Dynamic Lift Up-stream Pumping (USP) Seal Technology as Applied to Water Injection Services

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Synopsis

Water injection services have given pumps and seals problems for many years. With a greater emphasis on the costs and legislation associated with water injection these duties have become technically more challenging. Dynamic Lift Up-stream Pumping (USP) seal face technology has allowed the operation of simpler sealing solutions, to be used within these applications by providing improved seal face lubrication and greater reliability at lower asset operating cost.

1.0 Water Injection – The State of Play Today

Oil and gas extraction is normally accompanied with the extraction of water, often vast amounts of it. This is the formation water, or previously injected water from the structure being worked. As reserves mature, the volume of water required to maintain production increases, and these increases are necessary to maintain pressure and flow, which in many cases in the North Sea, for example, have increased by a factor of four since the structures were first worked. Unless permanent disposal is the primary aim, the quantity of water injected will not only depend on the volume of the oil bearing layer and the rate of depletion, but also on the effectiveness of the containment and confinement layers that are put in place to delimit acceptable injection zones. Figure 1 shows the principle behind water injection.

Injection of sea water or re-injection of produced water improves the recoverable hydrocarbon reserves from a reservoir. However the quality of the injection water is significant to the efficiency of the process. For most applications the injection water must be devoid of oxygen that will cause corrosion of the injection well piping and other associated metal work such as pumps and seals. The use of poor quality water can lead to restrictions in the structure and subsequent injection losses with a resultant decline in production. Often in these circumstances an increase in the injection pressure is required to sustain injection rates. However, well work-overs, re-perforating the wells, or the drilling of new wells will generally be required at some point, all at significant asset cost.

Injection water quality requirements are typically unique to individual reservoirs, and a whole industry exists around the identification, correction and management of the injection water for producers over the life of a reservoir.

In many maturing fields the water cut will increase, disposal may include re-injection into the source reservoir or disposed of into an underground aquifer. However with more stringent international environmental discharge legislation, operators are increasingly obliged to treat produced water to higher standards prior to disposal. For this reason they are increasingly using this water for re-injection into or below the production zone for pressure maintenance and reservoir sweep purposes.

This has already demonstrated economic benefits as the produced water has to be treated to a higher degree for simple disposal, than for re-injection. However, the produced water has to be treated and a full understanding of both the chemical and physical properties of that water, as well as local / regional discharge regulations, are all essential inputs into any successful treatment solution.

Local discharge regulations cannot be overlooked, and vary significantly, often according to local environmental concerns or regularity bodies. Some regulate the oil

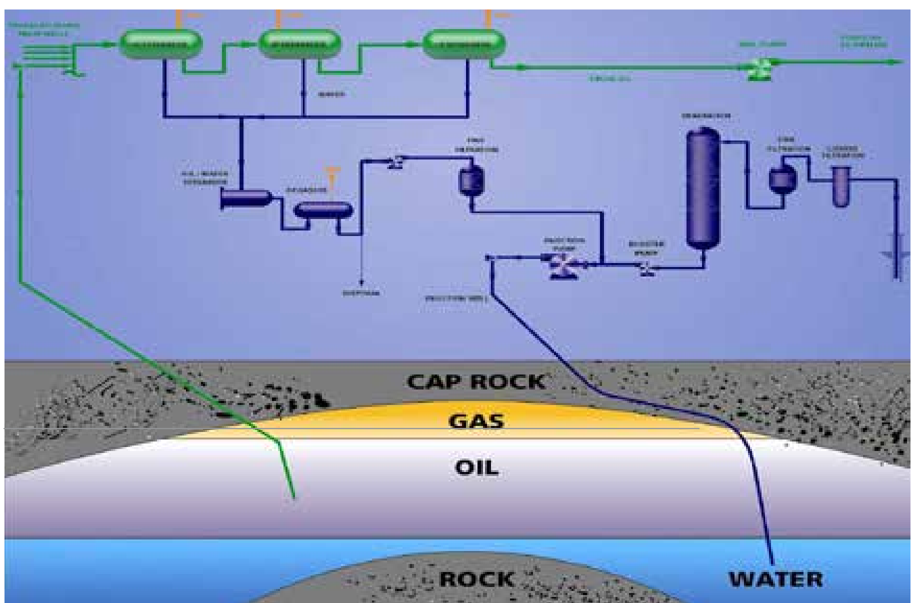

FIGURE 1 – WATER INJECTION PROCESS OVERVIEW

content of the water, others, sometimes bordering the same reservoir, monitor and regulate many (up to 33) different water quality parameters, including metals, organics, treatment chemicals, radioactivity, and temperature.

2.0 Scale Management

Scales form within injection waters when the thermodynamic driving force for precipitation from water overcome the kinetic factors that inhibit mineral growth. These circumstances can be caused by a number of processes, such as:

- The mixing of incompatible waters
- Chemically significant pressure and temperature changes (including localized heating or cooling) during production or injection
- Changes in pH values due to gas breakout

Therefore the presence of scale in production and / or injection systems has a number of consequences, all of which can have significant impact on asset effectiveness.

Scale indexes, and the potential to scale at, or within pump performance operating curves will have a significant impact on mechanical seal performance, and hence the type / style or arrangement of seal chosen on injection duties. Typically uncontrolled (even controlled) scale results in costly and time consuming equipment damage. In the context of the well or reservoir this may also present other problems, such as under-deposit corrosion, further reservoir plugging and lost production due to the need for work-overs. Finally, when it is all over, high or increased abandonment costs. A major operator in the North Sea has been quoted at spending approximately US$ 12 million p/a on scale management alone, even then, control is not totally effective and 20 percent of well losses are still attributable to scale elements. The net cost to this operator is estimated at US$1/bbl oil produced.

3.0 Costs

The operating cost implications of poorly performing mechanical seals on the overall asset effectiveness can be qualified by referring to some statistics from a North Sea injection duty where produced water has now become the primary injection medium. In the 12 months post change to produced water, 3 injection pumps suffered 8 failures associated with the seals, with the resultant costs to the operation:

No. of outages	7
Pump downtime per outage (days 7+2+2)	11
Injection water lost (bbl/day)	100,000
Total injection water lost (bbl)	7,700,000
Deferred oil (bbl)	5,133,333
Value of deferred oil (@ $56.40 per bbl)	**$289,519,981**
Value of deferred oil (@ £46.23 per bbl)	**£237,300,031**

(Costs at time of example)

A mechanical seal may only be a small element of the process but the consequences on asset effectiveness and the relating costs cannot be overlooked. We will now explore in more detail the technology and the applications.

4.0 Overview of Current Sealing Solutions for Water Injection

The key objectives of the pump seal for a water injection application are to:

- Minimize maintenance, lowering asset operating costs
- Control leakage of seawater, or potentially aggressive produced water, which would otherwise cause external corrosion and increase drainage requirements
- Improve asset uptime by increasing the reliability of the seal and seal system solution

A) Single Seals

Single seals, defined in API682 as arrangement 1, are the simplest and cheapest method of achieving a seal for a high pressure pump. See Figure 2. The mechanical seal faces are lubricated by the process fluid.

If reliable, the solution is very low maintenance, and the required piping plan is extremely simple.

Unfortunately, all mechanical seals leak. A single mechanical seal allows leakage of process fluid to atmosphere. When seawater is the process medium, problems of crystallization

Plan 11 Single Seals

Description: Plan 11 is the most common flush plan in use today. This plan takes fluid from the pump discharge (or from an intermediate stage) through an orifice(s) and directs it to the seal chamber to provide cooling and lubrication to the seal faces.

Advantages: No product contamination and piping is simple.

General: If the seal is set up with a distributed or extended flush, the effectiveness of the system will be improved.

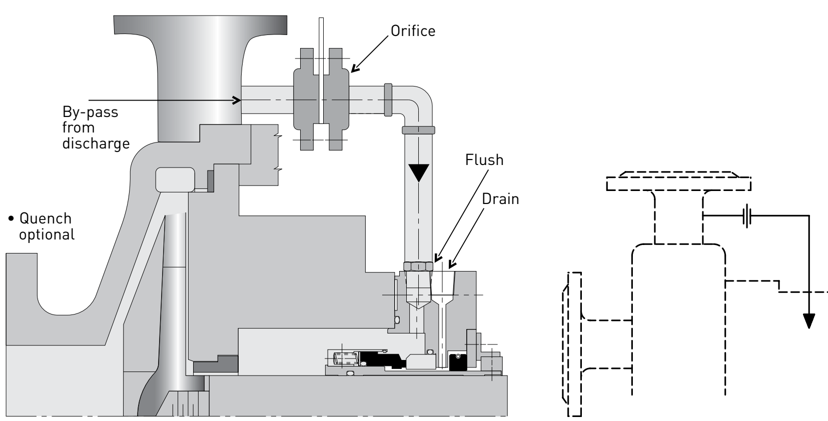

FIGURE 2 – API PIPING PLAN FOR ARRANGEMENT 1

arise due to the salt content of the seawater. Salt crystals must be expected to become deposited behind the seal and potentially increase the leakage rate.

If crystallization occurs around the face loading springs, these can become fouled-up causing 'hang-up' of the seal and accelerating the leakage rate and seal failure.

On produced water applications, there is the additional complication of scale formation on both process and atmospheric sides of the seal, formed due to the mineral content of the water coming out of solution. The factors affecting the rate of scale formation are widely documented, and in general seal vendors aim to minimize temperatures in a bid to reduce the rate of scale formation.

B) Tandem Seals

Tandem seals, or dual unpressurized seals, defined in API682 as arrangement 2, utilize an unpressurized buffer fluid between two pairs of seal faces. See Figure 3. The inner seal faces are lubricated by the process fluid. Any leakage across the inner seal is absorbed by the buffer fluid and dissipated in a controlled manner. However, as the salinity of the buffer fluid builds up, it will be necessary to change out the fluid from time to time, depending on inner seal leakage rates.

Leakage of process fluid (Figure 3 – API Piping Plan for Arrangement 2) to atmosphere is reduced, but cannot be considered zero as the buffer fluid inherently contains some process fluid.

C) Double Seals

Double Seals or Pressurized Dual Seals, defined in API682 as arrangement 3, utilize a barrier fluid pressurized above the process pressure. Any leakage across the inner seal face will

Plan **52** Dual Seals, Unpressurized

Description: Plan 52 uses an external reservoir to provide buffer fluid for the outer seal of an unpressurized dual seal arrangement.

Advantages: In comparison to single seals, dual unpressurized seals can provide reduced net leakage rates as well as redundancy in the event of failure.

General: Cooling coils in the reservoir are available for removing heat from the buffer fluid.

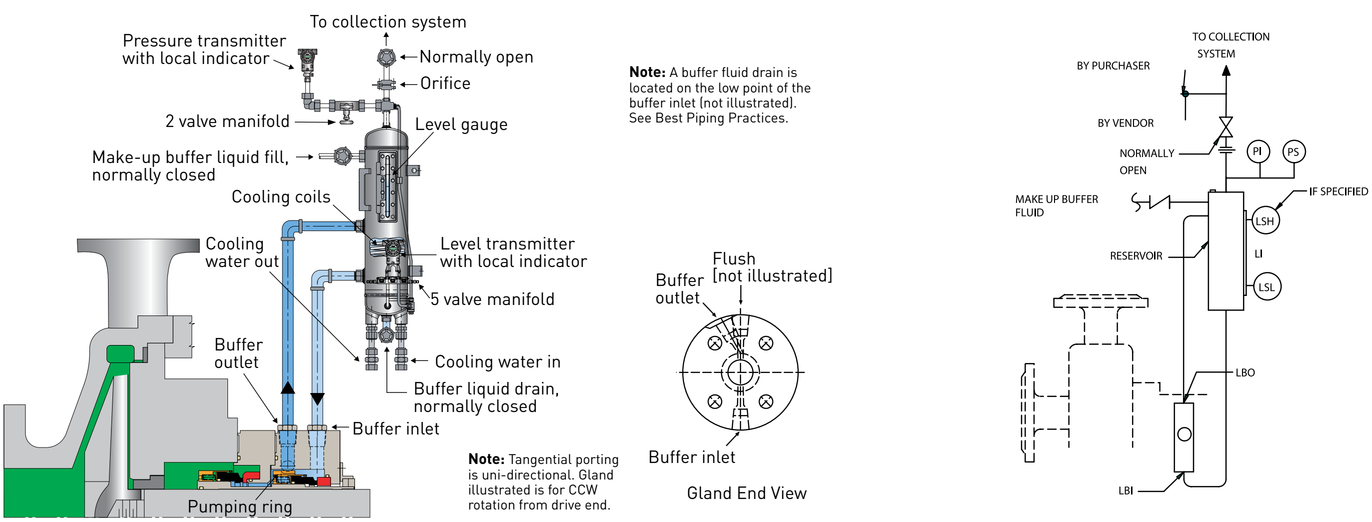

FIGURE 3 – API PIPING PLAN FOR ARRANGEMENT 2

therefore be from the barrier fluid into the process fluid. See Figure 4. The seal faces are lubricated by the clean barrier fluid.

The main uses for a double seal are for anti-pollution, safety or where an outward process fluid leakage will cause problems.

This is the most expensive option due to the complications of providing a pressurized barrier fluid system.

With the introduction of this complexity, a new failure mechanism emerges – Reverse Pressure. This is when the process pressure becomes higher that of the barrier fluid. This may be due to either malfunction or mismanagement of the barrier fluid system, or elevated process pressure.

In general, and until relatively recently, single seals have been supplied in most injection applications. Where any external salt crystallization has led to hang up problems, this has usually been avoided with the simple addition of an unpressurized water quench, or in the most serious of applications, the unpressurized tandem approach.

However, with the increasing desire to re-inject produced water the pressurized double seal has become the preferred option, often specified at contractor level. While clearly addressing the technical requirements of the service it does add significant cost and the relative improvement in reliability often falls below expectation.

5.0 Dynamic Lift Up-stream Pumping Technology - An Alternative to Pressurized Double Seals

One seal interface technology to be developed is Dynamic Lift Up-stream Pumping. Spiral grooving on the seal faces is employed to produce the same result as the pressurized double seal, without the need for a complex pressurized seal support system.

A 'spin-off' from the non-contacting dry running gas compressor seals, the same spiral groove technology is used to generate hydrodynamic lift. In this case however the active fluid is a liquid rather than a gas and the spiral grooves form the inner portion of one of the seal faces, as shown in Figure 5.

With shaft rotation, the spiral grooves take the unpressurized barrier fluid and generate a pressure at the exit of the spirals greater than the pressure in the seal chamber. This provides clean lubrication for the seal faces as well as generating enough lift to guarantee face separation. The outer portion of the seal face, between the spiral exit and the process fluid, is a lapped region known as the sealing dam. The pressure

Plan **53B** Dual Seals, Pressurized

Description: Plan 53B, previously termed 53 Modified, uses an accumulator to isolate the pressurized gas from the barrier fluid. A heat exchanger is included in the circulation loop to cool the barrier fluid. Flow is induced by a pumping ring.

Advantages: Should the loop be contaminated for any reason, the contamination is contained within the closed circuit. The make-up system can supply barrier fluid to multiple dual pressurized sealing systems.

General: The bladder accumulator isolates the pressurized gas from the barrier fluid to prevent gas entrainment. The heat exchanger can be water cooled, finned tubing or an air-cooled unit based upon the system heat load.

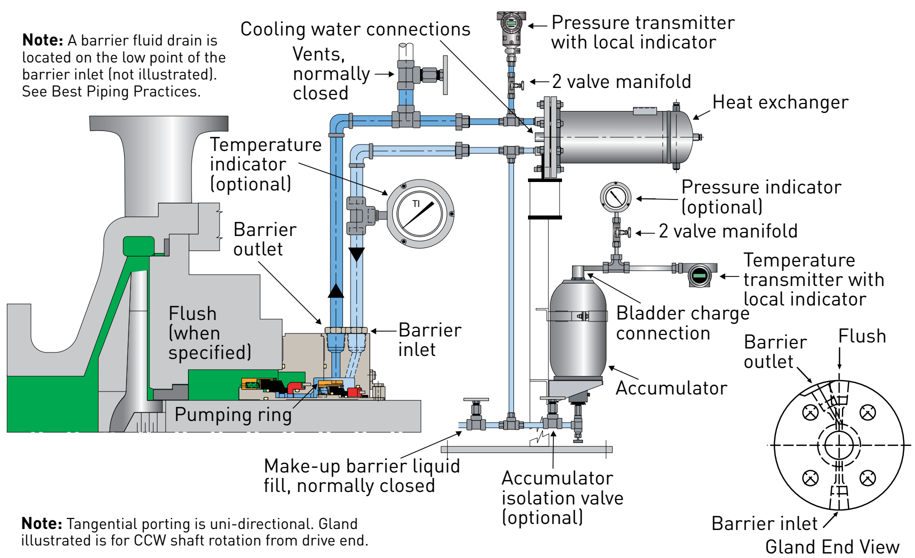

FIGURE 4 – API PIPING PLAN FOR ARRANGEMENT 3

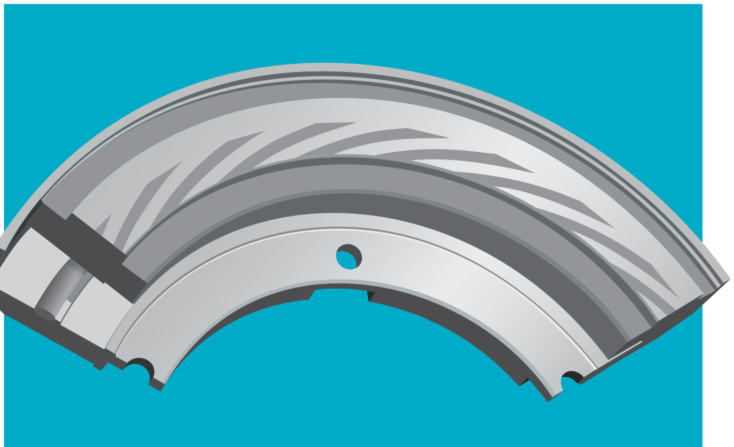

FIGURE 5 – DYNAMIC LIFT UP-STREAM PUMPING (USP) GROOVES

differential across this sealing dam, together with the microscopic sealing gap between the seal faces, determine the amount of fluid flow which takes place from the barrier side to the process side. For a given design, as the process pressure increases, the rate of 'up-stream pumping' reduces, While a non-contacting, sealing gap between the seal faces is maintained.

Figure 6 shows the configuration of a USP seal.

Dynamic Lift Up-stream Pumping technology offers several advantages over the traditional dual seal approach:

1. The technology is 'non-contacting' and therefore the usual PV[1] limitations imposed by contacting seals, and the resultant wear, does not apply.
2. The power consumed is significantly lower than a double or tandem seal arrangement.
3. The positive flow of clean fluid into the seal chamber can provide a cleaner sealing environment.

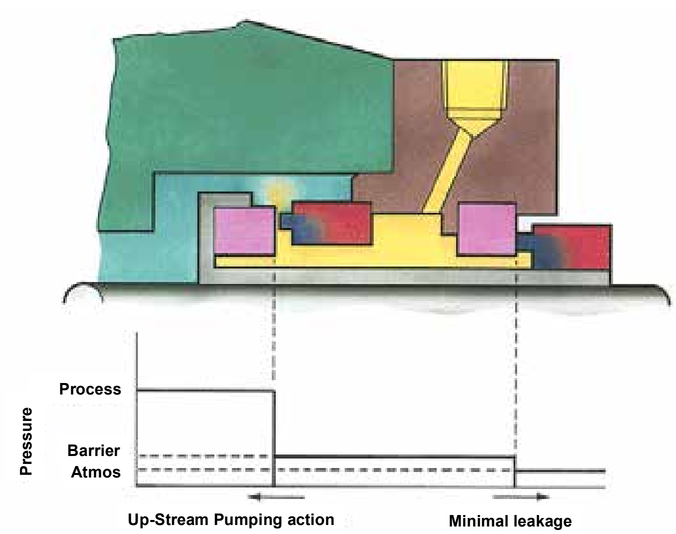

FIGURE 6 – USP CONFIGURATION

4. Compared to a non-pressurized tandem seal, a USP seal has the advantages of clean fluid lubrication and non-contacting operation.
5. Compared to a pressurized double seal, a USP seal requires a much simpler support system, and Reverse Pressure is inherently eliminated.
6. The process fluid is on the outside diameter of the seal faces – solids suspended in the process fluid are centrifuged away from the seal faces and secondary seal area.
7. Barrier fluid leakage to atmosphere is significantly reduced when compared to a pressurized dual seal – where the outboard seal can often operate at considerable pressure.
8. The concept allows a simple upgrade of single or multiple seal services, where process changes have rendered the process fluid a poor seal lubricant.
9. In services where the process pressure is variable, or where pressure spikes are likely, the spiral groove constantly regulates against this varying pressure, maintaining a sealing gap at all times.
10. The non-contacting seal faces generate little heat compared to a conventional solution. The seal faces are cooler, and therefore much less likely to encourage scale formation.

An additional and very important advantage is that filtered sea water may be used as the buffer fluid. For offshore installations, this allows a very attractive 'once-through' seal system to be used – eliminating both auxiliary cooling and the need for barrier fluid reservoirs and the associated fluids.

6.0 USP Technology in Service

In 2003, the first high pressure USP seal to be used in oil and gas production was installed on a Test Separator pump in the North Sea. These pumps handle a mixture of crude oil and water (with varying concentrations) and contain large quantities of sand – potentially more demanding conditions than those found in water injection duties.

Commissioned in the early 1990's, the original unpressurized tandem seals on this service grew increasingly less reliable over a period of time as the sand content increased. Relying on the pumped product to lubricate the seal faces, the seals were suffering from erosion and 'hang-up' – a lack of flexibility, leading to short lifetimes in the region of 1 to 2 months.

Although a pressurized tandem arrangement would have been a typical upgrade for such a symptom, recent developments in high-pressure USP seals allowing them to be applied up to 40 bar, made this technology more attractive. In particular it was felt that this seal face principle would provide a cleaner environment for the seal to operate in, also providing optimum lift conditions between the seal faces.

The 75 mm / 2.95" seal design shown in Figure 7 was tested under the following operating conditions:

[1] Pressure multiplied by rotational face velocity (often used as a measure of the severity of a seal duty)

Shaft speed:	3600 rev/min
Seal chamber pressure:	5 to 40 bar g (75-590 lbf/in^2)
Seal chamber temperature:	160-175 °F /70-80 °C
Process Fluid:	water, water/oil/sand (20% wt. sand)
Barrier fluid:	seawater

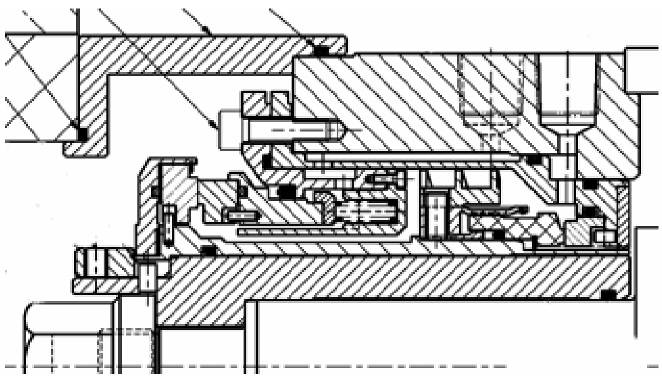

FIGURE 7 – 1ST HIGH PRESSURE USP ARRANGEMENT

Figure 8 shows the condition of the seal components following the slurry testing phase over a 200 hour period. The seal faces appear as new.

Following these tests, the first seal was successfully commissioned offshore in October 2003. The seal cartridge was supplied with 7 liters/min of seawater from the seawater ring main via a simple duplex filter. This flush was then sent to drain through a back pressure control valve.

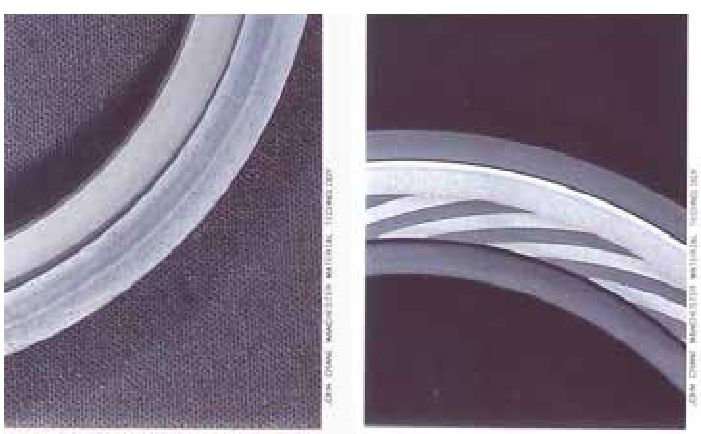

FIGURE 8 – SEAL FACES POST-TEST

After the first year of operation, the seal was stripped and inspected, and found to be in excellent condition with seal faces undamaged by contact, scale or abrasives. At the time of writing, these seals have now operated trouble free for 41 months (compared to the 1 to 2 months with the original seals).

7.0 Technology Enhancements: Achieving Higher Pressure Capability for Water Injection

Since the initial success on the Test Separator application, development work has focused on extending the capability with respect to operating pressure, process temperature, and shaft speed.

The technology is now available for process pressures up to 100 bar g, with laboratory testing carried out at pressures as high as 250 bar g.

The key element influencing the seal vendor's ability to develop USP solutions for higher pressure applications is the availability and integrity of their modeling and simulation software. In this respect the CSTEDY FEA/CFD package used to further develop USP designs has been crucial to achieving success.

Where a seal design is dependent on some form of hydrodynamic pressure generation, it is vitally important to have a stable design, capable of near parallel face presentation throughout the envelope of operation. Whereas earlier solutions were capable of operation in process pressures of up to 10 bar, the development of CSTEDY has allowed optimization of the seal face design, to increase this limit 10 fold.

In order to achieve this, it is necessary to:

- Control and minimize pressure distortion
- Control and minimize thermal distortion
- Eliminate face waviness transmitted by contact with metal components

In the USP seal, transmitted waviness is eliminated by supporting the seal faces on Elastomeric Support Rings. These are carefully designed to prevent contact with the metal carrier While minimizing the gap to avoid extrusion. See Figure 9. Since the support ring also acts as a static seal on the rear of the seal ring (rather than part way along the bore or outside diameter as with other designs) the pressure differential acts evenly across the component – a good starting point for pressure-stable design. Using FEA/CFD software, the designer can further optimize pressure distortion by changing the profile of the seal face components.

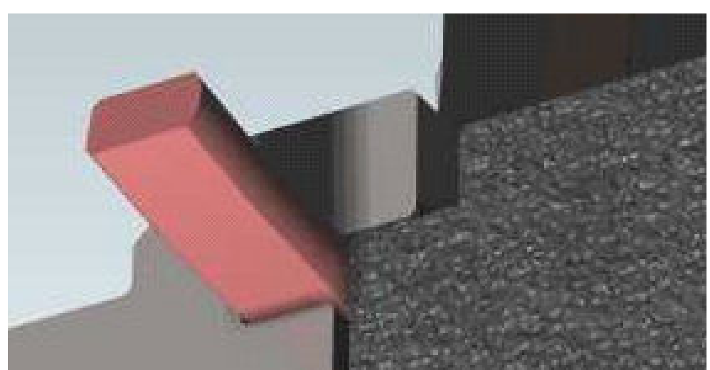

FIGURE 9 – ELASTOMERIC SUPPORT RING (ESR)

Figure 10 shows the CSTEDY result for pressure distortion using the latest High Duty USP design. The process pressure applied is 100 bar g. The pressure distortion at the face is 2.6 helium light bands – less than one micrometer. In comparison, a standard API seal might deflect up to 10 times this amount, at a much reduced pressure.

Thermal distortion can be caused by:

- Heat generation at the seal interface
- Differential temperature between process and buffer fluid

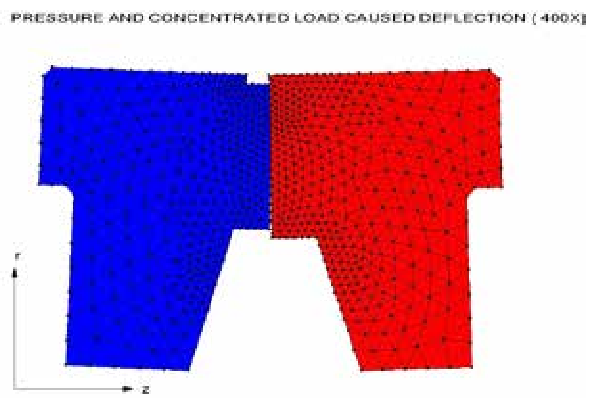

FIGURE 10 – CSTEDY PRESSURE DISTORTION

Since the USP seal generates little heat at the interface (typically only a few hundred watts) minimized distortion due to heat generation is an inherent benefit. See Figure 11.

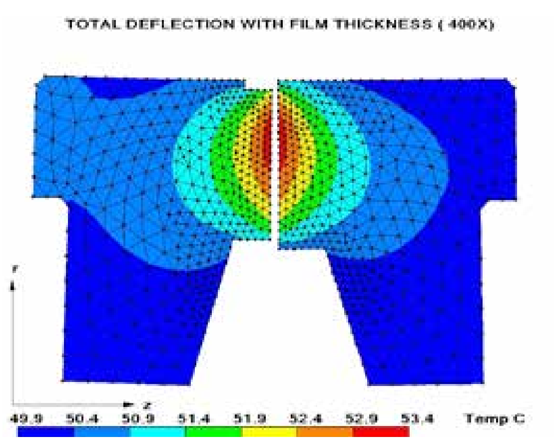

FIGURE 11 – CSTEDY – LOW HEAT GENERATION

Differential temperature presents more of a challenge. If the front of the ring is hotter than the back, then 'rotational' distortion is encouraged leading to convex face presentation. If the outside of the ring is hotter than the inside, then 'keystone' distortion occurs leading to concave presentation. By optimizing the heat transfer boundary (choosing exactly how much of the seal face outside diameter is directly exposed to the turbulent process fluid) it is possible to manage thermal distortion by balancing these effects. This is illustrated in Figure 12.

While stable face presentation provides the foundation for extending the operating capability of this technology, there still remains the matter of lift generation itself – the optimization of both the lift, and the amount of fluid pumped across the sealing dam.

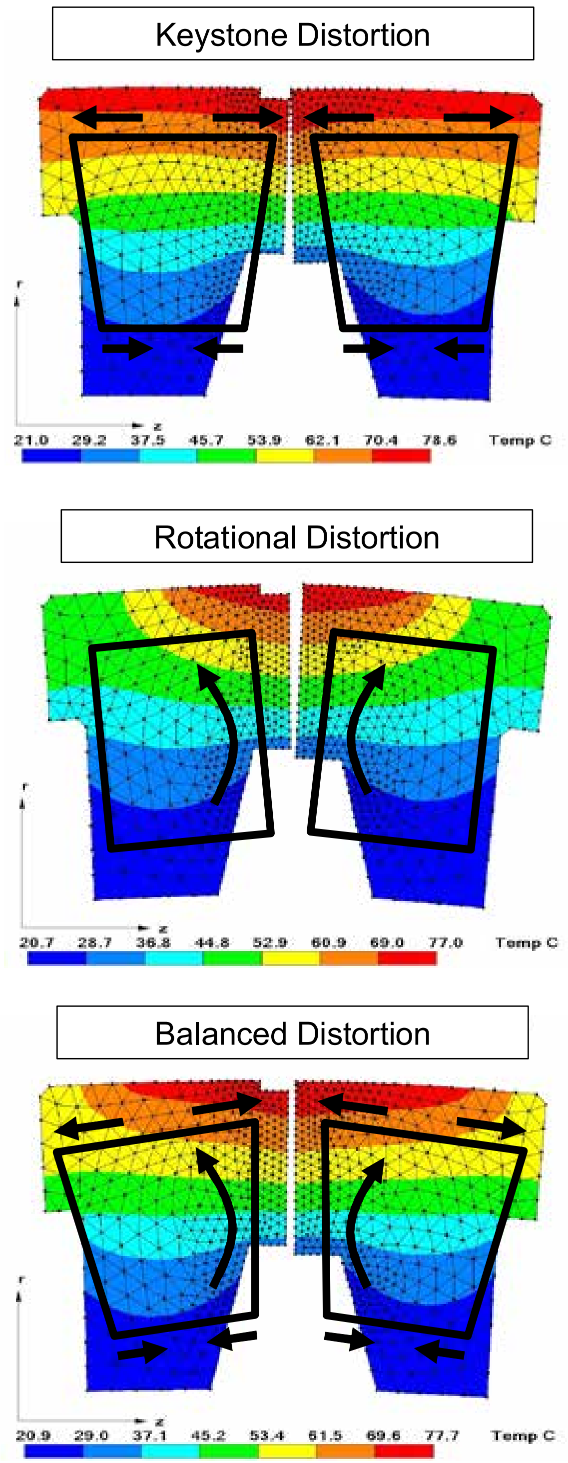

FIGURE 12 – CONTROLLING THERMAL DISTORTION

It has been widely documented that the profile, quantity and depth of any grooved structure on a gas seal face can influence the degree of hydrodynamic lift. The same is true within the wet seal arena. Traditionally, significant re-testing of alternative structure designs was necessary. The CFD enhancements within CSTEDY have allowed computational optimization of these structures, achieving a balance between lift and fluid pumped without the need for extensive test programs.

Within the face design of one of the critical features is the dam ratio — the ratio of the area of the sealing dam to that of the entire seal interface. Figure 13 shows how for a given design, a change in the dam ratio results in a significant reduction in fluid pumped, while maintaining an acceptable degree of lift and establishing a non contacting regime.

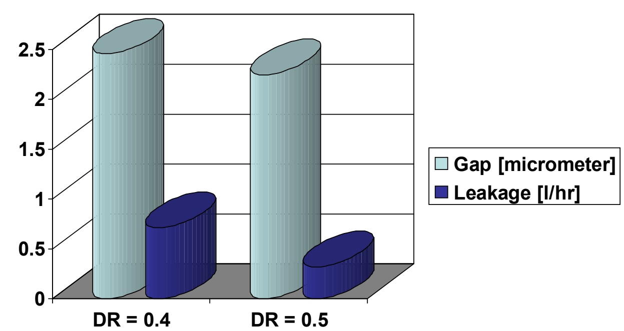

FIGURE 13 – OPTIMIZATION OF SEALING DAM

8.0 Seal Support Systems

By nature of the design and operation of Dynamic Lift Upstream Pumping mechanical seals, the required support system complexity is greatly reduced compared to that used with a conventional pressurized dual seal (e.g. plan 53B – see Figure 4).

Where seawater is available, the seal system will consist of a filter solution upstream of the seals, and a simple control panel to control flow and pressure at the seals themselves, and provide protection, over-pressure relief and isolation for the filter solution and any downstream pipe work. Filtered seawater (typically 5 liters per minute) flows once through the seal and then to drain. No auxiliary cooling device is therefore required. Figure 14 shows a piping and instrumentation diagram.

As the filter solution and simple control panels do not need to be adjacent to the pump, there is flexibility when positioning

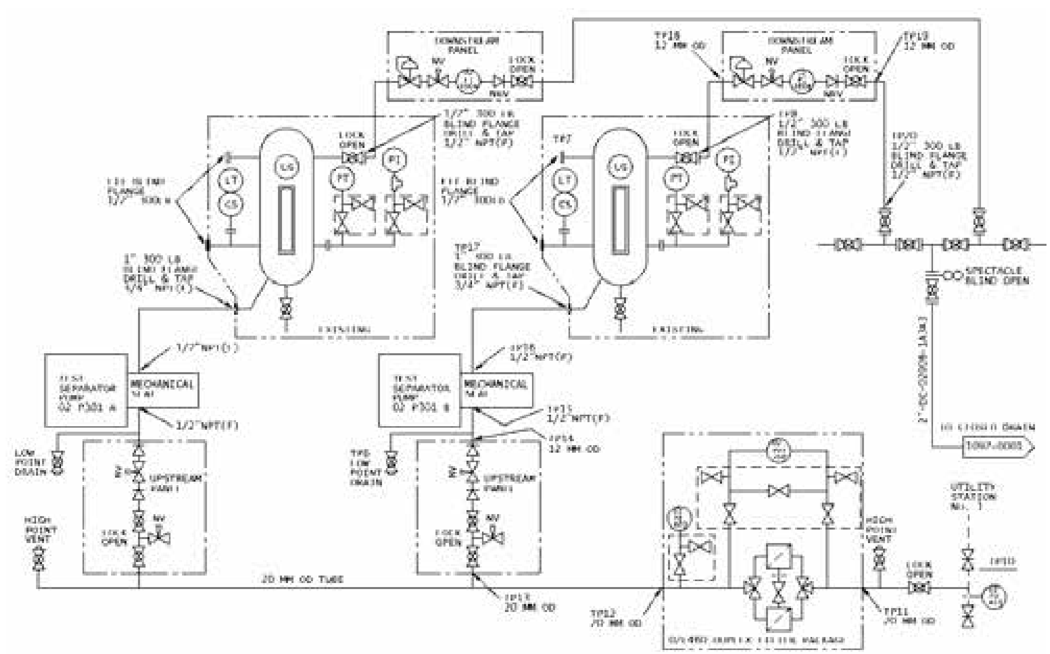

FIGURE 14 – PIPING AND INSTRUMENTATION DIAGRAM

equipment. This is a great advantage, particularly when upgrading single seals where space available for new system equipment is restricted. Figure 15 is a photograph of the simple seal connections required.

FIGURE 15 – SIMPLICITY OF INSTALLATION

9.0 Field Experience

The number of High Duty USP seals in service has increased exponentially since their introduction in 2003. In addition, the process pressures found on services to which these seals are applied is also increasing.

10.0 Conclusions

Dynamic Lift Up-stream Pumping (USP) seal technology has been available to the marketplace in various shapes or forms for many years, however it is only in the last ten years or so that the technology has been available to allow these designs to operate at pressures suitable for water injection services.

As the industry is encouraged to clean up these services, reducing the environmental impact of the injection process, improved seal technology is seen as one dimension that could help to reshape the way water injection services are dealt with.

– Poor mechanical seal performance in these duties is, in most instances, a symptom of differing duty conditions as water injection technology and requirements change

– By focusing on the key areas which effect seal reliability it is now possible for seals to operate for extended periods in these new conditions, which is fundamental to improving asset reliability.

– The cost to operators of adopting such technologies is favorable when compared to the operational losses or deferrals that asset down time produces.

The relative simplicity of the design and operation of seals equipped with Dynamic Lift Up-stream Pumping technology has allowed a significant improvement in not only the reliability, but the operating costs of the associated assets. As user confidence levels increase, this technology is being applied more frequently to increasingly demanding applications.

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