

Extending Equipment Life through Improved Sealing Technology

by

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ABSTRACT: Bearing failure in power generation equipment significantly impacts operating expense and profitability due to costly equipment rebuild and equipment downtime. The primary sources of bearing failure are lack of lubrication and contaminant ingress. Industrial sealing devices are the primary protection against bearing failure. When the sealing device fails, bearing failure is imminent. Therefore, extending the life of sealing devices extends bearing life and in turn improves equipment uptime. The primary measurements of equipment uptime are: Mean Time Between Failures (MTBF) and Mean Time To Repair (MTTR). Each of these metrics is discussed in detail including their primary methods of calculation. Once established as measurable values, attention is then given to improving MTBF and MTTR through sealing innovations. In examining MTBF, common causes of premature seal failure and new technological developments to extend time between failures are considered. In examining MTTR, new products available to facilitate and streamline the repair process are the central focus.

Executive Summary

At the heart of most power generation equipment is a bearing system. When the bearing system fails, high expenses are incurred in costly equipment rebuild and equipment downtime. Bearing failure analysis has revealed that most failures are not due to surface fatigue but rather are a result of lubrication issues. Primarily these issues relate to the loss of lubrication due to seal failure as well as contaminant ingress. Therefore, improving seal life results in improved bearing life; and improving bearing life results in increased equipment uptime.

This article examines the root causes of bearing failure, identifying seal failure as the primary cause. The principles of sealing technology are discussed as well as common sealing methods. In order to provide a means of quantifying the effect of seal performance on equipment uptime, the industry standards for equipment reliability and maintainability are explained in detail with emphasis on improving these metrics through sealing technology innovations.

Finally, the two most common of these measurements, Mean Time Between Failures (MTBF) and Mean Time To Repair (MTTR) are examined as they relate to sealing improvements. Several new innovations are discussed that improve MTBF by keeping the sealing system in service for longer intervals, allowing extended time between maintenance periods. To improve MTTR, sealing products that significantly reduce the time of the maintenance period are discussed in detail.

Understanding Bearing Failure

Whether the equipment in question is a pulverizer, a turbine, conveyance equipment, or something else all together, there is usually a bearing system either driving or being driven by the equipment. In any application where power is transmitted from one point to the next, a bearing system is used to support rotating elements (usually a shaft) and to support the related loads, while at the same time reducing power losses due to friction. The most common types of bearings are ball and roller bearings.

Under textbook conditions, typical ball and roller bearing failures occur due to surface fatigue. Either the bearings or the raceways will begin to pit, resulting in an audible indicator in the form of noise.¹ As the rolling elements continue to degrade, noise and vibration increase and eventually the rolling elements will fracture. This ruins the bearing system and possibly damages connected elements.

A standardized method of predicting bearing failure is the L10 life (also called B90 or C90 life), which is based on the theorem that 90% of a random sample of bearings can be expected to meet or exceed a stated number of revolutions at a given size and load. In actual applications, bearing failure is not so straight forward.

Most bearing systems fail to meet their predicted life due to issues other than fatigue failure. Says one expert on bearing failure: “Only 1% [of bearings] actually fail due to pure fatigue. The majority of bearing failures are from a lubrication-related issue.” This means that approximately “95% of bearing failures can be either prevented or have their service life extended.”² Thus by determining the modes of failure and methods of prevention of these ‘lubrication-related issues,’ bearing life can be drastically improved, avoiding the costly expense of bearing failure.



Figure 1 – Failed Roller Bearing Elements

Understanding the Sealing System

The primary system to protect and extend the life of bearings is the sealing system. When compared to the costs of repairing or replacing the bearing system, the sealing system is much more economical to address. Typically, the sealing system protects the bearing in two ways: it reduces excessive bearing temperatures by retaining lubricant and it prevents damage from foreign material by excluding external debris. Common sealing devices for rotating equipment include: compression packings, labyrinth seals, mechanical face seals, radial lip seals, and hybrid combinations of these seals. For decades radial lip seals have been the most common form of industrial bearing protection. In recent years labyrinth seals (or bearing isolators) have increased in popularity due to their non-contact features.

Radial Lip Seals

A common misconception about radial lip seals is that the lip portion of the seal is intended to be in direct contact with the sealing surface at all times. While this was the case with early lip seal designs, modern lip seals include specialized geometries to create a hydrodynamic sealing element. These designs may include “raised helical or parabolic ribs, triangular pads, or sinuous wavy lip elements.”³ The hydrodynamic effect causes lubricant to recirculate under the sealing lip and back into the bearing system, causing the seal to ride on a thin meniscus of oil which significantly reduces friction and seal element abrasion. The meniscus film is typically 0.00018” (0.0046mm) thick (see figure 2).

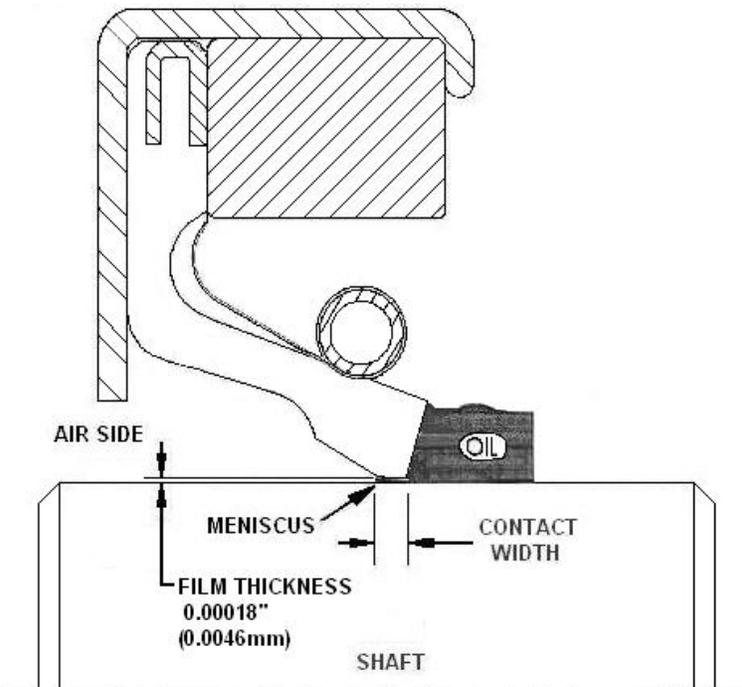


Figure 2

In order to achieve hydrodynamic sealing it is necessary that the shaft be appropriately prepared for dynamic sealing. Therefore, most radial lip seals require a shaft surface finish of 10 to 20 μin (0.25 to 0.50 μm) Ra. In addition to the appropriate surface finish, the shaft must have the appropriate surface hardness. Most seal manufacturers recommend a minimum hardness of 30 Rockwell C (RC). If the surface hardness of the shaft is less than this value, grooving of the shaft can occur, resulting in leakage.

It is also necessary to understand that single lip seals are unidirectional – they can either act to retain lubricant or exclude debris, but cannot necessarily do both. For the seal orientation shown in figure 2, the seal will only retain oil. It will not act to exclude foreign debris from the bearing system. To exclude debris in a light duty environment, a seal with a dust or scraper lip may be used. For heavily contaminated environments, a positive excluder lip design is required (see figure 3).

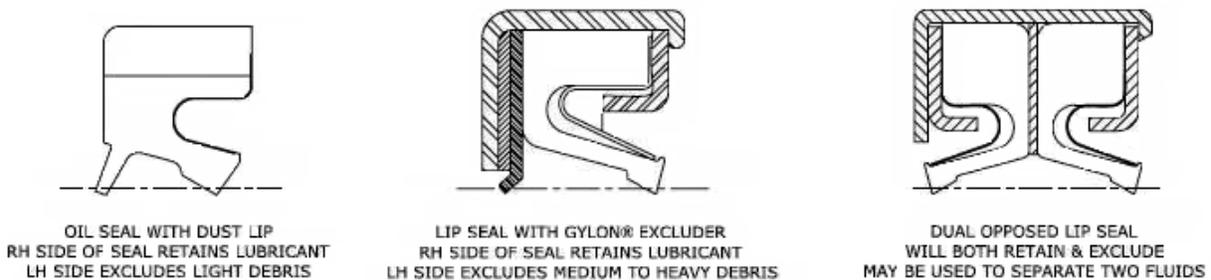


Figure 3

Although in principle radial lip seals ride on a meniscus of oil, in practice this is not always the case. There will be periods, particularly at start up and shut down, when the seal lip is in direct contact with the shaft, resulting in power losses. As hydrodynamic sealing is achieved, this power loss is reduced. Further, the direct contact of the sealing lip against the shaft leads to seal abrasion and eventual failure. The friction and abrasion properties of the sealing material, therefore, play an important role in seal performance. Other factors that will affect seal performance include, but are not limited to: operating temperature, pressure, misalignment & runout, and bore condition.

Labyrinth Seals

As the need for energy conservation has increased, non-contact seals have become more common-place in industry. The most common type of non-contact seal is the labyrinth seal. Traditional labyrinth seals use a torturous pathway to block both the escape of fluids and the ingress of contaminants. They include a static portion that is mated to the application housing and has one or more inside diameter grooves. A dynamic portion of the seal is mated to the shaft and has one or more protrusions (sometimes referred to as teeth or knives) that run inside the grooves of the static portion of the seal. For this reason, the static portion of the seal is referred to as the stator, while the dynamic portion of the seal is referred to as the rotor (see figure 4).

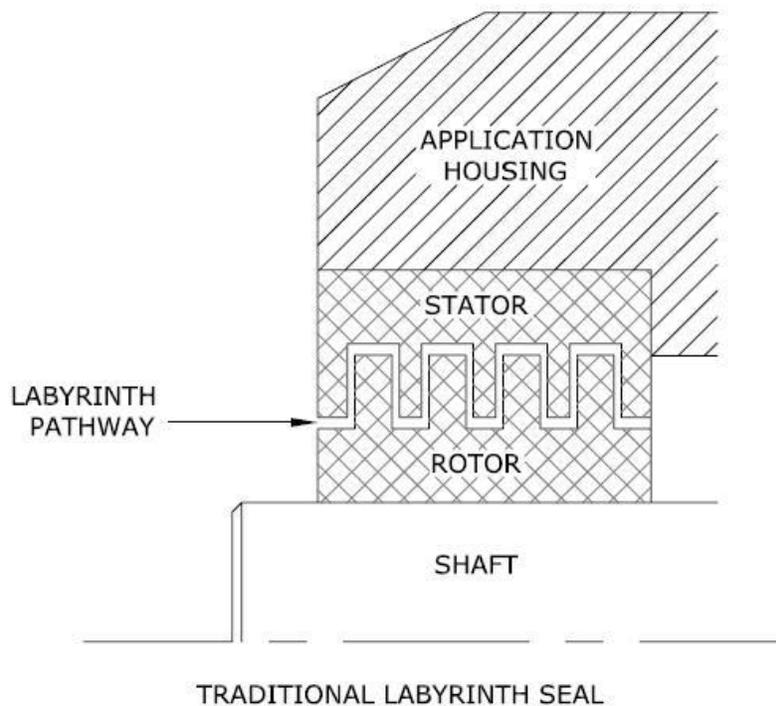


Figure 4

The principle of operation for a basic labyrinth seal is based in statistical motion of a particle on either side of the labyrinth. The more complex the pathway, the less likely that the particle can penetrate from one side of the labyrinth to the other. Early labyrinth seals were considered an option only in applications where some degree of leakage was allowable. Today, labyrinth seals have evolved into bearing isolators (hybrid labyrinth designs), which utilize basic labyrinth technology along with other methods of retention/exclusion including centrifugal force, pressure differential, and drain back design. Today, bearing isolators can provide a much higher performance sealing solution than traditional labyrinth seals.

Standards for Equipment Reliability and Maintainability

With a basic understanding of primary sealing methods, the issue of improving equipment efficiency through innovative sealing technology can be addressed. First, however, a method is required to measure equipment performance. The basic factors used in measuring equipment performance are based in statistics. Primarily, the ratio of uptime verses downtime is involved. In quantifying equipment performance, there are two established standard indicators defined as follows:

1. *Reliability* – the probability that the equipment will perform its intended function, within stated conditions, for a specified period of time.
2. *Maintainability* – the probability that the equipment will be retained in, or restored to, a condition where it can perform its intended function within a specified period of time.

The reliability indicator is quantified by comparing the productive time to the number of failures occurring within a specified time period. The most common method of measurement is the Mean Time Between Failures (MTBF). This value is calculated by the total productive time, which only refers to events occurring during the manufacture of product, divided by the total number of failures during the given productive time. The result is the “average time the equipment performed its intended function between failures.”⁴

$$MTBF = \frac{PT}{N}$$

Where:

MTBF = Mean Time Between Failures

PT = Productive Time

N = Number of Failures That Occur During Productive Time

The maintainability indicator deals with the time required to retain or restore equipment to a state such that it will continue to function as designed. The primary value used to measure this indicator is the Mean Time To Repair (MTTR). It is defined as follows:

$$MTTR = \frac{RT}{N}$$

Where:

MTTR = Mean Time To Repair

RT = Total Repair Time

N = Number of Failures

Innovations in Sealing Technology Improve MTBF

In order to improve the MTBF, the life of the operating components must be extended. It has already been noted that bearing failures rarely occur due to actual fatigue of the bearing surfaces, more often occurring due to lubrication related issues. Therefore, by improving the system's ability to retain bearing lubrication and prevent bearing contamination, the life of the bearing system will be extended significantly.

There are two modes where seal failure affects MTBF. In the first case, the seal fails, the failure is noted, and the system is shut down to replace the seal. Some amount of downtime is incurred to replace the seal. In the second case, the seal fails, but the failure is *not* noted until bearing failure occurs. Significantly more downtime (and cost) is incurred than in the first case. However, in both cases extending seal life is vital to reducing MTBF and the significant costs associated with bearing failure.

Understanding Seal Failure

In determining how to improve seal life, it is first necessary to understand how seals fail. Modes of failure include: thermal degradation, excessive wear due to abrasion, lack of lubrication, chemical degradation, and changes in physical properties while in service.

As noted earlier, in an ideal sealing application the seal lip never directly contacts the shaft surface, but rather rides on a thin film of oil called a meniscus. In typical applications, there are likely periods of dry running of the sealing element (this condition is especially noted during start up). This condition increases the underlip temperature and may cause the seal lip to become hard and brittle. When this occurs, the seal lip can no longer follow the eccentricities of the shaft and leakage results. The direct contact of the seal lip and the shaft also contributes to the abrasion of seal material. This abrasion will eventually decrease the seal's radial cross-section such that the seal lip no longer completely contacts the shaft, again resulting in leakage. A lack of lubrication or actual dry running of the seal exacerbates these conditions.

When exposed to chemicals not compatible with the seal material abnormal swelling may occur. Also, over the course of a seal's service life, the physical properties of the sealing elastomer may significantly change, again resulting in leakage. Properties subject to change include: hardness (durometer), tensile strength, elongation, volume, wear width, and Taber wear factor.

Material Innovations Improve Seal Life

The factors that contribute to seal failure are directly related to the properties of the materials used to manufacture sealing products. For contact seals, elastomers are typically used due to their resilient nature, although some thermoplastic materials are also utilized. Common sealing materials include: Acrylonitrile Butadiene (Buna-N, NBR), Hydrogenated Nitrile Rubber (HNBR), Fluoroelastomer (FKM, Viton[®]), Silicones, and Polytetrafluoroethylene (PTFE, Teflon[®]).

In addition to these materials, Garlock Klozure[®] engineered the Mill-Right[®] family of elastomers. These elastomers offer significant improvements in performance over industrial grade sealing materials. Specific areas these elastomers focus on include improvements in abrasion resistance, chemical resistance, and physical property retention.

Abrasion Resistance

In order to improve a material's wear resistance, a method of quantifying this property is needed. The most common method of measuring a material's resistance to abrasion is the Taber wear test (ASTM D4060). The Taber wear test starts with precisely weighed sample specimens of a particular elastomer. The specimens are "mounted to a rotating turntable and subjected to the wearing action of two abrasive wheels, which are applied at a specific pressure."⁵ When the test is completed the specimens are re-weighed to determine how much material was abraded away. Results are reported in mg loss/1000 cycles. Therefore, the lower the reported value, the better the seal's durability.

Typical Nitrile Rubbers have a Taber Wear Factor of 500 mg loss/1000 or greater. Garlock Klozure's new Mill-Right[®] N reports a Taber Wear Factor of 145.5 mg loss/1000, a 73% improvement in wear resistance over industrial grade nitrile rubber. Similarly, the resistance of HNBR was increased 65% and that of FKM 90%. For specific results see table 1.

	Industrial Grade NBR	Garlock Klozure [®] Mill-Right [®] N	Industrial Grade HNBR	Garlock Klozure [®] Mill-Right [®] ES	Industrial Grade FKM	Garlock Klozure [®] Mill-Right [®] V
Taber Wear Factor (mg loss/1000)	548.0	145.5	113.2	39.2	481.4	49.2

Table 1 – Taber Wear Factor Comparison

Industrial grade nitrile rubber (NBR) loses 548 mg per 1000 cycles in testing. Compare this to Mill-Right N where only 145.5 mg are lost under the same testing conditions. The material loss of Mill-Right N is only ¼ that of industrial grade NBR. Therefore, seals made from Mill-Right N are likely to be in service significantly longer than those made from industrial grade nitrile.

The improvement in material abrasion resistance is highly significant as it directly relates to service life. As abrasion occurs, the lip geometries responsible for hydrodynamic sealing begin to disappear. Further, the required interference between the sealing lip and the shaft reduces, making the seal less capable of handling misalignments in the system. Abrasion may continue to the point where this interference becomes virtually nonexistent. Therefore the less a material abrades away the longer it will continue to perform.

Chemical and Physical Properties

Two common methods of determining a material's ability to retain its physical properties over time are Heat Aging Testing and ASTM 903 Oil Immersion Testing. This testing requires that properties such as hardness, tensile strength, elongation, and volume are measured prior to exposing the sample to heat or oil and are retested after a specified time of exposure.

When exposed to chemicals or heat all elastomers will experience some change in physical properties. The baseline for property retention is perfection – no changes when exposed to chemicals or heat. However, no elastomer will perform perfectly in service. The goal is to get the elastomer to perform as close to perfection as possible. This is a difficult task since the processing and formulation required to maintain certain properties, may have an opposite effect on other properties. Therefore, material formulation and development often ends up being a trade off between the retention of various properties.

If the properties of a sealing material change in service, this will have a significant effect on the overall performance. For instance, changes in volume may affect sealing effectiveness in two ways: if the material shrinks in service, the necessary interferences will be decreased; if the material swells, interference will be excessive. A decrease in interference may affect the seal's misalignment and retention capabilities. An increase in interference may reduce the hydrodynamic effect and result in excessive temperatures.

The Mill-Right materials have dramatically improved the retention of physical properties. The radar charts located in the appendices show the specific improvements regarding each property. The baseline of perfection is noted on these graphs. The deviation from perfection is noted for both the specific Mill-Right material and the industrial grade material.

Other Material Innovations – Gylon®

On April 6, 1938, DuPont chemist, Dr. Roy J. Plunkett made a profound discovery that would change the course of material science history. While working to develop a refrigerant, Dr. Plunkett discovered Polytetrafluoroethylene (PTFE). This was a remarkable discovery, since up to that time it was believed that chlorinated and fluorinated ethylenes could not be polymerized. In 1945, DuPont registered this new material as Teflon. PTFE has desirable sealing qualities because it is virtually inert to all chemicals, has very low coefficient of friction, and does not absorb moisture from its environment. However, unfilled PTFE has a tendency to cold flow (permanently deform under load) while in service, making it questionable as a sealing material. Also, being a very rigid material, when used as a radial lip seal PTFE often lacks the ability to consistently follow the shaft eccentricities found in a typical sealing system.^{6,7}

In the 1960's Garlock developed a new method of manufacturing PTFE and named this proprietary material Gylon®. Originally intended for use in gasket applications, this new material incorporated special fillers to increase stability such that cold flow in service was virtually eliminated. Later this technology was applied to radial lip seals. Garlock Klozure's P/S®-Seals, employ a thin Gylon gasket rolled into a radial lip configuration. This thin feature reacts similar to an elastomer in following shaft eccentricities in a sealing system. The advantages of this type of seal include the ability to run dry without abrading, an extremely low coefficient of friction, and the ability to handle high pressure applications up to and even exceeding 150 psi. However, these seals will not handle excessive shaft-to-bore misalignment or speeds in excess of 2000 feet per minute. Examples of P/S-Seals are shown in figure 5.

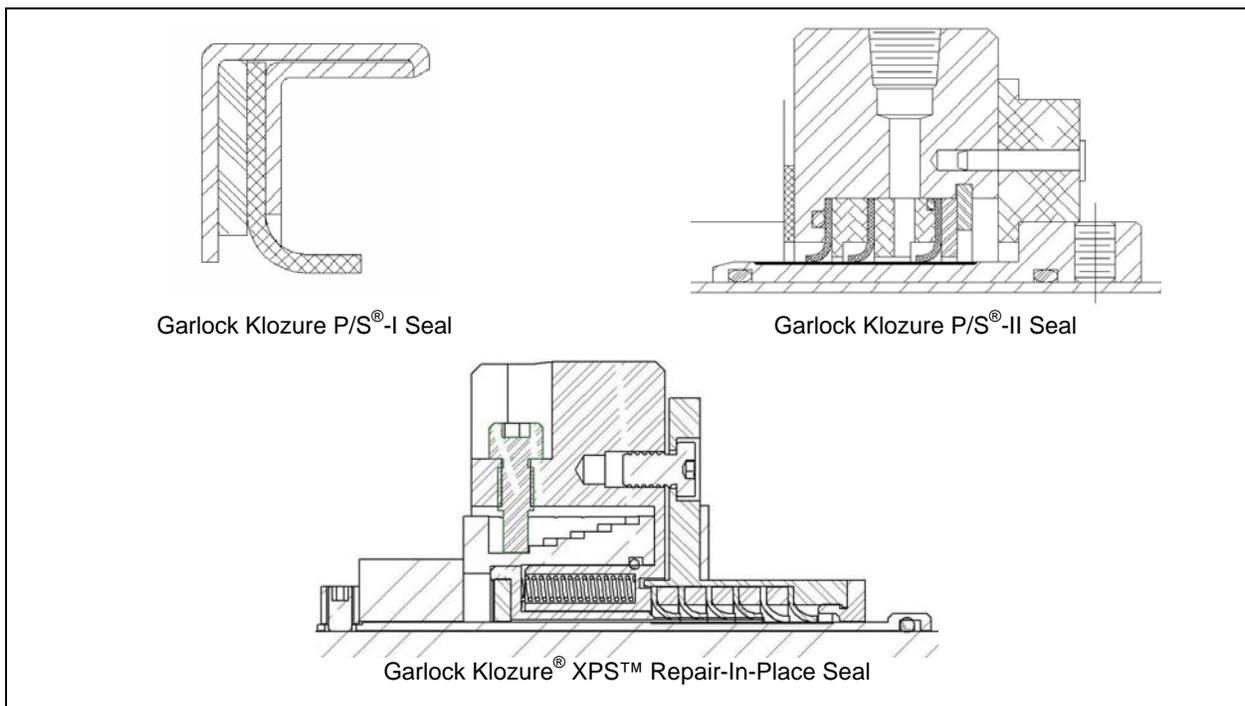


Figure 5 – Garlock Klozure P/S®-Seals

Sealing Product Innovations – Bearing Isolators

Radial lip seals can provide a consistent, reliable sealing system for most applications. However, there are drawbacks. The elastomer materials can be aggressive when applied to the surface of a soft shaft material. If the shaft surface hardness is less than 30 RC, grooving can occur over time. This groove becomes a leak path for lubricant or contaminants. The radial lip seal can also induce a power loss in the system due to the drag force of the seal against the shaft surface. Although this power loss may be small relative to the power consumption of the entire system, increasing demands for power conservation may drive end users to seek alternative sealing methods. In conveyance systems where multiple idle rollers may be driven from a primary source, frictional losses from sealing devices can add up significantly. Other considerations include the fact that most radial lip seals cannot run dry and that most radial lip seals are unidirectional in sealing capacity. For these and other reasons bearing isolators are becoming more commonplace in industrial sealing systems (see table 2).

	Radial Lip Seals	Bearing Isolators
Require Min 30 RC Shaft Surface	YES	NO
Noted Power Loss	YES	NO
Dry Running	NO	YES
Offer Both Retention & Exclusion	NO*	YES
Pressure Sealing	YES	NO

*Assuming single lip oil seal

Table 2 – Comparison of Common Capabilities of Radial Lip Seals and Bearing Isolators

Bearing Isolators, developed from labyrinth seals, incorporate the concept of a tortuous path for fluid sealing with concepts such as centrifugal force, pressure differential, and drain back design. Garlock Klozure’s bearing isolator family of seals incorporate a unitized two-piece design consisting of a rotor and a stator. The rotor is mated to the shaft by means of an o-ring, while the stator is mated to the housing bore in a similar fashion. The stator is statically engaged in the housing bore, while the rotor rotates with the shaft. Any wear occurs internal to the bearing isolator. This is minimized by using low-friction materials of construction, resulting in a highly extended service life. Typically, a Garlock Klozure bearing isolator, when properly specified and installed, will have a service life equal to or greater than the bearing system.

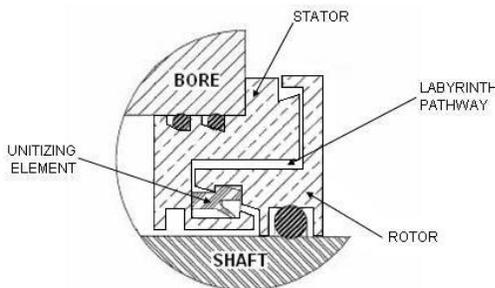


Figure 6 – Garlock Klozure® Guardian™ Bearing Isolator

One industry that has pushed the demand for non-contact seals is wind power generation. Testing by Chitren & Drago, targeting wind power applications, showed that an average oil seal consumes 285 watts of power during normal operation, while during start up the power consumption spikes to 670 watts. Under similar conditions a bearing isolator only consumes 120 watts during normal operation, with spikes up to 150 watts during start up. Other case study data showed the service life of bearing isolators to be up to 65 times that of traditional oil seals.⁸

Innovations in Sealing Technology Improve MTTR

To significantly improve MTTR, it is necessary to identify the steps involved in sufficiently repairing equipment and the time related to each step. In seal maintenance and repair, the most time consuming steps include the disassembly and reassembly of bearing equipment. This may include the disassembly of pillow blocks, motor housings, pump housings, etc. with the necessary realignments and adjustments required after reassembly. One of the main reasons for this is that solid seals must be installed over the free end of a shaft with all attached components removed from the assembly. The innovation of a split seal allows the user to install the sealing device without having to completely disassemble the equipment, drastically reducing maintenance time. The concept of splitting an elastomeric seal has existed for several decades, while this concept has only recently been applied to bearing isolator seals. Another innovation to improve MTTR are seals that can be repaired without removing the seal from service, known as repair-in-place seals.

Split Radial Lip Seals

A split radial lip seal is a relatively simple concept. It involves removing a section of an all rubber seal, to create a seal with a single split point. The seal can be opened along the axis of rotation to allow easy assembly over the diameter of the shaft. Some split seals include a garter spring which needs to be assembled around the shaft onto the seal during installation. This can be cumbersome and even a possible source of equipment failure if the spring becomes dislodged during installation of the seal into the housing bore. Most Garlock Klozure split seals include a molded-in finger spring which eliminates the need for a garter spring and contributes to even load distribution at the contact point on the shaft.

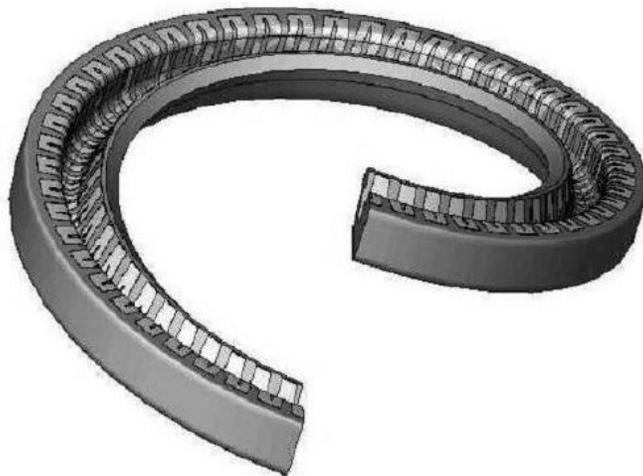


Figure 7 – Garlock Klozure® Model 23 Split Seal

Most split seals require a cover plate in order to be retained within the housing bore. Otherwise, they may “walk” out of the equipment. A cover plate is simply a flat metal plate (either whole or split) that can be bolted against the housing to retain a split seal (see figure 8).

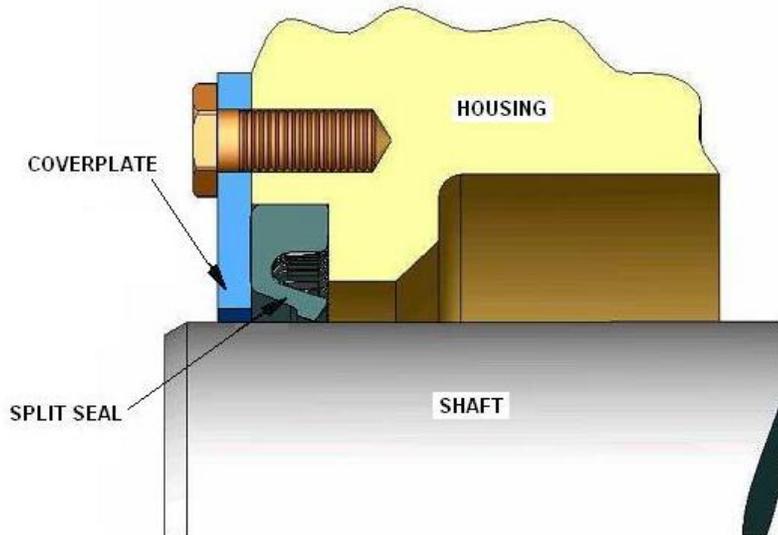


Figure 8 – Split Seal with Cover Plate

It is vital that the seal width and bore depth be properly fitted so that there is appropriate axial retention of the split seal. Some seals like the Garlock Klozure model 26 split seal include a reinforced heel molded into the rubber to improve bore retention. Due to the heel reinforcement, the model 26 split seal does not require a cover plate for housing bores under 10.000 inches (254mm) in diameter (see figure 9).



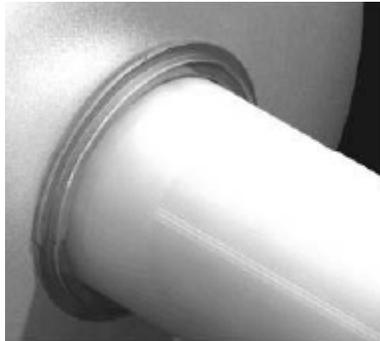
Figure 9 – Garlock Klozure® Model 26 Split Seal

Split Bearing Isolators

A project recently developed and currently in field testing at the time of this writing, is the Garlock Klozure Guardian™ split bearing isolator. This seal uses the same labyrinth technology, including a unitized rotor and stator incorporated into a seal that is split into two halves at the 3 o'clock and 9 o'clock positions. This new seal has similar performance specifications as the original Guardian bearing isolator seal, but allows for easier installation.



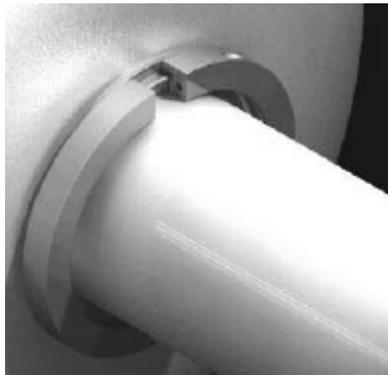
PLACE SPLIT HALVES OF STATOR AROUND SHAFT



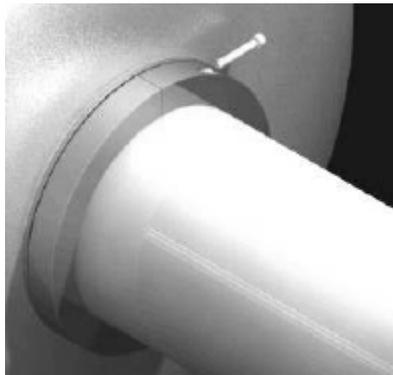
PRESS STATOR HALVES INTO HOUSING BORE



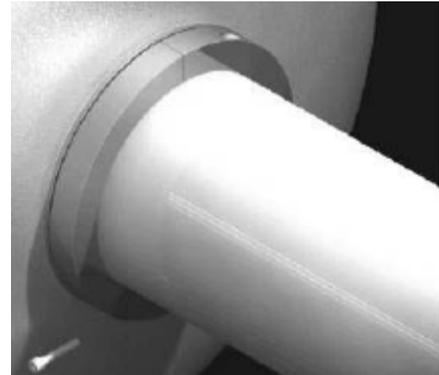
SLIDE ROTOR HALVES AROUND SHAFT



SNAP ROTOR HALVES INTO PLACE AROUND STATOR



THREAD IN RETAINING BOLT 1



THREAD IN RETAINING BOLT 2

Figure 10 – Installation of Garlock Klozure® Guardian™ Split Bearing Isolator

The First Repair-in-Place Seal

While many innovations seek to reduce MTTR, few if any have been able to completely eliminate it. The Garlock Klozure XPS™ mechanical seal was recently developed with this concept in mind – completely eliminate the need for seal replacement!

The XPS seal uses PS-type sealing technology, which involves a thinly formed Gylon lip running on a hardened sleeve. The seal includes a total of 6 Gylon lips, however only two are initially deployed. Four additional sealing elements are stored behind the primary elements on a deployment sleeve. When failure of the primary sealing elements is noted, or when dictated by the preventative maintenance cycle, a simple turn of the deployment screw moves a fresh set of sealing lips into place without any significant downtime.

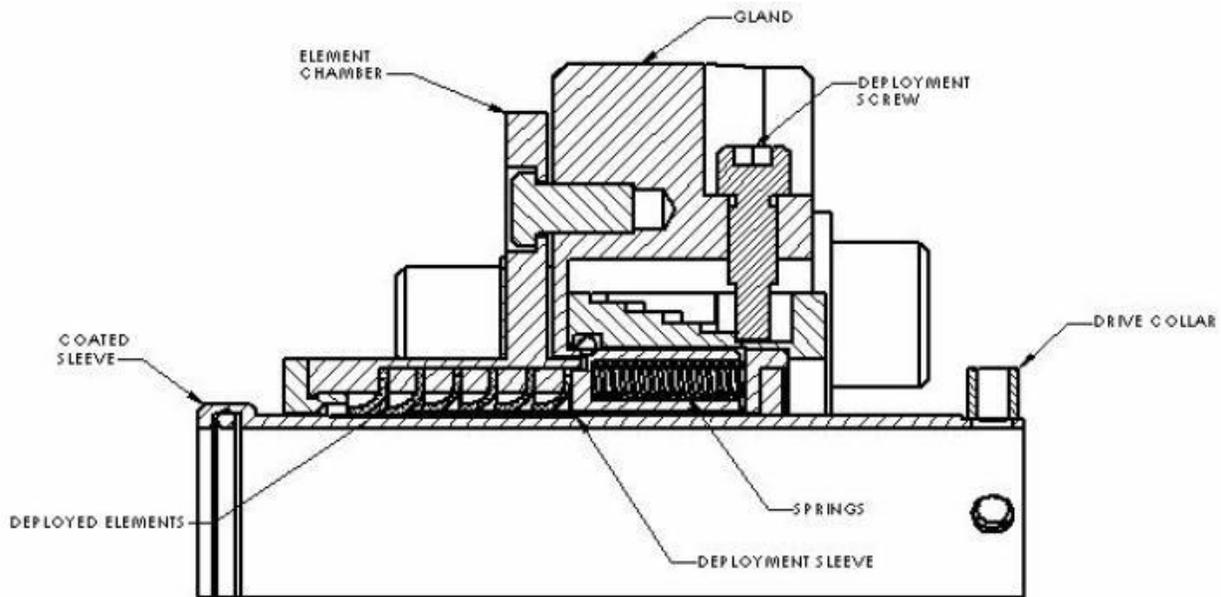


Figure 11 –Garlock Klozure® XPS™ Mechanical Seal

Common sealing applications for the XPS Mechanical Seal may include boilers, scrubbers, pumps, motors, conveyors, and gear boxes. Common sealing media may include water, caustics, and petroleum-based lubricants. When the last set of sealing lips has exhausted its service life, the cartridge-based deployment section can be refurbished, allowing the XPS seal to be reloaded for further in-place repairs.⁹

Conclusion

Improving equipment life is not a simple task. Equipment needs to be broken down into systems, systems into sub-systems, and sub-systems into components. However, since the bearing system is one of the key elements of power generation equipment, significantly improving its life will have a profound effect on the overall equipment performance. Appropriate sealing devices are critical to bearing efficacy. Utilizing tools such as Mean Time Between Failures and Mean Time To Repair provide the necessary metrics to gauge system performance. New innovations such as advanced sealing materials and non-contact seals help to improve these indicators as well as meet requirements for increased power conservation. Innovations such as split seals and bearing isolators, as well as repair in place technology can significantly reduce maintenance costs.

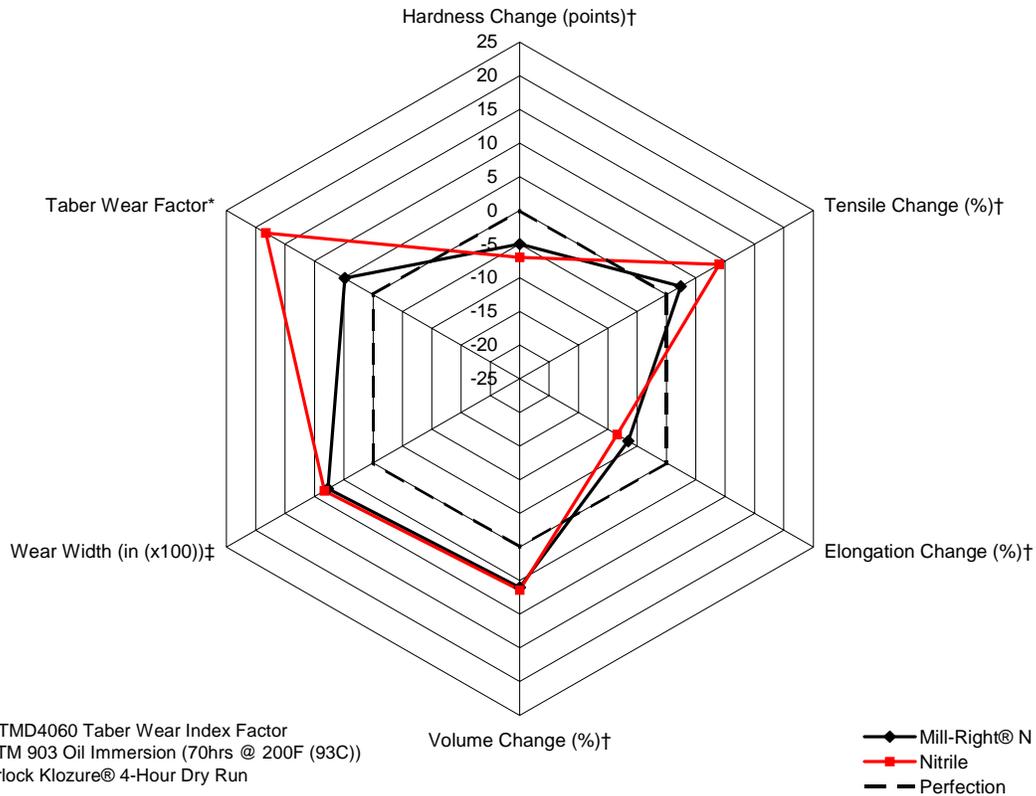
Improving Equipment life is a continuous process. Demands for increased efficiency and decreased power consumption will continue. Thus the need to innovate will continue, building on existing technologies and developing new ones.

Appendix A – Mill-Right® Data

Mill-Right N Radar Chart

This chart compares Mill-Right N's ability to retain its physical properties over time with that of industrial grade Nitrile rubber.

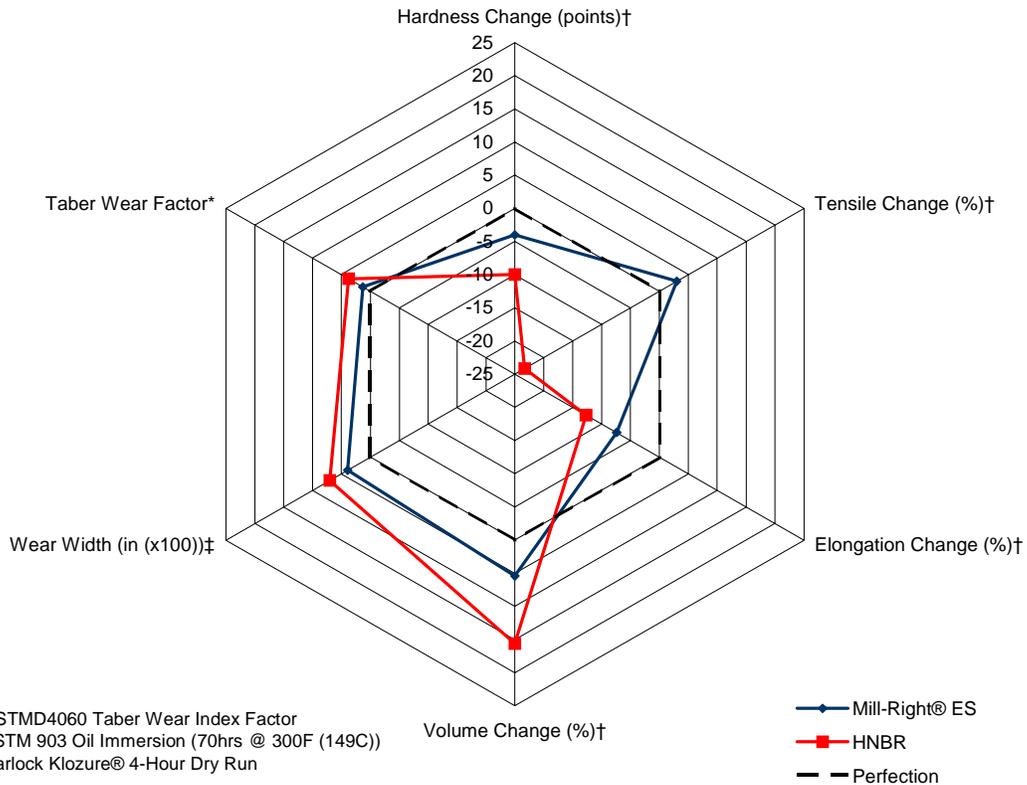
Garlock Klozure® Mill-Right® N Vs. Nitrile



Mill-Right ES Radar Chart

This chart compares Mill-Right ES's ability to retain its physical properties over time with that of industrial grade Hydrogenated Nitrile rubber.

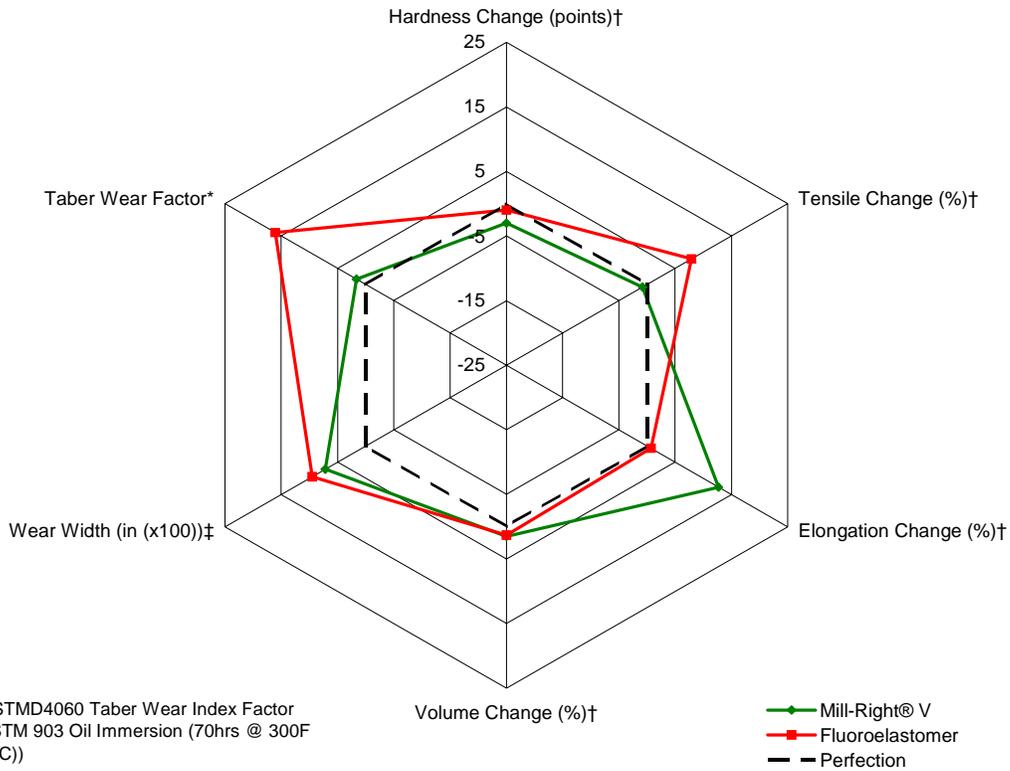
Garlock Klozure® Mill-Right® ES Vs. HNBR



Mill-Right V Radar Chart

This chart compares Mill-Right V's ability to retain its physical properties over time with that of industrial grade Fluoroelastomer.

Garlock Klozure® Mill-Right® V Vs. Fluoroelastomer



Appendix B – References

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