Chapter 5

Failure of mechanical shaft seals

1. Introduction to failures
2. Lubrication failures
3. Contamination failures
4. Chemical, physical degrading and wear
5. Installation failures
6. System failures
7. Shaft seal failure analysis

1. Introduction to failures

Failure of the mechanical shaft seal is the most common cause of pump downtime. The shaft seal is exposed to widely varying operating conditions. Sometimes operating conditions change to become quite different from the specific conditions for which the seal was intended.

The diagrams below show that shaft seal failure is by far the most common cause of pump system failure. See figures 5.1 and 5.2.

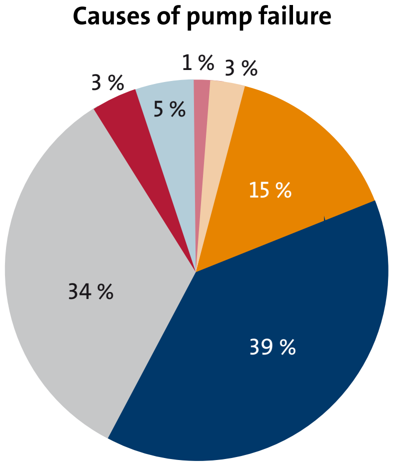


Fig. 5.1: Analysis of pump failure. Mechanical seals account for 39 % of pump failures. [1]

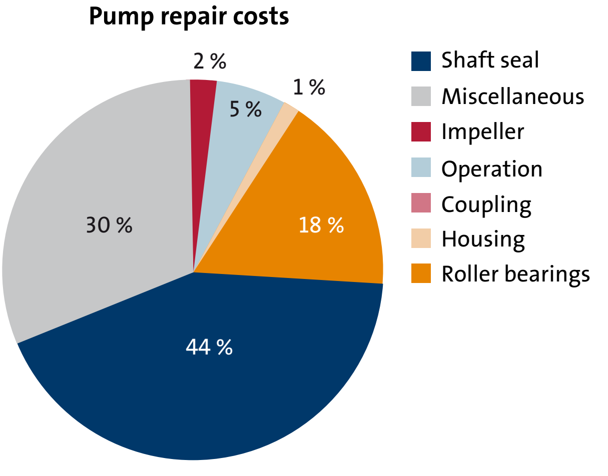


Fig. 5.2: Analysis of pump repair costs. Mechanical seals account for 44 % of pump repair costs. [1]

Typical shaft seal failures depend highly on the seal type and material pairing. O-ring-type shaft seals with dynamic O-ring and one seal ring in carbon-graphite typically have problems with wear on seal faces and seal hang-up, which prevents axial movement of the dynamic O-ring and seal ring. Mechanical shaft seals with hard/hard seal face material pairings usually experience problems associated with dry running.
Detailed information is required to make a failure analysis of a damaged shaft seal and subsequently prevent new failures. On the damaged shaft seal, it is possible to observe what is damaged, but the reason for the damage must often be found on the basis of knowledge of the pump and the application. This information should be recorded in a damage report, including details on the operating conditions of the equipment and components around the shaft seal.
See shaft seal failure analysis, pages 89-91.

In the following, examples of common causes of failure of mechanical shaft seals will be discussed.

2. Lubrication failures

Proper functioning of mechanical shaft seals with hard/hard seal face material pairings depends on lubrication by the pumped medium. Dry running and poor lubrication can produce the results described below.

Dry running

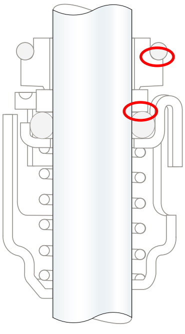


Fig. 5.3: Surface damage due to high temperature on EPDM and FKM secondary seals

Dry running occurs when there is no liquid around the seal, either due to the absence of pumped medium in the pump or poor venting, resulting in the formation of air around the seal. The absence of lubricating film causes the friction between the seal faces to increase. Consequently, the temperature rise dramatically.

As there is no pumped medium in contact with the seal rings, the heat must be transported away through the seal. Many seals with hard seal faces reach a temperature of several hundred degrees Celsius on the seal faces within few minutes. The typical damage caused by dry running is burnt elastomeric parts. The damage occurs where the O-ring is in contact with the hot seal ring. See fig. 5.3.

Poor lubrication

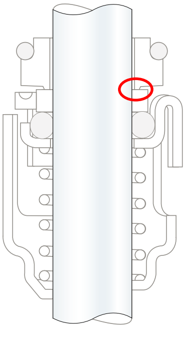


Fig. 5.4: Severe thermal cracks in WC seal face caused by poor lubrication

Similar to dry running, the frictional heat generated on the seal faces as a result of poor lubrication may also cause problems. Poor lubrication may occur when the viscosity of the pumped medium is very low or if the temperature is well above the boiling point at atmospheric pressure.

Under these conditions, the frictional heat dissipating in small areas on the seal face can be very high. The alternating local heating and cooling of the seal faces may cause small, radial, thermal cracks in the seal faces. See fig. 5.4.

Noise

When lubrication is poor or totally absent, shaft seals with seal rings made of hard materials tend to generate a loud noise. Depending on the seal design, the hard materials used and the system, the noise can be at a constant level of intensity and frequency or be more random.

When noise is generated from the mechanical shaft seal, some parts of the seal vibrate. This may reduce the life of the seal. Metal bellows seals in particular have a tendency to fatigue on account of vibrations.

3. Contamination failures

The pumped medium is often a mixture of miscible liquids and a solution of solids, in addition to small suspended insoluble particles.

The lubricating film in the sealing gap is subjected to large gradients in temperature, pressure and velocity. This increases the risk of precipitation and sedimentation in or near the sealing gap.

Hang–up

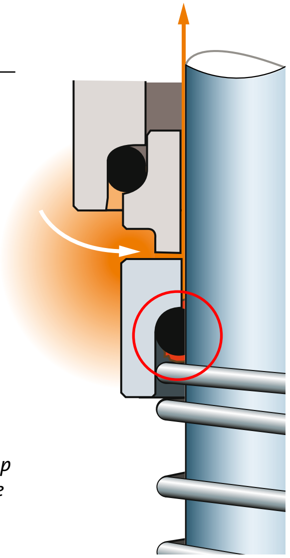


Fig. 5.5: Sketch of seal hang-up due to blocking of the axial movement of the dynamic O-ring

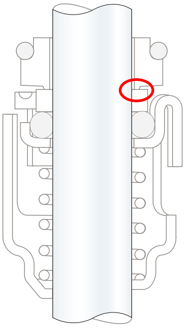
Hang-up of a mechanical shaft seal means that the axial movement of the rotating part of the shaft seal is blocked. Hang-up mainly occurs in connection with O-ring-type seals, but is also seen in connection with bellows seals, although the underlying mechanism is different.

In connection with O-ring-type shaft seals, settlements or precipitations may build up on the shaft beside the O-ring, preventing the O-ring from sliding freely. When the temperature or pressure in the system change, the dimensions of pump parts change likewise. As a result, the O-ring must be able to slide freely on the shaft or sleeve to continue to function correctly. See fig. 5.5.

If a rubber bellows seal is operated at temperatures close to the permissible maximum limit of the rubber type and close to the maximum permissible pressure limit of the seal, the inner surfaces of the bellows tend to stick to the shaft. This results in hang-up. The same failure mechanism results in hang-up of O-ring-type shaft seals, as the dynamic O-ring may stick to the shaft. Some rubber types such as FKM have a high tendency to stick to stainless steel.

A hang-up failure is not always possible to observe during an analysis, as the seal has already been disassembled.

Opening of the sealing gap



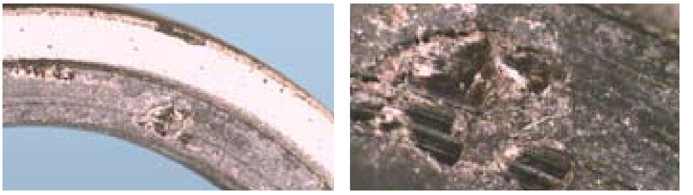


Fig. 5.6: Deposits on carbon graphite seal face

Some suspensions and solutions tend to cause build-up of scattered deposits on the seal faces.
As the deposits only cover part of the seal faces, the sealing gap opens correspondingly. The result is a leaking shaft seal. The leakage is small at the beginning, accellerating as more liquid passes the sealing gap. The settlement accelerates, because the temperature is higher on the surface of the already anchored deposits. See fig. 5.6.

Clogging

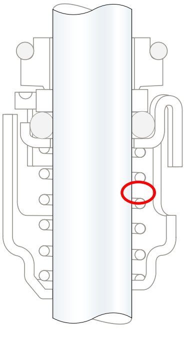
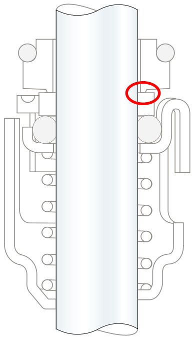


Fig. 5.7: Metal bellows seal clogged by lime scale build-up

When the pumped medium has a high content of suspended particles and fibres, the seal can fail due to precipitation or consolidation of the particles and fibres on or at springs, bellows, seal-drivers or O-rings.
The sedimentation rate is affected by the pumped medium and the flow conditions around the seal.
In extreme cases, the sedimentation on metal bellows shaft seals may prevent the axial spring action of the bellows. Subsequently, the seal can open when the operating conditions are changed. See fig. 5.7.

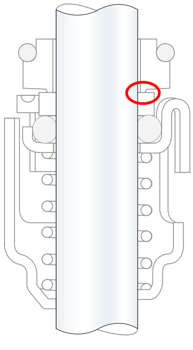
If a change in operating conditions necessitates an axial compression of a bellows clogged by sediments, the closing force of the seal can be extremely high. This may result in excessive mechanical stress on the seal components or failure due to poor lubrication.

Particles and deposits



Small amounts of hard particles on the seal faces result in increased wear, especially when using hard/soft seal face material pairings. In such cases, small, hard particles might be squeezed into the soft seal ring from where they act as a grinding tool on the hard seal ring.
Impurities between seal faces result in a high leakage rate, permanently or until the impurity has been grinded and flushed away. As an example, a human hair is 50 to 100 μm thick, as compared to the 0.3 μm (height) of a sealing gap operating under normal operating conditions. Thus, a human hair of 60 μm is 200 times the width of a normal sealing gap. The leakage rate is proportional to the sealing gap raised to third power, see formula 2, page 18. If a human hair is trapped between seal faces, the leakage rate will be 200^3 = 8,000,000 times the leakage rate of a shaft seal with clean seal faces.

Sticking/seizure



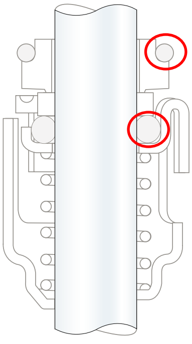
Sticking (British) and seizure (American) are two different terms with the same meaning. In the following, we shall use the term "sticking".
Sticking occurs when the two seal rings are locked or partially welded together. The locked state results in a failure if the interconnection is higher than the starting torque of the motor. It may also result in mechanical damage of seal parts.
Sticking can have different causes. Mainly hard/hard seal face pairings have a tendency to sticking. The main causes of sticking are precipitation of sticky materials from the pumped medium on the seal faces or corrosion of the seal faces.
Sticking is only possible on shaft seals of pumps with start/stop operation. The period it takes for the seal rings to stick together ranging from a few hours and up, depending on the pumped medium. The process accellerates at elevated temperatures.

4. Chemical, physical degrading and wear

All parts of the mechanical shaft seal must have adequate resistance to the chemical and physical environment to operate properly during the expected working life. Elevated temperatures and severe chemical or mechanical loading reduce the expected working life of the seal. This applies up to certain limits; above these limits, degeneration and malfunction will rapidly occur.

The polymer elastomeric parts may exhibit many signs of degradation, including blisters, cracks, voids or discoloration. In some cases, the degradation can be ascertained only by measuring the physical properties. Incompatibility with the chemical and/or thermal environment contributes to the degradation.

Swelling of rubber parts



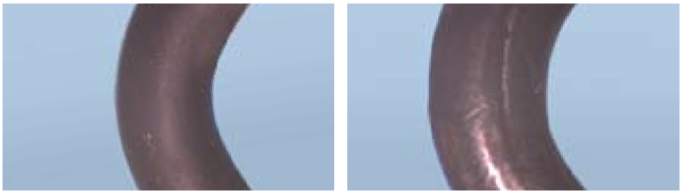
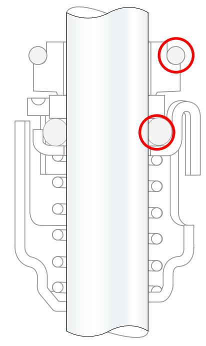


Fig. 5.8: A fresh EPDM O-ring (left) and a swollen EPDM O-ring (right) exposed to water containing mineral oil

Swelling of rubber is an increase in volume and a decrease in hardness due to absorption of a solvent. The volume increase depends on the type and grade of rubber, the type and concentration of the solvent as well as the temperature and time of exposure. In extreme situations, the linear dimensions of a swollen rubber part can be doubled.
The function of many types of shaft seals depends to a great extent on the geometry of the rubber parts. Consequently, even tiny changes in dimensions can be critical. The reduction in hardness is associated with changes in other mechanical properties of the rubber.
The commonly used EPDM rubber material shows a high degree of swelling when exposed to mineral oil. EPDM swelling takes place irrespective of the concentration of mineral oil in water, however, the lower the concentration level, the longer the period of operation before failure. See fig. 5.8.

Other types of rubber also show swelling when exposed to non-compatible liquids.
Volume swelling, as described above, is only one indication of incompatibility with the pumped medium and may be based on the solubility parameter alone. In addition, attack by the pumped medium on the back-bone and/or cross-link system of the elastomer may appear as a change in physical properties such as tensile strength, elongation at break and hardness. Elevated temperatures and extended exposure times may create more aggressive conditions.

Ageing of rubber parts



In addition to the above degradation process, an ageing process takes place. Ageing often results in a change in physical parameters such as tensile strength and hardness. Ageing is divided into these two categories:

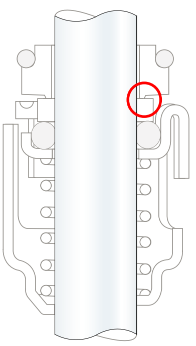
- shelf-ageing
- atmospheric ageing.

Shelf-ageing is basically oxidative degradation. Apart from the obvious influence of oxygen, the catalytic effects of heat, light, internal and external stresses or strains and pro-oxidant metals should be considered.
As opposed to shelf-ageing, atmospheric ageing is characterised by the attack of ozone on the rubber. It is essential to know that this is not merely another form of oxygen-induced degradation the mechanism is quite different. If the rubber is exposed to any sort of stress, the result is atmospheric cracking in which the cracks are perpendicular to the direction of elongation. Atmospheric ageing is well-known from old bicycle or automotive tires. Here several concentric cracks can be observed where the tire has the highest deflection during operation.

Explosive decompression

Explosive decompression occurs on polymeric parts as blisters, pits or pocks on its surface. When the pumped medium has a high partial pressure of a gas-phase, the gas diffuses into the rubber. If the pressure is decreased and the absorbed gas in the material cannot escape as fast as the pressure is decreased, an internal overpressure builds up. If this pressure exceeds the strength of the material, an explosion takes place due to the decompression. An elastomer with high gas solubility and low mechanical strength is exposed to explosive decompression.

Corrosion



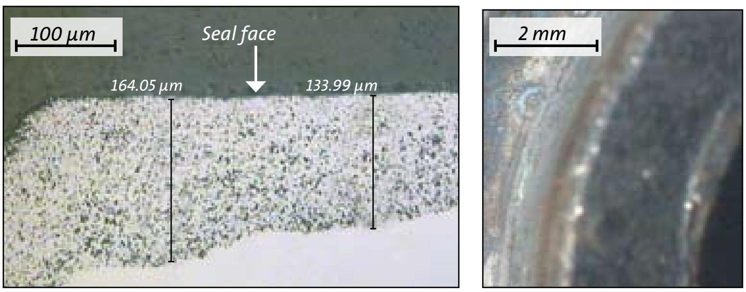
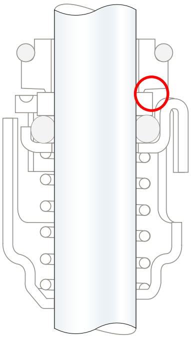


Fig. 5.9: Selective corrosion in cemented tungsten carbide. The metallic binder phase is corroded resulting in reduced wear resistance

Most seal rings materials are made of composite materials. In order to prevent selective corrosion, all phases of the seal ring material must be resistant to the pumped medium. Corrosion in cemented tungsten carbide is typically seen as an attack on the metallic binder phase. The result of this attack is loss of the



mechanical properties, including decrease in wear resistance. When the metallic binder phase disappears, the surface becomes matted. The selective corrosion of the binder phase may induce stresses, leading to cracks in the seal rings. See fig. 5.9.

On other surfaces of the seal rings, heavy erosion can occur where the binder phase is corroded. See fig. 5.10.
In stainless steel pumps and pipe systems, tungsten carbide with cobalt binder corrodes in tap water.

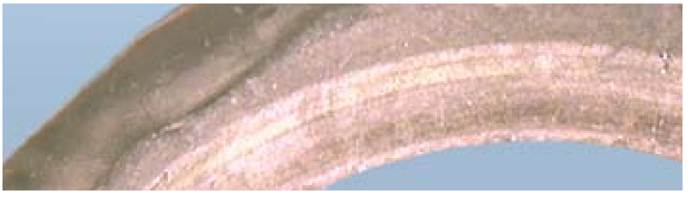


Fig. 5.10: Corrosion of the binder phase followed by severe erosion on a tungsten carbide seal ring with cobalt binder phase

In ceramic materials such as aluminium oxide, the process of a corrosion attack often dissolves or oxidises the glass phase, resulting in a decrease in wear resistance.
When the glass phase has disappeared from the surface of the seal ring, the porosity increases. This affects the mechanical strength of the seal ring. The strength can be reduced with a few percentages or it can totally crumble, depending on the material grade and pumped medium.

Corrosion seldom occurs on the metal parts of the seal in stainless steel pumps. The reason is that seal metal parts are commonly made of a higher grade of stainless steel than other pump metal parts.

Wear

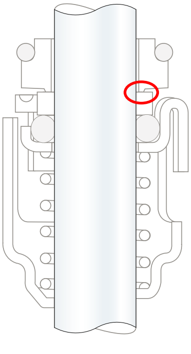


Fig. 5.11: Normal wear on surface of tungsten carbide seal ring

Because the thickness of the lubricating film is of the same order of magnitude as the surface roughness, the seal faces will wear to some extent. This normal wear on well-performing seals will be so small that the seal will be able to survive for many years. See fig. 5.11. In special cases, wear can cause problems, but often seals work perfectly with severe wear up to 0.5–1 mm, even with heavily grooved seal faces, as long as the axial flexibility of the seal ring is maintained.

Wear, continued

Fig. 5.12: Deep seal face grooves close to the pumped medium side

Fig. 5.13: Grooves on seal faces at the evaporation zone

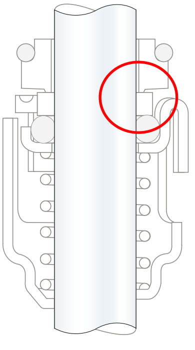
Deep seal face grooves close to the pumped medium side indicate that hard particles from the pumped medium have entered the sealing gap. See fig. 5.12.

Deep grooves close to the atmospheric side indicate that hard precipitates from the pumped medium have been created where the lubricating film evaporates. See fig. 5.13.

5. Installation failures

Some mechanical seal failures come from wrong mounting and handling. Examples can be shaft misalignment, seats not mounted perpendicular to the shaft, axially moving shaft and wrong assembly length, etc.

Misalignment



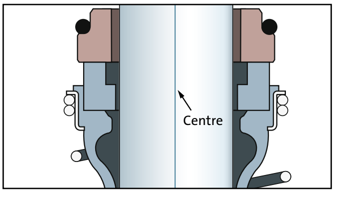


Fig. 5.14: Well-aligned shaft seal

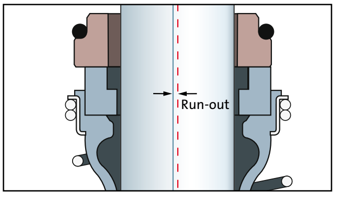
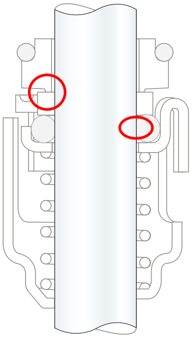


Fig. 5.15: Shaft seal with radial run-out

The position and width of wear tracks on the seat indicate various problem areas.
If the width of a wear track on the seat is the mirror of the sliding face of the opposite seal ring, the shaft seal seems to be well aligned with no run-out of the shaft. See fig. 5.14.

If the sliding face of the seat is broader than the rotating sliding face, a wider track on the seat all way around indicates a high run-out of the shaft. See fig. 5.15.
This can also be seen if, for some reason, there is an unbalance of the rotating mass.

An uneven depth of the wear track around the seat indicates a tilted/crooked mounting of the seat. See fig. 5.16.



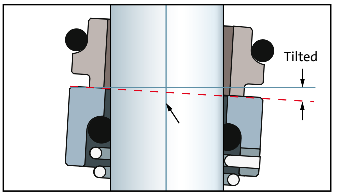


Fig. 5.16: Uneven depth of wear track on the seat caused by tilted/crooked mounting

Fig. 5.17: Wear on dynamic O-ring at the point where it seals against the shaft

Abnormal wear on the dynamic O-ring is observed, if the seat of an O-ring seal is tilted. Wear on the dynamic O-ring is followed by axial scratches on the inner surface. See fig. 5.17.

Wear on the dynamic O-ring is caused by a movement between the shaft or the sleeve and the O-ring. The movement can be an axial movement of the shaft (vibration) or a misalignment of the stationary seat (the seat face is not perpendicular to the shaft).

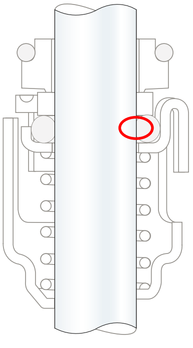


Fig. 5.18: Corrosion on shaft below dynamic O-ring caused by axial movement of the shaft

Axial movement of the shaft caused by vibration or a tilted seat, can cause wear on the shaft or sleeve below the dynamic O-ring. The O-ring rubbing on the shaft continually removes the protecting oxide layer on the shaft, causing corrosion. See fig 5.18.

Assembly

Where a mechanical shaft seal is installed in rotating equipment, the axial movement of the shaft must not exceed the shaft seal flexibility.
Axial movement of the shaft exceeding the permissible flexibility of the rotating part of the mechanical shaft seal may cause extended wear on the seal rings or permanent damage to individual parts of the shaft seal.

Fitting

Many shaft seals have assembly lengths according to standards. This allows users to change from one type of seal to another with improved performance for the actual application. Even if two different seals have the same total length, the sliding faces are not necessarily placed at the same height. If components from two different seals are mixed, the result can be inferior or excessive compression of the seal.

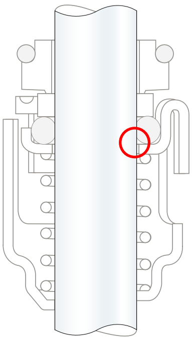
6. System failures

When operating pump systems, the operating parameters may differ slightly from what the system was designed for. A change in operating conditions may affect the seal performance. These parameters affect the performance of a mechanical shaft seal:

- the pressure in the seal chamber
- the temperature around the shaft seal in the seal chamber
- the pumped medium
- the speed
- the shaft seal dimensions.

If the above parameters are not correct for the application in question, the result may be malfunction or damage to the shaft seal.

Pressure



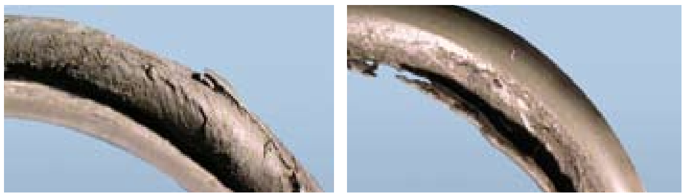


Fig. 5.19: O-rings extruded on account of high pressure

The pressure at the pumped medium side of the seal must be within limits defined by the seal design, the materials and the pumped medium.
When the pumped medium pressure on the shaft seal exceeds the level it was designed for, various failures may occur:
The friction between the seal rings may increase and cause damage either directly due to the friction forces or to the secondary seals in the seal.
Extruded O-rings is a commonly known failure mechanism. If the temperature approaches the maximum operating limit of the rubber, the rubber material becomes softer and thus susceptible to extrusion. See fig. 5.19.

Temperature

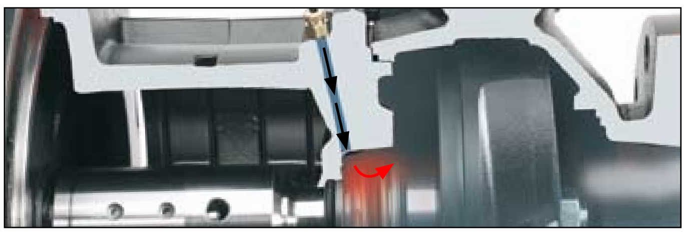


Fig. 5.20: Removal of frictional heat by means of circulating the pumped medium across the shaft seal in the seal chamber

The friction between seal faces in normal operating conditions generates heat. Consequently, the temperature in and close to the seal is higher than the temperature of the pumped medium.

This temperature increase is often 10 to 20 K.
The temperature specification of a shaft seal is given for the actual temperature of the seal. This must be taken into account by the system designer. See fig. 5.20.
Exceeding the maximum temperature of the seal may cause damage to elastomeric parts. Another typical failure due to elevated temperatures is poor lubrication resulting in a higher wear rate. See lubrication failures, page 77.

No or insufficient flow

No flow occurs when the pump contains pumped medium and the pump is running against closed valve. The heat generated by friction in the shaft seal and the heat generated on account of turbulence around the impellers result in a high temperature increase in the entire pump. The increased temperature can damage the elastomeric parts of the shaft seal in particular.
In addition to the temperature increase, the risk of dry-running is also increased, when there is no or insufficient flow through the pump and the seal chamber.

Poor venting

Under certain conditions, it is possible to collect air around the shaft seal, depending on the design of the shaft seal chamber, the operating conditions and the pumped medium. Poor venting resulting in continuous or periodic dry running has disastrous consequences to the life of most mechanical shaft seals.

Vibration

Mechanical vibrations result in higher forces on each part of a mechanical shaft seal. The result is extended wear on all parts, chipped seal rings and possibly opening of the sealing gap.
Vibrations can be generated from friction between seal faces if the operating conditions are exceeded. Otherwise, vibrations are often associated with worn bearings or special liquid flow conditions.
The width of the wear track on the seat will be extended in case of radial vibrations of the shaft occur. See fig. 5.15

Summary
The main causes of failures on mechanical shaft seals used in pumps are described.
It is difficult to state causes of shaft seal failures exactly, even with knowledge of the pump system.
A detailed failure analysis is needed to reduce future failures on shaft seals.

[1] OMV AG, Pumps in Process Engineering 2002

7. Shaft seal failure analysis

The previously described failures have been collected into a failure analysis scheme.
See pages 89 - 90.
The purpose of the scheme is to assist in troubleshooting and give input to possible improvements of seal usage and manage shaft seal parameters involved.

We shall refer to these main shaft seal components:

- complete shaft seal
- seal rings
- elastomers
- metal parts
- shaft/sleeve.

The first column contains the main component.
The second column shows the result of the inspection.
The figures indicate possible causes of failure.

See the “Key to failure analysis scheme”, page 91.

Shaft seal failure analysis scheme

		Possible cause					
		Plant/process influence				Poor thermal control	
Component	Result of visual inspection	Poor lubrication	Cleaning (treatment)	Conta-mination	Corrosion (chemical attack)	Cooling	Heating
Complete shaft seal	Clogged			15/17/41			
	Good condition			1		1	1
	Hang-up			1		1	1
	Noise	13				20	15
	Sticking				11		
Seal rings (1) - (2)	Chipped edges				11		
	Cracked/fractured	3			11		
	Deposits outside seal faces			1/17/38			
	Etched/decomposed		5		11		
	Pitted		5		11		
	Scored/scuffed/galled	13				20	15
	Wear track:						
	No track						
	Blistered/flaked	13/24		23/18	31		
	Deposits			8/9/17			
	Excentric						
	Grooved	20		8			
	Incomplete track				39		
	Matted				11/21		
	Narrow or wide						
	Normal						
	Thermal cracks	13/20				20	15
	Wear on atmospheric side	13		8			
	Wear on pumped medium side						
Elastomers	Burnt	3			11		
	Cuts/nicks						
	Decomposed		11		11		
	Extruded						
	Fractured (bellows)						
	Lost flexibility	3					12
	Ruptured						
	Swollen		11		11		
	Wear, dynamic (3)						
	Wear, stationary (4)	3		34	34		
Metal parts	Cracked/fractured			34	34		
	Deformed			34	34		
	Discoloured	3	11		11		
	Etched/decomposed		5/11		11		
	Pitted		11		11		
	Worn	13					
Shaft/sleeve	Cracked/ruptured	13	11				
	Pitted		11		11		
	Worn			8	11		

(1) Rotating seal ring (2) Stationary seat (3) Dynamic O-rings (4) Stationary O-rings

s of shaft seal failure

Incorrect installation			System faults					
Assembly	Fitting	Misalign-ment	Flow	Pressure	Tempera-ture	Poor venting	Vibration	Other
2/19	2							
				1		1	1	
	7			15/35	13	36	16	
	10						16	
	10		4			3	16	37
	5		11					
	7			35	13	36		
1	2							
	22				15			
		26						16
19	7					4		
38		40						
		19/40						16
			4	15		36		
			4		13	3		
10/19	25							
					12	3		
19	10			13	13			
	7	26						
		28			12	3		
		28		27/30				
19/26		19/26/40		29			16/32	
						3		
19		26		13/29	13		16	
7/37	7			13	13			
19	32					3		
					33			
		26					14	
10	10			29			16	
	6			29			16	
	6	26		29			32	

Key to failure analysis scheme

	Possible causes of failure
1	Seal faces open due to locking of axial movement of the dynamic seal ring. Axial movement is needed to compensate for thermal and pressure-induced axial expansion.
2	Seal is not built into the correct assembly length, resulting in no contact between seal ring and seat.
3	Seal faces are running dry, resulting in overheating. High torque on seal faces made of hard materials can generate heat that can be transmitted to elastomers, resulting in hardening and burning.
4	Closed pump outlet valve results in excessive temperature or failure no 3.
5	Chemical reaction with an oxidizing agent, e.g. nitric acid.
6	Seal or sleeve is not fastened properly.
7	Overcompression due to incorrect assembly length.
8	Solid particles, such as sodium hydroxide crystals, precipitate out of liquid across sliding faces.
9	Volatile elements of liquid evaporate in seal gab, leaving highly viscous sticky layers on sliding faces.
10	Damage due to mishandling (or overcompression).
11	Seal material not chemically resistant to liquid or contaminant.
12	(Elastomer) material has decomposed due to temperature beyond limitations.
13	Seal has been exposed to pressure/temperatures in excess of limits.
14	Continual removal of passive film due to relative movement.
15	System pressure is below or close to vapour pressure.
16	Bearings possibly worn.
17	Liquid is saturated with scale.
18	Solid particles in pumped medium.
19	Wrong assembly of main shaft seal components.
20	Viscosity too low for the actual shaft seal.
21	Corrosion makes tungsten carbide appear mat grey or green.
22	By electrochemical deposition, metals such as copper may form on the sliding faces due to missing or poor electrial grounding on the pump.
23	In water of a conductivity below 5 micro µS/cm, some SiC grades can corrode.
24	Excessive heat dissipation may cause blistering of resin-impregnated carbon.
25	Elastomer fitted on uncleaned surfaces.
26	Seat is misaligned.
27	Explosive decompression due to fast pressure release.
28	Heat build-up may take place due to misalignment.
29	Start/stop at excessive system pressure with hard seal faces.
30	Extrusion of rubber at high pressure and/or temperature.
31	Swelling of impregnation can cause blistering of impregnated carbon/graphite.
32	Undesired axial movement of shaft and shaft seal.
33	Cavitation in seal chamber.
34	Sticking of hard seal rings (SiC/SiC or WC/WC).
35	Partly dry running due to atmospheric pressure exceeding liquid pressure around seal.
36	Partial dry running due to air, air boubles around seal faces.
37	Extreme handling/drop of pump or shaft seal.
38	Seal ring or seal chamber is unsymmetrical, deformed by pressure or other forces.
39	Corrosion under a (soft) seal ring that is supported by a stiff corrosive material.
40	Misalignment of seal rings.
41	Hair or mud contamination.