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HIGH SPEED ARRANGEMENT 1 SEALS IN WATER INJECTION SERVICE

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ABSTRACT

As the pressure in older oil wells decrease over time, water injection services are becoming more prevalent on offshore platforms. Water injection is used to maintain the pressure in the wells and displace the oil from the reservoir, which improves the output and can extend the life of the formation. Formation pressures are normally high and require equal or higher pressure to force the water in. These applications are typically handled by high speed, high pressure barrel pumps that can see frequent start/stop cycles. The high peripheral speed and unique operation procedures for these services is a severe duty for any mechanical seal. The seawater process fluid also presents a difficult challenge due to its marginal lubrication properties.

Conventional flat face technology results in very high temperatures at the seal faces, which can cause vaporization, thermal distortion and excessive face wear. These effects can be minimized by controlling the amount of heat generated as well as how the components of the seal react to increased temperature.

Other specific operating conditions of water injection services must be accounted for as well. These requirements can be met by implementing a strong design evaluation including Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD) as well as a test program that accurately represents the conditions in the field.

INTRODUCTION

Well pressure decreases naturally as wells age and the oil and natural gas are removed from the formation. Increasing the pressure by injecting fluid back into the formation can increase production rates and extend the life of an existing well by many years. Water injection methods for extracting higher oil flow rates from old wells have been in place for many years (Sebastian 2012). The process has recently been adapted to offshore applications where clean injection fluids and space for equipment are limited.

Seawater is a plentiful resource on offshore platforms so it is a reasonable choice as an injection fluid. However, it is also corrosive and contains biologic contamination that can foul piping and clog passageways in the reservoir. These issues can be addressed by treating the water to remove particles, bacteria and oxygen before it reaches expensive injection equipment.

The injection pumps are typically high pressure barrel pumps operating at 5,000 to 10,000 RPM driven by electric motors through a gearbox or by high speed gas turbines. These pumps may see continuous duty or multiple start/stop cycles per day. They may also be subject to slow rolling conditions during shut down as well as hard stops that can result in water hammer. Discharge pressure is specific to the formation and can range from 5,000 psig up to 10,000 psig or more. Seal chamber pressures are typically much lower since the design of the pump puts the seal at suction conditions. Suction pressures range from 500 psig up to 2,000 psig depending on the booster equipment upstream and the amount of differential head the injection pump can produce. Specific operational characteristics will vary between users and locations.

Conventional seal designs using flat faces have difficulty handling the high peripheral speed and pressure of water injection applications. Engineered face topography can be used to create a stable fluid film under all operating conditions to reduce heat generation and prevent face contact.

EARLY FIELD EXPERIENCE

Two high speed pumps installed for water injection service on a major offshore production facility were experiencing frequent seal failures. This Arrangement 1 design used silicon carbide faces throughout due to potential contaminants in the process fluid and concerns about pressure and thermal stability.

Process conditions are typical for a water injection application:

- Seawater at 75°F
- 500 psig suction
- 7500 psig discharge (10,500 psig max)
- 8000 RPM

The mechanical seals experienced short life and the failures were sudden and severe enough to flood the pump bearing housing with seawater and contaminate the bearing oil system. The gas turbine driver shares the same bearing oil system as the pump so the chances of major damage are very high. The facility uses a pressure switch reading the pressure between the seal and gland bushing to indicate failure and this system proved inadequate. These failures started a large scope program aimed at addressing issues with high speed Arrangement 1 seals in water injection applications.

Multiple seal investigations showed similar failure modes; heavily worn seal faces (Figures 1 & 2) and signs of high vibration on parts with small design clearances. Fixing the issue of face wear and vibrational damage would be difficult enough. However, further investigation into how the pumps were operated revealed that the service was more demanding than originally expected. The pumps go through at least one start cycle per day. They also have a very long roll down period where the seals are operated well under the minimum speed requirement causing face contact. Lastly, the end user reported multiple instances of severe water hammer, some large enough to extrude the pump suction flange gasket.

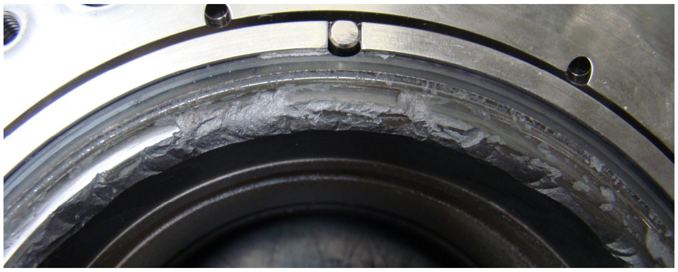

Figure 1: Stationary Face Damage

Figure 2: Rotating Face Damage

A root cause analysis (RCA) was completed and identified four shortcomings in the seal design:

- Inadequate flush flow to the seal faces
- Inadequate slow roll capability
- Inadequate start/stop capability
- Excessive vibration damage between parts

The RCA also identified potential causes that could be eliminated

- Seal face distortions
- Gasket performance
- Basic hardware configuration

Any new seal design would have to address the issues found without affecting the areas that were performing well.

PRELIMINARY IMPROVEMENTS

The RCA results showed areas for improvement that could be implemented without dynamic testing: inadequate flush flow to the faces and excessive vibration damage between parts. The first area to address was flush recirculation at the faces.

Flush Flow Optimization

Seals at high peripheral speed generate a large centrifugal force that acts to push the fluid away from the faces. This can cause the same effect on the seal faces as running the pump dry since the faces are running without lubrication. Seal chamber pressure in high speed pumps must be maintained high enough to prevent this effect. Water injection pumps do not normally have this problem when installed in the field since they are fed by booster pumps, which provide sufficient suction pressure to prevent face dry running.

However, high speed can also create a thermal stratification in the seal where warmer fluid gets trapped at the faces due to the lower density. Cooler fluid coming in from the seal flush supply is heavier and is therefore pushed to the outside of the seal chamber by the centrifugal forces. This then prevents cool water from getting to the interface and further heats the water that is already there, which exaggerates the problem.

Computational Flow Dynamics (CFD) were used to analyze the existing flush flow and verify this effect. The high speed of the application was indeed causing a local recirculation at the faces that was not allowing cooler flush fluid to remove sufficient generated heat (Figure 3).

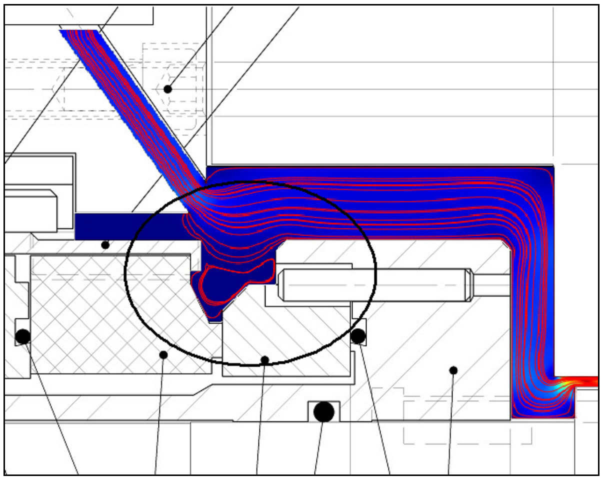

Figure 3: CFD Flush Flow Model

A flush baffle can be used to drive fluid down to the face edge and break up any local recirculation. References of seals in similar high speed applications were used to determine a design for a baffle to direct flush flow to the faces. The baffle was then modeled in CFD and the shape and size were tuned to provide sufficient flush velocity and to break up any internal recirculation (Figure 4).

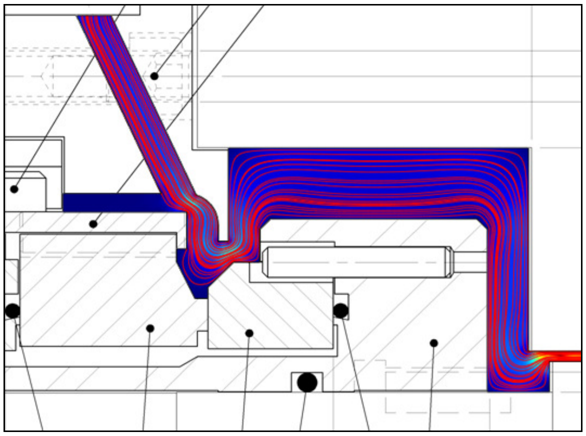

Figure 4: Flush Flow with Baffle Installed

Vibration Damage Reduction

Overall equipment vibration levels on the pumps in the field were very low. The damage seen in the seal parts was not coming from the equipment movement but from high-frequency movement between the seal parts. This is a result of the high fluid velocity around the seal and the relatively tight clearances between the parts. Vibration damage was centralized around the stationary face drive features. A T-shaped pin is used to hold two parts together and transfer torque from the stationary face to the seal gland. The combination of vibration and excessive clearance between the pins and the other parts in the assembly caused damage to the pins and the holes they engaged (Figures 5 & 6).

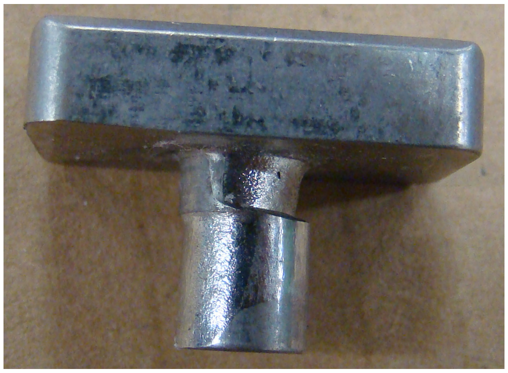

Figure 5: Pin Damage from High Frequency Vibration

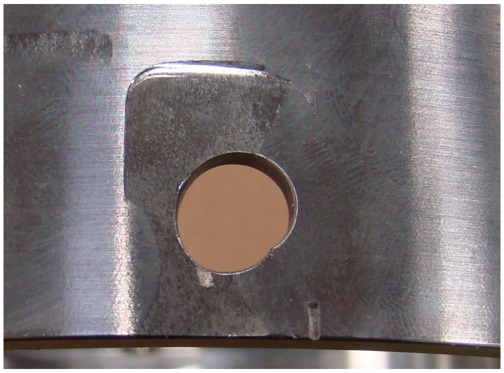

Figure 6: Pin Hole Damage from High Frequency Vibration

This problem had not resulted in failure but was clearly a sign of problems to come. The allowable movement increased as the pin holes enlarged and ultimately, the assembly would not be driven once the pins sheared. Failure of the drive mechanisms in this service would cause a major seal failure and could even damage the pump if not identified quickly.

The pin holes are typically drilled separately in the two mating parts so clearances were kept loose to allow easy assembly. The holes needed to be drilled in both parts at the same time so that the clearance and tolerance could be reduced without affecting assembly. A match-machining fixture was designed that holds the two parts together along with a dummy spacer to represent the stationary face. The holes could then be made using a high precision reamer bit rather than a standard drill bit. The parts would be marked to indicate their angular position when drilled to speed assembly.

Reducing the clearance between the parts minimized the allowable movement but did not prevent the vibrations from occurring. Absorbing the energy would also help prevent the movement from ever happening. A gasket was placed between the parts to dampen the vibrations and prevent movement (Figure 7). This gasket has no sealing purpose; it is only a vibration control feature.

The addition of the flush baffle and improvements to the stationary face seal drive required only small changes to the existing seal hardware. They were incorporated into the design immediately and sent out for installation while the test program was developed and executed.

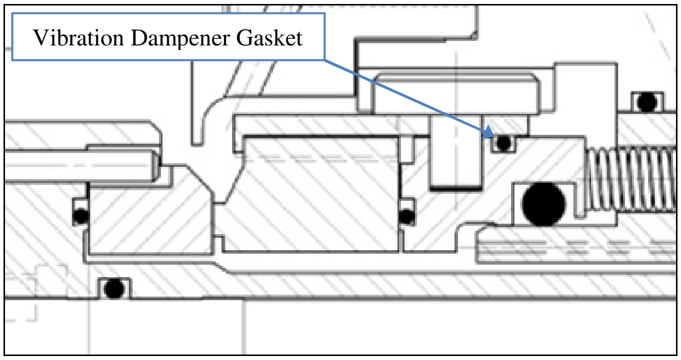

Figure 7: Seal Assembly Showing Vibration Dampener Gasket

TEST PROGRAM

The remaining issues identified in the RCA required dynamic seal testing to design and verify. The hard face combination selected for stability could not tolerate face contact with a water process fluid so a face feature was required. The original feature was designed to create lift while running at rated speed while still providing low leakage. Multiple seal failures showed that the faces were seeing hard contact that was wearing away the features and damaging the faces. The multiple start/stop cycles and slow roll operation were identified as the most likely times for face damage since the lift created was dependent on shaft speed. A new face feature design was needed to provide lift over the entire speed range including off-design conditions such as slow roll.

Finite Element Analysis (FEA) was used to optimize the stationary face and to design the face features used to provide load support and film thickness (Figure 8).

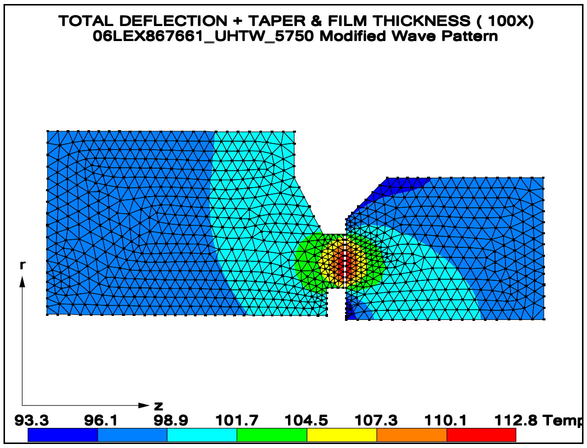

Figure 8: FEA Results for Final Face Design (8400 RPM)

The original face features needed more than 750 RPM for non-contacting operation. The face feature pattern designed for testing produced full non-contacting operation under static pressure. This insures that the faces would not contact under any speed

Plan Development

The test plan was developed with the end user to insure that all the elements of field operation were included. This required an extraordinary amount of involvement from operators and engineers to examine operational data for the application. The final plan included four different test stages.

Qualification Testing was performed at rated pump speed and pressure for 100+ hours. This was used to establish and evaluate equilibrium operating conditions, seal leakage, seal face temperatures and face wear rate.

Pressure and Speed Variation Testing was performed at four different speeds and four different pressures to evaluate the effects of changing operating conditions (four speeds with four pressure points at each speed).

Start/Stop Testing was performed to evaluate the effects on the seal performance from multiple start/stop cycles. A total of 7 cycles would be performed with the seal running for one hour under rated conditions before the stop occurred.

Slow Roll Testing was performed to verify full lift off at low speed. This test would operate at 180 RPM, which is the minimum stable speed for the tester. This stage would be performed at both minimum and maximum rated seal chamber pressures.

Each stage was intended to test the limits of the seal design and to provide data for any required redesigns. A successful seal could complete the entire test plan without face damage while providing an acceptable leak rate under all conditions. The end user agreed to a maximum leak rate of 1.5 gallons per hour since the process fluid is seawater and any leakage is easily disposed.

The tester design requires two identical seals in a back-to-back arrangement to balance the thrust load on the shaft. Both seals used a silicon carbide rotating face but the thrust balance seal used a metallized carbon stationary face while the test seal used a silicon carbide stationary face. This allowed both face materials to be tested at the same time under identical conditions. The carbon face was geometrically tuned to provide pressure distortion similar to the silicon carbide stationary face.

Test Program Results

The test program using the improved seal was completed and witnessed by the end user. Each stage of the test was completed with no damage to the seal faces and with leakage below the acceptable rate. Certain portions of the test plan were adjusted based on discussions with the end user during the witnessed portion. The slow roll and start/stop testing portions were run longer than planned at the customer request.

The primary indicators of seal health for this test were seal face temperature and leakage. Monitoring seal face temperature in relation to bulk fluid temperature gives a good representation of face contact and the associated heat generation. It is also a good predictor of face damage and film thickness changes. Seal leakage is a sign of face damage also, though it is a trailing indicator rather than a leading indicator like face temperature. Monitoring these two parameters simultaneously along with flush flow, temperature, shaft speed and pressure provides exceptional control over the conditions and an accurate reading on the health of the seal.

Seal face temperatures were less than 15°F over bulk seal chamber temperature for the entire test protocol (Figures 9, 10, 11 & 12). This is slightly lower than the pre-test FEA predictions and is much lower than predictions for flat faces under the same conditions.

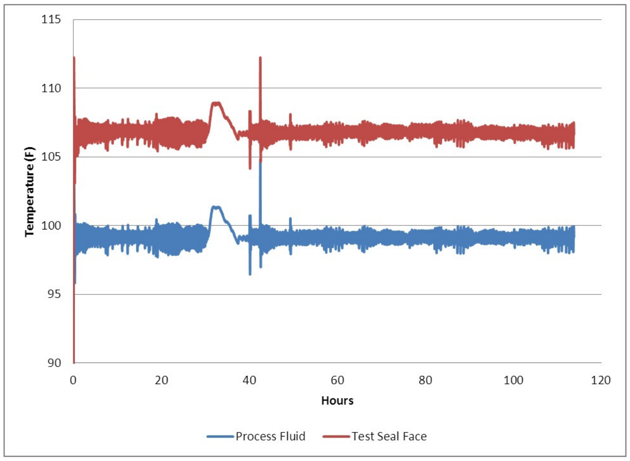

Figure 9: Qualification Test Temperatures

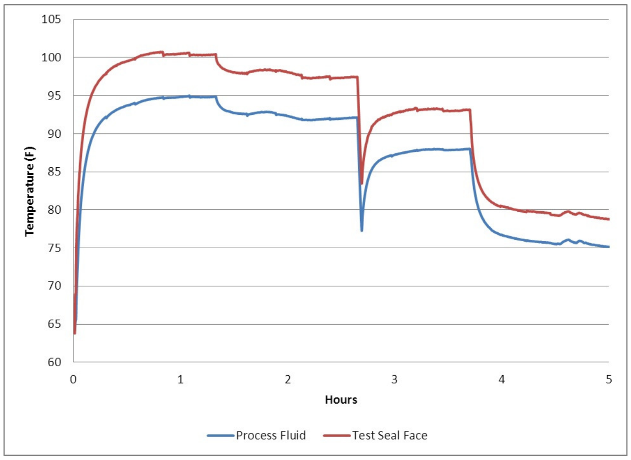

Figure 10: Pressure/Speed Variation Stage Temperatures

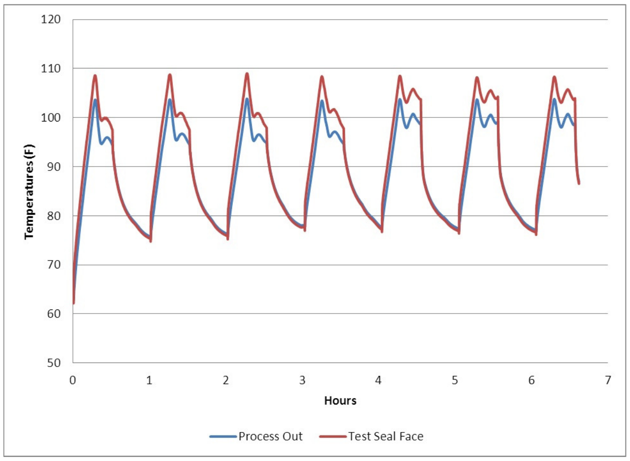

Figure 11: Start/Stop Stage Temperatures

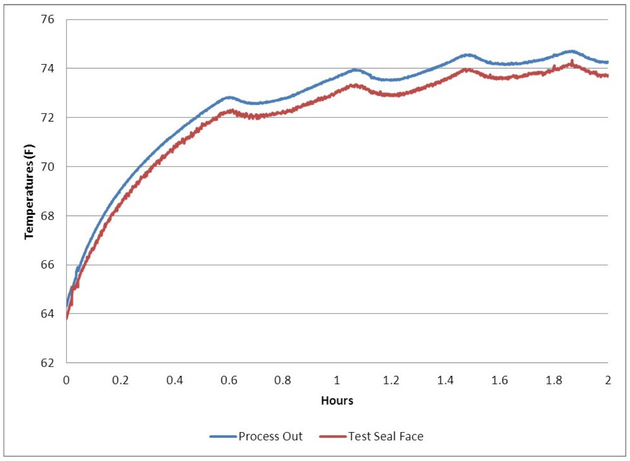

Figure 12: Slow Roll Stage Temperatures

The leak range stabilized at 1.3 gallons per hour during the qualification test. Leakage readings showed localized spikes when the tester was started due to displacing accumulated leakage with shaft rotation. Leakage at all other stages of the test were lower than during the qualification stage and in good agreement with pre-test FEA predictions.

The faces were inspected for damage after each stage. No damage was found and the faces were simply wiped with solvent and re-installed for the next test step. A very faint circumferential track is seen on the rotating face (Figure 13). Post-test profile traces show there is no depth to this mark, only a slight polish that changes the surface finish (Figure 14). There were no marks on the stationary face and profile traces showed no signs of contact (Figure 15).

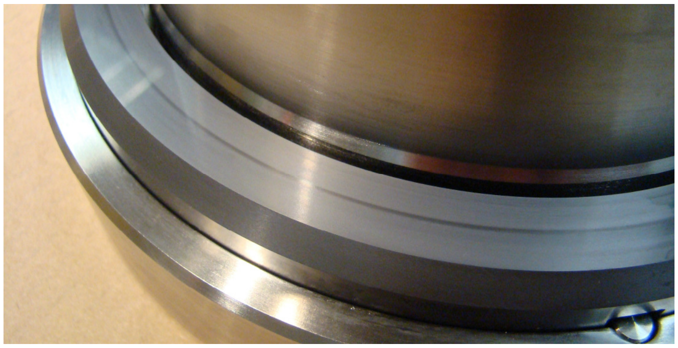

Figure 13: Rotating Face Post Test

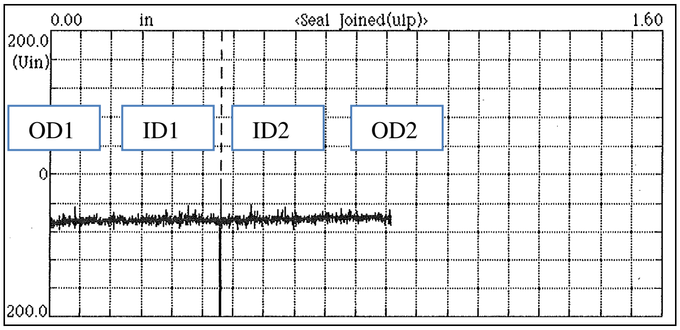

Figure 14: Post-Test Rotating Face Profile

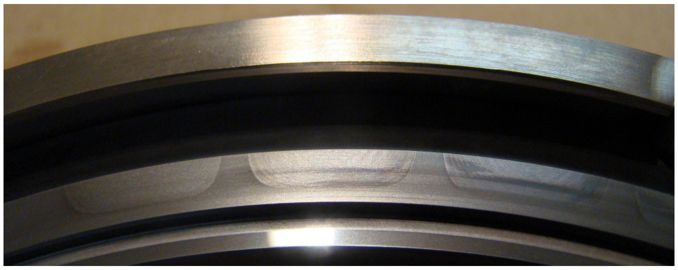

Figure 15: Stationary Face Post Test

The carbon face used in the thrust balance seal was also undamaged and was not repaired throughout the entire test program (Figure 16).

Figure 16: Post-Test Thrust Balance Seal Stationary Face

The thrust balance seal carbon face produced more erratic leakage under all conditions. This is likely a result of the lower stiffness and thermal conductivity as compared to silicon carbide (Lebeck 1991). The silicon carbide face was chosen for the final design since the leak rate was consistent and there was no face damage. Silicon carbide also provides the highest resistance to water hammer damage since it has a very high compression strength.

The seal components did not experience any vibration damage during testing. However, the test duration was short as compared to run time in the field and the tester conditions are closer to ideal when compared with real life operation in the equipment. The true test of the improvements aimed at vibration control will come in the field installation.

The slow roll testing was performed again using the original face feature pattern after the entire test plan was complete. This was done to verify that the damage seen on previous failures was a result of insufficient face separation at low speed. The test ran for 20 minutes at 1200 RPM when the seal face temperature rose quickly and a grinding sound was heard from the tester. The faces showed hard contact damage when removed (Figure 17).

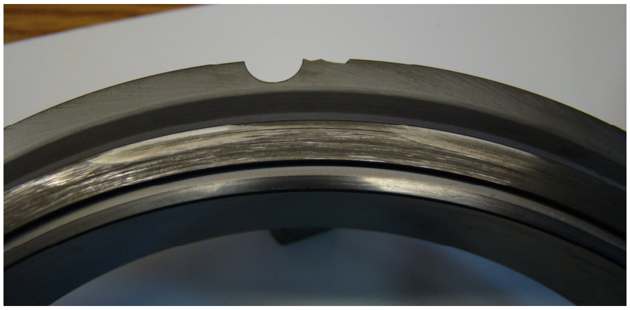

Figure 17: Test Seal Stationary Face After Slow Roll Testing

The test seal was refurbished and run again under the same conditions. The temperatures spiked and a grinding sound was heard at 700 RPM on the second iteration. The faces showed hard contact damage when removed. This testing verifies that the hard contact at low speeds would occur with the previous face feature design and provides a link to previous failures.

The test program was a success and validated a robust seal design that is well suited to handling the demanding conditions of the application. It also validated the root cause of previous failures through slow roll testing using the originally supplied face features.

FINAL RECOMMENDATIONS

Seal Design

The improvements implemented through CFD, FEA and manufacturing engineering produced a seal better able to handle the high speed of the application. Improvements validated through dynamic testing resulted in a seal that could handle the wide range of operating conditions of the application without face damage while still meeting the end user leakage requirements. The final seal design included the following features:

- Vibration dampener between close fitting parts
- Flush baffle to direct flow at the faces and prevent local recirculation
- High precision machining to reduce clearances where applicable
- Silicon carbide face materials for thermal and pressure stability throughout the operating range
- Aggressive face feature design to provide load support and sufficient film thickness at all conditions

Although the specific application for this seal is water injection, the preliminary design changes and test program produced a seal design that could be applied in any similar application.

Field Recommendations

Successfully sealing a unique application such as offshore water injection requires thorough knowledge of the real operating conditions. This includes the typical parameters such as pressures, temperatures, fluid, size and speed. It also requires a deep understanding of how the equipment will be operated such as slow roll conditions, frequency of start/stop cycles, probability and magnitude of water hammer and other issues that are unique to the application. Offshore environments are notoriously difficult and equipment is used differently than in a refinery or petro-chemical application. Working with the customer to identify all of the operating scenarios is vital in providing a reliable solution.

FIELD INSTALLATION STATUS

The seal design features discussed have been implemented in three different applications for offshore water injection.

Application 1

Seal Size: 5.750”
Shaft Speed: 8000 RPM
Seal Pressure: 500 psig

Mean Time Between Failures (MTBF) for the original seal design was three months. Seals using the newly developed design features have not failed since being installed over two years ago. The installed pump can be seen in Figure 18 below.

Figure 18: Application 1 Installed Pump

Application 2

Seal Size: 6.250”
Shaft Speed: 5320 RPM
Seal Pressure: 1500 psig

MTBF for this application with the original seal design was approximately one year. Seals using the design features discussed have not had a failure in over two years.

Application 3

Seal Size: 5.000”
Shaft Speed: 6890 RPM
Seal Pressure: 1340 psig

This application was a new unit purchase and the seals were supplied with the newly developed design features. It has been running successfully for over six months with no issues.

RECENT DEVELOPMENTS

The improvements made on this application have been applied to recent test programs. The latest was in a water service for a new pump development under very difficult conditions. The equipment requires a 6.750” seal operating at 10,000 RPM, which equates to a peripheral speed of 294 ft/s. The face features and design fundamentals developed for water injection were used in this program with outstanding results.

Recent testing in hot water applications has also lead to a new face feature design that can significantly reduce start up torque while producing low leakage rates. This new feature design may be applicable to water injection and provide lower leakage without sacrificing low speed operation. Any future test programs on high speed applications should consider this feature design as an option.

CONCLUSION

Offshore water injection pumps are a challenge for conventional seal design methodology and require special features to seal consistently. Design features developed through field experience, computer modeling and testing give excellent field performance under these difficult conditions. Face features also allow the use of hard seal faces that can resist distortion while still providing long term reliability.

NOMENCLATURE

FEA = Finite Element Analysis
CFD = Computational Flow Dynamics
MTBF = Mean Time Between Failures

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