance of black oil can be disturbing from an operator's standpoint, its effect on overall rolling element bearing life has yet to be accurately quantified.

CONCLUSION

The problem of "black oil" and the subsequent solution show that the installation of a successful rolling element bearing is not simply a matter of considering bearing life. The entire bearing system must be considered in order to ensure that each element is compatible with the whole system.

Testing and systematic analysis must form an integral part of the design process to ensure that the final product performs as expected.

Work still needs to be done to improve bearing performance and reliability. There are limitations with the conventional 40-degree paired angular contact bearings. In the future, further testing may be done to establish the usefulness of alternative bearing arrangements such as:

- 40 to 15-degree matched angular contact bearings
- Misalignment tolerant bearings such as spherical roller bearings
- Nonmetallic or partial nonmetallic rolling element bearings such as silicon carbide ball bearings.

APPENDIX A
TEST RESULTS

Table A-1. Test Results for Between Bearings Test Setup.

TEST NUMBER/ DESCRIPTION	THRUST BEARING OIL SUMP AT	THRUST BEARING TYPE	OIL GRADE	THRUST BEARING OIL COLOR	THRUST BEARING WEAR (visual observations)	Oil sample visually acceptable
#1 Original design bronze oil ring 2 hours test duration	68	Medium Clearance	TURBINE VG32	Black+lots of fine bronze	Gross skidding of unloaded bearing with cage wear. Loaded bearing had some cage wear	NO
#2 New design bronze ring 2 hours test duration	55	Medium Clearance	TURBINE VG32	Mid brown+lots of fine bronze	Skidding of unloaded bearing with cage wear Loaded bearing had slight cage wear.	NO
#3 New design reverse rotation bronze oil ring 2 hours test duration	73	Medium Clearance	TURBINE VG32	Black+lots of fine bronze	Skidding of unloaded bearing with cage wear Loaded bearing had similar cage wear.	NO
#4 New design 2 hours test duration	72	Medium Preload	TURBINE VG32	Slightly darker and some clouding+fine bronze	Little or no skidding of unloaded bearing with slight cage wear Loaded bearing had similar cage wear.	YES
#5 New design see figure 5 bronze oil ring 2 hours test duration	57	Medium Clearance	TURBINE VG32	Mid brown+lots of fine bronze	N/A	NO
#6 New design bronze oil ring Same bearing as test 5 2 hours test duration	53	Medium Clearance	ANTI WEAR VG46	Virtually unchanged +lots of fine bronze	N/A	YES
#7 New design bronze oil ring Same bearing as test 5 2 hours test duration	68	Medium Clearance	ANTI WEAR VG68	Virtually unchanged +some fine bronze	N/A	YES
#8 New design bronze oil ring Same bearing as test 5 2 hours test duration	53	Medium Clearance	TURBINE VG32	Virtually unchanged slight darkening +some fine bronze	Skidding of unloaded bearing with slight cage wear. Loaded bearing had similar slight cage wear.	YES
#9 New design bronze oil ring 2 hours test duration	63	Medium Clearance	ANTI WEAR VG32	Mid-brown+fine bronze	N/A	NO
#10 New design bronze oil ring 2 hours test duration	60	Medium Clearance	ANTI WEAR VG46	Slight darkening +fine bronze	N/A	YES
#11 New design 2" oil trough bronze oil ring Same bearing as test 10 test duration 2 hours	70	Medium Clearance	ANTI WEAR VG46	Slight darkening +fine bronze	N/A	YES
#12 New design 2nd oil trough bronze oil ring Same bearing as test 10 test duration 2 hours	65	Medium Clearance	ANTI WEAR VG32	Virtually unchanged +some fine bronze	N/A	YES
#13 New design non metallic oil ring test duration 8 hours	71	Medium Preload	TURBINE VG46	Slight darkening no bronze	N/A	YES
#14 New design non metallic oil ring Same bearing as test L13 test duration 8 hours	67	Medium Preload	TURBINE VG32	Virtually unchanged no bronze	N/A	YES
#15 New design non metallic oil ring Same bearing as test L13 test duration 8 hours	70	Medium Preload	ANTI WEAR VG68	Virtually unchanged no bronze	N/A	YES
#16 New design non metallic oil ring test duration 8 hours	78	Medium Clearance	TURBINE VG32	Slight darkening +some fine bronze	N/A	YES
#17 New design non metallic oil ring Same bearing as test L16 test duration 8 hours	81	Medium Clearance	TURBINE VG46	Virtually unchanged no bronze	N/A	YES
#18 New design bronze oil ring Same bearing as test L16 test duration 8 hours	66	Medium Clearance	TURBINE VG32	Virtually unchanged +some fine bronze	N/A	YES
#19 New design bronze oil ring Same bearing as test L16 test duration 8 hours	60	Medium Clearance	TURBINE VG32	Slight darkening +some fine bronze	N/A	YES
#20 New design bronze oil ring test duration 2 hours	60	Medium Clearance	TURBINE VG32	Slight darkening +some fine bronze	N/A	YES

Note:

- Old design is defined as a bearing arrangement fitted with an interbearing shim (Figure 6).
- New design is defined as a bearing arrangement not fitted with an interbearing shim.

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Table A-2. Test Results for Overhung Process Pump Test Setup.

TEST NUMBER/ DESCRIPTION	RUN TIME MINS	THRUST BRG OIL SUMP AT	OIL RING BEHAVIOR	THRUST BEARING OIL COLOR	COMMENTS
A Standard Pump With fan	90	25	N/A	Black	
B without fan Same bearing as test A	172	66	IBD ring rough at startup. Smooths out at running temp	Black	
F with fan Same bearing as test A	95	N/A	N/A	Black with lots of fine bronze	
G Standard Pump with fan Same bearing as test A	90	30	Slight bouncing of oil rings. Some surging	Mid brown with lots of fine bronze and slivers of bronze	
H without fan VG68 oil	180	80	N/A	As for G but slightly more	
I without fan AW VG46 oil	183	70	N/A	Slight darkening and traces of fine bronze	
J without fan, VG32 oil, Preload thrust bearing New oil rings	180	61	Oil rings very rough OB ring worst at startup At running temp rings still rough OB ring slightly smoother.	Mid brown with lots of fine bronze and a few slivers of bronze	
K without fan VG32 oil, Preload thrust bearing. New oil rings Same bearing as test J	180	55	IB ring bouncing at startup. OB ring smooth Intermittent bouncing out of groove for OB ring	Same as J	New rings hand picked to within 0.003" roundness Rings observed to be hitting casing rib causing erratic behavior
L without fan, AW VG46 oil, preload thrust bearing Same bearing as test J	180	65	Both rings erratic	Slight darkening and traces of fine bronze	
M without fan, VG68 oil, preload thrust bearing Same bearing as test J	185	75	Both rings erratic	Slight darkening and traces of fine bronze	
N without fan, VG46 oil, preload thrust bearing Same bearing as test J	180	66	Rings erratic at startup, smoothed out later	Slight darkening and traces of fine bronze	
O without fan, VG32 oil, clearance thrust bearing, steel oil rings Same bearing as test O	180	76	Oil ring operation fairly smooth	Slight darkening NO traces of fine bronze Traces of steel	Rings hit the casing rib occasionally
P without fan, VG46 oil, clearance thrust bearing, steel oil rings Same bearing as test O	184	86	Oil ring operation fairly smooth	Slight darkening, NO traces of fine bronze Traces of steel	Rings hit the casing rib occasionally
Q without fan, GST VG46 oil, preload thrust bearing, Nitronic oil rings	8 hours	68	Oil ring operation fairly smooth	Slight darkening, NO traces of fine bronze Traces of steel/Nitronic	Rings hit the casing rib occasionally
R without fan, VG46 oil, preload thrust bearing, non metallic oil rings Same bearing as test Q	180	75	Oil ring smooth in operation. Runs continually against the rib	*Slight darkening *Traces of steel	Best oil delivery of all the ring designs *Contamination from parts washer suspected
S without fan, VG46 oil, preload thrust bearing, non metallic oil rings Same bearing as test Q	180	70	Oil ring smooth in operation. Runs continually against the rib	Oil pristine	Housing flushed with oil twice after test R Best oil delivery of all the ring designs
T without fan, VG32 oil, clearance thrust bearing, non metallic oil rings	180	75	IB oil ring rough at startup. Smooths out in operation. Runs continually against the rib	Slight darkening. Traces of steel	Oil delivery not a good as tests R, S. Oil seems to fall back off ring into the sump or be thrown out as a mist.

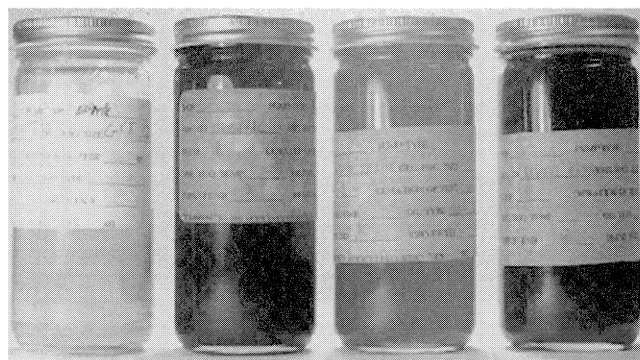


Figure A-1. Control and Tests 1, 2, and 3.



Figure A-2. Control and Tests 4 and 5.

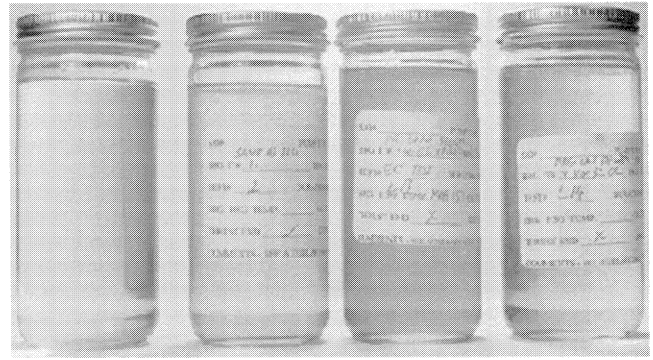


Figure A-5. Control and Tests 12, L13, and L14.

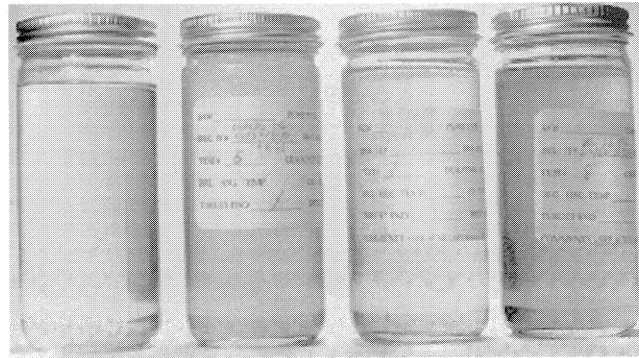


Figure A-3. Control and Tests 6, 7, and 8.

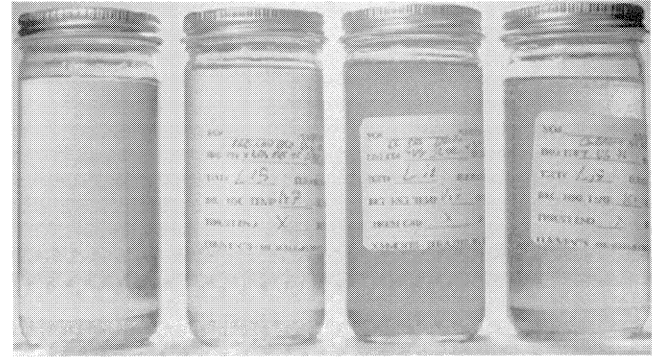


Figure A-6. Control and Tests L15, L16, and L17.

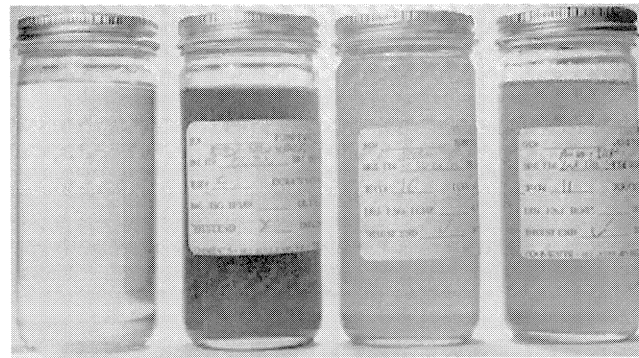


Figure A-4. Control and Tests 9, 10, and 11.

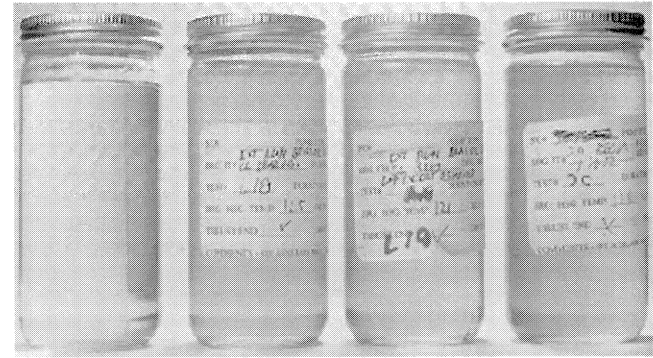


Figure A-7. Control and Tests L18, L19, and 20.