Remedy to Black Oil Problems in Centrifugal Pumps with Ball Bearings

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BACKGROUND & INTRODUCTION

Oil lubrication degradation and predicted operating life for anti-friction ball bearings are critical subjects to the plant engineer who has the essential responsibility for maintenance and safe reliable performance of his rotating machinery. Tribology, which is the study of wear, friction and lubrication between two moving surfaces is becoming an essential area of knowledge for every pump design engineer and plant reliability engineer. Sophisticated electronic technology, both laboratory and portable computer equipment, has been developed to define oil characteristics and levels of oil contamination.

The sampling and analysis of pump bearing oil is becoming another parameter, along with hydraulic performance and vibration testing and thermography to determine bearing condition analysis and predicted life. Oil analysis computer hardware and software tools are now capable of predicting bearing degradation several months before methods which involve vibration signature characteristics. The oil analysis technology defines oil degradation and bearing metallic wear particle contamination. As the focus increases on bearing oil integrity, many machines are coming under extremely close scrutiny. The pump designer must have a clear understanding of the critical parameters affecting bearing life and lubrication integrity.

This case study involves a 3600 rpm, 700 horsepower multi-stage centrifugal pump (and its associated ball bearing system) which has been critically analyzed. (Figure 1). The pump features a duplex (back to back) ball thrust bearing arrangement. The impellers are arranged in series (in-line impellers). The pump also features a flange-type balance drum (or balance disk) to counter-balance the rotor axial thrust.

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Figure 1.

Flowserve Corp. HMTA model pump. Multistage, axially split, in-line impellers, balancing drum, ball bearing - centrifugal pump.
Pumps are often operated at very low flow rates, as process demands vary or have been reduced from the original system design. During this low flow operation, the pump generates elevated radial and axial thrust loading. High piping vibration and pressure pulsations are often experienced. This results in pump thrust load components that are both static and dynamic. These increased loads on the bearings often cause bearing heating and oil discoloration.

A major source of this energy is rotating fluid stall and re-circulation in the pump's impeller and diffuser passages (Figure 2). The resulting high dynamic and static loading on the bearings can result in ball bearing "skidding" and outer race "fretting corrosion." These degradation modes will contribute to oil discoloration sometimes referred to as "black oil." Elevated oil temperatures and "black oil" may also be caused by varying oil levels, improper balance drum settings variances, improper bearing fit-up dimensions, improper bearing preload and "stray currents" (electromagnetic precipitation). The oil in the constant (Trico) oiler glass bulb may be discolored as a result of exposure to the sun's ultraviolet rays; the oil in the reservoir may be satisfactory. Many users will drain, flush, refill and rerun pumps in an attempt to achieve "acceptable" oil clarity.

Although discolored, oil lubrication integrity, as measured and defined by industry standards for particulate contamination and oxidation, may not be compromised. Reliability engineering personnel often will declare a pump "inoperable" when oil color is defined as (perceived to be) "blackened," or burnt. It is therefore essential that the design and materials be upgraded to improve oil and maintain oil clarity during the high thrust loading conditions.

The author's company has invested extensive time and funding to analyze several pump designs and bearing construct ion configurations.

**BLACK OIL CONTRIBUTORS**

Extensive experience with pumps, during field operation and in testing facilities has confirmed several contributors to "black oil." Precision dimensional control and attention to detail are always fundamental to ensuring satisfactory in-service operability. In addition, several factors confirmed to affect in-service oil quality are as follows:

- Improper axial clearance setting of the axial thrust balancing drum.
- Improper axial clearance (end play) of the thrust bearing in the housing.
- Misalignment through the bearing due to out of parallelism / perpendicularity.
- Improper bearing inner race fit to the pump shaft (either too tight or too loose).
- Insufficient oil film (lubrication) on the bearing races and balls upon start-up after extended idle periods. [Starting without sufficient oil film (lubrication protection) on ball bearings will result in heating, oil shearing, oxidizing (burning), and discoloration].
- Oil ring grooves and side wall radii causing wear and instability.
- Oil ring and mating journal sleeve material compatibility.
- Oil ring material loss.
- Journal sleeve material loss.
- Improper oil level (too high or low).
- Oil (slinger) ring stall, when immersed too deep.
- Lack of bearing housing reservoir coating (not epoxy painted).
- Loose clearance between bearing outer race and bore of the thrust bearing housing. [Fretting corrosion is a major contributor to oil shearing, oxidation and formation of particulate contamination].
- Excessive high bearing internal preload.
- Insufficient bearing preload.
- Bearing skidding (of the unloaded bearing in a duplex set).
- High rotor unbalance will "spall" the balls, inner and outer races and shear the oil.
- Axial shuttling of the pump rotor, causing fretting and shearing of the oil.
Potential causes of axial rotor shuttling are:

- Lack of centralization of impeller and diffuser hydraulic passages.
- Low flow hydraulic energy and pressure pulsations resulting from separated and stalled flow between the impeller and the diffuser.
- System interaction, pipe vibration and piping pressure pulsations.
- Use of assembly grease and anti-seize lubricants which discolor the oil.
- "Stray currents"—electromagnetic precipitation; often misdiagnosed as mechanical fretting corrosion. This phenomenon occurs when residual magnetism of the rotor sets up a current field where levels exceed "3 Gauss." "Sparks" occur across the tight running clearances in the bearing ball and journals, and bearing housing assembly, causing pitting and frosting of the metal, and discolored black oil. The rotor may have residual magnetism due to a previous magnetic particle (MT) examination, "shock induction" due to an event where the rotor and stator rubbed ("wiped"), previous weld repairing of the parts or if the parts were originally machined using a magnetic chuck in the lathe. Some hypothesize that lightning strikes near the equipment or pumps oriented east to west (earth's north-south magnetic fields) result in problems with "stray currents." Another contributor to residual magnetism is induction heating of ball bearings during assembly. A recommended shop practice is to inspect parts for Gauss levels prior to shipment or assembly. Equipment is available to de-Gauss components, in the shop and field installations.
- Ultraviolet rays of the sun will discolor the oil in a constant oiler bulb, i.e., Trico. Awareness of this basic potential is essential to trouble-shoot discolored oil.

**Figure 3.**
Research and Development test loop and instrumentation setup.

**Figure 4.** Impeller/Diffuser Upgrades—Improved Pump Flow “Rangeability”

**UPGRADE DESIGN MODIFICATION**

**ORIGINAL DESIGN**

**NEW DESIGN**

Impeller and diffuser A, B-gap and C-overlap. Note the flow distortion and separation resulting from pump low-flow operation.

**DESIGN ANALYSIS AND IMPROVEMENT PROGRAM**

The multistage pump was tested in the author's company's 85,000 square foot production and Research and Development testing facility. (Figure 3). This pump was of the original 1960s design, and was not equipped with the currently preferred impeller and diffuser arrangement to optimize A/B/C gaps-overlaps. A description of these A/B/C gaps-overlaps is shown in Figure 4.

The extensive Research and Development scope of the design and operational analysis program was as follows:

- Conducted a design review of the existing pump design and plant operation, and proposed upgrade features. Preliminary design layouts were reviewed. Bearing assembly upgrades and A/B/C-gap upgrades previously applied were used as a guideline.

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• Updated the pump design layout to incorporate the “Schnorr spring” (spring-loaded thrust bearing arrangement) for the 7411-, 7311- and 5311-size bearing designs. Figure 5 describes the Schnorr spring design upgrade applied to the thrust bearing housing assembly. The Schnorr-type belleville spring arrangement simplifies axial setting of the thrust balancing flanged drum, during assembly. The rotor is thereby allowed to axially position itself at the balance drum flange to minimize axial load on the thrust bearing assembly.

• Manufactured and procured upgraded bearing components. This included “sleeving” the original cast iron bearing housing with an AISI type 410 stainless steel material, precision machining the bearing housing, and manufacturing a new bearing housing end cover. The 410 stainless steel will reduce fretting corrosion resulting from any possible axial shuttling.

• Installed a new Schnorr spring equipped bearing assembly arrangement consisting of an original 7411-size duplex set of 40 degree contact angle bearings mounted back-to-back. This arrangement was tested with various bearing configurations and preload values both before and after impeller and diffuser modification to incorporate optimum vane gaps. In addition, bearing temperatures and oil analyses were conducted for each configuration. Vibration and piping pressure pulsation data was recorded.

• Conducted tests with various degrees of bearing internal preload – 0" pounds, 20 pounds, 50 pounds and 100 pounds. Oil analyses were taken after four hours of initial operation and bearing temperature stabilization. The housing was then flushed, and, with same bearing installed, was rerun to stabilization temperature.

• Assembled and installed a new assembly containing a 7311-size bearing and compared operational characteristics. Bearing oil temperatures with the 7311 bearing size were reduced approximately 30 F below the temperatures recorded with the 7411 bearing size.

• Modifications to the impellers and diffusers were performed to achieve optimum A/B/C-gap-overlap dimensions.

• Hydraulic performance testing was conducted to define Total Developed Head (TDH) vs. pump flow capacity characteristic—before and after the A/B/C “gapping” modification.

• Pressure pulsation testing and pump vibration testing was conducted for each bearing arrangement. Significant pipe shaking and high pressure pulsations were observed at low (20% BEP) flows.

• Procured the duplex sets of 7311 bearings, with a “thin-dense-chrome” (TDC) coating and equipped with ceramic balls; this bearing design is illustrated in Figure 6. These bearing designs are presently installed in nuclear submarine pumps and aircraft engines.

• Dismantled the conventional design 7311 duplex bearings and replaced them with the new IR-TDC/Ceramic 7311 bearing set. Pump testing and oil analyses were again conducted with this bearing set.

• A type 5311 double row bearing was installed and tested, without an oil ring, and with the oil level set at the centerline of the lowermost ball.

ESSENTIAL ELEMENTS FOR SUCCESS

The development program to eliminate black oil was successful. The following conclusions and results were achieved:

• Design dimensional control—clearance, perpendicularity, parallelism and concentricity—is essential.

• The presence of an oil-film lubrication (lubricity) within the bearings is a key factor in preventing “start-up” friction, oxidation, particle separation and “oil blackening.”

• Rotor centralization is also an important feature control to minimize impeller-to-diffuser secondary flows.

• The combination of a duplex 7311-Ceramic/TDC thrust bearing and a 5311 bearing with oil flood lubrication and no oil ring bearings maintained desired oil clarity.

• Lightly preloaded (20-pound preload) bearings appear to provide an optimum combination of resistance to oil discoloration low operating temperature.

• Fretting corrosion of the bearing outer races and ball skidding of the unloaded bearing in a duplex bearing set, (when the Schnorr springs are not installed to preload the bearings) are major contributors to
black oil.

- Flushing and rerunning after an initial four-hour run (when the balls and races are bathed in oil) result in clearer oil.

- Utilization of the TDC/Ceramic bearing design, which provides inherent lubrication between the "slippery" chrome and hard/stiff ceramic balls, is the only arrangement tested which resulted in clear oil during the initial start-up runs. The vibration on the thrust bearing housing equipped with the stiffer TDC/Ceramic bearing set was approximately one-half that of the conventional ball bearing.

- Tests of the 5311 bearing lubricated by maintaining the oil level located at the centerline of the lowest ball and without an oil ring, also resulted in acceptable oil clarity. The clarity improved even further after a subsequent flushing and rerunning.

- Oil grade ISO 68 (as opposed to the initially prescribed ISO 32) appeared to provide the optimum lubrication, while minimizing the potential for bearing skidding.

- The "gapping" and "centralizing" of the impeller and diffusers lowered the pressure pulsations.

- The performance curve characteristic, however, did change after the "gapping" modification (see Figure 7). The TDH at lower pump flows was slightly higher than the original. The A-gap "filter" reduces the secondary flow loss that otherwise flows back around the impeller shrouds and therefore produces higher head at low flow rates.

- The pressure pulsations were somewhat reduced; however they were still capable of shaking the test stand suction and discharge piping, at a frequency of approximately 8 Hz.

- Oil temperatures were reduced approximately 30 F.

- Oil discoloration and temperature were comparable to the pre-gap testing.

**CONCLUSIONS AND RECOMMENDATIONS**

The modification to the 7311 and the 5311 bearings was successful. The pump was installed and started at the customer facility. The pump operated at low flow for several days. The pump operated "smoother" than any time in its history. The pump achieved required flow and pressure specifications. The oil clarity was maintained. Oil analysis found no degradation or evidence of contamination. This is the first time the oil did not require drain, flush, and rerun to achieve acceptable oil quality, i.e., black oil was greatly diminished. Because of the careful procedures performed prior to the outage, as outlined above, the plant outage turnaround was accomplished in record time. <<

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