Mechanical Seal Failure Modes

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Mechanical seals are used in industrial pumps, compressors, and other applications to provide a leakproof seal between component parts. There are many different designs of a mechanical seal to meet specific applications. A mechanical seal may be an assembly designed to form a leakproof seal between flat, rotating surfaces to prevent high-pressure leakage. It may be a device to join systems or mechanisms together by preventing leakage (e.g., in a plumbing system), containing pressure, or excluding contamination. A mechanical seal may be a device which prevents leakage of fluids along rotating shafts, the primary seal function at right angles to the axis of rotation between one stationary ring and one rotating ring. Or it may be designed to prevent leakage between a rotating shaft and its housing under conditions of extreme pressure, shaft speed and temperature. Thus, a mechanical seal can be either a dynamic design with spring elements mounted in the dynamic (rotating) part of the seal system. It can also be a stationary seal with spring elements mounted in the stationary part of the seal system to compensate for misalignment of the shaft and seal.

Mechanical seals for rotating shaft applications move the point of the seal away from the shaft to specially designed sealing faces that gradually wear down. This design provides an extended service life compared to a lip seal that contacts the rotating shaft directly. Lip seals may wear a circumferential groove into the rotating shaft, requiring its eventual replacement, while mechanical seals provide a gradual wear of the sealing faces thus extending the service life and preventing shaft damage. In one design two highly polished carbon seal faces provide the seal. One is attached to the fixed part of the machine, the other to the rotating part. A system of springs is used to ensure the carbon seal faces are kept in contact. Single acting mechanical seals have one sealing gap; the lubrication film required by the sliding seal faces is provided by the medium to be sealed. In double acting mechanical seals the lubrication film required by the seal faces is provided by a higher pressure sealant liquid that is compatible with the product under pressure. The sealant liquid is under a higher pressure so that any leakage across the seal faces will be the sealant liquid into the system product. This buffer serves to separate the product and the atmosphere.

Depending on the application, mechanical seals may be a pusher type design, non-pusher, unbalanced or balanced. Pusher type seals use an axially mounted spring on the shaft sealing assembly to apply a fixed sealing force to the sealing faces. Non-pusher seals use a sealed bellows instead of a spring for pushing the seal faces together. A balanced mechanical seal is designed so that the effective contact pressure is always less than the fluid pressure, reducing friction at the seal faces. The result is less rubbing wear, less heat generated and higher system fluid pressure capability. In an unbalanced seal, fluid pressure is not relieved by the face geometry; the seal faces withstand full system fluid pressure plus surge pressures and spring pressure. Thus, the face contact pressure is greater than or equal to system fluid pressure. The balanced seal design is more expensive than the unbalanced design but provides higher reliability and longer life. Regardless of the specific design of our mechanical seal, we can expect it to have three basic parts including seal faces, secondary sealing elements (O-rings, rubber boots, bellows, polymer wedges) and metal parts (springs, retaining rings, drive pins, set screws, compression rings).

Some mechanical seals wear out with use and some fail prior to wearing out. The seal face is the only part of a mechanical seal designed to wear out. Mechanical face seals should last until the carbon face wears away. If the seal starts leaking before that happens and the seal requires replacement, then the seal has failed. More than 85% of all mechanical seals fail long before they wear out. A failed seal will have seal face material remaining. What causes a mechanical seal to fail? One possibility is that the seal face has opened because it became jammed on the rotating component. The other possibility is that one of the seal components such as the spring was damaged by contact, heat, corrosion, etc. The reliability of a mechanical seal depends to a very large extent on its ability to maintain a thin film in the gap between the mating surfaces and at the same time minimizing the mechanical contact of the face surfaces. Too much contact may cause overheating of the face materials and insufficient contact may cause excessive leakage. Over time common modes of seal failure are by fatigue-like surface embrittlement, abrasive removal of material, and corrosion. Wear and sealing efficiency of fluid system seals are related to the characteristics of the surrounding operating fluid. Abrasive particles present in the fluid during operation will have a strong influence on the wear resistance of seals, the wear rate of the seal increasing with the quantity of environmental contamination. A good understanding of the wear mechanism involved will help determine potential seal deterioration. For example, contaminants from the environment such as sand can enter the fluid system and become embedded in the elastomeric seals causing abrasive cutting and damage to shafts.

Wear often occurs between the primary ring and mating ring. This surface contact is maintained by a spring. There is a film of liquid maintained between the sealing surfaces to eliminate as much friction as possible. For most mechanical seals, the three common points of sealing contact occur between the following points:

(1) Mating surfaces between primary and mating rings

(2) Between the rotating component and shaft or sleeve

(3) Between the stationary component and the gland plate

Wear and sealing efficiency of fluid system seals are related to the characteristics of the surrounding operating fluid. Abrasive particles present in the fluid during operation will have a strong influence on the wear resistance of seals. Seals typically operate with sliding contact. Elastomer wear is analogous to metal degradation. However, elastomers are more sensitive to thermal deterioration than to mechanical wear. Hard particles can become embedded in soft elastomeric and metal surfaces leading to abrasion of the harder mating surfaces forming the seal, resulting in leakage.

A failure mode especially applicable to low pressure applications is compression set. Compression set refers to the permanent deflection remaining in the seal after complete release of a squeezing load while exposed to a particular temperature level. Compression set reflects the partial loss of elastic memory due to the time effect. Operating over extreme temperatures can result in compression-type seals such as O-rings to leak fluid at low pressures because they have deformed permanently or taken a set after used for a period of time.

Failure modes of a mechanical seal can be identified by three main causes of failure: temperature, pressure and velocity and a combination of these variables. For example, fluid pressure can create extra heat at the seal face which in turn can increase the rate of wear and other destructive failure modes such as material fracture and distortion and leakage. Elastomer seals can become extruded and damaged. As the pressure is increased, the probability of failure goes up.

Of greatest importance with mechanical seals is a properly designed seal face. Proper mating surface materials must be matched so that excessive heat isn't generated from the dynamic motion of the seal faces. Too much heat can cause thermal distortions on the face of the seal and cause gaps which can increase the leakage rate. It can also cause material changes that can significantly increase the seal face wear rate.

An important factor in the design of mechanical seals is the pressure velocity (PV) coefficient. The PV coefficient is defined as the product of the seal face or system pressure and the fluid velocity. This factor is useful in estimating seal reliability when compared with manufacturer’s limits. If the PV limit is exceeded, a seal may wear at a rate greater than desired.

There should be special consideration for tradeoffs involved with each type of seal material. For example, solid silicon carbide has excellent abrasion resistance, good corrosion resistance, and moderate thermal shock resistance. This material has better qualities than a carbon-graphite base material but has a *PV* value of 500,000 lb/in-min while carbon-graphite has a 50,000 lb/in-min *PV* value. With all other values being the same, the heat generated would be five times greater for solid silicon carbide than for carbon-graphite materials. The required cooling flow to the solid silicon carbide seal would be larger to maintain the film thickness on the dynamic seal faces. If this cooling flow can't be maintained, then an increase in wear would occur due to higher surface temperatures.

The various failure modes and causes for mechanical seals are listed in the following table.

Typical Failure Modes and Causes for Mechanical Seals

FAILURE MODES	FAILURE CAUSES
Accelerated seal face wear	- Misalignment - Shaft out-of-roundness - Excessive shaft end play - Excessive torque - Surface finish deterioration - Contaminants - Inadequate lubrication
Open seal face - axial	- End play - Thrust movement - Temperature growth - Impeller adjustment error - Dynamic elastomer not free to move on shaft* - Chipped edges – face separation - Spiral failure **
Open seal face - radial	- Bent shaft - Shaft whip - Shaft deflection

Typical Failure Modes and Causes for Mechanical Seals
(Continued)

FAILURE MODES	FAILURE CAUSES
O-ring failure	- Excessive temperature > 55 C - Excessive fluid pressure - Installation error
Small leakage	- Insufficient squeeze - Installation damage
Seal embrittlement	- Contaminants - Fluid/seal incompatibility - Thermal degradation - Idle periods between use
Fractured spring	- Material flaws - Stress concentration due to tooling marks - Corrosion - Misalignment
Clogged spring	- Fluid contaminants
Clogged bellows	- Fluid hardens during down time - Particles stuck at the inside of the bellows
Seal fracture	- Stress-corrosion cracking - Excessive PV value - Excessive fluid pressure on seal
Seal face edge chipping	- Excessive shaft deflection - Seal faces out-of-square - Excessive shaft whip
Axial shear	- Excessive pressure loading
Torsional shear	- Excessive torque due to improper lubrication - Excessive fluid pressure surges
Compression set and low pressure leakage	- Extreme temperature operation
Fluid seepage	- Insufficient seal squeeze (loss of spring tension) - Foreign material on rubbing surface
Seal face distortion	- Excessive fluid pressure on seal - Foreign material trapped between faces - Excessive PV value of seal operation - Insufficient seal lubrication
Excessive friction resulting in slow mechanical response	- Excessive squeeze - Excessive seal swell - Seal extrusion - Metal-to-metal contact (out of alignment)

* Oversize shaft, rough surface finish, excessive fluid temperature causing elastomer to stick to the shaft, contaminants.

** Spiral failure – caused by conditions which allow some parts of the ring to slide and others to roll causing twisting.

Application limits, minimum leakage requirements, and the seal environment must be considered when estimating the life of a mechanical seal. Steady state continuous applications are easier to predict than cyclic operations. Seal faces will obviously last a great deal longer when the lubrication film is consistent. With all the variables concerning the design and application of mechanical seals, how does one determine their reliability in the intended operating environment? The "Handbook of Reliability Prediction Procedures for Mechanical Equipment" published by the Carderock Division of the Naval Surface Warfare Center (CDNSWC) provides the procedures and equations for estimating the reliability of mechanical equipment. A software package is also available that automates use of the Handbook. Both products can be downloaded from the Navy website free of charge.

The best way of using the Handbook and estimating the failure rate of a mechanical seal is use of the Failure Mode, Effects and Criticality Analysis (FMECA). A mechanical seal will normally be a component part of a pump, compressor or other system component at a higher indenture level. Therefore, the failure mode at the higher component level may refer to the seal as damaged or in the case of a seal face as worn. Or the failure mode at the higher indenture level may list the failure mode as internal or external leakage with the seal listed as the failure cause. In either case the failure modes at the mechanical seal level must be evaluated and entered on the FMECA worksheets.

Failure Mode and Effects Analysis (FMEA) Worksheet

The FMECA is normally performed by first identifying the failure modes and then estimating the probability of occurrence for each identified failure mode. This section provides some guidelines for performing the FMEA for mechanical seals.

Function: The following guidelines assume that a hardware bottom-up analysis is being performed. The purpose of the FMEA is to identify all potential failure modes of the equipment. Since the mechanical seal is generally a part of a component at a higher indenture level, the seal must be evaluated for reliability considering the operating environment of the pump, compressor or other component where the seal is located. Therefore, the seal should be identified as a functional description as shown in Figure 1 below. This process permits a technical review of the seal function within the equipment and identification of all failure modes applicable to the seal design.

Failure Modes: It is important that the identified failure mode be directed toward a specific failure mode at the component level such as leakage. Only one failure mode should be entered for each row because of individual failure effects, α and β values and compensating provisions. Some failure modes will have a very low probability of occurrence or may not be applicable for a given application. They can be either eliminated from the worksheet or a 0.0 probability of occurrence assigned.

Figure 1. Partial FMEA Worksheet

Function No.	Function	Mode ID No.	Failure Modes	Cause ID No.	Failure Causes
1	Functional description of the mechanical seal at the next higher indenture level	1	Failure modes of the mechanical seal such as damaged seal face or compression spring	1	Description of all probable independent causes of this specific failure mode at the seal level such as bent shaft or
				2	Excessive heat due to friction
				3	Chipped seal face
		2	Only one failure mode should be entered for each row because of individual failure effects, α and β values and compensating provisions	1	
				2	

Failure Causes: The different causes of the failure mode occurring should be entered one row at a time so that the probability of occurrence of each failure cause can be entered. The operating environment needs to be considered so that all possible causes are entered such as contaminants, fluid incompatibility, pressure pulsations and excessive PV coefficient.

Failure Effects: Local failure effects are the consequences of the failure mode on the equipment at the part level. This entry may be the same as the failure cause or the failure effect at the component level depending on the complexity of the total equipment. The effect of the failure mode occurrence at the next higher indenture level is then entered. See Figure 2. The end failure effect is the consequence of the failure mode occurrence at the total system level. In some cases the failure effects for different failure causes will be the same.

Figure 2. Partial FMEA Worksheet

Mission Phase or Operational Mode	Local Failure Effect	Next Higher Failure Effect	End Failure Effect	Failure Detection Method
The mode in which the equipment is operating when the seal fails	Consequences of the failure cause on equipment operation at the part level	Impact of the failure at the next higher indenture level	Total effect of the failure mode on the operation, function or operational status	Method by which occurrence of the failure cause is detected

Failure Detection Method: The method by which occurrence of the failure cause is detected is entered on the worksheet which may be by many different means such as operator, warning device, sensing device or routine diagnostic maintenance.

Compensating Provisions: Provisions in the design or operator actions are entered on the worksheet that circumvent or mitigate the effect of the failure such as equipment redundancy, alarm provisions, safety features or alternate modes of operation. See Figure 3.

Severity Class: One of the following severity categories is recorded:

Class 1 is catastrophic, a failure which may cause death, total property damage or loss of mission (fire).

Class II is critical, a failure that may cause severe injury or extensive property damage (transmission failure).

Class III is marginal, a failure that may cause minor injury, minor property damage or mission degradation (excessive leakage).

Class IV is minor (a failure not serious enough to cause injury, property damage or mission degradation but may necessitate repairs at a later time (minor leakage).

Remarks: Remarks need to be entered that clarify or amplify other worksheet entries such as design features, safety provisions combination of entries, etc.

Figure 3. Partial FMEA Worksheet

Compensating Provisions	**Severity Class**	**Remarks**
Provisions in the equipment design which alter the effect of failure mode occurrence	Severity Class of I, II, III, or IV	Remarks that clarify or amplify worksheet entries

Criticality Analysis (CA) Worksheet

A Criticality Analysis (CA) is performed following the FMEA to determine the probability of occurrence that an identified failure mode will actually result in the defined end effect. In most cases the CA worksheet will repeat the columns that identify the component function, failure modes, failure causes, and ID numbers so that the entries can be traced from one worksheet to another. See Figure 4. This section provides some guidelines for determining failure rates and occurrence probabilities.

Failure Rate Data Source: The source of the part failure rate is entered such as RAC, OREDA, NPRD or NSWC Handbook.

Figure 4. Partial CA Worksheet

Failure Rate Data Source	Base Failure Rate	Adjustment Factors (π)	Part Failure Rate	Failure Effect Probability (β)	Failure Mode Ratio (α)
OREDA, RAC, NPRD, NSWC HDBK, etc.	Failure rate from source	Correction factors as required to convert acquired failure rate to application failure rate	Base failure rate multiplied by π factor	Conditional probability that identified failure mode will result in end effect (0.0 to 1.0)	Ratio of part failure rate related to identified failure mode

Base Failure Rate: The failure rate of the part as provided by the data source is entered on the worksheet.

Adjustment (π) factor: If the failure rate is obtained from a source where the operational environment is different from the intended operating environment of the equipment being analyzed, an adjustment factor may need to be applied. An O-ring for example may be a static seal within the dynamic seal assembly or part of a sliding-action dynamic seal. Depending on the failure rate source, a duty cycle may need to be considered in determining an adjustment factor.

Part Failure Rate: This entry is simply the base failure rate multiplied by the π factor.

Failure Effect Probability: The failure mode may directly result in the listed end effect or it may not always result in the listed end effect. It is an engineering judgment as to the probability of occurrence after reviewing the failure causes and the operating environment of the equipment.

Failure Mode Ratio: The part failure rate will be the total failure rate of the component containing the seal under normal operating conditions. This failure rate needs to be subdivided per the particular component failure rate. The total of all the α values for each equipment item (function) entry will be equal to 1.0.

Failure Mode Criticality Number: This number is a combination of the part failure rate, failure effect probability and failure mode ratio. This number establishes a reference that can be used to compare the occurrence probability of this particular failure mode with other failure mode probabilities. See Figure 5.

Part Criticality Number: A criticality number for the part is sometimes valuable for evaluating the criticality of the particular valve being analyzed in relation to other components of the system. The part criticality number is simply the summation of all the failure mode criticality numbers for the component.

Severity Class: The severity class from the FMEA worksheet is normally repeated for informational purposes.

Remarks: Remarks are included on the worksheet to clarify or amplify other entries on the worksheet such as explanations of failure rate sources, modification numbers, and calculations.

Figure 5. Partial CA Worksheet

Failure Mode Criticality Number, C_N ($\lambda_p \times \beta \times \alpha$)	**Part Criticality Number $\sum C_N$**	**Severity Class**	**Remarks**
Failure mode criticality number establishes reference for comparison purposes	Part criticality number establishes reference for comparison purposes	The severity of the failure mode copied from the FMEA worksheet	Remarks to clarify or amplify other worksheet entries such as failure rate sources and adjustment factors

SUMMARY

The "Handbook of Reliability Prediction Procedures for Mechanical Equipment" provides the procedures for performing a FMECA and determining the component failure rates. The Handbook along with a supporting software package can be downloaded free of charge.

The Handbook was developed by the Carderock Division of the Naval Surface Warfare Center. Support Systems Technology Corp. (SSTC) was the primary contractor on this development project and we continue to provide research in maintaining the Handbook and the supporting MechRel software program. To obtain a complete copy of the Handbook and the MechRel software package at no cost, contact us at sstc@mechrel.com

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