Improving the Reliability of Mechanical Seals

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Mechanical seals provide an important contribution to the operation of many different industries. These ubiquitous devices are found in centrifugal pumps, reactors, mixers, blowers, compressors and some positive-displacement pumps. Despite their widespread use though, they are often given little consideration. With a better understanding of seals, their selection, material considerations, and operational requirements, users can greatly improve equipment reliability and reduce operating costs.

Many chemical processes require variable operating conditions or batch processing. Fluctuations in pressure or temperature, the addition or creation of intermediate compounds, and start/stop operations are not unusual. Equipment may require cleaning, steaming or sterilization between batches. Due to these large variations, users tend to oversize equipment to allow for changes or future increases in capacity. This results in pumps running well away from their best efficiency point (BEP). As a result, pump reliability, bearing life and seal performance are compromised.

Material selection is also a challenge in some processes. While austenitic stainless steels and fluoroelastomers are used in most industries, chemical processing can push material selection to the edge of current technology. Exotic materials, such as titanium or zirconium, may be required for metallic materials. Gasket materials may include polytetrafluoroethylene (PTFE), perfluoroelastomers and flexible graphite. Seal face materials may require special chemically resistant grades of carbon and ceramics.

By far the most challenging aspects of seal selection are due to the nature of the fluids themselves. Almost every fluid in a refinery is a good lubricant. Very few fluids in chemical plants share this property. Process fluids can polymerize on the seal components or crystallize on exposure to the atmosphere. There may be wide swings in fluid properties during a batch or between processes. The seal and system must be designed to tolerate all of these.

Pump selection and operating requirements

It is impossible to define a comprehensive list of factors that could cause a mechanical seal to fail due to the variety of chemicals and processes. By looking across many different industries and end users, though, it is possible to see some repeating patterns that lead to success or failure. By addressing these factors users can improve the performance and reliability of their pumps and seals.

Most chemical industries rely on chemical duty pumps for the majority of their pumping duties. Most of these are based on established standards such as ASME B73. While these standards have evolved over time, they have generally targeted low pressure and moderate temperature applications. They were also historically based on the use of packing for pump sealing, although virtually all pump standards now include or default to the use of mechanical seals.

Most chemical duty pumps are thought of as standardized units. Their designs allow for relatively easy changeouts between design options and manufacturers. This allows users to stock a relatively small number of pumps (or just power ends) to cover a large number of installations. While this does lower inventory levels, it also can encourage users to try to make one pump cover too wide of a range of operating conditions. The majority of pumps chemical plants are not operated near their design or BEP. Dozens of studies have been performed and published that correlate pump and seal reliability to the operating point on the pump curve (*1*). All of these cite a decrease in reliability as the operating point moves away from the BEP.

The initial pump-selection phase is critical to operating pumps at or near their BEP. Unfortunately, many engineers apply liberal “safety factors” when establishing the pumping requirements. One specific user in the chemical industry sizes equipment 50% larger than calculated values.

For oversized pumps that are already in use in a specific application, measures can be taken to move them closer to the BEP. The most common is the use of a recirculation line. Fluid from the discharge line is routed back to the suction piping or vessel. This keeps the flowrate through the pump near the BEP, although only the required flowrate is passed into the discharge system. Trimming the impeller on a pump will reduce the head generated and lower the flowrate into a given system. This should only be done with a full understanding of the pump and system curves and the required pressure in the discharge line. For pumps that must operate over a large range of flows and pressures, consider using variable-speed drives that can adjust the pump output to more closely match the operating requirements.

Mechanical Seal Basics

Mechanical seals provide a seal between a pump casing and a rotating shaft. While this description is simple, it is a significant engineering challenge. Current customer expectations and environmental regulations require no visible leakage for many applications. For many chemicals that are toxic or hazardous, the seals and systems must be designed such that there is no atmospheric leakage under any conditions. One of the fundamental concepts of a mechanical seal is to create a very small separation between the rotating and stationary seal faces. This film must be small enough to control leakage, but not allow excessive face contact. Actual fluid films are on the order of 0.5 mm (or 20 millionth of an inch) on typical seal application. Any condition that jeopardizes this film will affect seal performance.

The pump, piping, baseplate, mechanical seal, seal support systems, coupling, and driver are all integral parts of the pumping system. Failure of any of these components will cause failure of the entire system. At an operating level, degradation or misapplication on any one of these components may show up as a failure in different component. Mechanical seals often act as the barometer for systems integrity. Pipe strain, cavitation or coupling misalignment may all show up initially as a seal failure. Seals are often identified as the problem rather than the symptom of another problem. This is where users with good equipment reliability differ from those with poor reliability — the ability to investigate and understand the factors that affect performance.

Small-bore stuffing boxes vs. large-bore seal chambers

The term “stuffing box” has historically been used to describe the cavity where the pump shaft enters the pump casing. Packing was “stuffed” into the cavity and mechanically compressed to limit leakage out of the pump. While modern mechanical packing and packing flush configurations have evolved to become relatively sophisticated, the principle remains the same.

Due to the requirements for packing, stuffing boxes are designed with a small radial cross-section or clearance between the shaft and stuffing box bore. For most chemical duty pumps, this ranges from approximately 5/16 in. (7.94 mm) to 7/16 in. (11.11 mm) to accommodate the square cross-section packing. Mechanical seals can be applied into these stuffing boxes. In fact, every mechanical seal manufacturer has designed seal models specifically to fit into standard-bore stuffing boxes. This should not be interpreted as an endorsement from the seal industry. In doing so, there are design compromises that can affect seal performance. Parts and clearances must be very small. Fluid flow paths around the seal are very restricted, which can prevent adequate cooling. Higher temperatures and shear may drive some fluids into polymerization. To address these concerns and allow for better seal designs, pump manufacturer can provide larger-bore seal chambers.

Seal chambers are appropriately named. They are designed to accommodate mechanical seals. The most striking difference between stuffing boxes and seal chambers is the size of the radial cross-section. Seal chambers range from approximately 3/4 in. (19.09 mm) to 1.0 in. (25.4 mm). This allows for the installation of more robust seals that can tolerate a wider range of operating conditions. The added clearance also provides better circulation of process fluids around the seal chamber. To maximize the effect of the clearance, pump manufacturers provide several options for seal chambers. A standard large-bore seal chamber is designed to accommodate a throat bushing when seal chamber isolation is required. An open-bore seal chamber allows for better interchange of the seal chamber and pump process fluids. Tapered-bore seal chambers pro-

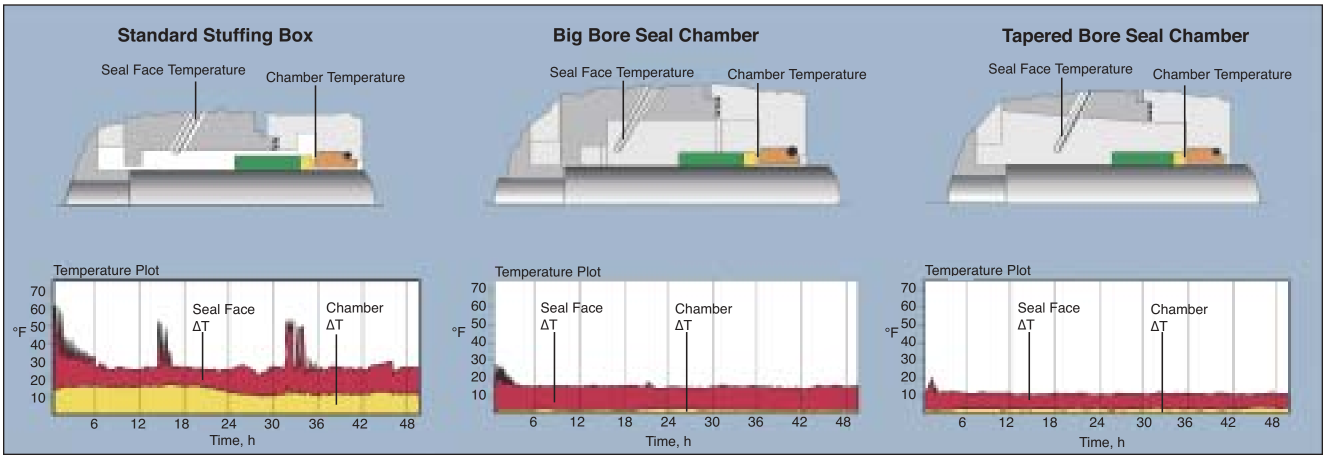


Figure 1. Tests show that seal chambers had significant decreases in the temperatures around the seal and at the seal faces when compared to a standard stuffing box (*2*).

vide for even better fluid interchange and solids rejection. Finally, tapered-bore seal chambers with flow modifiers provide maximum circulation in the seal chamber.

The user may ask if these seal chambers really do provide better operating conditions than stuffing boxes. The simple answer is yes. A series of tests were run to evaluate the effects on temperatures in the pump, seal chamber and seal faces with different seal chambers and stuffing boxes (*2*). The operating conditions (speed, pressure, test fluid) and seal design were constant over the tests. The results showed that seal chambers had significant decreases in the temperatures around the seal and at the seal faces when compared to a standard stuffing box (Figure 1). It is also important to notice the stability of the temperature under steady-state operation. The restricted flow around the seal in a stuffing box allows for spikes in temperature between the seal faces, which can cause flashing or degradation of the process fluid.

Since these results and many more studies have been published to illustrate the benefits of seal chambers (*3*), it is surprising that all pumps with mechanical seals are not equipped with seal chambers. Unfortunately, in many plants over half the pumps may still use stuffing boxes. By changing from stuffing boxes to seal chambers, the user has a greater selection of seals options, benefits of improved seal cooling, and potential for greater seal reliability.

Nature of chemical process and fluids

As stated earlier, mechanical seals operate on a very thin fluid film. This fluid film hydrostatically separates and provides lubrication between the faces. The seal designer has many options for face materials and face loading conditions to accommodate most fluids. It does require that the user understand and communicate exactly what the process conditions are and how they can change during the operation of the equipment.

Some chemical processes operate in a continuous manner where the operating conditions for a piece of equipment are relatively constant over time. In these cases, it is easy to document the application conditions and make equipment selections. Other processes may require variable conditions or batch operations, including starts and stops, or changes in pressures or temperatures. It may involve changes in the composition of the fluid stream over time. A subtle, but potentially important, factor related to this is the formation of intermediate chemicals that are not listed as either inputs or products of a process. These can affect fluid properties and have implications on material selection.

Many batch operations will run in a reactor or vessel that is filled, processed and drained during one cycle. In the draining operation, pumps and seals may be run dry in an attempt to fully evacuate the vessel. The system may then be cleaned and purged with chemicals, steam or nitrogen prior to beginning the next batch. Other systems are designed to be flexible depending upon the needs of the plant. To the extent possible, the variability and duty cycle of these processes must be considered during equipment and material selection.

Oil refineries can provide the ideal environment for seal applications, since many of their primary products are clean lubricants. Chemical processes can be far more challenging. Many solvents, such as acetone, have no lubricating properties. Some fluids must be processed at higher viscosities, which makes it difficult to form a fluid film between the seal faces. Some fluids can be driven into polymerization based on the added heat and fluid shear between the faces. Process fluids can also solidify upon exposure to atmosphere or create deposits due to vaporization of the solvent. Consideration for these effects on seals cannot be obtained by merely looking at a pump datasheet. These effects can only be known by having experience with a given fluid and chemical process. Fortunately, seal manufacturers have a large database of installed seals that provides excellent guidance to what has worked successfully in the same or similar processes. This will include not only seal selection, but also seal configurations and piping plan requirements.

Material selection

Mechanical seals are manufactured from a variety of components that have very different material requirements based on their function. Metal parts form the structure of the seal and must be capable of supporting the pressures and loads of the application. Gaskets provide sealing between other components and must allow for motions and variation in tolerances and thermal growth. Seal faces must provide a good tribological pair to allow for low wear and low friction in operation. All of the components must be rated for the operating temperature and the chemical environment of the application. All of these materials must also work together to allow the seal to function properly. Fortunately, all seal manufacturers have done extensive research into materials and narrowed the selection down to a finite number of options that can meet most application needs.

Metallic materials. Metals are used throughout most chemical processes. Piping, valves and pump components are generally made from metals, and careful consideration goes into their selection.

In most cases, relatively common materials such as austenitic stainless steels (*e.g.*, AISI 316) can be used. In extreme cases, exotic materials, such as zirconium and tantalum, must be used. When material costs become very high, users will often consider service life against initial cost. While there are some up-front cost savings with this approach, the service life is defined with the initial purchase.

Common seal metallic materials are listed below:

- AISI 316 (UNS S31600) — general-duty chromium alloy with a wide range of chemical resistance
- Alloy C-276 (UNS N10276) — nickel-molybdenum-chromium alloy with good resistance in many strong acids and chlorides
- Alloy 20 (UNS N08020) — nickel-chromium-molybdenum alloy with especially good resistance in hot sulfuric acid
- Alloy 400 (UNS N04400) — copper-nickel alloy with excellent resistance in hydrofluoric acid applications
- Inconel 718 (UNS N07718) — excellent corrosive properties and strength at high temperatures
- Titanium — excellent resistance in oxidizing acids and salts
- Zirconium — excellent chemical resistance in strong acids such as nitric and sulfuric acids.

Gaskets. Gaskets form a seal between the various components in the mechanical seal and with the pump. These materials must be not only provide a seal, but also allow for some movement, thermal expansion, and tolerances between components.

In most seal applications this requires a resilient, elastomer-based gasket. Generic names such as ethylene propylene rubber (EPR), nitrile and fluoroelastomer are commonly used to describe elastomer materials. This can be very deceptive since compounding and curing processes have a large effect on physical properties and chemical resistance of elastomers. Perfluoroelastomer selection is even more demanding since these are used in the most aggressive applications and compounds selection can be very application-specific.

Some of the most common gasket materials are:

- Ethylene propylene — copolymer of ethylene and propylene with good resistance in some ketones, alcohols and hot water but not compatible with hydrocarbons
- Nitrile — a copolymer of acrylonitrile and butadiene with good general compatibilities and excellent low temperature properties
- Fluoroelastomers — best standard-duty elastomer with excellent overall chemical capability
- Perfluoroelastomers — a wide range of specific elastomer compounds with superior chemical compatibility and high-temperature properties
- Polytetrafluoroethylene (PTFE) — near universal chemical compatibility, but no resiliency
- Flexible graphite — near universal chemical compatibility and high-temperature capability, but no resiliency.

Seal faces. In most seal applications, the face materials consist of a hard face and a soft face. This combination has proven to provide a low coefficient of friction and best tolerance of face contact. The soft face can also wear to match the profile of the hard face, resulting in a thin fluid film and low leakage. The hard faces in modern mechanical seals are almost exclusively ceramic materials. The soft face is a blend of amorphous carbon, carbon graphite, impurities, and impregnants. In the most aggressive services, some seals will use the two hard faces for the maximum chemical resistance and tolerance of impurities.

The most common hard-face materials are:

- Tungsten carbide with cobalt binder — low-duty WC with cobalt metal phase having poor chemical resistance
- Tungsten carbide with nickel binder — general-duty WC where compatibility is limited by nickel metal phase
- Reaction-bonded silicon carbide — general-duty SiC with free silicon, which limits its use in caustics and strong acids
- Alumina oxide — homogenous ceramic materials with excellent chemical resistance, but poor thermal shock characteristics
- Direct-sintered silicon carbide (also referred to as alpha-sintered SiC or direct-sintered SiC) — homogeneous ceramic SiC material with excellent chemical resistance.

The most common soft-face materials are:

- Metalized carbon — carbon grade with metal phase, which improves strength, but limits chemical compatibility
- Resin-impregnated carbon — general-duty carbon with excellent chemical resistance
- Acid-grade carbon — carbon-grade with low impregnant and ash content to provide superior chemical compatibility.

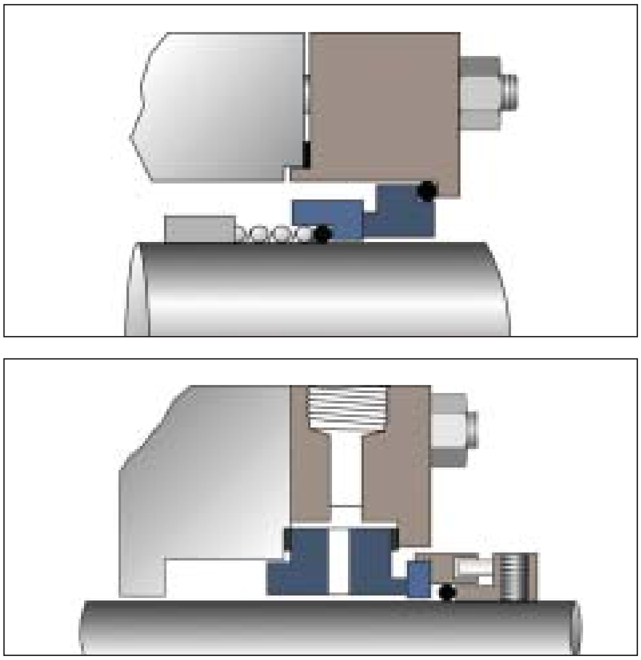
The options listed above are generally arranged in order from the least chemically resistant to the most chemically resistant. This ordering is highly dependent on the actual chemical, concentration, temperature and exposure conditions. Different corrosion mechanisms can also be present depending upon the application and contact with other materials in the seal and pump.

Seal selection

Mechanical seal designs can be divided into two main categories — pusher seals and bellows seals. Pusher seals are designed so that the flexible seal face is sealed against another seal component with a dynamic gasket. This allows the seal face to move axially to compensate for shaft motion, thermal growth, misalignment or seal face wear. The flexible gasket in most pusher seals is a standard cross-section O-ring. This allows easy availability of the gasket in a large number of elastomer compounds. Because the face must remain free to move, any swelling or degradation of the gasket may cause excessive leakage or seal failure.

Bellows seals, on the other hand, do not rely on a dynamic gasket to allow for motion of the flexible face. This design uses a bellows element to provide sealing and motion for the seal face. The most common bellows seal design involves a welded metal bellows. Thin metal diaphragms are welded at the outer and inner diameters to form a continuous barrier between the process fluid and atmosphere. The primary advantage to this design is that there are no dynamic gaskets. Larger amounts of swelling are allowed on the static gaskets without adversely affecting seal performance. In some designs, other static gasket materials, such as PTFE or flexible graphite, are used to provide near universal chemical compatibility for a seal. Bellows seals are also less likely to have the flexible element hang-up due to debris, polymerization or crystallization.

Seal designs can also be categorized according to their exposure to the pump process fluid. In a standard rotating flexible element configuration, many of the seal's metal components are exposed to process conditions. This can create areas where debris may collect or where there will be corrosion of thin metal components, such as springs. To minimize exposure of the metal components, a stationary spring design can be used to remove these components from the process environment. The most extreme option involves removing all of the metal parts out of the process and designing the seal in an outside mounted configuration (Figure 2). While these options can provide benefits in terms of corrosion, there will always be some exposure of the components to the process, so the most compatible materials must be selected.



■ Figure 2. Inside (top) vs. outside (bottom) mounted configurations.

For seal selection, there are design options to handle most applications. Clean products with minimal gasket compatibility issues can successfully use almost any design. As products become more contaminated, change physical properties (crystallize or polymerize), or suffer from elastomer compatibility issues, bellows seals become the preferred selection. For services where the chemical compatibility of metal parts is challenging, outside mounted seals may provide the best service.

Seal support systems

In some cases, pumps contain a single seal operating on the process fluid in the pump. In other cases, multiple seals may be used where leakage of the process fluid must be avoided. There may be still other cases where the process fluid cannot be successfully sealed and a barrier fluid or external fluid must be provided to the seals. Process fluids in the seal chamber may also require cleaning or cooling to improve seal performance. All of these situations are defined and documented in the seal piping plans.

Piping plans are standardized definitions of the piping, control, monitoring and conditioning of the fluid around the mechanical seals. The most common definitions are documented in ASME B73 and API 682. At the simplest end, a seal may run dead-ended in a seal chamber (Plan

02). At the more complex end, a dual pressurized seal will require a barrier fluid and external reservoir (Plan 53). The success of the pump and seal depends upon the correct selection and maintenance of the support system.

One of the most commonly overlooked areas in system maintenance involves dual-seal support systems. Barrier or buffer fluids are used in these systems to provide the environment between the two seals. When a reservoir is first installed and filled with fresh barrier fluid, the environment is known. After long periods of operation, the barrier fluid may become contaminated by process fluid or break down under high temperatures. Most users continue to operate with the same barrier fluid until the seal fails. In many cases, the seal failure is actually hastened due to the poor condition of the barrier fluid. After a seal fails, a surprising number of users simply refill the reservoir and restart the pump. Any contamination or debris in the reservoir or connecting piping is left to re-contaminate the barrier fluid.

Whenever a seal is replaced, the seal support system should be inspected and cleaned prior to operation of the equipment. For all dual-seal systems, the old barrier fluid should be drained and properly discarded. If the barrier system was contaminated with process fluid, the system should be flushed with a compatible fluid. This is also true if there is evidence that debris from the seal failure circulated through the barrier system.

Operator training

Some of the most common causes of seal failures can be traced to operator training. From an operator's perspective, an installed pump and seal should be ready to run whenever required. In reality, many steps need to be taken to ensure a successful start-up. This can include priming the pump, venting the seal, filling the seal support systems, or turning on cooling water, depending upon the application. Many of these requirements may be ignored at a time when there are many other activities requiring the operator's attention. This is especially true when an operator does not fully understand how a pump and seal really work at a detailed level. It is unlikely that operators will become seal experts, but they should be given the knowledge necessary to operate the equipment correctly. This includes training on pump and seal basics. Whenever there is a change in seal or system design, they should be given training on the new requirements or changes in the procedures.

Even after years of training and experience, aircraft pilots go through a checklist before every flight. This ensures that no step will be forgotten or taken for granted. Operating a pump and seal in many processes can be just as dangerous and deserves an equal focus on following established procedures. Whenever possible, training should be documented with a written procedure. To help make the procedure relevant to the operators, it should be documented onto a checklist that the operators can carry with them during the commissioning and operation of a pump and seal.

Think outside of the box

Knowledge is only effective if it is put into action. The author was involved in a troubleshooting exercise at a major chemical plant. Documentation was prepared to conclusively describe the cause of the problems and copies of previously published studies were provided for the users' review. After a few minutes, they looked up and stated that they already knew all of this. This is the way they operated their pumps and they wanted to know what could be done to improve the pumps' performance. Although the meeting went on for some time, it effectively ended when they stated that they were unwilling to correct conditions that were causing their problems. If you change nothing, nothing will change.

Improving pump and seal reliability starts with a change of focus away from initial cost and speed of repair. This requires a recognition of total cost of ownership from a management level. It also requires a dedication to making improvements in existing equipment and systems that are not providing acceptable reliability. Finally, it requires a consistent reliability program to put these concepts into procedures. Although initial efforts may seem high, the results provide excellent medium- and long-term savings. CEP

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