UPSTREAM PUMPING: NEW DEVELOPMENTS IN MECHANICAL SEAL DESIGN

by

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ABSTRACT

Conventional mechanical seals are arranged to prevent leakage from a high pressure source. When leakage occurs, it is expected to be from the high pressure area to the lower pressure surroundings. The basic concept of the upstream pumping seal is that the conventional seal is replaced by a low volume, high pressure "pump"—the upstream pumping seal. This "pump" propels a minute quantity of barrier liquid along the path normally sealed by the mechanical seal and *into* the product side. Because the product side is at a higher pressure than the barrier liquid, this seal is said to pump "upstream."

INTRODUCTION

There are many different types of mechanical seals and regardless of their differences in appearance, they fit into certain categories. Classification can be made by design characteristics or by positional arrangements (Figure 1). Balanced/unbalanced, rotating head/stationary head and pusher/non-pusher are design classifications, while classification by arrangement addresses orientation and arrangement of the seal(s) regardless of design.

As sealing capabilities of single seals became exhausted, multiple seals soon made their appearance. During the last few years, they have found their way into industry at an increasing rate. API 610 5th Edition recognized multiple seals as a "double" arrangement and offered a choice between S (single) and D (double) in the five character API seal code. A double seal arrangement was the answer to difficult services—toxic, abrasive slurry, nonlubricating, and gaseous services. Two mechanical seals mounted back-to-back (Figure 2) operated in an artificially created desirable environment for the seal provided by a clean, lubricating pressurized barrier fluid. The life of the seal was basically a function of size, speed and pressure, totally ignoring the sealed product.

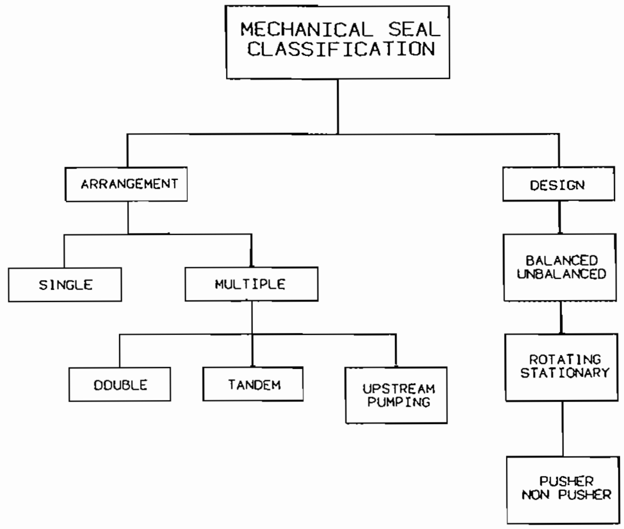

Figure 1. Mechanical Seal Classification.

The safety of the environment and long seal life comes with a price tag; a pressurized seal support system is essential. The high pressure barrier fluid ensures that leakage would occur only from the barrier fluid region into the product side and/or from the barrier fluid region into the atmospheric side. API Plan 53 and 54 are present day support systems for such double seal arrangements. It must be noted here that a high pressure system is essential for seal operation. Should a pressure reversal occur resulting in a pressure at the throat of the seal cavity lower than the pressure between the two seals, the inboard seal will "blow" open causing the product to enter the buffer area. With a nonlubricating slurry or abrasive product, a seal failure becomes imminent. This loss of buffer fluid pressure could be caused by:

- loss of pressure source - nitrogen blanket or failure of circulating and pressurizing unit.

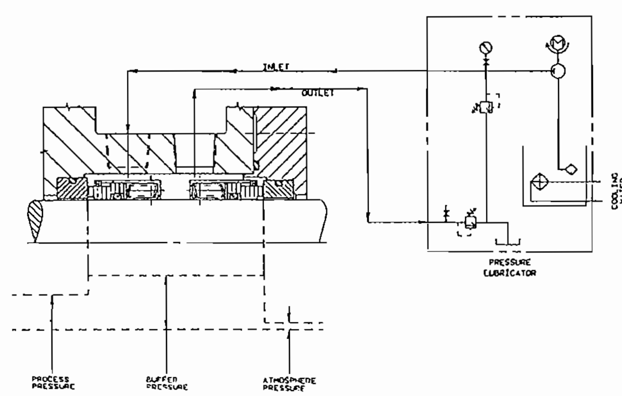

Figure 2. Conventional Double Seal Arrangement.

- failure of outboard seal.

Tandem seals are a trend of the present day sealing technology. API 610 recognizes its ever increasing popularity, and in the 6th edition, introduced the letter "T" in its five character seal code to designate and classify tandem arrangements. Tandem seals consist of two single seals mounted in the same direction (Figure 3) with a secondary neutral fluid at or near atmospheric pressure between the two seals. Tandem seals are utilized for three main reasons:

- Redundancy—as a safety back-up; in the event of a failure of the primary seal, the secondary seal will prevent spillage/leakage into the environment.
- Contain a quench fluid—cryogenic services and services with dissolved solid (caustic, sugar).
- Arrest fugitive emissions—sealing of light hydrocarbons/VOCs.

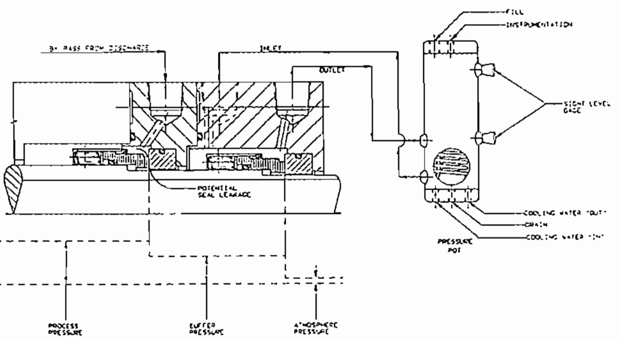

Figure 3. Conventional Tandem Seal Arrangement.

With the creativity of the seal designer and the end user, it is not unusual to find a combination of a stationary head seal inboard and a rotating head seal outboard. While in design and intent, it is a true tandem seal, to the untrained eye however, the back-to-back appearance might lead one to conclude that it is a double arrangement. Multiple seals, thus, had to be redefined. Since appearance could be misleading, the support system a seal arrangement utilizes is a more logical criteria. Accordingly, multiple seals have been redefined as:

Tandem seals: Multiple seal arrangement that utilizes a low pressure seal support system. API Plan 52.

Double seals: Multiple seal arrangement that utilizes a high pressure seal support system. The barrier fluid pressure, at all times, is maintained at a level higher than the pressure at the throat of the seal cavity.

By definition, thus, one can conclude that in a tandem arrangement, the barrier fluid is continuously contaminated by the product because of the leakage of the high pressure product to the low pressure barrier fluid. This contaminated fluid eventually will make its way to the atmospheric side by leaking across the secondary seal. A tandem arrangement, however, is inherently safer than a double arrangement, since the secondary seal can contain the product in the event of a failure of the primary seal.

In a double arrangement, the high pressure barrier fluid will lead one to believe that leakage can only occur from the barrier fluid to the product side or from the barrier fluid to the atmospheric side. This added security comes with the necessity of maintenance of a high pressure buffer fluid. In addition, should the outboard seal fail, the inboard seal will fail immediately due to the pressure reversal.

UPSTREAM PUMPING

Upstream pumping is a "hybrid" between a tandem and a double arrangement. In design and concept, it appears like a redundant end face mechanical seal arrangement with a low pressure barrier fluid between the two seals. In function, however, it operates like a double seal. A pumping mechanism in the primary seal generates pressure which results in a minute amount of controlled pumpage from the low pressure barrier region to the high pressure product side. The conventional end face primary seal is replaced by a low volume, high pressure "pump"—the upstream pumping seal. This "pump" propels a minute quantity of barrier liquid along the path normally sealed by the mechanical seal and into the seal cavity. Because the seal cavity is at a higher pressure than the barrier fluid, this seal is said to pump "upstream."

APPLICATIONS

In general, complexity of a system is inversely proportional to reliability—the more complex the system, the less reliable. Because external systems are unnecessary with a single seal, it has the highest reliability. Multiple seals are more complex than single seals, and amongst themselves, vary in degree of complexity depending upon double or tandem arrangement. All multiple seals require external systems but the external systems for tandem seals are less complex than double seals; and hence, the overall reliability of tandem sealing system is greater than double sealing system. Indeed a multiple seal system may be less reliable overall because of either:

- the constant contamination of the barrier fluid in a tandem arrangement, or
- the higher level of complexity of the seal support system for a double arrangement.

Moreover, in a double arrangement, it is normally assumed that leakage occurs only from the barrier fluid into the process. Unfortunately, this is not always true. Leakage can occur from the process into the barrier fluid in spite of the pressure difference. Experimental data indicates that this "reverse flow" is an interface phenomenon which is not easily eliminated. It is noteworthy, however, that the upstream pumping seal completely eliminates leakage of the process into the barrier with a seal support system that is at a lower level of complexity, for most services, than the support system for conventional tandem arrangement.

The upstream pumping seal, thus, can be applied for:

- toxic and hazardous
- abrasive and slurry
- products with poor lubricity, and
- high PV services.

The first two categories are usually handled by ANSI pumps with low suction pressure and speeds at either 1800 or 3600 rpm fitted with double mechanical seals and API Plan 53 (pressure reservoir system) or a single mechanical seal and API Plan 32 (external clean flush). In either situation, the upstream pumping seal provides a simpler alternative with controlled and low product dilution (0.1 to 16 cc/min).

Products with poor lubricity such as supercritical CO_2, ethylene, etc., are usually high pressure services handled by API pumps, and almost always require double seals with complex, redundant seal support systems. At the author's location, work is presently near completion on an upstream pumping seal for high pressure super-critical CO_2 service with a significantly simplified seal support system.

The expression "PV" is routinely used by the seal manufacturers and users alike to identify the Pressure-Velocity limits of sets of face material combination in a given fluid. High speed pump applications are usually high "PV" services and the situation is worsened by the use of double seals due to the higher buffer pressure requirement. The high "PV" problem has been plaguing the high speed pump industry for a long time. The upstream pumping seal seems to be the solution the industry has been waiting for, by not requiring a higher barrier fluid pressure than the pressure at the throat of the seal cavity. The pressure component of "PV" is completely eliminated due to its essential non-contacting mode of operation.

FIELD EXPERIENCE

A partial list of successful field installation is shown on Table 1.

PRINCIPLES OF OPERATION

The upstream pumping seal operates on the principle of hydrostatic and hydrodynamic force balances. The seal head with the retainer, springs, and primary ring is mounted in a stationary configuration. The rotating mating ring is spirally grooved. The groove pattern is a series of logarithmic spirals which are recessed. The ungrooved portion of the face above the spiral pattern is called the sealing dam. When pressure is applied, the forces exerted on the seal are hydrostatic and are present when the mating ring is stationary or rotating. Hydrodynamic forces are generated only upon rotation. The spiral groove pattern plays a vital role as, upon rotation, it serves the purpose of a pressure generating system. The spiral groove pattern as shown on Figure 4 rotates in a counter clockwise direction. As the barrier fluid enters the groove, it is induced towards the OD where it meets the resistance of the sealing dam. Pressure is increased causing the flexibly mounted face to lift-off setting the sealing gap. A "pump-restrictor" principle is at play which results in a non-contacting mode of operation with liquid being pumped from a low pressure region to a high pressure region.

The forces which govern the seal operation are axial, shown graphically in Figure 5. Opening force F_o is the sum of the pressure generated by the spiral groove pattern plus the pressure drop across the face and the closing force F_c is the system pressure acting behind the face plus the spring force. Under ideal conditions, the seal will establish its operating gap creating a pressure distribution as represented in Figure 6. If, as a result of some disturbance, there is a decrease in the sealing gap, the forces within the film considerably increase. Similarly, if the gap increases, there is a reduction of the forces within the film. In both cases, the original gap is quickly restored. Unlike the purely hydrostatic type of seal, which produces the sealing gap by pressure only and is independent of speed, the upstream

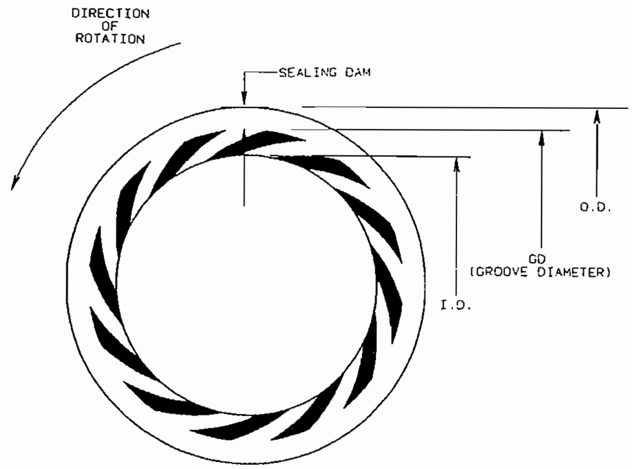

Figure 4. Typical Upstream Pumping Seal Face.

pumping seal is both hydrostatic and hydrodynamic, thus making it speed and pressure dependent.

EFFECTS ON PRESSURE AND HEAT

Increased pressure in the product side of a pump subjects the primary ring to radial and angular distortions due to the non-uniformly distributed moment acting about its centroid. This type of distortion leads to a convergent fluid film as indicated in Figure 7, which may choke fluid flow across the seal faces. Parallel faces are essential to optimum performance of the seal and a near zero moment can be achieved either by selecting the right geometry and/or using material with a higher modulus of elasticity.

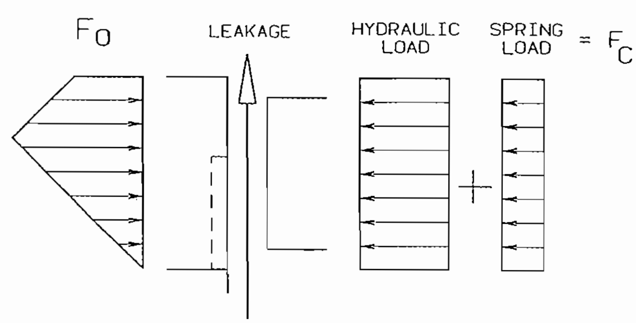

Figure 5. Opening and Closing Forces.

Table 1. Upstream Pumping Seal Installation Experience.

Installed at	Seal Size	Process Liquid	Buffer Liquid	Temp (° F)	Pressure (PSIG)	Speed (RPM)	Date Installed
Exxon Chemical	1.625	Sour Water	Water	150 Max	80	1800	12-86
Shell Oil	1.875	Caustic	Water	150 Max	100 Max	1800	7-87
Arcadian Chemical	1.875	Caustic	Water	—	—	1800	9-87
Tosco Avon	1.375	Foul Water	Water	100	125	3600	4-88
Tosco Avon	2.375	Sour Gas	Water	75	70	3600	4-88
Tosco Avon	3.250	Gas. Products	Water	90	16	1800	4-88
BASF	1.875	2% Nitric Acid & Water	Water	200	20	3600	2-88
IBM (Rainey Engr)	1.875	Pyrophosphate Copper	Water	140	10	1800	3-88

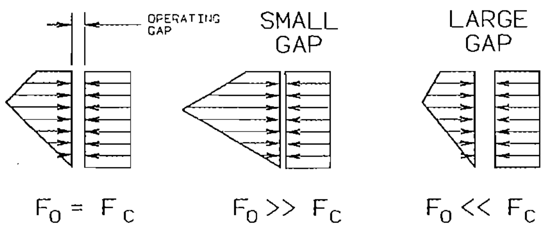

Figure 6. Operating Gap Stability.

Excessive heat has an effect opposite to that created by pressure. The result here is a divergent fluid film which essentially has the same effect—choking of fluid flow. While this is a concern, it really is not a problem since the heat generation is very low due to the essentially non-contacting mode of operation.

SEAL PERFORMANCE AND CALCULATIONS

A simplified analysis for estimating seal performance is as follows:

Closing Force: Regardless of seal design and type, the closing force of a seal is a function of the axial hydraulic load and the mechanical loading due to the springs and is represented by Equation (1) (Figure 5).

$$F_c = \pi P_o (r_o^2 - r_b^2) + \pi P_i (r_b^2 - r_i^2) + F_{sp} \qquad (1)$$

Opening Force: The arithmetic product of the face area and the pressure profile of the film of fluid between the two seal faces generate the force opening.

For conventional mechanical seals, leakage is from the OD to the ID which is represented by a decreasing pressure gradient (Figure 8) represented by Equation (2).

$$F_o = \pi k (P_o - P_i)(r_o^2 - r^2) + \pi P_i (r_o^2 - r_i^2) \qquad (2)$$

where k represents the pressure gradient. The value of k can range from 0.0 to 1.0 and is approximately equal to 0.5 for parallel seal faces.

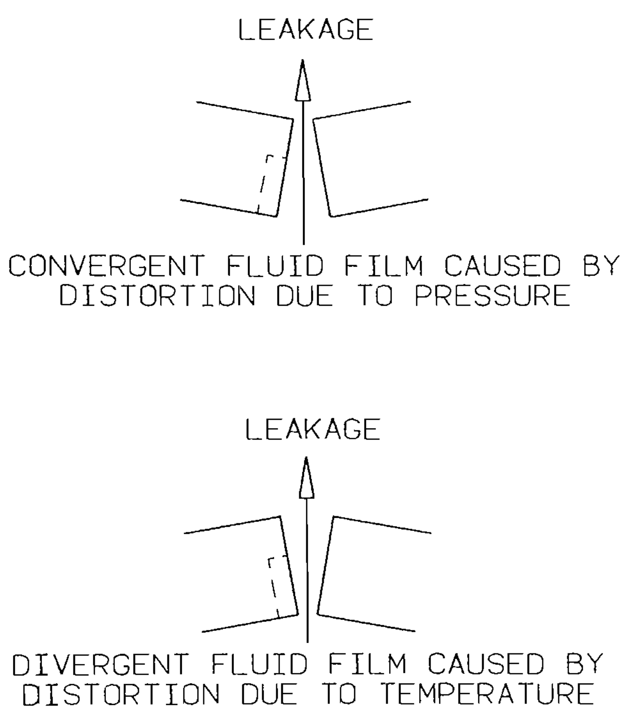

Figure 7. Pressure and Temperature Effects.

For upstream pumping seals, however, the leakage is from the ID to the OD and the pressure gradient k_{di} is increasing from P_i to P_d due to the pumping mechanism, and the pressure gradient k_{do} is decreasing from P_d to P_o due to the sealing dam functioning like a conventional mechanical seal (Figure 9). Both k_{di} and k_{do} can be assumed to be approximately 0.5 for parallel seal faces. force opening F_o, thus is given by

$$F_o = \pi k_{di} (P_d - P_i)(r_d^2 - r_i^2) + \pi k_{do} (P_d - P_o)(r_o^2 - r_d^2) + \pi P_i (r_d^2 - r_i^2) + \pi P_o (r_o^2 - r_d^2) \qquad (3)$$

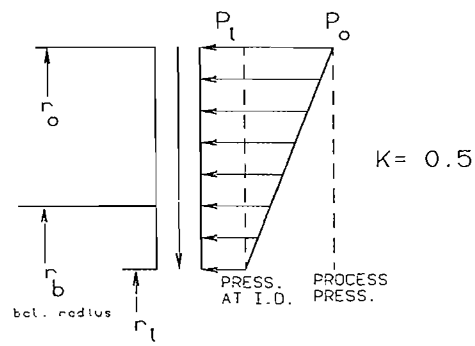

Figure 8. Pressure Profile of Conventional Mechanical Seal.

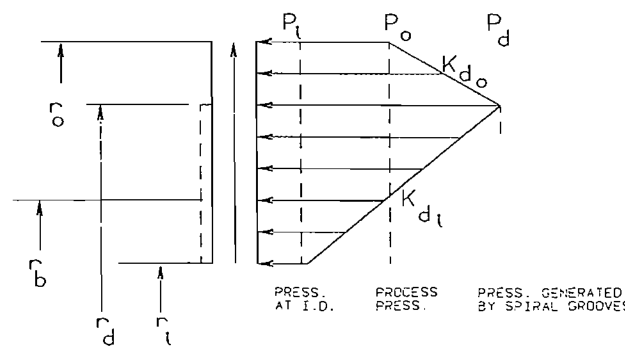

Figure 9. Pressure Profile of Upstream Pumping Seal.

Force Closing/Force Opening Ratio: For conventional mechanical seals, in order for the two seal faces to be intimately in contact with one another and operate with zero visible leakage, the force closing F_c has to be greater than the Force opening F_o. Typical F_c/F_o ratios range from 1.2 to 3.0.

In an upstream pumping seal, however, during dynamic condition, the seal operates with a controlled minute gap. The closing and opening forces must equal one another in order to maintain this constant gap. F_c/F_o thus, must always equal one. As a result, the net pressure P on the seal face equals zero

$$P = (F_c - F_o)/A \qquad (4)$$

where A equals face area.

Heat Generation: Total heat generation of an operating mechanical seal is the sum of frictional heat and heat generated by viscous shear

$$Q = PVAF + uAV^2/h \qquad (5)$$

As has been discussed earlier, P for an upstream pumping seal equals zero which reduces the frictional heat to zero. Consequently, heat generation is only due to viscous shear and, thus, is a function of viscosity (u), face area (A), mean surface velocity (V), and operating gap (h). Typical operating gap of the upstream pumping seal varies from 60 to 120 μin which affects the seal heat generation inversely and linearly. It must be pointed out that the total magnitude of the viscous shear heat is very small; so small, in fact, that the heat is dissipated by the rotating and stationary hardware of the seal.

Pumping Rate: While relatively independent of viscosity and specific gravity, the pumping rate basically is a function of size, speed, groove design (angle, depth, number of grooves), and pressure. Computation of pumping rate is beyond the scope of this paper, but some typical rates are illustrated in Figure 10, which range from 0.1 to 16.0 cc/min.

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Shaft Speed              = 3600 RPM
Process Temperature      = 100.0 Deg F
Barrier Pressure         =   0.0 Psig
Barrier Temperature      = 100.0 Deg F
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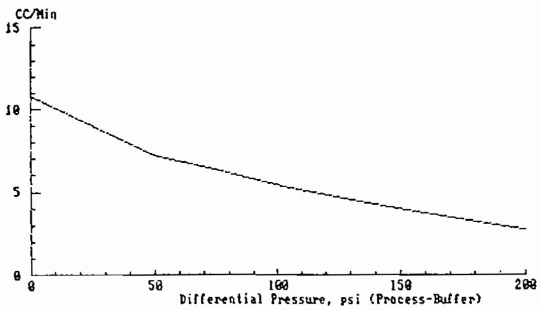

Figure 10. Typical Upstream Pumping Seal Pumping Performance.

SEAL ARRANGEMENT AND SUPPORT SYSTEM

A typical upstream pumping seal arrangement is shown in Figures 11 and 12. The inboard seal head is mounted stationary, operating against a spirally grooved rotating mating ring, which is coupled to the sleeve by an axial pin. The O-ring is strategically located for the seal head to have the property of dual balance (ID/OD balance); and the springs are isolated from the pumped product which is desirable for slurry services. The outboard seal is a conventional contacting mechanical seal rotating with the shaft and operating against a stationary mating ring.

Support system for the seal takes the form of a simple reservoir with an auto fill valve connected to the plant water line. The auto fill valve will provide constant replenishment of the barrier fluid which will be consumed at the pumping rate—0.1 to 16 cc/min (5 fl oz to 6 gal/day).

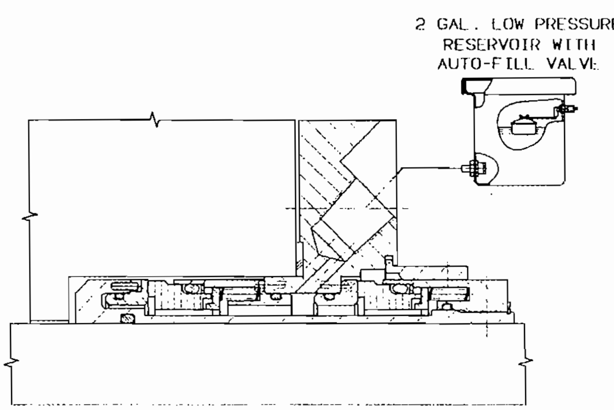

Figure 11. Typical Upstream Pumping Seal Arrangement.

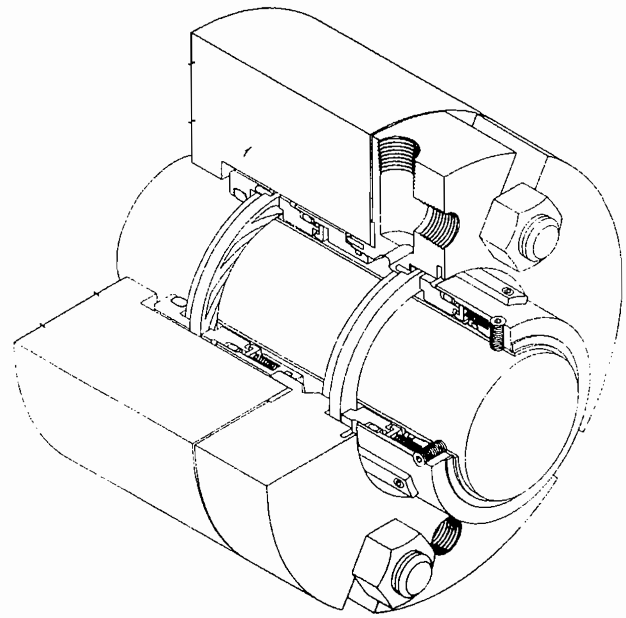

Figure 12. Typical Upstream Pumping Seal Arrangement.

A good barrier fluid is a cool, clean lubricating liquid that is compatible with the process liquid. Compatibility is specially important since the barrier fluid will be pumped into the process. Typical barrier fluids are water, alcohol, automatic transmission fluid, and kerosene with a viscosity range of 0.4 to 10.0 centipoise and a vapor pressure less than 5.0 psia.

While the inboard seal generates negligible heat, the outboard seal heat is basically a function of size, speed and spring load. Recommended piping connection depending upon seal heat is as follows:

Btu/hr	Piping Connection
Up to 1000	Two connections (inlet and outlet) to the barrier fluid to enhance thermosyphon action
1000 & above	Some positive means of circulation is recommended

FEATURES AND ADVANTAGES

In summary, the upstream pumping seal is a highly sophisticated multiple seal arrangement with the following features:

- Capability of pumping upstream.
- A self-flushing seal face.
- Inside seal is noncontacting, therefore, generating little or no heat.
- Outboard seal has low load which also generates low frictional heat.
- Stationary seal head design.

These features translate to the following advantages:

- Reduced or no buffer pressure requirement.
- Eliminates requirement for conventional bypass from discharge for seal flushing, thereby increasing pump efficiency.
- Elimination of barrier fluid contamination by process.
- Elimination of hangups by abrasive particles due to stationary seal head design.

- Reduced PV, therefore
  - reduced heat generation, and
  - reduced flush rate requirement
- Savings on maintenance.

It opens up doors to difficult services with a simple and efficient arrangement.

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