COMPRESSOR SEAL SELECTION AND JUSTIFICATION

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ABSTRACT

The sealing of rotating equipment has always presented a special challenge for rotating equipment manufacturers and end users. Shaft seals are provided to restrict or prevent the escape of process or sealing fluids to atmosphere. They are required to comply with environmental regulations, prevent monetary losses, and for personnel safety. Dry gas seal technology has demonstrated reliability and cost savings for most applications of new compressors. Compressors built prior to the 1980s used earlier seal technology with varying amounts of success. In some cases a retrofit to a dry gas seal can easily be justified. In other cases, maintenance or improvements to existing seals can increase reliability and reduce costs with a lower initial investment when compared to a dry gas seal retrofit. Typical seal designs are reviewed along with recent improvements. Several applications with common seal problems are also presented. A listing of factors to consider when contemplating a seal retrofit is included for reference. Finally several case studies of seal retrofits are described.

INTRODUCTION

Retrofits from wet seals to dry gas seals have been performed on numerous centrifugal compressors for the last 15 plus years. Nearly all new compressors have dry gas seals specified to the original equipment manufacturer (OEM). However, many older compressors are still operating with wet seals or even labyrinth seals. Is a retrofit justifiable, and why?

Many factors play a role in the decision. Initial cost of the retrofit, existing seal cavity dimensions, comparative operating costs of wet and dry seals, type of service, existing seal problems, and existing support system problems are some of the more important factors. Other, less quantifiable, factors like standardization, "new technology," and initial application for operational experience can be considered as well.

OVERVIEW OF COMPRESSOR SHAFT END SEALS

Shaft end seals are provided to restrict or prevent process gas leaks to the atmosphere or sealing fluid leaks into the process gas stream. Seals can be divided into three main classes:

- Clearance seals (labyrinth and restrictive ring seals)
- Oil seals (mechanical/contact and liquid film seals)
- Self-acting dry gas seals

Here is a brief description of each of these types of seals as well as recent improvements where applicable.

Labyrinth Seals

A labyrinth seal may be specified where the process to be sealed is at low to moderate pressures and relatively high leakage flows are tolerable. Users may specify a labyrinth seal because of favorable operating experience, cost, or a dislike of mechanical seals. Air compressors generally will always use a labyrinth seal.

As shown in Figure 1, the labyrinth seal is made up of a number of evenly spaced thin strips, sometimes called teeth or fins. The diametral clearance between each of the seal teeth and the rotating shaft is equivalent to a series of orifices. The gas flow is restricted at each orifice and then quickly expands into the space between the teeth before being restricted by the next tooth. The leakage rate is proportional to this clearance, i.e., by the size of the orifices. Therefore, gas flow can be reduced by simply minimizing the openings.

The entire seal is considered a wearing, replaceable part. If the process gas is corrosive, the stationary labyrinths will likely be made of stainless steel. Clearance for a stainless steel labyrinth will be large in order to minimize the potential for contact and a severe rub between the steel seal and the steel shaft during periods of high rotor vibration. If stainless steel is not a material requirement, then the stationary labyrinth is usually made from a softer metal such as aluminum or bronze. Clearance can be reduced since the relatively soft seal will sustain damage if there is contact, but not the shaft. However, a mushrooming effect occurs during a seal rub, which, in turn, increases clearance and flow, respectively, as seen in Figure 2.

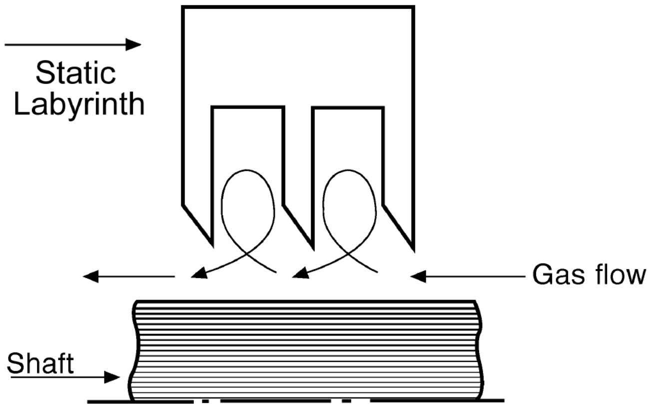

Figure 1. New and Clean Labyrinth Seal. Turbulence Creates Resistance to Leakage Flow.

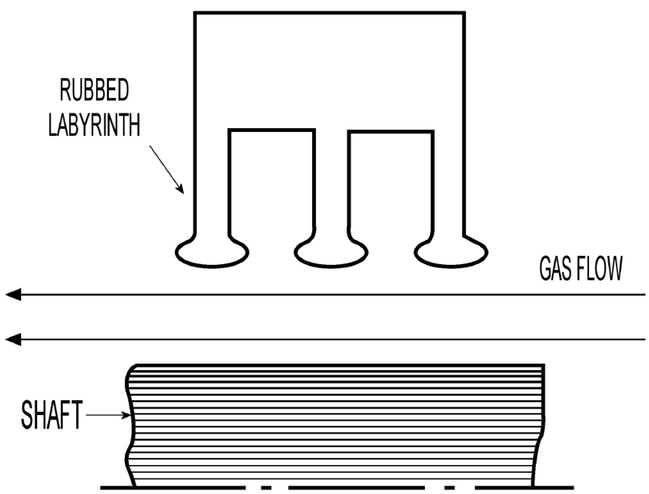

Figure 2. Rubbed Labyrinth Seal. Clearances Increased, Turbulence Decreased, and Leakage Increased.

In a similar concept, gas flow will increase across the seal when fouling occurs in dirty machines. Figure 3 is an example of a fouled labyrinth seal. The dirty grooves decrease the turbulence causing an increase in gas flow between the shaft and the seal.

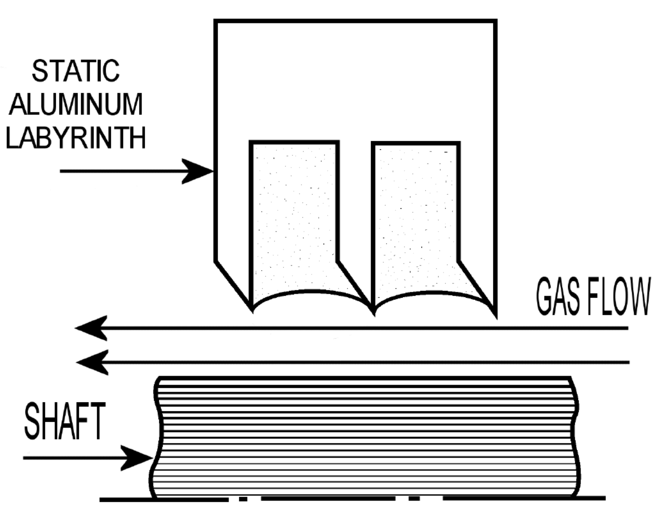

Figure 3. Fouled Labyrinth Seal. Turbulence Decreased and Leakage Increased.

In the last decade, manufacturers have addressed the rubbing issue with updated materials that are abradable or rub tolerant. These designs permit tighter clearances, thus minimizing leakage and allowing a rub to occur with very little to no effect on the overall performance of the seal. Figure 4 exhibits a rubbed abradable seal and the minor effect it has on the seal performance. Note that for abradable seals the labyrinth teeth are steel and rotate with the shaft, while the abradable material is stationary.

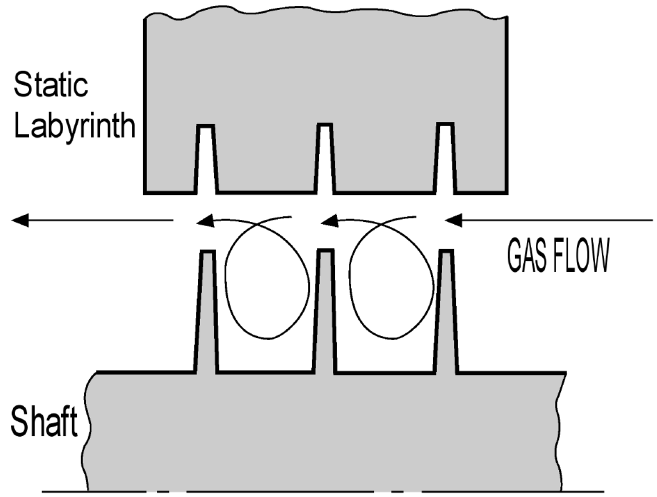

Figure 4. Rubbed Abradable. Clearance Unaltered, Turbulence Continues Resistance to Leakage Flow.

Figure 5 shows a rub tolerant tooth design. The thermoplastic material has a "memory" that allows it to be deflected by contact with the shaft and then return to its original shape. Along with the ability to resist wear, the polymers chosen are capable of withstanding many corrosive gases.

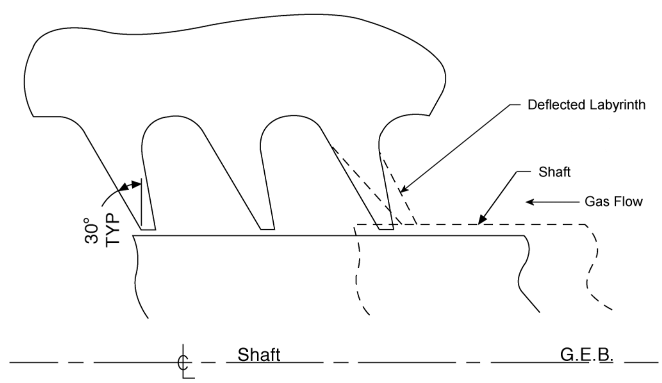

Figure 5. Rub Tolerant Polymer Labyrinth Seal. Maintains Original Shape and Clearance after Shaft Rub.

Labyrinth seals as a main shaft seal may require the addition of a buffer gas for several reasons:

- To keep extreme hot or cold process gas away from bearing oil
- To prevent bearing oil from migrating into the process gas when the compressor suction pressure is subatmospheric
- To prevent contaminated, toxic, or corrosive process gas from leaking to atmosphere
- For any process gas that may be flammable when mixed with air

The buffer gas must be compatible with the process gas. The buffer gas must be maintained after the compressor is shut down if process gas leakage to atmosphere is not permitted.

Buffer systems for labyrinth seals can range from very simple to complex. A single pressure regulating valve is all that is necessary for an air compressor with a subatmospheric inlet. A wet gas compressor may employ a complex system using sweet natural gas as a buffer gas and steam or process gas as motive fluid for multiple ejectors, plus differential pressure transmitters and numerous valves. Operational problems can occur if supply and vent pressures are not correct. Seal rubs or fouling can increase leakage rates and overpressurize vents or overwhelm ejectors.

Figure 6 shows a typical buffered labyrinth seal for use with a process gas compressor. Nitrogen is used as a buffer gas, injected at Port A. Port B is plugged and Port C is vented to atmosphere. Table 1 provides a comparison of typical leakage rates into the process and to atmosphere for the different seal materials that have been discussed.

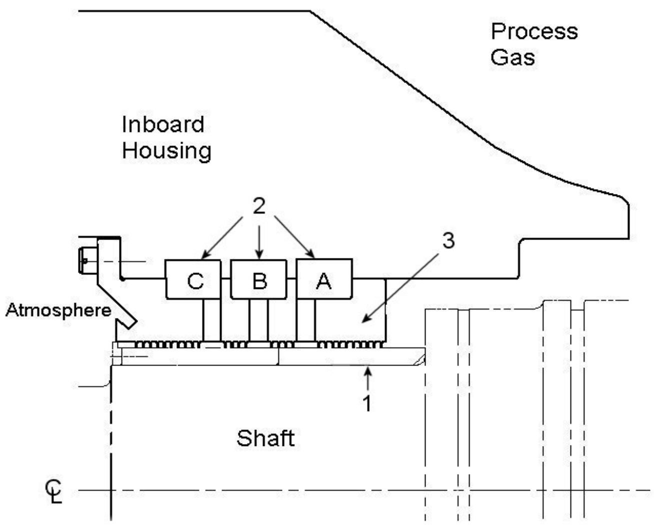

Figure 6. Typical Buffered Labyrinth Seal B. (1) Shaft Sleeve (Rotating), (2) Injection or Ejection Ports, (3) Stationary Fins (Labyrinth).

Table 1. Clearance Seal Leakage Rates.

Process Gas Pressure:	64.7 PSIA
Buffer Gas Composition:	NITROGEN (N2)
Buffer Gas Supply:	69.7 PSIA @ 100 F
Shaft Diameter:	4.75 INCHES

LABYRINTH SEAL MATERIAL	Approximate Diametral Clearance	Number of Fins Inboard	Number of Fins to Vent	Number of Fins Outboard	Leakage to Process (SCFM)	Leakage to Atmosphere (SCFM)
Stainless Steel	0.026	9	8	9	63.4	164
Aluminum	0.017	9	8	9	32.7	84.9
Rub Tolerant	0.012	9	8	9	22.3	54.8
Abradable	0.008	9	8	9	13.3	32.7

RESTRICTIVE RING SEAL MATERIAL	Approximate Diam. Hot Clearance	Number of Rings Inboard	Number of Rings Outboard	Leakage to Process (SCFM)	Leakage to Atmosphere (SCFM)
Carbon	0.008	2	5	2.421	7.746

Restrictive-Ring Seals

Application of restrictive-ring seals to centrifugal compressors is desirable when minimizing leakage (compared to a labyrinth seal) is important. The seal rings are typically made of carbon or another suitable material. These rings are mounted in retainers or spacers and may operate dry or with a sealing liquid. However, they are typically used with a buffer gas. Rings seals have an excellent operating history for chlorine service compressors. Ring seals can be designed with closer clearances than labyrinth seals since the rings can float with the shaft. Operating hot clearances may be made smaller than bearing clearances. However, since the carbon ring material has a lower coefficient of thermal expansion than steel, initial clearances must be made large enough so that the shaft does not grow into the rings.

As shown in Figure 7 the standard arrangement of carbon ring seals may contain several rings. Buffer gas may be supplied between a specific group of rings. There are a few considerations that are necessary when deciding upon buffer location. One case with the buffer closest to the outside of the seal has been used for low and subatmospheric pressure inlet conditions. The second case with the buffer inboard is normally used for units with higher inlet pressure. Typically, buffer supply pressure has been maintained at 3 to 5 psi above the highest downstream pressure, either the chamber behind the balance piston or atmosphere. The buffer gas must be maintained after the compressor is shut down if process gas leakage to atmosphere is not permitted. Other systems have been used in applications with ejectors and/or having process gas throttle through the rings, but these types of systems should be specifically designed for the application. As with labyrinth seals, operational problems can occur if supply and vent pressures are not correct. Carbon ring rubs or damage can increase leakage rates and overpressurize vents.

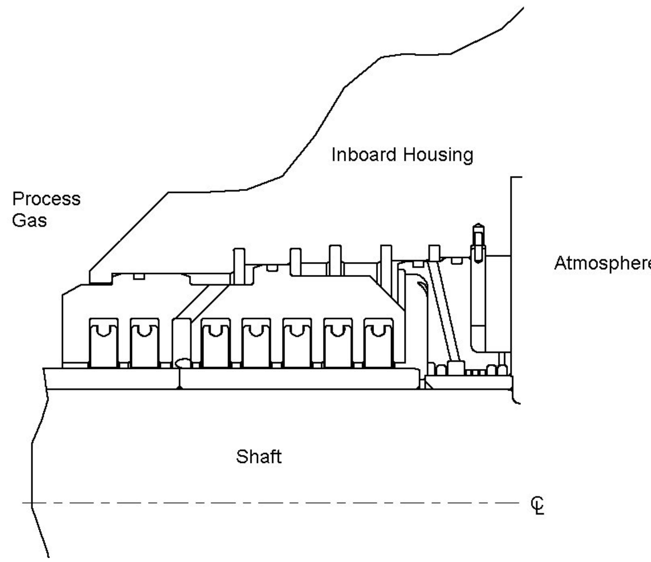

Figure 7. Restrictive Ring Seal.

Table 1 shows the typical leakage rates into the process and to atmosphere for a restrictive ring seal under the same conditions as for the labyrinth seals described previously.

Mechanical (Contact) Face Seal

A typical example of a mechanical (contact) face seal is shown in Figure 8. These seals are typically provided with labyrinth seals inboard of the sealing surfaces for use with optional buffer gas. The mechanical seals are designed to minimize leakage of process gas, while the compressor is pressurized and in the process of being shut down. They are also capable of sealing in the event of sealant failure.

A mechanical face seal is based on the concept of several components, a stationary seat, a rotating seat, and, in this example, a carbon ring sandwiched in between, each requiring a high degree of contact to form sealing faces between them. The seal surfaces are held together by a combination of hydraulic and mechanical forces. The hydraulic forces are produced by the seal liquid, while the mechanical forces are normally produced by some type of spring.

The mechanical face seal uses a liquid, such as oil, to lubricate, cool, and create a positive sealing action to the sealing components during normal operation. The lubricant pressures and flows may vary from compressor to compressor depending upon the speed and size. A differential pressure is supplied at 35 to 50 psi above the compressor suction pressure; thus a slight flow of seal oil takes place across the faces toward the process gas, which prevents outward flow of gas to atmosphere. Normally, the flow across a mechanical face seal can be expected to be 10 gallons per day or

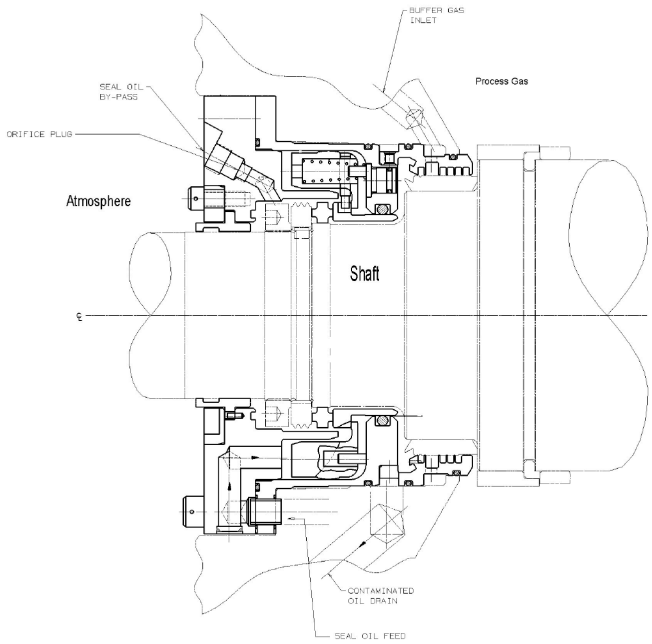

Figure 8. Mechanical (Contact) Face Seal.

less, depending on the seal pressure and size of the compressor. This leakage is considered to be dirty or contaminated and is drained to a separate area from that of the clean (sweet) seal oil and lubrication oil. Inboard of the contaminated seal oil drain is a shaft labyrinth, which prevents the seal oil leakage from entering the process gas stream. In some cases the labyrinth may not be adequate to keep the oil out, so a buffer gas supply is desirable. As previously mentioned above there are several other reasons that a labyrinth seal may be buffered. Table 2 illustrates the buffer supply and process gas leakage to the vents and atmospheres for each of the mechanical face, liquid film, and dry gas seals, along with the necessary flows and pressures required to adequately seal the units in question.

Table 2. Oil and Gas Seal Leakage Rates.

Process Gas Pressure:	64.7 PSIA
Buffer Gas Composition:	Methane (CH_4)
Buffer Gas Supply:	69.7 PSIA @100^{o}F
Speed:	10,000 RPM
Shaft Diameter:	4.75 INCHES

	Pressure	Maximum	Seal Oil	Contaminated Oil	Buffer Leakage (SCFM)	
SEAL TYPE	Differential	Sealing Pressure	Flow (GPM)	Leakage (GPD)	Into Process	Vent
Mechanical Face Seal		750 psig				
Without Buffer Supply	35-50		18.25	14	0	11.7
With Buffer Supply	3-5		18.25	14	57.6	11.7
Liquid Film Seal		*3900 psig				
Without Buffer Supply	5		9.68	**13	0	11.7
With Buffer Supply	3-5		9.68	**13	57.6	11.7
Dry Gas Seal	5	**5000 psig	0	0	50.9	0.1
***N_2 Separation Gas	1-2 psig		0	0	50.9	0.49

* Sealing gas pressure is limited by the seal oil pump ratings.
** Based on a Windback design. 17 GPD on a straight bore.
*** Sealing gas pressure is based on the use of a triple tandem seal; Higher pressures are possible, but require special design.
**** Use of a Carbon Ring separation seal.

For many years a maintenance issue with the mechanical face seal was dealing with the numerous loose components while installing the seals during repairs and overhauls. In the last few years, customer requirements have pushed manufacturers to supply cartridge type seals for mechanical seals similar to those typical of dry gas seals.

Mechanical Seal Oil Supply System

The main purpose of the seal oil supply system is to supply clean, cool oil to the seals at the required pressures and flows. The system generally consists of an oil reservoir, oil pumps, coolers, filters, and regulators to precisely control the pressures and temperatures required for the compressor seals. Figure 9 is a typical oil supply system for a mechanical face seal. For cost and space savings the seal system may be incorporated with the lubrication system to allow for additional oil capacity and flows.

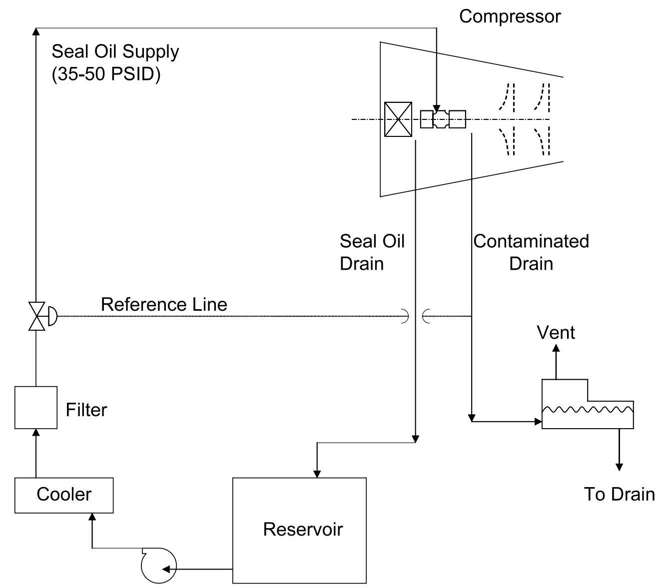

Figure 9. Seal Oil Supply System for Mechanical Face Seal.

Seal oil systems are now all closed loop systems to allow for reuse of the oil. However, older seal systems drained the contaminated seal oil to sewers, which can no longer be done due to environmental constraints, or directly to the reservoir.

As previously mentioned, the closed loop for a seal supply system must take into consideration contaminated oil leakage that is produced in any oil seal. The contaminated seal oil is normally collected by gravity drain(s) to automatic float-type drainers or seal pots. The oil is then separated from the gas flow coming from the inboard labyrinth, either buffer or process gas, as mentioned above and recycled or "reconditioned."

If the contaminated oil is reconditioned, it must first be sent to a degassing tank to release the entrained gas by heating the oil. This eliminates the possibility of contaminating the fresh lube and seal oil reservoirs. Then it is sent directly to the reservoir to be reused again.

Liquid Film Seal

A liquid film seal may be specified where the process to be sealed is at too high a pressure for that of a mechanical seal. Some users may specify a liquid film seal for lower sealing pressures because of favorable operating experience or a dislike of mechanical seals.

A typical example of a liquid film seal is shown in Figure 10. Oil is supplied to the seal between two floating bushings that run at close clearance to the shaft, or, more commonly, a replaceable sleeve. The seal functions on the principle of maintaining a film of oil between the gas side seal bushing and the shaft sleeve. The oil is supplied at a pressure slightly higher than that of the process gas that is being sealed. By maintaining the oil pressure 5 to 10 psi above the gas pressure, the process gas is prevented from leaking to atmosphere. Close clearances and precisely controlled pressure differential minimize the amount of oil that leaks inward to the contaminated oil trap. Contaminated oil leakage can be 20 to 40 gallons per day per machine, depending on the seal pressure and size of the compressor. The majority of the oil supplied exits the seal by flowing across one or more atmospheric side floating bushings. The volume of oil flowing through the seal cavity both lubricates and cools the seal. The seal rings are typically lined with a bearing type tin- or lead-based babbitt to minimize shaft wear. Inboard of the contaminated oil drain is a shaft labyrinth, which prevents the seal oil leakage from entering the process gas stream. In different cases this may not be adequate to keep the oil out, so a buffer gas supply is desirable. As previously mentioned above, there are several other reasons that a labyrinth seal may be buffered.

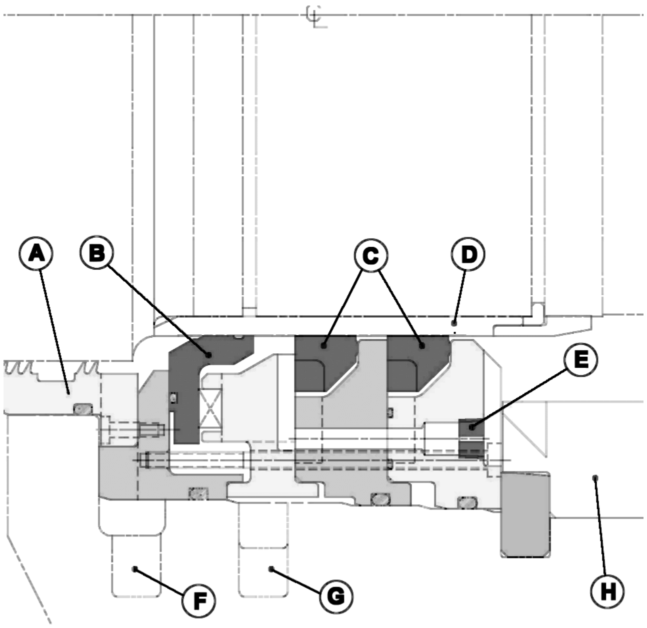

Figure 10. Upgraded Two Bushing Oil Sleeve Seal for Case Study C. A) Peek Labyrinth Seal, B) Gas Side Seal Bushing, C) Atmospheric Side Bushings, D) Hardened Shaft Sleeve, E) Oil Bypass Orifice, F) Contaminated Seal Oil Drain, G) Seal Oil Supply, H) Sweet Oil Drain.

A common problem with liquid film seals is hydrogen sulfide (H_2S) and/or chlorides in the process gas attacking the babbitt and the resulting buildup of corrosion products reducing clearances. The reduced clearance results in localized overheating of the tin-based babbitt and "washing out" of the babbitt. The build up of corrosion products and lack of babbitt also results in scoring of the shaft sleeves. The end result is increased clearance and extremely high leakage rates for the sweet oil as well as contaminated oil. Oil supply flowrates will increase until either pump capacity is exceeded or pressure losses in the pipes become equal to the design oil to gas differential pressure. In either case, an oil pressure higher than the process gas pressure cannot be maintained and gas escapes to atmosphere. Life of seals with these issues can be as low as six months to a year, depending on the particular situation. Addition of a sweet buffer, if available, can eliminate this problem.

If a suitable buffer gas is not available then material changes to seal parts have proven effective. In addition to material changes, many older liquid film seals from the 1960s and 1970s can benefit from design changes. New bushing designs are available to reduce contaminated leakage rates, and new cartridge assemblies can reduce maintenance time.

Liquid Film Seal Oil Supply System

The seal oil supply system for a liquid film seal is essentially the same as for a wet mechanical seal. The major difference is the amount of pressure difference between the oil and gas, and how the pressure difference is maintained. A mechanical seal needs to provide oil at 35 to 50 psi above a gas pressure on the order of 400 psi. This can easily be done with a pressure-regulating valve. A liquid film seal may be required to provide oil at 5 to 10 psi above a gas pressure of 2500 psi. The general practice to maintain this type of pressure difference is to use an overhead tank as shown in Figure 11. Here a seal oil level is maintained by a level control valve. With gas pressure on top of the seal oil, the static oil head automatically provides the correct pressure differential.

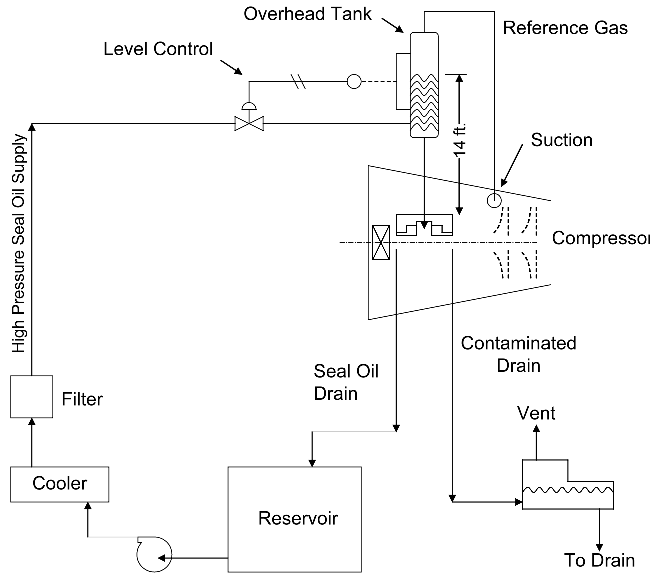

Figure 11. Seal Oil System for Liquid Film Seal.

Gas in contact with the oil in the overhead tank can be another source of contamination of the oil. This is sometimes addressed by the use of a transfer barrier between the oil providing the static head and the fresh oil supply to the seals.

Dry Gas Seals

Nearly all new centrifugal compressors ordered in the last 10 years have had dry gas seals specified by the customer. Therefore, many new compressor designs have adopted the dry gas seal as a standard, rather than an alternative. Reliability in most services is very high, and utility and environmental benefits are well documented. Due to these advantages, dry gas seal retrofits to older compressors have become a common practice.

A dry gas seal uses gas, typically the process gas, as a sealing medium. The gas leakage to atmosphere is minimized and controlled by a small, self-regulating gap between a rotating seal ring and a stationary seal ring. A balance of spring forces, hydrostatic forces, and hydrodynamic forces acting on the stationary seal ring controls the width of this gap. The hydrodynamic forces are generated by a pattern of shallow grooves in the sealing surface of the rotating seal ring. A secondary seal, typically an O-ring, is located behind the stationary seal ring to prevent gas from bypassing the gap. Gas pressure is broken down across one or two sets of seal rings, and the leakage is vented to the flare system. A second or third set of seal rings serves as a backup in the event of damage to the primary set (Figure 12).

Figure 12 illustrates a single seal arrangement, i.e., one set of sealing faces, rotating and stationary. Other arrangements are available. A tandem seal is two sets of sealing faces arranged in series. Older seals for very high pressures used a triple arrangement with three sets of sealing faces arranged in series. The pressure to be sealed was distributed across the first two sets with the third serving as a common backup. Another arrangement is the double opposed, where two sets of sealing faces face each other, and the buffer gas is injected between them. Double opposed seals are commonly specified when the process gas is not suitable as a buffer gas and an inert buffer gas is supplied.

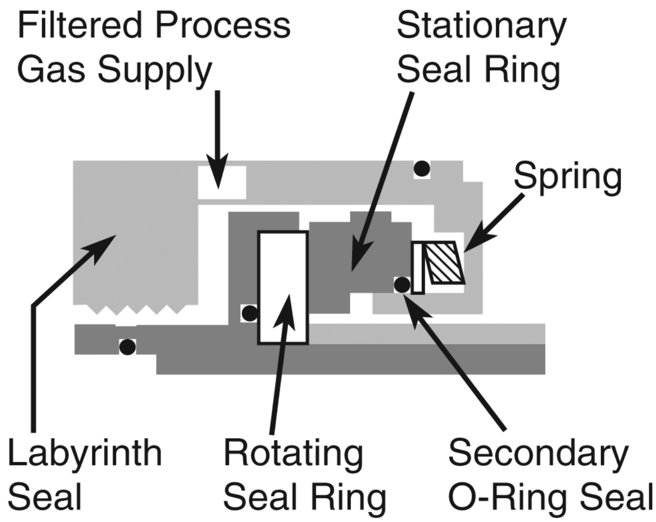

Figure 12. Typical Dry Gas Seal.

While the basic concept of the dry gas seal is common to all designs, different seal manufacturers provide different features or optional features. The pattern of the grooves in the sealing surface may work in only one direction of rotation (unidirectional) or can work in either a clockwise or counterclockwise direction (bidirectional). O-rings may be used as static seals between parts, or nonelastomer designs are available to address temperature extremes and explosive decompression.

Dry Gas Seal Buffer System

To function properly, dry gas seals require a steady flow of gas that is both clean and dry. This is provided by a buffer gas system that consists of filters, a regulating device, and instrumentation. The amount of gas supplied to the seals is determined by supplying it at a pressure 5 to 15 psi above the pressure to be sealed, or supplying a certain minimum flow. In either case, the excess flow of filtered gas returns to the process across a labyrinth seal inboard of the gas seal cartridge. A supply system based on differential pressure is shown in Figure 13.

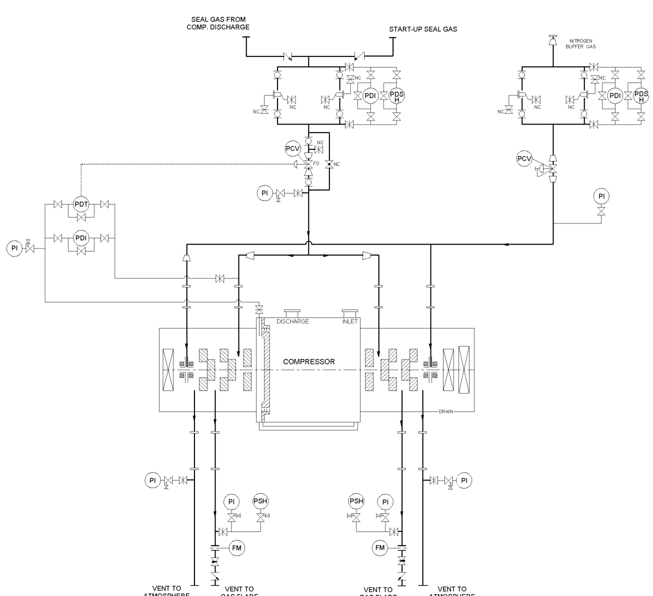

Figure 13. Buffer System for Dry Gas Seal.

The buffer gas is typically process gas taken from the discharge of the compressor. If this is the case, an external supply of startup gas should be supplied to the seals during periods when the compressor is pressurized but not rotating. If the process gas is extremely hazardous, toxic, or dirty, an external gas may be used as a continuous buffer. If a startup gas is not available at a high enough pressure, air operated booster systems are available to raise the pressure of the process gas enough that it can be fed through the buffer system and into the gas seals for startup.

The main gas seal contains the process gas within the casing. Additionally, a separation seal is required between the main gas seal and the compressor journal bearings. This seal protects the dry gas seal from contamination by lubricating oil. It can be a labyrinth seal or a circumferential carbon ring seal and will be buffered with either nitrogen or instrument air.

If the process gas is used as a buffer gas for the main seal, and the process is dirty or prone to liquid condensation, additional gas conditioning devices may be required to ensure reliable dry gas seal operation. These may be two-stage filters, knockout vessels, or mechanical separators. Heating the buffer gas with an external heater or steam tracing the lines may be employed to keep the gas above its dew point and prevent liquid formation.

PROCESSES

There are a vast number of industries using compressors: chemical, petrochemical, and refining just to name a few, and they all incorporate numerous processes to meet specific objectives. Below, several different processes with unique sealing problems are described. While these different processes possess unique characteristics in each plant, many basic elements and components required are common to each.

Hydrogen (H_2) Recycle

Hydrogen recycle compressors are used in a variety of refinery processes including catalytic reforming (platforming), hydrocracking, and hydrotreating. While these different processes have unique operating pressures, temperatures, and catalysts, many basic elements are common to them all. Since hydrotreating to remove sulfur is currently an important topic in refining, a simplified process schematic of this process is shown in Figure 14 as an example.

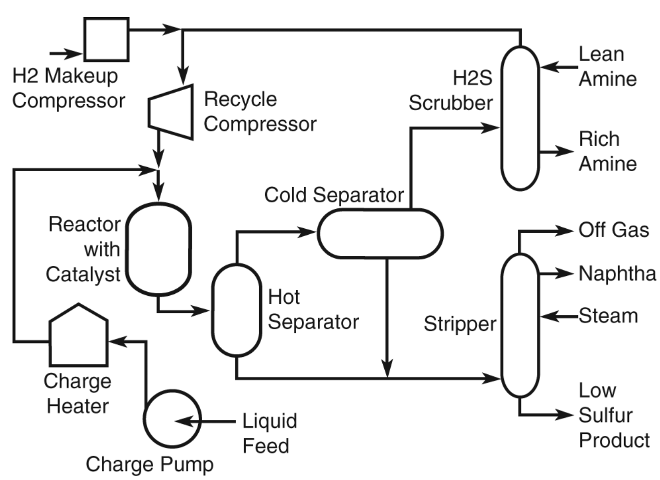

Figure 14. Simplified Hydrodesulferization Process.

A liquid feedstock is sent to a heater by a charge pump. The liquid is heated by a combination of heat exchangers and a fired heater, but no exchangers are shown to simplify the diagram. The heated charge is combined with hydrogen rich recycle gas and fed to a reactor. Within the reactor, in the presence of a catalyst, sulfur compounds are decomposed to form a hydrocarbon and hydrogen sulfide. Other reactions can take place as well. Oxygen compounds are converted to hydrocarbons and water. Nitrogen compounds are converted into hydrocarbons and ammonia (NH_3). Olefins and other unsaturated hydrocarbons are saturated by the addition of hydrogen, producing stable hydrocarbons. Metallic impurities are absorbed physically onto the catalyst surface. The reactor effluent then is cooled and flows through a series of gas/liquid separators. A water wash of the effluent may be included. In this example, a steam stripper removes gas and naphtha leaving the low sulfur product. The gas from the final separator flows to an H_2S scrubber where liquid amines are used to remove H_2S from the recycle gas. Gas from the scrubber enters the inlet of the recycle compressor. Since hydrogen is consumed by the chemical reactions, a makeup compressor supplies additional hydrogen to the loop. This compressor is typically a reciprocating unit.

Seal design for hydrogen recycle compressors has always been a challenge to the compressor OEM and a potential source of downtime for the user. Some of the seal design challenges are:

- High pressure—up to 2500 psi.
- Rotordynamic considerations—the low molecular weight of hydrogen recycle gas demands many stages (a long rotor) and high rotational speeds for just a moderate pressure rise. Seals can contribute to vibration problems on an already sensitive rotor.
- Venting of flammable process gas.
- Contamination from process gas.

While all these considerations are important, it is the contamination issue that causes most seal related shutdowns. In the past liquid film seals were always used due to high pressure. Over the past 15 years there have been numerous gas seal retrofits. These have not been without their own particular problems; therefore, careful consideration is required before choosing a retrofit.

Chlorine (Cl_2)

Chlorine compressors are unique and pose their own difficulties in operation and control. However, chlorine in itself is the most threatening factor in its production, and the handling of it can be treacherous. Chlorine in a gaseous or liquid form is nonexplosive and nonflammable. However, it is toxic and an oxidizer, therefore capable of supporting combustion. Chlorine also reacts readily with many organics, sometimes violently.

The majority of all chlorine produced presently and in the past 50 years is manufactured by means of electrolysis of salt brine. A basic and simplified schematic of the process is shown in Figure 15. As seen in the schematic, the process consists of an electrolytic cell where chlorine is produced along with sodium hydroxide (caustic soda) and hydrogen.

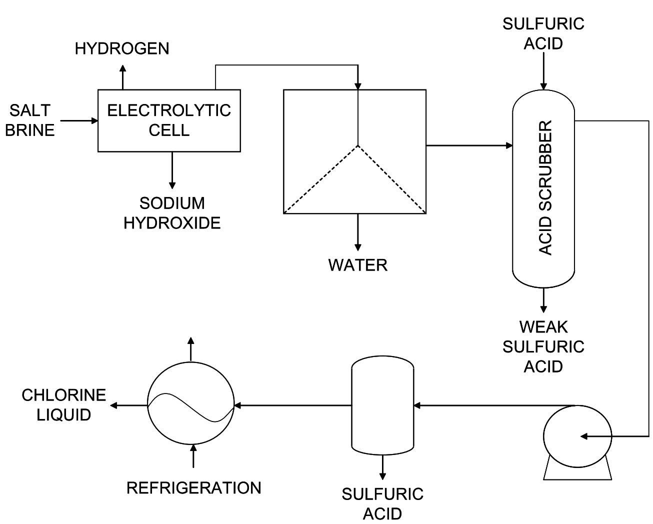

Figure 15. Simplified Chlorine Process.

Chlorine gas containing a considerable amount of water vapor is collected and sent to coolers to condense out a majority of the water vapor. The chlorine gas is then sent to drying towers (sulfuric acid scrubbers) where it is scrubbed and sent off to the compressors. The compressor is typically used to control the suction pressure. The chlorine temperatures must be kept below 250°F to avoid any extreme reactivity. This is why chlorine compressors are typically intercooled.

The gas from the compressor discharge is then sent to the expansion drum where any residual sulfuric acid remnants can be discarded. The chlorine stream is then passed through a refrigerated condenser to lower final temperatures for storage.

Seal consideration for such a compressor can be a difficult task to accommodate the very necessary requirements for this erratic process stream. Some of the challenges are:

- Subatmospheric pressures.
- Process stream reactivity with organics.
- Positive seal required due to toxic nature of gas.
- Contamination from process gas.

Even though all the challenges mentioned are important, the highest priority toward the handling of Cl_2 is the environment, safety, and health (ES&H). These reasons are why an oil seal cannot be utilized, and a restrictive-ring or dry gas seal must be chosen to minimize the posing dangers.

Ethylene (C_2H_4) Refrigeration

The refrigeration process is a simple cycle in even the most complicated systems. All refrigerants function in a similar fashion, but the physical properties may vary from one to the other. Refrigeration systems are made up of the same essential components: compressor(s), condenser(s), receiver, expansion valve, and evaporator. A common layout of a refrigeration unit can be seen in Figure 16.

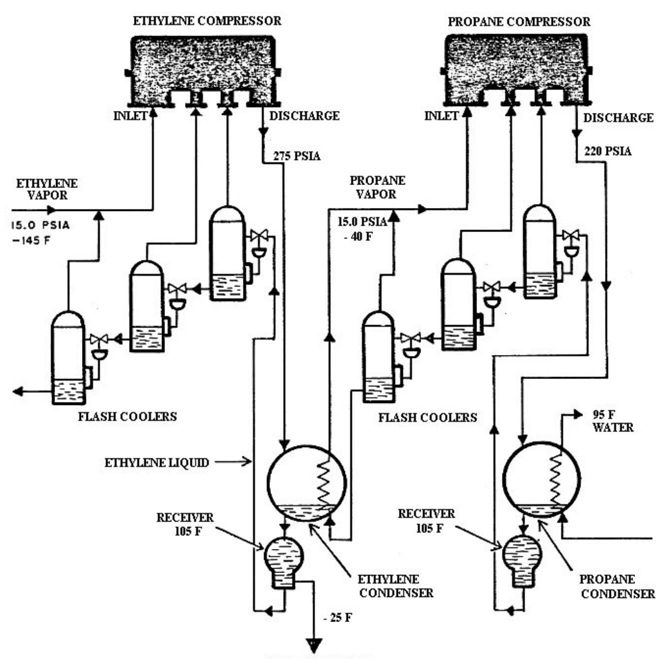

Figure 16. Simplified Ethylene Refrigeration Process.

Liquid refrigerant evaporates through an expansion valve to the required area or process to be cooled. The vapors are then compressed to the necessary pressure for condensation to occur. The stream is then passed by a cooling medium to promote condensation. The condensate is then returned to the receiver for reuse.

Seal consideration for such a compressor is probably one of the simplest given the desire for a clean and oil-free process. Some of the challenges are:

- Low inlet temperatures.
- Risk of product contamination.
- Nonequalized (pressure) seals.

Wet Gas

Varying from site to site, the definition of a "wet gas" stream may differ depending upon the specific development of the gaseous mixture. However, we are going to discuss the "wet gas" stream that is produced in a gas concentration unit or during gasoline manufacturing. Figure 17 is a simplified schematic of a gas concentration unit involving a "wet gas." The "wet gas" spoken of here is a gas mixture saturated with hydrocarbons, where additional condensing may occur in the suction piping; therefore, the compressor in consideration is a "wet gas" compressor. The following is a brief description of the process involved in producing this "wet gas" and what it entails.

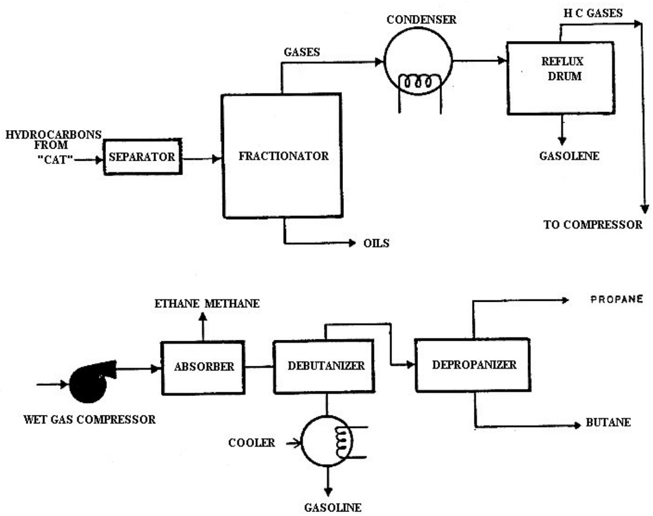

Figure 17. Simplified Wet Gas Process.

The gas concentration unit described trails a fluid catalytic cracker system releasing hot cracked petroleum vapors (hydrocarbons). These vapors are separated into various components depending upon boiling points, by going to the fractionating tower. Low boilers such as gasoline come off the top, and various oils come off the sides and bottom (heavies).

Good gasoline is made up of pentane (C_5), hexane (C_6), heptane (C_7), octane (C_8), nonane (C_9), and decane (C_{10}), otherwise known as the components that will not boil in your gas tank during the warmer months. The gasoline stream produced above will contain a few unsaturates, butylenes and pentylene, which are undesirable as exhaust constituents. Gasoline is then cooled and liquefied and sent to a knockout drum where the liquid is separated (knocked out) from the gas. This gas known as the "wet gas" goes directly to the compressor.

The compressed gas is then sent through an additional sequence of absorbers and separators to produce a number of different products from gasoline to natural gases, such as methane, ethane, propane, and butane.

Seal consideration for such a compressor can be a difficult task to accommodate the very necessary requirements for this erratic process stream. Some of the challenges are:

- Dirty process.
- Low pressure.
- External buffer required.

As with other compressor applications, the dry gas seal has been the seal of choice for retrofitting and installation for new wet gas compressors. However, the dirty process poses a tremendous problem to the supply of clean and dry buffer gas to the seal.

Natural Gas (CH_4)

Natural gas consists of numerous gases, mainly hydrocarbons; however, its composition is primarily methane (CH_4), with ethane (C_2H_6) as the next most prominent constituent. The composition varies from location to location and no two mixtures are alike. The gas transmission or repressuring (injection) systems are the two compression processes that are being focused on in this section.

Gas transmission by pipeline requires a tremendous compressor capacity and is the largest segment in the natural gas industry involving compressors. These units are usually set up in secluded stations that may be spaced 100 miles apart. In this service, compressors are utilized to restore the pressure loss due to friction of the flowing gas in the pipelines. The centrifugal compressor is particularly adaptable to steady output conditions as found on long-distance, large-volume, high-pressure lines. Natural gas is usually delivered to the local market and distribution systems at relatively high pressure and does not require auxiliary compressors.

Another common use for natural gas compression is incorporated in the production of oil. The natural gas is initially separated from the oil that flows from the well, compressed, and sent back to the underground reservoir to assist with recovering oil after the pressure falls off. Sometimes this process is called repressuring or injection. Figure 18 is a simplified compression system for use in the oil well injection process.

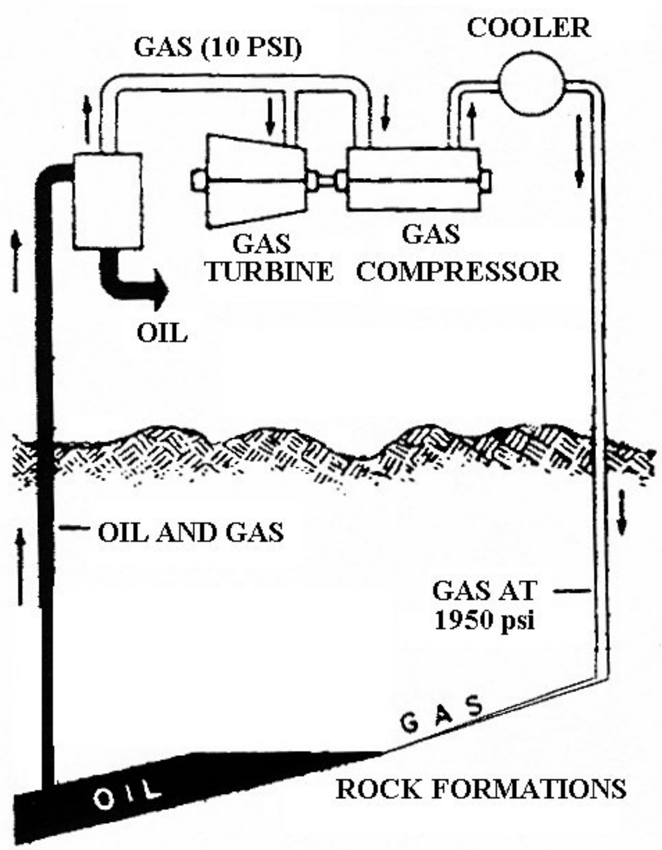

Figure 18. Simplified Natural Gas Reinjection.

Both processes are simple, but pose their own difficulties for sealing and maintaining a long life with little to no supervision. Crude natural gas is quite dirty and wet, but once filtered and purified can be handled easily. However, in most pipelines a large number of reciprocating compressors are found, therefore creating a problem for the centrifugal ones being put in place. It is well known that most reciprocating compressors deposit small quantities of condensation and heavy hydrocarbons (oil) into the gas flow, not allowing the use of this gas to be utilized as a clean buffer without extensive filtering and preparation.

FACTORS INFLUENCING RETROFIT DECISIONS

Retrofits from labyrinth, mechanical, and liquid film seals to dry gas seals have been performed on numerous centrifugal compressors for the last 15 plus years. Most new compressors are specified to use dry gas seals. Should an older compressor be retrofit to dry gas seals as well? Would a retrofit to a different type of seal be more suitable? Can the retrofit be economically justified?

Many factors play a role in the decision. Initial cost of the retrofit, existing seal cavity dimensions, comparative operating costs of wet and dry seals, type of service, existing seal problems, and existing support system problems are some of the more important factors. Other, less quantifiable, factors like standardization, "new technology," and an initial application for future operational experience can be considered as well.

Feasibility

Some seal retrofits may not be feasible, or at least not without incurring a great deal of cost and affecting other areas of compressor design. Some of the things to consider:

- Shape of the existing seal cavity. Is there enough axial and radial space for dry gas seals, including an inboard labyrinth seal and a separation seal next to the bearing? Can the seal cavity be modified? Is another style of seal a better fit? Can the rotor be modified without having an adverse effect on rotordynamics?
- Distance between shaft ends. Many older compressors are close coupled, i.e., the distance between shaft ends is much less than the current 18.00 inches, sometimes as small as 5.00 inches. Most new seal designs, dry gas seals and newer wet seals, are made as a cartridge for ease of assembly. Can the cartridge fit between the shaft ends for assembly? Can the compressor or driver be easily moved to allow access? Can the cartridge be designed as two or more smaller subassemblies?
- Existing porting for injection points, vents, or drains. Are enough connections available? Are they properly sized? Can others be added?
- Buffer supply. If an inert buffer such as nitrogen is required, is it available in sufficient quantities? Is the process gas clean enough to be suitable as a buffer for a dry gas seal? Is a startup gas available for a dry gas seal?

Financial

For a dry gas seal retrofit to be financially justifiable a number of costs need to be considered:

- Cost of new seals plus spares
- Cost of new buffer system. Will a standard system be sufficient? Are there additional requirements such as nitrogen supplies, startup gas supplies, additional filters/separators, or boosters to provide startup gas?
- Cost for elimination or modification of the original seal system. Is the original seal system a combined lube, seal, and control (turbine drive) oil system? What modifications are necessary to delete the seal oil requirements?
- Cost of nitrogen for separation seal buffer

These costs will be compared with potential savings:

- Reduced power loss in shaft rotation for oil seals versus dry gas seals
- Elimination of utilities power for oil pump, cooling water pump, or cooling fan
- Reduced gas loss due to venting
- Process improvements due to elimination of oil ingestion
- Reduced maintenance

The variables above play a tremendous role in determining the economic justification for possibly retrofitting from one type of seal to another. However, there is no single value that can be given to each of these variables.

Table 3 is a simple comparison, comparing the initial costs for the different seals and the supporting systems for each. As mentioned above, a comparison or calculations for savings on a specific job are not adequate for any other compressor in use by another party. Therefore, the cost values given are based on a single size compressor with 4.0 inch bearings and the same process parameters.

Table 3. Seal and Support System Cost Comparison.

SEAL TYPE	SUPPORT SYSTEM	PER SEAL	SUPPORT	TOTAL
Labyrinth	Buffer Gas	\$7,500 - \$15,000	\$25,000 - \$40,000	\$32,000 - \$55,000
Ring-Seal	Buffer Gas	\$7,500 - \$15,000	\$25,000 - \$40,000	\$32,000 - \$55,000
Mechanical Face Seal	Seal Oil	\$33,000 - \$38,000	\$60,000 - \$80,000	\$93,000 - \$118,000
Oil Film Seal	Seal Oil	\$32,000 - \$37,000	\$70,000 - \$80,000	\$102,000 - \$117,000
Dry Gas Seal	Buffer Gas	\$34,000 - \$39,000	\$90,000 - \$115,000	\$124,000 - \$154,000

Environmental

Current environmental regulations may warrant a seal retrofit despite financial considerations. In some cases other alternatives are available.

- Ineffective labyrinth or restrictive ring seals may benefit from changes to their buffer supply system.
- Contaminated seal oil can no longer be dumped to a sewer. Addition of a degassing tank to the system can allow contaminated oil to be reused. High contaminated seal oil leakage rates can be improved with new designs of mechanical or liquid film seals.
- Sour oil drainer vents can be returned to compressor suction. Often in this case drainer vent orifices must be resized. Addition of a buffer gas may be required.
- Dry gas seals offer the lowest leakage rates.
- If no product can be vented to flare or atmosphere, double opposed gas face seals may be an option or a tandem arrangement with the use of a secondary buffer of nitrogen.

Reliability

Some reliability issues are caused by outdated seal designs. Some can be improved with material upgrades. Other reliability issues are caused by the support system: oil pumps, coolers, overhead tanks, controls. A review of the system design as well as maintenance procedures may be in order before undertaking an expensive retrofit.

Seals can have a large influence on rotordynamics of a compressor, particularly for high speed and high pressure units. If a machine already has questionable rotordynamics, a new study should be performed before a seal change is made. Oil seals can provide positive damping, which is a benefit, or provide cross coupled forces, which is a detriment. Dry gas seals will typically add weight to the rotor. The amount of additional weight depends on the choice of materials for the rotating components.

CASE STUDIES

Case Study A

Background

Numerous duplicate propane and mixed component refrigerant (MCR) compressors were in operation at a liquified natural gas

(LNG) plant in Indonesia. All the compressors utilized mechanical contact seals without any significant problems or troubles, but oil ingestion into the process had been a concern. Refer to Table 4 for operating conditions.

Table 4. Case A—Operating Conditions.

Compressor String	Wet Gas
Driver	Steam turbine
Speed (RPM)	7,220
Inlet Pressure (PSIA)	50.5
Inlet Temperature (^{o}F)	100.5
Discharge Pressure (PSIA)	244.7
Discharge Temperature (^{o}F)	197.6
Power (HP)	4382
Molecular Weight	36.2
Capacity (ICFM)	8838

Problem Resolution

Oil-free dry gas seals were installed to prevent oil ingestion. The work was performed during a scheduled plantwide overhaul of the compressors. A tandem design dry gas seal was installed, so that one of the seals could handle the full pressure drop while one remained as a backup. It was recommended that the seal housing be remachined to incorporate the gas seal, but this was not feasible due to the required downtime. So the dry gas seal was designed to fit into the existing housing. A new rotor was installed for performance reasons, but was modified to accept either the original mechanical contact seal or the new dry gas seal. This was a typical request during older retrofits for the reason that the dry gas seal may not have performed as expected.

The installation of a new buffer system to support the dry gas seal was required, which was very similar to that of Figure 13.

Case Study B

Background

A wet gas compressor was originally supplied with a buffered labyrinth seal. The labyrinth buffer supply was steam, but with time, extensive wear would increase flowrates and overload the ejectors. Refer to Table 5 for operating conditions.

Table 5. Case B—Operating Conditions.

Compressor String	1 LP	1 HP	2 LP	2 HP
Driver	Steam turbine	Same	Steam turbine	Same
Speed (RPM)	8640	8640	10370	10370
Inlet Pressure (PSIA)	233	439	550	965
Inlet Temperature (^{o}F)	100	100	100	130
Discharge Pressure (PSIA)	449	768	975	1565
Discharge Temperature (^{o}F)	228	217	246	273
Power (HP)	2467	2315	2142	2143
Molecular Weight	7.7	7.0	5.5	5.5
Capacity (ICFM)	2420	1265	817	495

Problem Resolution

It was retrofit with a dry gas seal, buffered from compressor discharge, with an optional fuel gas available. A seal oil system did not exist, due to the use of the labyrinth seals. The lube oil system capacity would have to be increased to include the seals; therefore a separate seal oil system would have to be constructed.

Case Study C

Background

Four hydrogen recycle compressors operating at an oil refinery in Louisiana had been having seal problems for many years. Contaminated seal leakage rates were several barrels a day and higher. The time between seal parts change outs was as little as six months. Chemical attack of the babbitt had forced a change to cast-iron bushing parts with no lining at all in the bores. Wear and scoring of the shaft sleeves required complete removal of the compressor bundle and replacement with a refurbished spare rotor whenever seal leakage rates became too high. At times, raised metal of the sleeve required the use of a cold chisel to allow removal of the bushings. The basic seal design dated from the 1970s and was difficult to assemble. Missing or pinched O-rings often led to startup delays. In operation the compressor internals would foul with chlorides and require frequent water washing to maintain performance. The process gas was dirty and there was no alternate source of gas available. Refer to Table 6 for operating conditions.

Table 6. Case C—Operating Conditions.

Compressor String	Mixed Refrigeration
Driver	Gas turbine
Speed (RPM)	4,670
Inlet Pressure (PSIA)	178.6
Inlet Temperature (^{o}F)	95
Discharge Pressure (PSIA)	665
Discharge Temperature (^{o}F)	262
Power (HP)	25,221
Molecular Weight	25.91
Capacity (ICFM)	17,098

Problem Resolution

Dry gas seals were quoted but rejected due to cost and concerns with reliability using the process gas as a buffer. A cartridge design oil film seal assembly was suggested by the user and agreed to by the compressor manufacturer. This would allow the seals to be bench assembled and checked prior to installation, thus eliminating concerns about damaged or missing O-rings. It was obvious that improved materials were necessary. New seal bushing parts with gold babbitts were installed. The inboard labyrinth seal, located between the process and the oil seal assembly, was made from carbon filled polyetheretherketone (PEEK) thermoplastic instead of aluminum. The spare rotor was reworked with tungsten carbide coated shaft sleeves and installed (Figure 10).

Additionally, tungsten carbide spray coating was applied to the vertical surfaces of the housings where they are contacted by the floating bushings. This coating provides two related benefits. The hardness of the coating minimizes the chance of the bushing brinelling the surface of the housing. This has occasionally happened on high-pressure seals. If the damage is severe, it can prevent the bushing from floating with the shaft and cause it to act like a bearing, creating subsynchronous rotor vibration. The other benefit is the smooth surface finish of the coating will reduce the coefficient of friction between the bushing and the housing; again helping the bushing to float and remain centered on the shaft.

Oil passages were enlarged on the new design to reduce internal pressure drops of the supply oil and to promote better drainage of the contaminated or sour oil. The contaminated drain was a particular concern to the user, as the traps would no longer be vented. The series of eight radial slots in the drain area was replaced by two large bottom slots aligned with the casing drain and two slots in the top that connect to an equalizing line with the overhead seal oil tank.

During a scheduled turnaround at the end of October 2001 all the affected compressors and turbines from the refinery were sent to two of the manufacturer's service shops. The compressors receiving upgraded seals were disassembled, cleaned, and inspected. Any worn or damaged parts were replaced. The casings were machined to add larger annuluses in the seal oil feed areas. Any restrictions in internal oil passages were removed by grinding. Vents were drilled into the sweet oil drain cavities, as these were not included in the original design.

Before startup the oil system was cleaned by hydroblasting. The first two compressors were started November 16, 2001. The new seals continue to operate with leakage less than 1 gal/2 hours/seal, or about 10 to 12 gal/day, which is better than expected for seals of this diameter with an oil to gas differential pressure of 8 or 9 psid.

Case Study D

Background

A hydrocarbon mix compressor of a very old design in an East Coast refinery employed a single mechanical contact seal between the drive coupling and the casing. All bearings operated in contact with the process gas. Refer to Table 7 for operating conditions.

Table 7. Case D—Operating Conditions.

Compressor String	Mix Hydrocarbons
Driver	Steam turbine
Speed (RPM)	7,010
Inlet Pressure (PSIA)	21.6
Inlet Temperature (^{o}F)	37
Discharge Pressure (PSIA)	105.7
Discharge Temperature (^{o}F)	?
Power (HP)	2,450
Molecular Weight	55.5
Capacity (ICFM)	9,100

Problem Resolution

The mechanical seal was removed, and single face dry gas seals were used to replace small buffered labyrinth seals located inboard of the bearings. The seal cavity was too small for anything but the single face arrangement, and even it required specially designed parts. There was concern about the condition of the O-ring sealing surfaces in the seal cavity of the old compressor. Additional porting was required for the separation seal gas. The additional connections were added with internal tubing. The casing design has less than perfect sealing, along the splitline in the seal area; therefore allowing some leakage along the outside diameter (OD) of the seal cartridge itself.

CONCLUSION

There are many items to consider when a user is deciding if a dry gas seal retrofit is justified. For some applications the decision will be simple, others will require more study. In most cases the decision will be simple economics. In cases of dirty process gas, there may be technical and reliability concerns as well. Improvements to older seal technology can offer a reliable and cost-effective alternative.

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