HIGH TEMPERATURE SEALING ADVANCMENTS FOR NON-CONTACTING GAS SEAL TECHNOLOGY

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ABSTRACT

Non-contacting dual pressurized gas lubricated seals for use in pumps have been in service since the early 1990’s. The application of these seal designs has expanded over time into very high temperature applications up to 800°F (425°C) where emissions, pumped fluid contamination and overall operating/lifecycle costs are a major concern. Sealing technology using metal bellows is needed due to the high process fluid pumping temperatures, mainly in the oil and gas refining and petrochemical industries. Traditional non-contacting gas seal designs utilize a non-interference fitted seal ring to a seal ring adapter. Reliability issues have been encountered with non-interference fitted seal ring assemblies in hot, dirty services. The predominant factor affecting long term reliability of the mechanical seal has been seal ring distortion caused by a build-up of hard particulate from the process fluid in the region of the non-interference fitted seal ring to seal ring adapter assembly. The distortion can lead to higher than desirable barrier gas consumption rates, a loss of non-contacting seal operation and reduced mean-time-between-repair (MTBR). Recent advancements have been made in high temperature non-contacting gas lubricated seal technology for industrial use in pumps and other rotating equipment. A study of the latest technology is provided, particularly in the design of an interference fitted seal ring adapter assembly for high temperature non-contacting gas seal design which is both thermally compliant and pressure stable in these applications.

INTRODUCTION

For many years, traditional wet seal designs have been implemented as standard sealing solutions across the industry. As applications became more challenging, wet seal designs and their support system apparatus became more elaborate catering to these challenges. Such as, contacting wet single seals using a clean flush (API plan 32) or dual contacting wet pressurized high temperature mechanical seals with dedicated seal support systems (API plans 53A/B/C or 54). The single seal approach with plan 32 (a flush stream brought in from an external source to the seal) is expensive for the plant operator as it requires the use of a clean refined product to be continuously flushed into the seal chamber. The dual seal approach uses a seal support system to provide a source of a clean and compatible barrier fluid, a method to pressurize it, a mechanism to circulate the barrier fluid and the capability to dissipate heat that is absorbed into the barrier fluid from the heat generated by the mechanical seal and conduction of heat from the hot process fluid and pump. In many of these contacting wet seal applications, non-contacting gas lubricated seals can be applied as an improvement, increasing reliability, MBTR and reducing the complexities of the wet seal support systems needed, only requiring a Plan 74 to provide a barrier gas.

Sealing hot hydrocarbon applications (above 400° F (200° C)) can be extremely challenging as they can contain suspended solids such as coke fines, catalyst carryover, or precipitating solids (aka colloid solids). Precipitation of these solids can lead to reduced reliability of traditional (non-interference fitted) non-contacting gas seals. The solids formation (see Figure 1 and Figure 2) can cause seal ring distortion (see Figure 3). These solids can form a "coke" like material, deposited around the outside diameter of the seal ring face and/or between the OD of the seal ring and the ID of the seal ring adaptor.

Figure 1:Example of solids build-up on ID of seal ring adaptor, non-interference fitted design

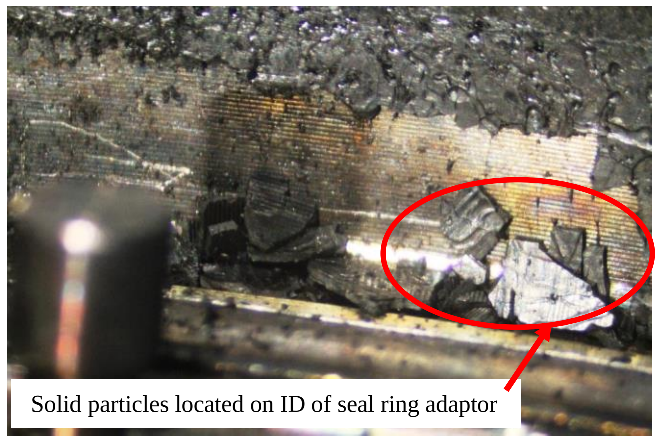

Figure 2: Example of solids build-up on ID of seal ring adaptor, non-interference fitted design

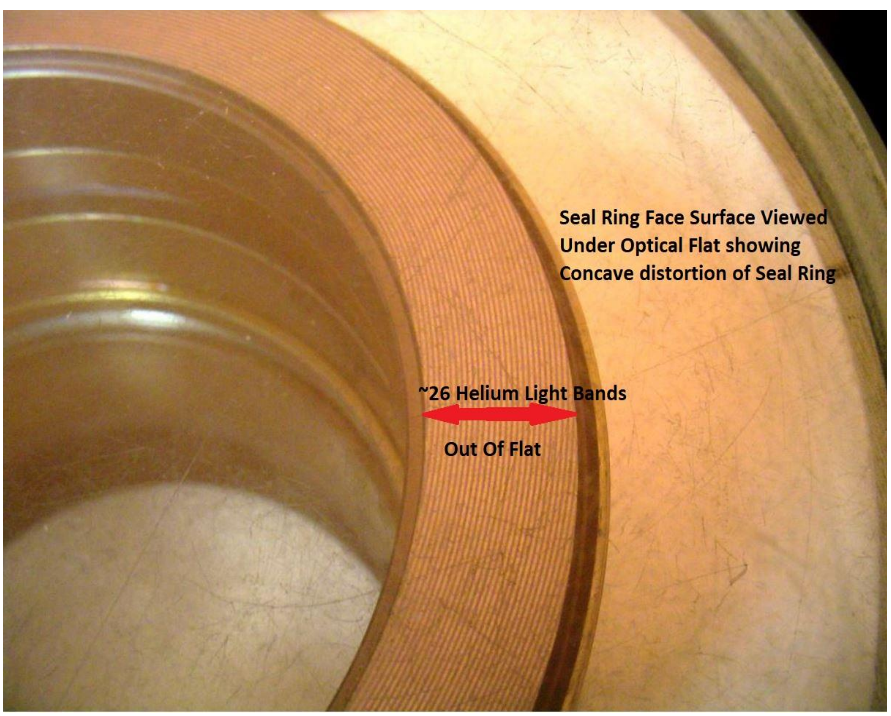

Figure 3: Example of severe distortion of seal ring due to coking, installed non-interference fitted design

The advanced technology was developed to enhance dual gas seal performance in very hot, dirty applications and to mitigate the effects of any debris formation on the seal ring face resulting in lower MTBR due to solids precipitating out of solution.

Integrating an interference fitted seal ring assembly with non-contacting gas seal technology was key to eliminate the process fluid from solidifying in this region of the seal ring interface and to ensure that barrier gas consumption rates would be maintained at an acceptable level.

SOLUTION AND DETAILS OF DEVELOPMENT

Integration of an interference fitted seal face ring assembly coupled with spiral-grooved non-contacting technology has led to a high level of reliability in the most demanding high temperature hydrocarbon services.

The concept solution was born by the merging together of two already proven technologies. These are:

1. High-temperature corrosion-resistant welded metal bellows is well established in the industry for reliably sealing fluids in harsh hot corrosive environments [3]. This in an engineered interference-fitted design of the seal ring in a seal ring adaptor that provides superior face stability at elevated temperatures. See Figure 4.
2. Non-contacting gas lubricated seal technology, where a high-pressure barrier gas film between the seal faces effectively produces a zero-emission seal [4]. See Figure 5.

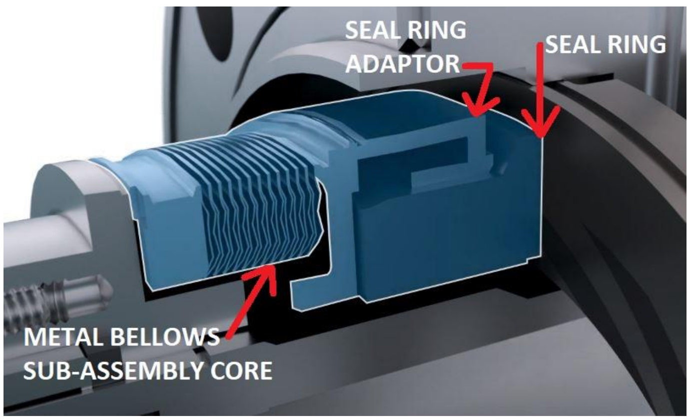

Figure 4: High temperature corrosion-resistant welded metal bellows

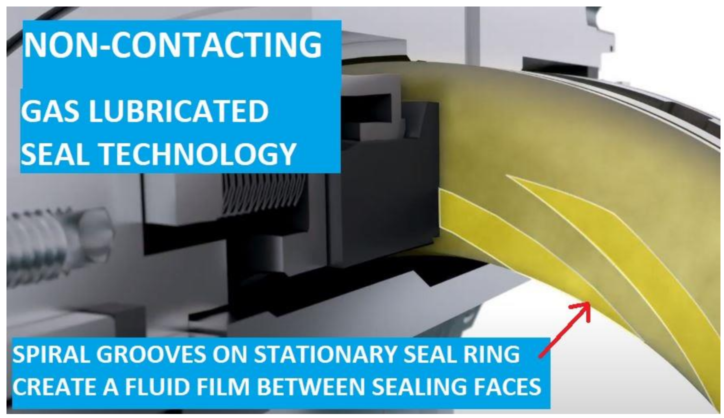

Figure 5: Non-contacting gas lubricated seal

A solution combining both technologies has significant advantages over conventional non-contacting designs such as:

- Enhanced seal ring stability for desirable barrier gas consumption rates [3].
- Interference fitted seal ring assembly to mitigate unwanted debris formation.
- Spiral grooved mating ring design for increased film stiffness and lower barrier gas consumption rates than other face profiles.

This solution can significantly reduce life cycle costs and improve operating efficiency as compared to liquid lubricated seals and systems. In addition, sealing applications demand more as they need to help plant operators meet environmental requirements and to deliver a lower carbon footprint.

Applying High-Temperature Corrosion-resistant Technology

A FEA (Finite Element Analysis) is completed to design the interference fit geometry of the Silicon Carbide sealing ring as it fits into the seal ring adapter. Figure 6 below represents interference stresses at the mating location of a seal ring inside the seal ring adaptor. The placement of the seal ring and geometry of the seal ring adaptor has been optimized to induce minimal thermal and pressure distortions of the seal ring. The interference fit surface is engineered to effect a near-zero net moment about the center of gravity of the seal ring. The seal ring will remain free of any net twisting moment due to the contact pressure at its “fully stressed state”. This allows the seal ring to remain flat without any perceptible coning [3]. FEA modeling is conducted across the full application temperature and pressure range of the seal to optimize the assembly and keep distortion to a minimum.

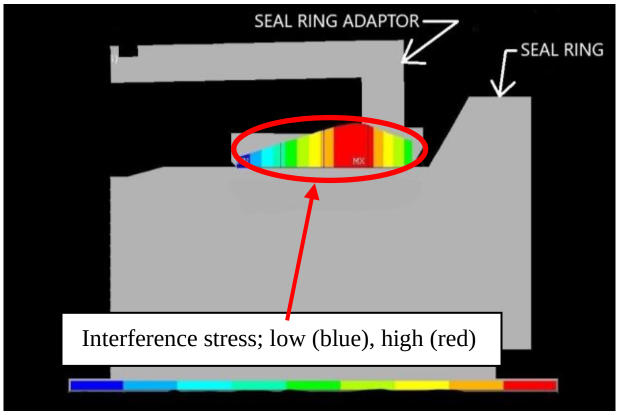

Figure 6: FEA Analysis of Interference fit between seal ring adaptor and seal ring

Effective Balance Diameter (“EBD”)

Mechanical seals have a balance diameter; the diameter of which pressure acts to provide a closing force on the seal faces. In a metal bellows seal, the balance diameter (as defined for a traditional pusher seal) does not physically exist [5]. The hydraulic balance is no longer a constant and changes with pressure as bellows convolutions tend to collapse under an applied hydrostatic pressure.

To successfully apply a metal bellows seal, the effective balance diameter behavior of a bellows must be known. This is highlighted in Figure 7 below.

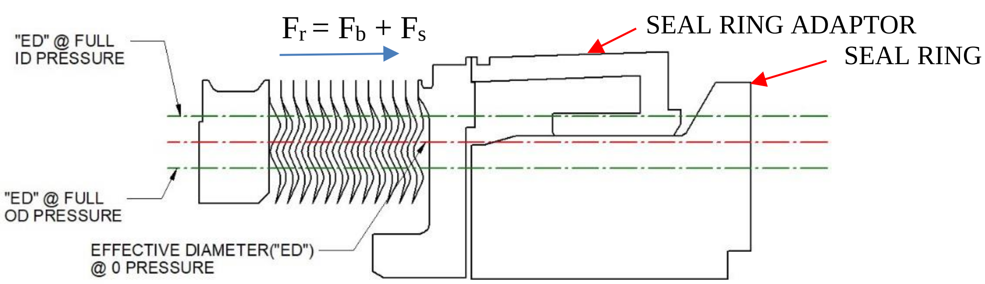

Figure 7: Effective Balance Diameter

The Effective Balance Diameter (EBD) is derived from the bellows closing force (F_b) due to pressure only, from the following equation:

$$F_b = F_r - F_s \quad (1)$$

where:

F_r = Bellows total reaction force, lb_f (N)

F_s = Bellows spring force, lb_f (N)

and,

$$F_b = PA_{EBD} \quad (2)$$

where:

A_{EBD} = Effective Balance Area, in^2 (m^2)

P = Differential pressure applied to bellows, psi (Pa)

To characterize the behavior of a bellows, empirical testing is performed, and the effective balance diameter is obtained by the formula:

$$EBD = \sqrt{\frac{4}{\pi P} F_b} \tag{3}$$

where:

EBD = Effective balance diameter, in (m)
Fb = Bellows closing force (due to pressure only), lb_f (N)
P = Pressure applied to bellows, psi (Pa)

The effective balance diameter can be plotted for a full pressure range (ID and OD) applied to the bellows. A typical plot is shown in Figure 8, note here that OD pressure is plotted on the negative x-axis.

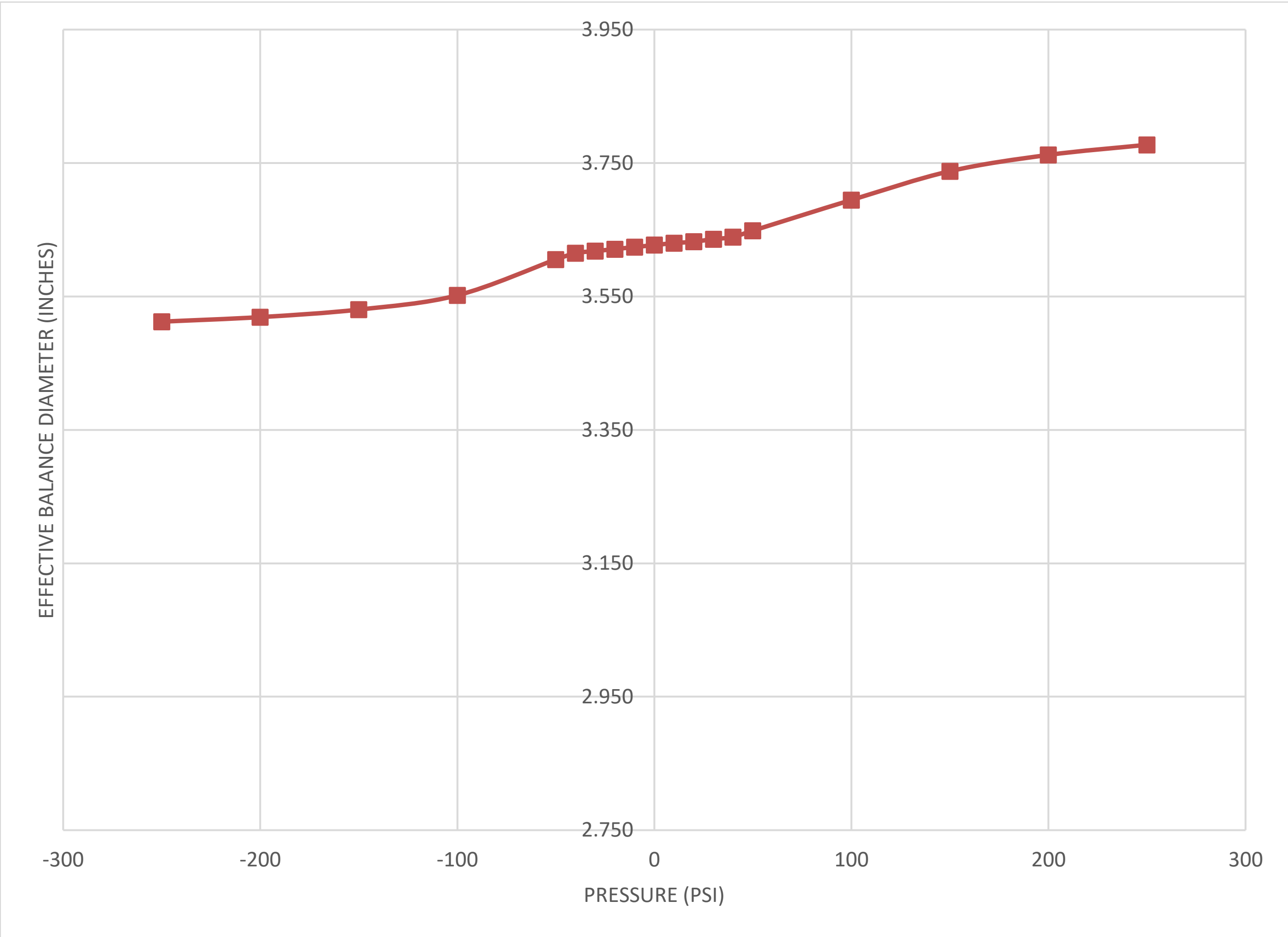

Figure 8: Typical Plot of Effective Balance Diameter Plotted against Pressure

NUMERICAL VALIDATION OF SEAL OPERATION

A thorough numerical validation on gas seal performance was performed prior to physical dynamic testing of the concept. FEA software was utilized to model the seal performance, the analysis was conducted on the application conditions below:

Process Temperature:	Up to 800° F (425° C)
Process Pressure:	Up to 230 psig (16 barg)
Speed:	Up to 3600 rpm, 5,400 fpm (27.4 m/s)
Barrier Fluid:	Nitrogen

A proprietary software program was used to predict gas seal load support and leakage. The program was used to optimize the seal face design of both the rotating and stationary seal rings. It considers the combined effects of pressure, temperature, materials of construction, fluid sealed, spiral groove information and distortion of the faces. The program predicts the face profile and film thickness. It also predicts stress and distortion due to temperature and/or pressure. Many different designs were run before prototypes were made and tested [4]. Output data was obtained for cases in the minimum and maximum manufacturing tolerance condition of the seal ring and mating ring. The predicted face separation of a gas lubricated seal (scale 400:1) is illustrated in Figure 9. Colors are indicative of temperature blue (cold) – red (hot).

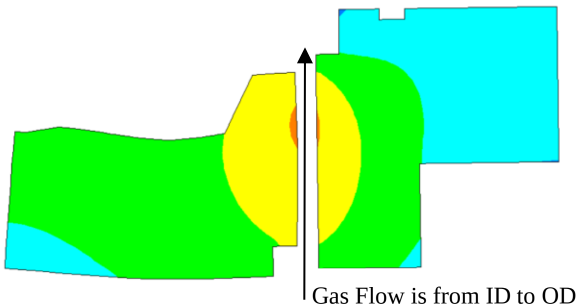

Figure 9: Face Separation of a Typical Non-contacting Gas Seal

VALIDATION TESTING

Validation testing was conducted on a variable speed test pod with pressurized circulation controls utilizing compressed air as a barrier fluid and water as a process fluid. A typical laboratory rig setup is shown in Figure 10. Multiple temperature pressure, speed and load sensors monitored seal performance. Data acquisition consisted of process fluid and barrier gas pressure and temperature as well as barrier gas flow/total consumption and barrier gas leakage to atmosphere. A summary of the test phases is below:

- Phase 1: Static Pressure Testing Up to 260 psig (17.9 barg)
- Phase 2: Breakaway Torque Measurement
- Phase 3: Reverse Pressure & Recovery Testing, see Figure 11 for data capture example, which shows the data captured during 5 cycles where barrier pressure is isolated and vented to atmosphere. This illustrates that upon restoring barrier gas the seal recovered after each cycle. This test phase simulates an upset condition if the barrier gas pressure is compromised
- Phase 4: Performance Evaluation and Barrier Gas Consumption Data Collection

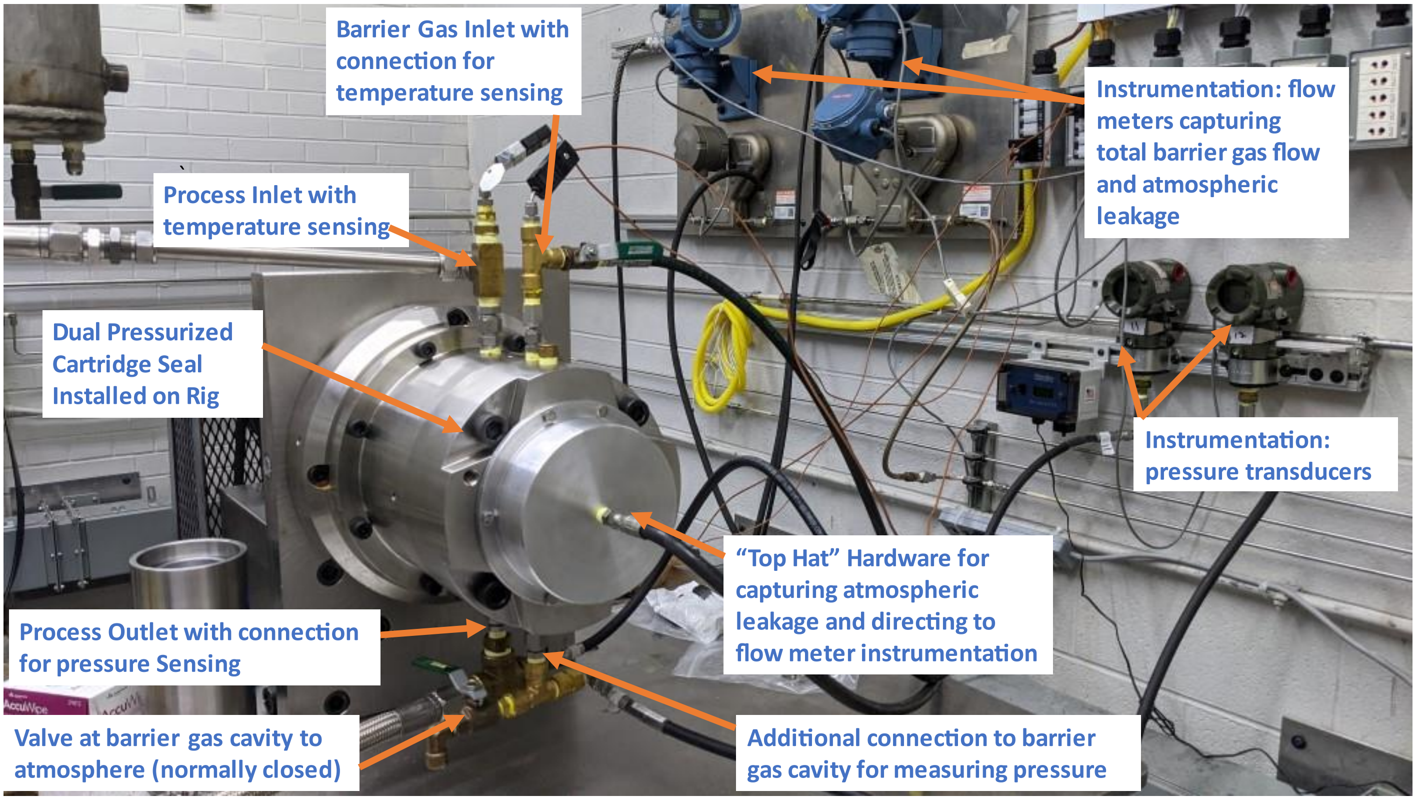

Figure 10: Typical Laboratory Setup for Validation Testing

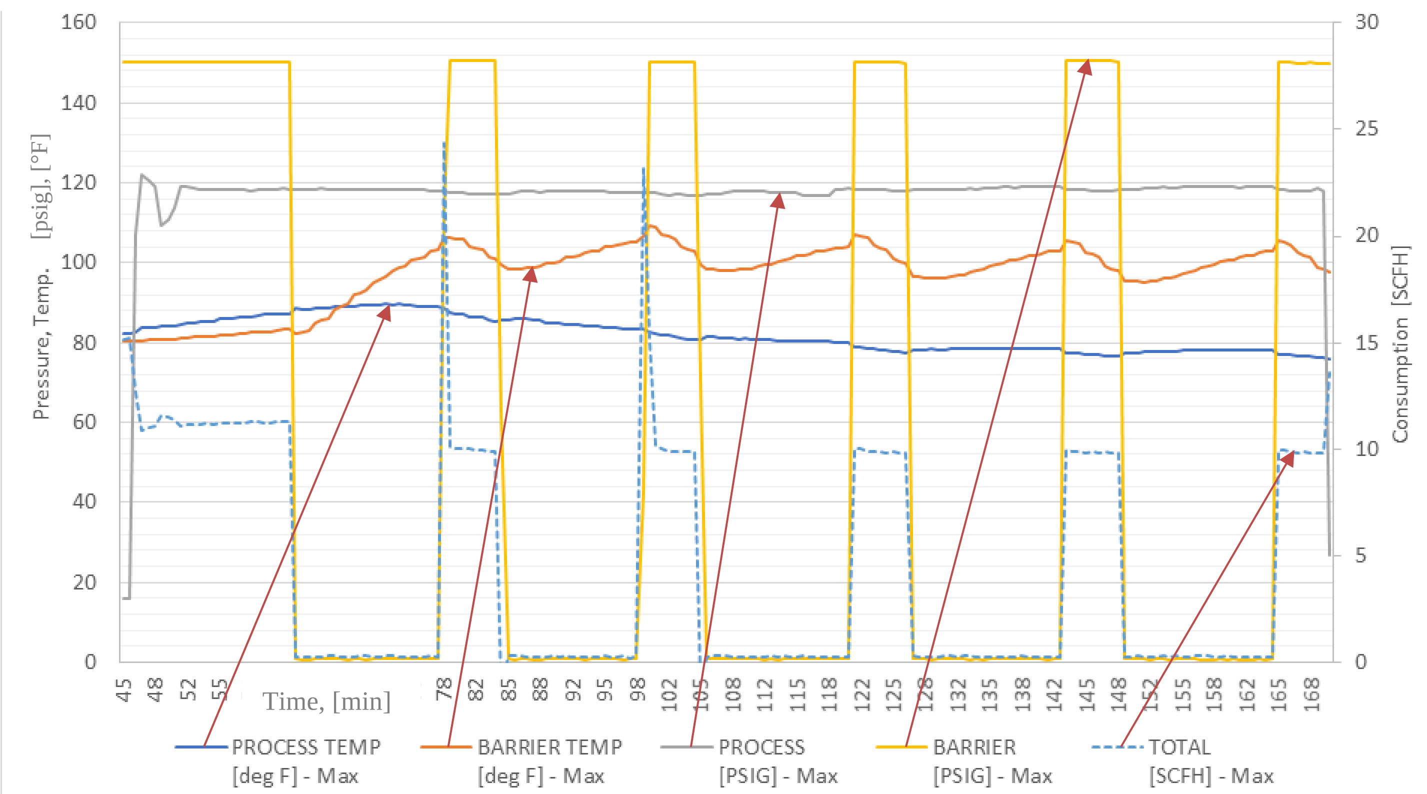

Figure 11: Data capture for reverse pressure and recovery testing

Additional validation tests were performed to demonstrate repeatability with multiple seal builds within normal manufacturing tolerance. Testing was also completed in various axial offset positions to simulate known pump shaft growth in high temperature rotating equipment.

Figure 12 and Figure 13 below are illustrate the typical post validation test condition of seal rings. These are standard photographic images showing an overview quarter section of the seal rings. No evidence of mechanical face contact is visible on the seal rings.

Figure 12: Typical Post-Test Condition of Stationary Spiral Groove Seal Mating Ring

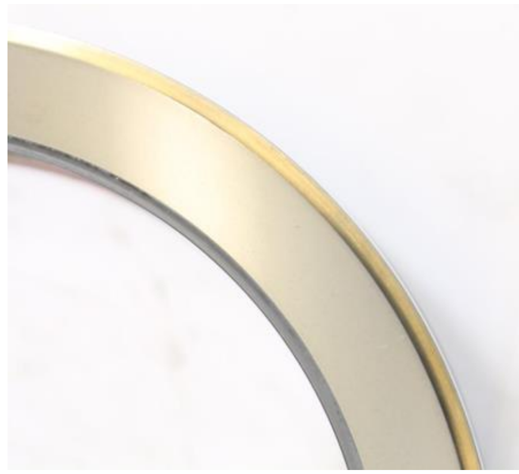

Figure 13: Typical Post-Test Condition of Rotating Seal Ring Assembly

API 682 4TH EDITION CERTIFICATION REQUIREMENTS

Seals that are certified to have passed API requirements must demonstrate reasonable assurance of meeting the performance and lifespan expectations of the standard. In order to meet API requirements, seal tests are conducted with a representative process fluid at typical operating conditions [2]. The test simulates static and dynamic operation at steady-state conditions as well as operation and running in 'upset conditions.' Extensive qualification testing was performed on the design to certify the design passes API 682 4th Edition requirements [1].

This test schedule includes:

- Minimum (100) hour steady state dynamic 3600 rpm. Process pressure @ 100 psig (6.9 barg), 500° F (260° C)
- (4) hour static
- (5) upset cycles with pressure and temperature fluctuations. 130-260 psig (8.9-17.9 barg), 300-500 °F (150-260 °C)
- Reverse Pressure – barrier gas upset test

Testing was completed on seals designed for two shaft sizes. Tests were performed to qualify silicon carbide composite rotating seal ring vs silicon carbide mating ring and silicon carbide composite rotating seal ring vs tungsten carbide mating ring material combinations.

Figure 14 shows a mating ring in post-test condition. No contact, face damage or chipping is visible, a surface profile trace did not show any wear or contact.

Figure 15 shows a seal ring in post-test condition. No contact or chipping damage occurred throughout the entire test regime including the upset condition reverse pressure test. Surface profile traces do not show any penetration or face wear as it remains in pristine condition.

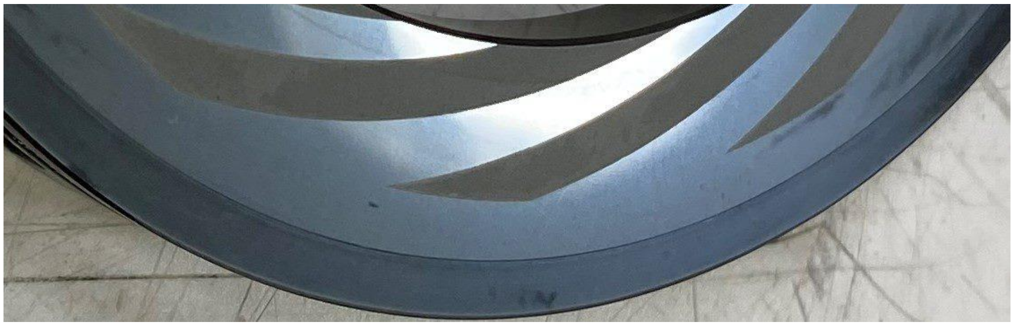

Figure 14: Typical Silicon Carbide Stationary Ring (post-test)

Figure 15: Typical Rotating Seal Ring, Silicon Carbide Composite (post-test)

TYPICAL APPLICATION EXAMPLE

A vacuum tower bottoms application in USA had been a "bad actor" for a refinery for many years. The pump is an old edition API 610 overhung pump with a single metal bellows component mounted seal design supported with a plan 32 flush, see Figure 16. The process fluid is at 680°F (360°C), suction pressure ranges from vacuum to 6 psig (0.41 barg) and discharge pressure is 145 psig (10 barg). The sealing chamber pressure is 15 psig (1.03 barg). The shaft speed of the pump is 3550 rpm. The MTBR had become unacceptable to the customer. The customer decided to upgrade the pump with the latest edition API bearing bracket and back pull-out design thus having seal chamber dimensions that could accept standard API 682 4th edition seal designs. The end user requested to upgrade the seal to a dual pressurized design and further wanted to move to a gas lubricated seal design supported by an API plan 74 dry Nitrogen gas barrier versus a wet contacting dual seal design with a dual pressurized wet seal support system.

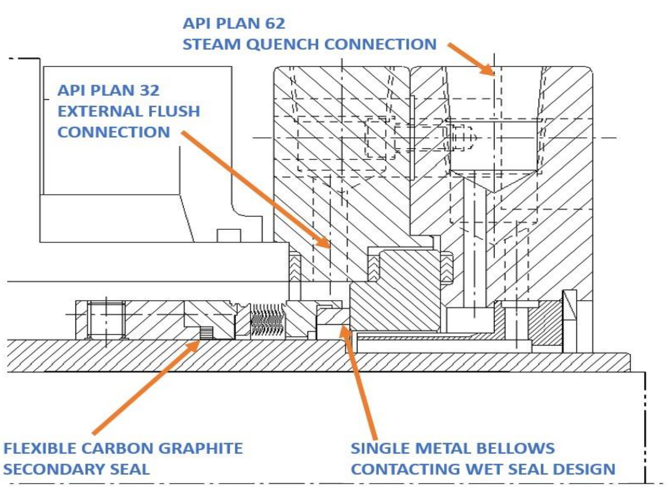

Figure 16: Original Seal Design

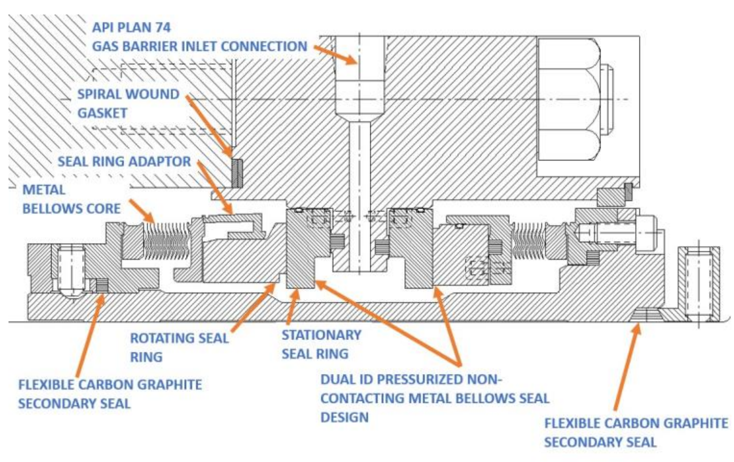

Figure 17: Upgraded Dual Pressurized Non-Contacting Gas Seal Cartridge Design

The pump was upgraded with a dual gas lubricated seal design utilizing the new technology, see Figure 17. The pump was operated without the need for an external plan 32 flush support. The gas barrier pressure for the seal plan 74 is set to 50 psig (3.45 barg). The barrier gas consumption rate is very low and as expected based on the seal design with uni-directional, tapered spiral grooved seal faces.

The seal has run without incident since the initial installation (July 2021). The refinery went through a scheduled turn-around where the pump was shut down so that plant personnel could perform maintenance on the vacuum tower unit. On previous vacuum tower maintenance where the single wet seal design was used, the bad actor pump and seal had to be completely removed and replaced. The newly upgraded pump with the next generation technology seal allowed the plant operators to leave the pump and seal in place, only having to remove the pump back plate to facilitate cleaning of the pump impeller from large "coke" debris formation, which is common in these applications. The seal was left untouched. The pump was re-assembled and restarted with no issue and barrier gas consumption rate remained at base line levels to those prior to the maintenance turnaround.

BUSINESS BENEFIT

Life Cycle Costs: The life-cycle cost of a non-contacting high temperature seal with API Plan 74 or steam support system is significantly less than that of a high temperature wet seal and seal support system [6]. The new technology enables plant operators to achieve cost reductions and to improve efficiencies within the plant. Extending rotating equipment mean time between maintenance and repair (MTBR) for process industries provides direct cost savings and can lead to extended time between unit and plant wide turn arounds.

Additional benefits include:

- Elimination of expensive API Plan 32 flushes in many applications
- Elimination of barrier fluids and disposal costs, cooling water requirements, fouled heat exchangers, and costs associated with emission monitoring programs
- Lower power (energy) requirements
- Reduction of carbon footprint
- Zero-emissions of pumped fluid to atmosphere

Some of the drawbacks that may be associated with adopting this new technology include:

- Barrier gas ingress into process stream (end user must be comfortable with this)
- Supply of barrier gas, API Plan 74, requires a supply of dry barrier gas (typically nitrogen) to a panel, the means to support the seal will typically involve compressed gas bottle supply if no other convenient supply is available at the facility
- The necessity to amplify the barrier gas pressure above that of the process fluid pressure, typically 30-50 psig (2-3 barg)
- As with any mechanical seal, there are limitations when adapting seal designs into older pumps not specifically designed for mechanical seals that have smaller seal chamber/stuffing box envelopes

CONCLUSION

This sealing advancement combines two established technologies— high-temperature corrosion resistant metal bellows interference-fitted technology with non-contacting gas lubricated technology. The design permits reliable operation with a pressurized barrier gas and significantly reduces lifecycle costs as compared to wet seals and systems. The interference-fitted seal ring design reliably operates in hot, dirty services which can mitigate the need for expensive external flushes. Empirical testing was conducted to validate the effective balance diameter characteristics of the metal bellows in tandem with utilizing advanced software to optimize the design for non-contacting operation. Seal designs have successfully undergone validation test and been certified to pass API 682 4th Edition requirements. High-temperature, dual pressurized gas lubricated seals provide a zero-emission solution for some of the most demanding hot process fluid applications and are simpler to maintain than dual wet seals and support systems.

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