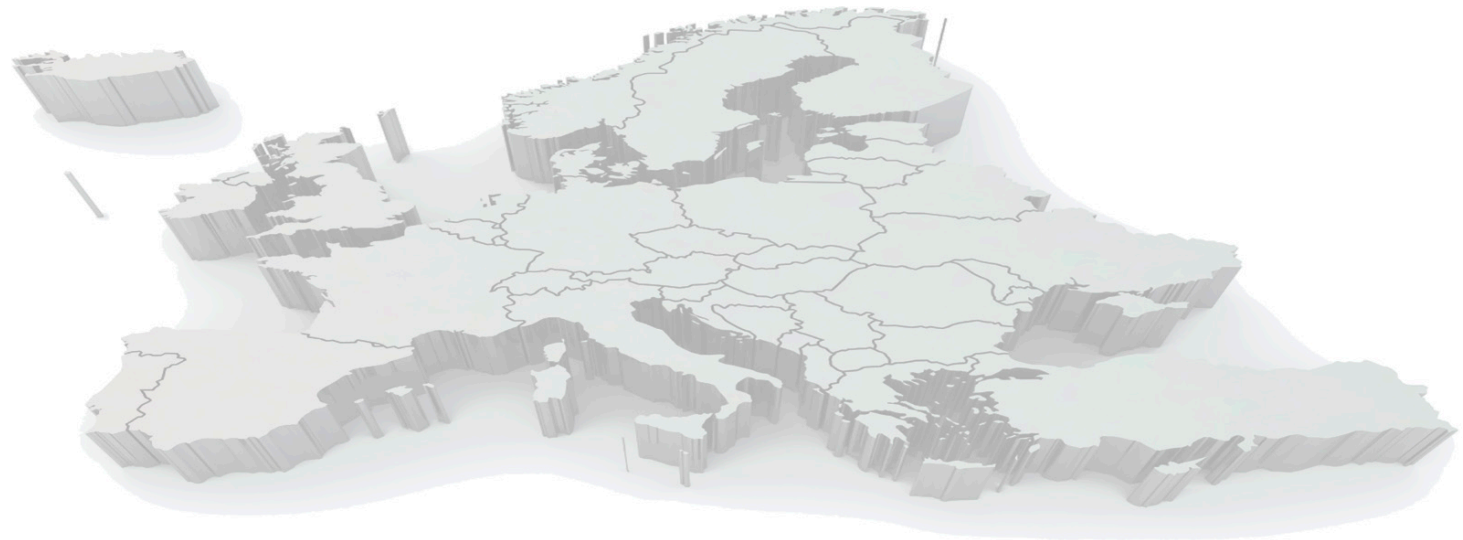




European
Sealing
Association e.V.



Successful sealing with elastomers

An interactive guide to diagnose and prevent seal failure

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The **European Sealing Association** (ESA) is a pan-European organisation, established in 1992 and representing a strong majority of the fluid sealing market in Europe. Member Companies are involved in the manufacture and supply of sealing materials, crucial components in the safe containment of fluids during processing and use.

The ESA is a non-profit-making trade association, registered in Neu-Ulm (D) as VR 713.

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How to use this document:

This document has been designed to be used in a number of ways:

If you have a failed sample, check against the [thumb nail photos](#) (on page 6, following the Contents page) to be guided to the relevant failure section where possible causes and recommendations are provided. Please click on the image or numbered link below the thumbnail to be forwarded to the appropriate section.

If concerned about a specific failure mode, the information provided may give guidance to prevent future damage.

In a number of cases more detailed information is provided in the [Annex](#) Sections.

If any terminology is unknown, please refer to the [glossary](#) for guidance.

Hyperlinks are provided from the thumb nail page, contents page, and throughout the document for ease of navigation.

Throughout this document, the following sub-section headings are used for quick reference:

Failure mode - failure types and aspects which lead to failure are shown in red

Influencing factors

Recommendations for optimising performance - follow these recommendations!

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	<p>© Bernhard Richter, O-Ring Prüflabor Richter GmbH, Großbottwar, Germany, www.o-ring-prueflabor.de</p> 		
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		<p>© Bernhard Richter, O-Ring Prüflabor Richter GmbH, Großbottwar, Germany, www.o-ring-prueflabor.de</p> 	
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2 Introduction

The development and application of elastomers has until recently been based on trial and error. In fact, the process of vulcanising rubber was invented accidentally by the Connecticut hardware merchant Charles Goodyear. Accounts tell us Goodyear dropped a mixture of natural rubber and sulphur onto a stove unintentionally. When he retrieved the material, it was no longer sticky, it did not get brittle in the cold, and if stretched, it snapped back to its original shape. Recalling Vulcan, the Roman god of fire, Goodyear coined the word **vulcanisation** to describe the process of heating rubber in the presence of sulphur. His discovery of vulcanisation, patented in 1844, has made rubber one of today's most useful materials; however this came after years of trials, reiterations and reformulations.

Since the days of Goodyear, elastomers have become more complex in their method of curing and formulations. Present day elastomers are formulated to achieve specific physical properties with various ingredients, the most important of which are the polymer itself and the curing agent together with additives, plasticisers and cross-linking agents. These advances have facilitated elastomeric components to become main-stream in various engineering systems.

Technical components made of rubber play a very important part in engineering processes and products. With seals, gaskets, hoses and vibration isolators there is a widespread and necessary use of rubber in engineering. In spite of this, the knowledge of rubber science and technology is rather uncommon.

Due to this lack of knowledge, design engineers might be insecure and avoid specifying rubber products if possible, even when as in many cases, a rubber part gives a simple and elegant solution to an engineering problem. Furthermore, in the face of failure, engineers may employ the trial and error method until succeeding. They may decide an elastomer is not the correct solution without understanding fully how the elastomer relates to the system and settle on a non-elastomeric solution.

It is fact that current applications in which rubber parts need to perform are numerous and ever more demanding. For this reason, the design engineer must consider the total scope of conditions before he or she decides what type of elastomer would be best for the job. Information is getting more and more accessible but since behaviour of elastomers to various influences is often determined by trial and error the question is what source of information is really reliable?

This is why the Elastomeric & Polymeric Seals Division of the ESA hereby offers you “**Successful sealing with elastomers**”; an interactive guide to diagnose and prevent seal failure”.

3 Failure modes of elastomeric materials

It is recognised that this is not a fully inclusive list, but the vast majority of elastomeric failure modes.

3.1 **Compression set / Stress relaxation**

Compression set is probably the most common form of failure in elastomeric seals and is the result of the loss of elastic “memory” within the material. This loss of memory is observed by a reduction in the dimensions of the seal perpendicular to the applied load, as shown in [Figure 1](#) to [3](#). This reduction in the cross section dimension of the seal results in lower contact sealing stresses being produced at the sealing contact as less “squeeze” deflection is achieved. This loss in sealing stress gives rise to term Stress Relaxation. It is this loss that results in leakage across the seal as the sealing contact stress falls below that required to withstand the pressure being applied to the seal.

Compression set (CS) is often quoted as a percentage reduction of the initial squeeze deformation of the seal and is calculated by the following equation:

$$CS = \left(\frac{h_0 - h_2}{h_0 - h_1} \right) \times 100$$

Where:

h_0 is the original seal cross section dimension

h_1 is the dimension of the deformed seal cross section (Groove depth)

h_2 is the seal cross section dimension following installation

Stress Relaxation is quoted as the percentage reduction in seal stress from that achieved at full deformation. The curves on a graph for stress relaxation and compression set, when plotted against % would not necessarily lie on top of each other but would meet at zero and 100%. For most purposes the compression set data is used and quoted as it is the most readily calculated and obtained. For more information see [Annex 4.1](#).

Failure mode

The major symptom of a seal suffering compression set is leakage, which ranges from intermittent “blow-by” leakage on initial pressurisation to constant leakage often at lower temperature ranges.

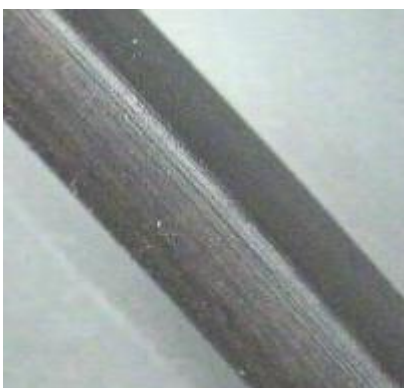


Figure 1

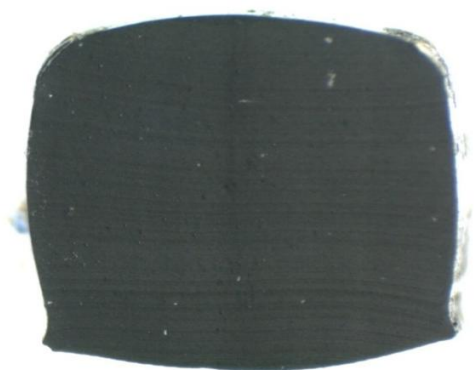


Figure 2



Figure 3

Figure 1_ above shows the surface of a once toroidal O-ring seal that has experienced compression set; the twin flattened surfaces of the O-ring have taken on the surface features of the hardware in which it was installed. The cross section of this O-ring shows its flattened contact surfaces. While Figures 1 and 2 show extreme cases of compression set Figure 3 shows the more normal cross section view of compression set which occurs on the Outer and Inner surfaces of O-rings installed in Piston and Rod seals, and on the radial faces (perpendicular to the O-ring axis) in face seals. The section on the right of Figure 3 is the original size of the O-ring before use.

The root cause of compression set in elastomeric materials lies in molecular rearrangements of the polymer chains within the material. This molecular rearrangement results in the loss of sealing force, this leads to leakage.

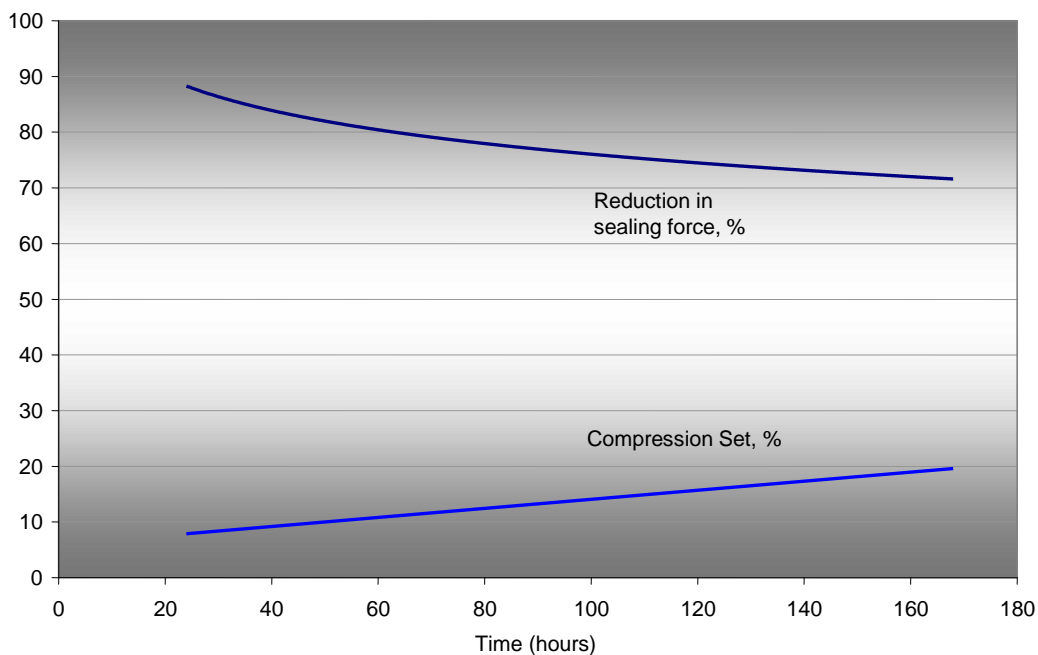


Figure 4 Compression set and corresponding reduction of sealing force of a sample Nitrile elastomer at 100°C

Influencing factors which affect the likelihood of compression set are the following:

- Squeeze
- Temperature
- Material
- Chemical Compatibility
- Pressure
- Time
- Size

Squeeze

In general the higher the squeeze on a component the greater the degree of compression set seen as the higher the stresses will be within the material. There is evidence that higher levels of squeeze, in the order of 25 percent reduce the amount of compression set seen in materials. With these high levels of squeeze the material is almost stress crystallised upon installation and so no further alignment, scission or cross-linking can occur and on removal of the constraints on the part is able to reform more of its original shape.

If Compression Set occurs in seals where squeeze levels are high, then reducing the squeeze will reduce the amount of compression set that occurs, however care should be taken as reducing squeeze will reduce the seals ability to resist initial pressure impulses.

Temperature

This is often the most common reason for compression set in elastomeric seals. As described earlier almost all of the molecular issues that cause compression set are energy related the most direct way of adding energy into a system is to increase its temperature. This increases the speed and amplitude of the molecular motion of the elastomer chains within the material. With increasing the temperature of the system in which an elastomeric seal is installed, the probability of the covalent bonds which make up the elastomer backbones and cross-links, becoming broken or achieving a low energy state is also increased. Chemical reactions, such as the breaking or creating of bonds require a certain energy level, the activation energy, to occur as a result compression set often increases dramatically at a certain temperature when the molecular rearrangement and bond scission occurs. For more information see [Annex 4.1](#).

Material

The choice of materials for use in elastomeric seals is large, each family of materials are selected for different properties, however the main reasons for choice are media compatibility and thermal performance, be it at high or low temperatures. Indeed it is often the compression set capabilities of elastomers that give them their upper temperature rating.

As a general rule to give low compression set figures two requirements are needed:

1. An elastomer with a large atom in the molecular chain, such as Silicon, and/or a bulky side chain pendant fraction such as those in EPDM.
2. Strong Covalent bonds between the atoms in the elastomer chain and cross-links such as those between Carbon and Fluorine.

Chemical compatibility

Elastomeric materials in contact with fluid media can affect the compression set of a seal in one of two ways: permeated media can act as a Plasticiser thereby facilitating compression set or will react with the bonds thereby making or creating bonds.

Media which swell elastomers often acts as molecular lubrication and allow the chains of the elastomer to rearrange easily, indeed lubricating oils, called plasticisers are often used to give this molecular mobility to increase the low temperature performance of the seal. Where the medium swells an elastomer, compression set in that medium is often higher. Swell of elastomers can often be followed by shrinkage as miscible compounding ingredients within the material are removed as the swelling media leaves the elastomer. Such shrinkage is often uniform and is not to be confused with compression set as no physical change in form occurs. Conversely limited amounts of volume swell can be beneficial to sealing by mitigating the effect of compression set.

The largest effect media can have on compression set of elastomers is through reactions with the bonds in the material generating chain scission. Highly reactive media such as oxidising acids can break bonds and increase compression set, this is the reason that air is used in the ISO815/ASTM-D395 tests as a media as the reactive oxygen at temperature is often capable of breaking weaker covalent bonds.

Pressure

Along with the compression set generated by squeeze and thermal effects, the pressure that the seal is subjected to can generate set on the low pressure side of the seal as can be seen in the left hand section of [Figure 3](#).

Time

The amount of time that a seal is installed in an application increases the amount of compression set that the seal will suffer. For further reading see [Annex 4.1](#).

Size

The cross sectional size of a seal can affect the amount of compression set that occurs. Small cross section seals yield higher compression set values than those of larger cross sections for the same percentage squeeze. It should be noted however that increasing the cross section of a seal will increase the contact load that the seal generates and requires larger hardware to accommodate it.

In general, compression set occurs with one or more of the following conditions:

1. Molecular alignment/rearrangement occurs due to excessive temperature, pressure and/or media permeation.
2. Molecular scission of the backbone chain or crosslink structure broken by the loads placed upon them or as a result of chemical attack. This scission can also be caused by elevated temperature.
3. Cross-links are generated within the elastomer material, which reduce the ability of the elastomer to move and recover following deformation.

Recommendations for optimising performance

1. Decrease the squeeze applied to the elastomer, but still ensure it will resist the initial pressure impulses and allow for housing tolerances.
2. Reduce system temperature and/or pressure or protect seals from them.
3. Change the material to one with higher compression set resistance under application conditions

3.2 Rapid gas decompression (RGD)



Figure 5 Rapid Gas Decompression

Rapid gas decompression occurs because elastomers are susceptible to the permeation of gases. It is also known as explosive decompression ED, but for the purposes of this paper it shall hereafter be know as RGD. These will diffuse through their surface until the elastomer is saturated and reaches equilibrium pressure with the pressure in the system. As long as this pressure remains constant, there is little risk of damage.

However, when the external gas pressure is rapidly reduced, the internal pressure remains high, as the seal can not degas at the same rate. This high pressure differential causes large pressure gradients to be set up between the interior and the surface of the seal. The seal will attempt to expand, resulting in blistering or crack formation and growth in unconstrained surfaces. In extreme cases the degree of damage caused can result in sudden and catastrophic failure of the seal and its complete disintegration.

Whether damage is actually caused depends on the elastomers ability to withstand the supersaturated condition and a host of other factors including seal and housing design, frequency of the RGD event, service media and operating temperature

Failure mode

Rapid gas decompression is a term used to cover structural damage caused by reducing the gas or gas condensate pressure to which a seal is exposed, from high to low.

RGD damage can manifest itself in a number of ways such as blistering, internal cracking, splitting and/or complete disintegration.

A. Blistering



Figure 6 Blistering caused by RGD

B. Internal cracking

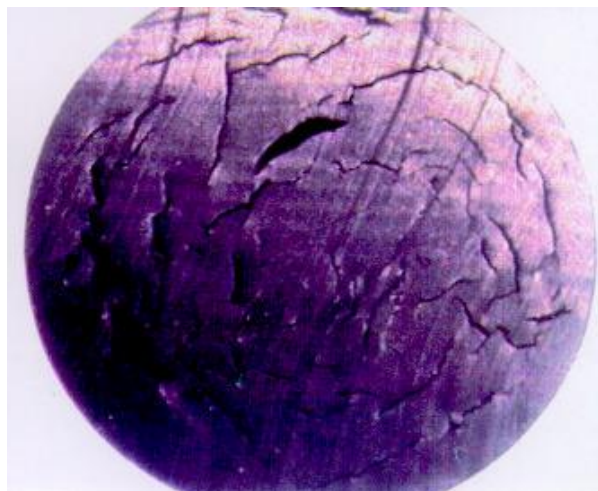


Figure 7 Internal cracking caused by RGD

C. Splitting



Figure 8 Splitting caused by RGD

D. Complete disintegration



Figure 9 Complete disintegration caused by RGD

Influencing factors which affect the likelihood of RGD are the following:

- Material properties
- Design factors
- Decompression factors

Material properties

- a. Gas concentration

The more gas a material will absorb before attaining saturation, the higher the supersaturated gas concentration will be after decompression, and the more gas there will be to attempt to instantaneously diffuse back out of the seal, leading to a higher the risk of seal damage.

- b. Gas diffusion coefficient

The lower the diffusion coefficient the more difficult it is for natural degassing to occur. This makes it less likely that the seal can attain the lower equilibrium state and therefore there is a higher the risk of RGD occurring.

c. Quality

Compound quality, batch to batch consistency and seal manufacture must be carefully controlled to minimize the formation of internal voids and reduce the likelihood of large inclusions being present within the seal. Voids and inclusions act as nucleation sites for crack and blister formation and so increase the chances of RGD being manifest.



Figure 10 RGD fracture initiated at void



Figure 11 RGD fracture initiated by inclusion (external contaminants or undispersed compounding ingredients)

d. Elastomeric modulus

A higher modulus material may have higher RGD resistance as it is less able to expand.

e. Elastomer tear strength

A material with higher tear strength can be more RGD resistant as the characteristic blisters, splits and cracks are less able to manifest themselves in the material.

f. Elastomer hardness

There is a misconception that harder materials are always more resistant to RGD damage. There is no direct correlation between hardness and RGD performance.

Design factors

a. Seal geometry/exposure profile area

The larger the surface area to cross-sectional area ratio of a seal, the greater its RGD resistance will be. This is because the larger this ratio is the easier it will be for gas to diffuse back out of the seal. However minimizing the exposure surface will have no real effect because ultimately the gas will reach equilibrium saturation.

b. Housing design/sample containment configuration

This is especially important for some fluorocarbon compounds which expand readily during decompression. Where the seal has been designed at an 85% groove fill there is only a small amount of room for this expansion to occur before it is prevented by the housing, thus reducing the risk of damage.

c. Seal loading constraints- squeeze

The level of squeeze is a delicate balance between maintaining a seal at low temperatures and preventing RGD damage. RGD and low temperature performance can be enhanced using higher squeeze levels than those stipulated in ISO3601/AS568 standards. Between 14% to 18% will give the desired effect, but 20% or more can create excessive compressive stresses and strain and may cause excessive compression set or even compressive fracture to occur in some materials.

Decompression factors

a. Rate of decompression

Initial decompression can be carried out at a rate of 2-3 MPa/min (300-450 Psi/min) until the pressure falls to 14MPa (2100 Psi) and RGD is not commonly observed. After the pressure has fallen to 14 MPa then the more rapid the decompression the higher the risk of RGD damage occurring as there is less time for degassing to occur. See the chart below for a recommended decompression regime.

Recommended decompression regime for RGD applications

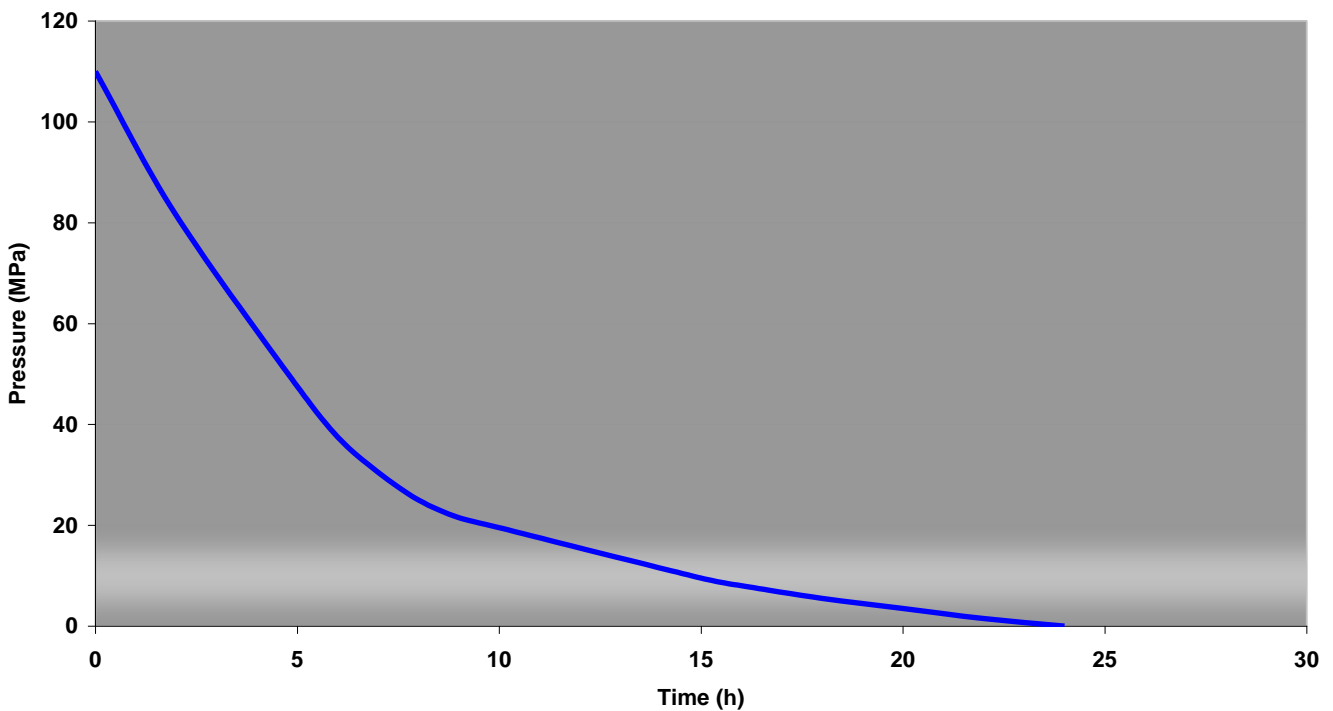


Figure 12 Recommended decompression regime for RGD applications

b. Temperature range and rate over which decompression occurs

The greater the range over which decompression occurs, the higher the pressure differential set up in the seal and the lower its RGD resistance will be. Decreasing temperature will increase the material modulus and increase its tear strength which will improve its RGD resistance.

In general, RGD occurs with one or more of the following conditions:

1. Medium permeates into the elastomer due to a high gas concentration and/or the elastomer has a low gas diffusion coefficient.
2. The elastomer has poor tear strength and/or low modulus of elasticity.
3. The seal has inclusions or voids
4. Decompression rate of the system is higher than recommended

Recommendations for optimising performance

Suggested solutions to the causes of RGD listed above are:

1. Reduce the amount of media permeation by appropriate elastomer selection.
2. Select a compound with proven track record and appropriate validation of RGD performance.
3. Select a seal with appropriate quality standard including the absence of nucleation sites such as voids or inclusions.
4. Control the rate of decompression where possible.

3.3 Low temperature effects

There are numerous applications that require elastomer sealing components to operate at low temperatures such as aerospace and environments at extreme latitudes where the ambient temperature is below 0°C for prolonged periods.

Compression seals rely on an initial squeeze which provides a sealing force between the contact faces. Pressure within the system further activates the seal, and increases the sealing force by that of the system pressure. The initial sealing force created by the squeeze on the seal, and maintained by the residual stress within it takes the overall sealing force above that of the system pressure. It is this balance of forces that forms the seal.

Whilst the seal is energised by the system pressure, the residual stress within the elastomer is critical to maintain a sealing force above the pressure being contained. Excessive stress relaxation over time caused by physical and chemical changes to the seal material inevitably will compromise its ability to function. At low temperatures, the residual sealing force can reduce to a point where the system will fail.

Failure mode

Low temperature effects can be difficult to identify because when removed from the cold environment the elastomer may revert to a state similar to that at installation. Low temperature effects manifest themselves typically as leakage during operation, due to a change in physical properties. These reversible effects are aggravated close to and below the glass transition (T_g) of the elastomer.

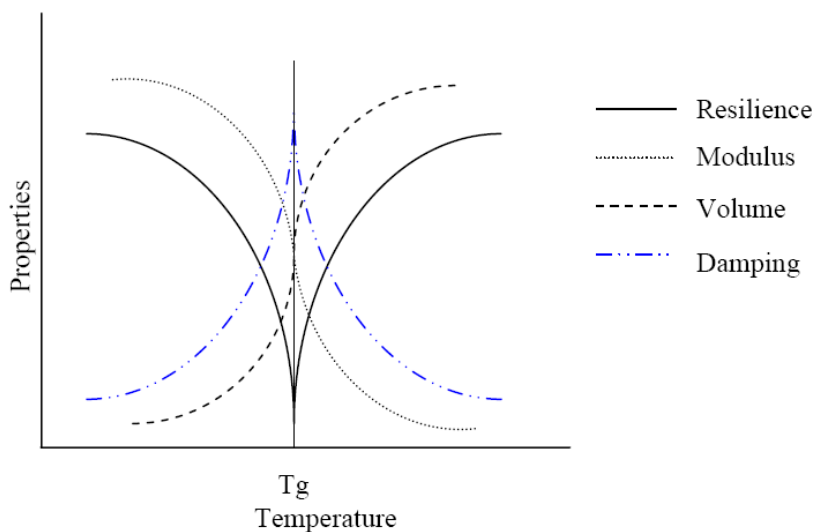


Figure 13 Properties versus temperature

As the temperature drops toward the T_g of the material, thermal contraction causes a reduction in volume and the resilience of the material is at a minimum. Damping effects peak at the glass T_g , while the modulus increases to a maximum below the T_g .

Hardening, embrittlement, snapping and/or low temperature compression set may be seen as a result of prolonged or excessive low temperature.

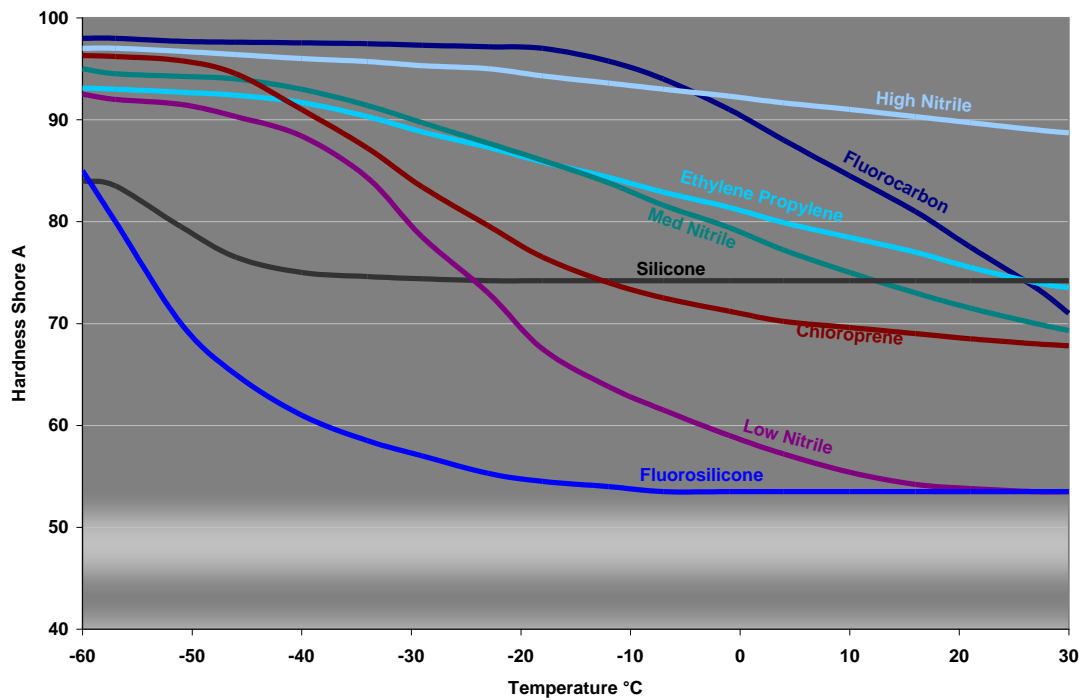


Figure 14 Effects of low temperature on rubber hardness

Influencing factors of low temperature effects are the following:

- System pressure
- Seal section /geometry
- Contact media
- Molecular structure
- Compounding additives

System pressure

At pressures of 5 MPa (750 psi) and above, the Tg of elastomers will shift due to this effect. The mobility of the polymer chains will be more restricted as they are forced closer together, and as a 'rule of thumb' for every 5 MPa (750 psi) pressure the Tg will increase by 1°C. In order to accommodate this shift in Tg the elastomer chosen must have the ability to remain flexible at temperatures lower than that of the application. For more information see [Annex 4.3](#).

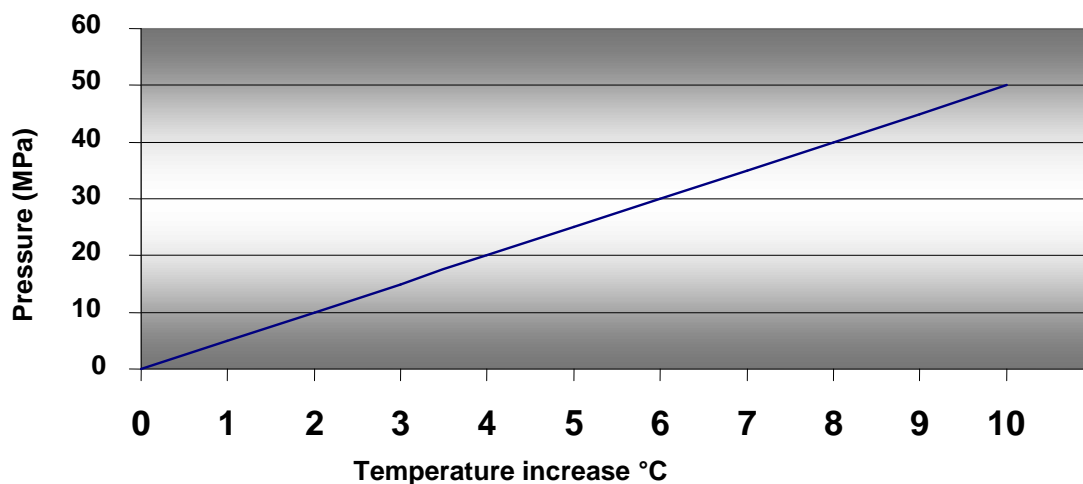


Figure 15 Approximate shifts in glass transition with increasing pressure

Seal section /geometry

Small section seals even when subjected to high levels of percentage squeeze/compression exert relatively low sealing force and may not conform to changes to housing geometry or poor surface finishes when subjected to high pressure in a stiffened, low temperature state. The use of large cross section seals which exert higher sealing stress for the same percentage compression and greater contact area are therefore preferred. Similarly, designs that incorporate multiple contact points or pressure responsive sealing lips that respond readily to changes in system pressure can be used. Increasing the shape factor (pressure loaded area/force free area) increases the compressive modulus of the seal section and this should be taken into account particularly when using mechanically energised seal designs.

Contact media

Whilst appropriate polymer selection should minimise absorption of contact media, small levels may find their way into the elastomers. These will act as a 'molecular lubricant' in a similar manner to a plasticiser. As a result, minor improvements to low temperature properties may be obtained. It is reported that higher levels of swell show further improvements in low temperature sealing. Such effects could be due to a combination of increased lubricity and spacing within the polymer structure, and increases in seal cross section. It must be remembered however that swelling will reduce the mechanical properties of the seal, and could lead to problems such as extrusion.

Molecular structure

The way an elastomer stiffens and embrittles at low temperatures is influenced by both the molecular composition of the polymer and by reversible changes in its molecular structure (for example, the acrylonitrile content in acrylonitrile butadiene or the proportions of various fluorine-containing monomers in FKM's, influence the low temperature performance of these elastomers). See [Annex 4.3](#).

Compounding additives

Low temperature performance can be influenced to a degree by changes in hardness, modulus, and in the case of some elastomers by the selective use of plasticisers. The maximum gain in low temperature flexibility by the addition of plasticiser will be in the region of 8°C below the capabilities of the un-plasticised polymer. If the elastomer is subjected to high temperatures before cooling, the effects of plasticiser loss will need to be considered. See [Annex 4.3](#).

With FKM, little can be done to change the Tg with regards to additives, though as with all elastomer types, lowering the hardness and/or the modulus can reduce the Tg typically by between 1 and 3°C. Perhaps the greatest compounding influence is the selective use of plasticisers, molecular lubricants, in NBR's (nitrile) and HNBR's. The maximum gain in low temperature flexibility by the addition of plasticiser will be in the region of 8°C below the capabilities of the un-plasticized polymer. However plasticiser addition also results in reduction of physical properties requiring selective use of fillers by the compounder to counteract it. A plasticiser loading of 10phr (parts per hundred rubber) is a typical compromise. However, if the elastomer is subjected to high temperatures, some of the plasticisers and therefore their effect on low temperature flexibility, may be lost, dependant on their volatility. See the thermal cycling section for further details.

To conclude, the low temperature performance can be influenced to a degree by changes in hardness, modulus, and contact media and in the case of some elastomer by the selective use of plasticisers. If the elastomer is subjected to high temperatures before cooling, the effects of plasticiser loss will need to be considered. High system pressures will cause a Tg shift, and this must be allowed for when selecting a suitable elastomer grade for the application.

In general, low temperature effects occur with one or more of the following conditions:

1. Prolonged low temperature near or below the Tg of the elastomer
2. Low squeeze or low system pressure allows the elastomeric molecular chains to rearrange to a low energy level state.
3. A material with a Tg close to the operating or ambient temperature is used

Recommendations for optimising performance

1. Select appropriate material for the given process conditions
2. Increase the squeeze or use seal profile that will respond to system pressure at operating temperature.
3. If possible pressurize seal prior to reducing temperature.
4. Provide localised heating to seal area
5. Provide additional energisation device such as a spring.
6. When using lubrication ensure it is also suitable for the operating temperature.

3.4 High temperature effects

When vulcanised elastomeric materials are subject to high temperatures for extended periods or to excessive temperatures for quite short periods, a complex combination of polymer and crosslink chain scission and recombination occurs. The resulting effect is that the properties of the elastomer will be changed permanently, resulting in differences in the way the seal will perform in service. For this reason elastomer manufacturers set limitations for high temperature use.

Note that with increasing temperature useful life of the polymer declines, but for each material type there comes a point at which catastrophic degradation of the polymer occurs.

Elastomer data sheets often state a limit for continuous operation and a limit for short excursions to high temperature.

For example: FKM Max Operating temperature = 200 deg °C
 With short term excursions = 250 deg °C

There is no definitive test for this assessment, and different companies will use a variety of criteria; For example: Temperature at which after 24 hours a reduction of 50% elongation is observed, or the temperature at which after 70 hours the compression set reaches 75%. In any case the high temperature limit is defined by an empirical change in elastomer physical properties.

In service at temperatures within the recommended operating limits properties of the elastomer will change temporarily. Hardness, tensile strength, tear strength and modulus all reduce with increasing temperature which can result in a reduction of sealing force or increased risk of seal damage.

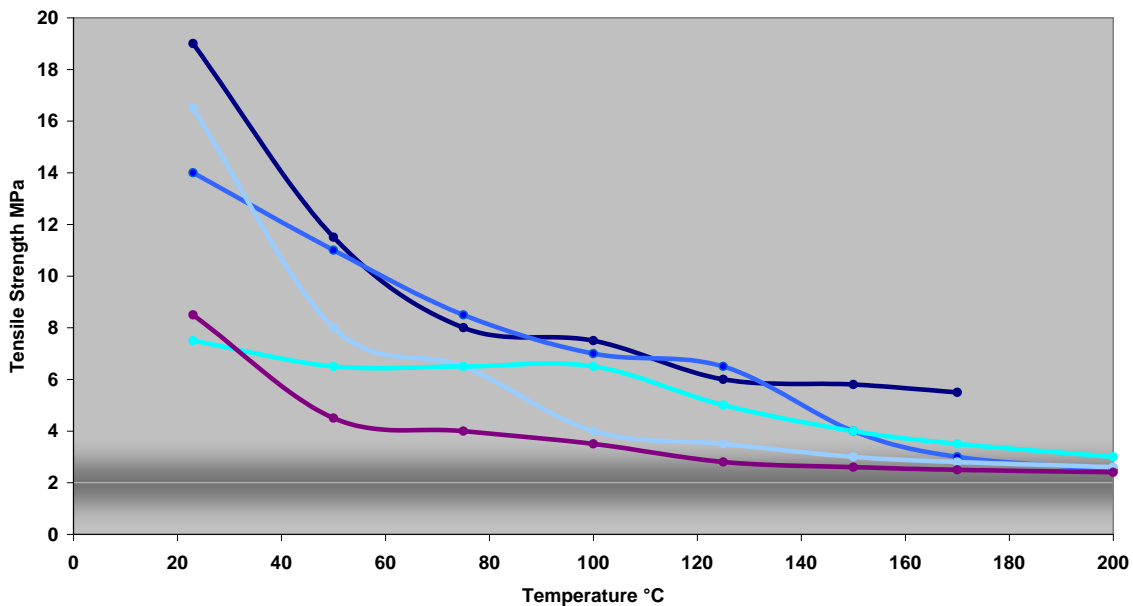


Figure 16 Tensile strength change of various materials with temperature
Note: Tensile strength shown measured at the test temperature

Failure mode

After being subjected to excessive high temperature or prolonged exposure to high temperature, most elastomers will exhibit increased cross-link density and ultimate embrittlement.

An increase in the cross-link density will cause a reduction in elongation and elastic properties and therefore sealing performance. There may be an increase in modulus, hardness and tensile strength (initially), followed by a fall in strength, before gross degradation occurs. Embrittlement can lead to cracking in the radial and/or axial direction thereby creating leak paths. See pictures below.



Figure 18 Embrittlement Cracking



Figure 18 Cracking



Figure 19: Cracking on lip seal

Natural, butyl, and silicone rubbers are notable exceptions, where softening and tackiness can occur. See [Annex 4.5](#) for more information.

All elastomeric materials will expand or contract characteristically with changes in temperature. Consideration of this is important in seal and housing design and this subject will be covered in a separate section. Thermal expansion may be difficult to identify once removed from the hot environment since the elastomer may revert to a state similar to that at installation.

Influencing factors which affect the likelihood of high temperature effects are:

- Exposure time to high temperature conditions
- High temperature exposure to aggressive media
- Friction (abrasion / dynamic fatigue)
- Localised effects

Exposure time to high temperature conditions

As previously mentioned, the continuous operating temperature and short term excursion temperature differ. Prolonged excursions may initiate the reduction of elastomeric properties since service life is dependent not just on temperature, but also time.

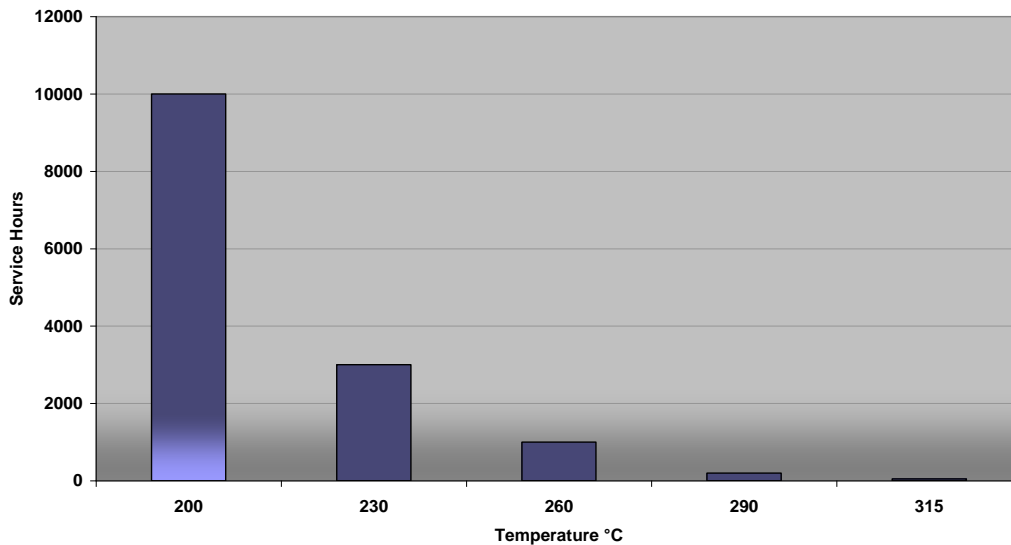


Figure 20 FKM heat resistance

High temperature exposure to aggressive media

High temperature exposure to halogenated compounds (such as chloroprene and fluoroelastomers) can release chlorine and fluorine which can create acidic conditions and contribute to other modes of material failure.

Friction (abrasion / dynamic fatigue)

High temperature thermal degradation can also be induced by heat generated from physical aspects of the application such as abrasion and dynamic fatigue. In practice the tearing and smearing that occurs with abrasion and the crack propagation generated with dynamic fatigue are the more damaging effect, nonetheless unnecessary application heat generation should be avoided.

When an elastomer in tension is heated, the tension within the rubber increases, a phenomenon known as the Gough-Joule Effect. Thus, if an elastomeric radial seal in tension is subjected to frictional heat, it tightens on the shaft to generate higher friction, wear, and more heat, reducing the seal's working life.

This can be overcome by having an interference fit with the housing bore. This puts the elastomer in compression, rather than tension, to avoid the cycle of frictional heat followed by increased tension and wear.

Localised effects

Elastomers near a Localised heat source such as mechanical seal faces can act as a heat sink. This could potentially cause the elastomer to operate at the high temperature limit. Lack of flush fluid from a piping plan designed to keep the mechanical seal temperature low, or within the stated operating range may cause the elastomer to see higher than expected temperatures. This can occur if there is not enough pressure in the cooling system, or if the elastomer is too far from the cool source.

In general, high temperature failures occur with one or more of the following conditions:

1. An elastomeric compound is selected which cannot withstand the upper operating limit or excursion temperatures.
2. Process conditions have changed and a new material needs to be selected
3. Excessive frictional or Localised heat is present

Recommendations for optimising performance

Suggested solutions to the causes of High Temperature Effects listed above are:

1. Appropriate choice of material type and grade for application temperature
2. Avoidance of excessive friction by careful consideration of design, tolerances and material grade.
3. Eliminate source of Localised heat damage such as at the seal faces.
4. Remember that the presence of ozone and aggressive chemicals will accelerate thermal degradation and the avoidance of such influences can postpone degradation.

3.5 Thermal cycling/ Thermal expansion and contraction

Processes subject to thermal cycling where the elastomer is exposed to large changes in temperature repeatedly can result in premature seal failure. Temperature changes in a system can result from varying process conditions, or from intermediate processes such as steam purging.

Failure mode

Signs that thermal cycling has occurred are compression fracture, compression set and/or extrusion. The surface of the elastomer may show blistering due to the exposure of high temperature, and/or cracking due to the repeated expansion and contraction of the material.

These effects of thermal cycling can result in the loss of sealing force leading to leakage.



Figure 21: Thermal Cycling

Influencing factors which affect the likelihood of thermal cycling are the following:

- Thermal expansion
- Thermal stresses caused by temperature gradients
- Stress relaxation
- Crystallinity
- Plasticiser

Thermal expansion

Table 8 shows the coefficient of thermal expansion is an order of magnitude larger for elastomers than for metals. This can cause problems when the sealing system is cycled from cold to hot as the rubber seal will expand 10 times more than the metal housing. An unrestrained elastomer would expand uniformly in all directions but most seals that work at low temperatures will have been fitted in a constrained condition and so can only expand in a plane perpendicular to the applied stress. If the housing is not designed with this extra expansion in mind, the seal may not have sufficient volume to expand and the resulting stresses can cause extrusion, hardware damage, comp-set problems (not due to the initial stress) and/or compressive fracture to occur.

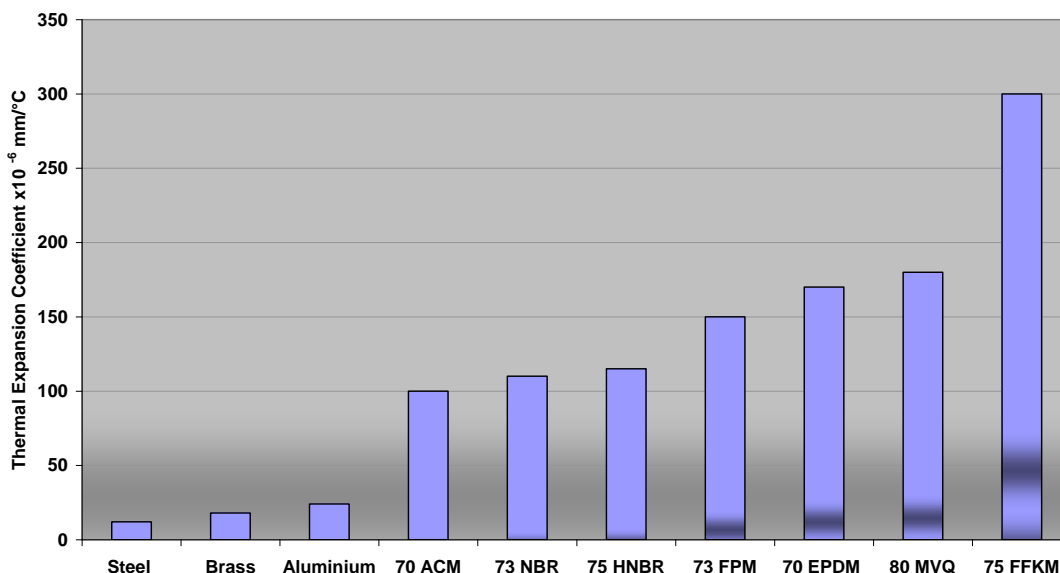


Figure 22 Comparison of Thermal Expansion Coefficients

In some cases thermal expansion of the elastomer can be beneficial in offsetting the loss in sealing load due to thermally induced softening.

Thermal stresses caused by temperature gradients

When an elastomer is heated or cooled, the internal temperature distribution will depend on its size, shape, thermal conductivity and the rate of temperature change. Upon heating or cooling this causes changes in the stress distribution within the seal. These stresses become larger the faster the rate of temperature change and larger the cross-sectional to surface area ratio. If they reach a critical level cracks can open up. This critical level will be lower if the quality of the seals is not high as voids and inclusions will act as nucleation sites.

<i>Material</i>	Conductivity W/(mK)
Aluminium	247
Brass	120
Steel	52
PE	0.4
70 ACM	0.2
IR	0.14
75 FFKM	0.00331
70 EPDM	0.0004
80 MVQ	0.0004

Figure 23 Various Conductivity Values

Stress relaxation

Temperature cycling increases the effects of stress relaxation because as the elastomer is heated it expands and flows more readily under the resulting higher compression. When cooled it retracts evenly from the deformed shape so applied stress on the seal decreases and the corresponding sealing force is also lost, which can result in leakage. For more information see [Annex 4.4](#).

Crystallinity

It has been shown that some elastomers perform better than others in sealing applications involving thermal cycling close to their T_g. This may be due to the retention of low temperature induced crystallinity after returning to the higher operation temperature.

Plasticiser

Plasticisers must be chosen with care as those which provide the best low temperature properties may be lost as volatiles when the elastomer is subjected to high temperatures. For more information see [Annex 4.4](#).

In general, failure mode occurs with one or more of the following conditions:

1. Large temperature cycles are inherent to the system and/or process
2. Hardware dimensions do not accommodate the thermal expansion of elastomer at high temperature
3. An improper material selection has been made

Recommendations for optimising performance

Suggested solutions to the causes of failure mode listed above are:

1. Isolate the sealing system from the large thermal gradient
2. Reduce the number of cycles between high and low temperatures
3. Review the material properties to ensure the properties are appropriate at low and high temperatures

3.6 Extrusion / Nibbling / Shaving damage

Extrusion, nibbling and shaving of the O-ring is a primary cause of seal failure in dynamic applications such as hydraulic rod and piston seals. However, it can also occur in static applications subject to high (pulsing) pressure which causes the clearance gap of the mating parts to open and close, trapping the O-ring between the mating surfaces.

Failure mode

A typical example of O-ring extrusion is when edges of the ring on the low pressure or downstream side of exhibit a “chewed” or “chipped” appearance. In an O-ring that has failed due to nibbling, it may have the appearance that many small pieces have been removed from the low pressure side. In some forms of extrusion, more than 50% of the O-ring may be destroyed before extensive leakage occurs.



Figure 26 Shaving damage

© Bernhard Richter, O-Ring Prüflabor
Richter GmbH, Großbottwar, Germany,
www.o-ring-prueflabor.de

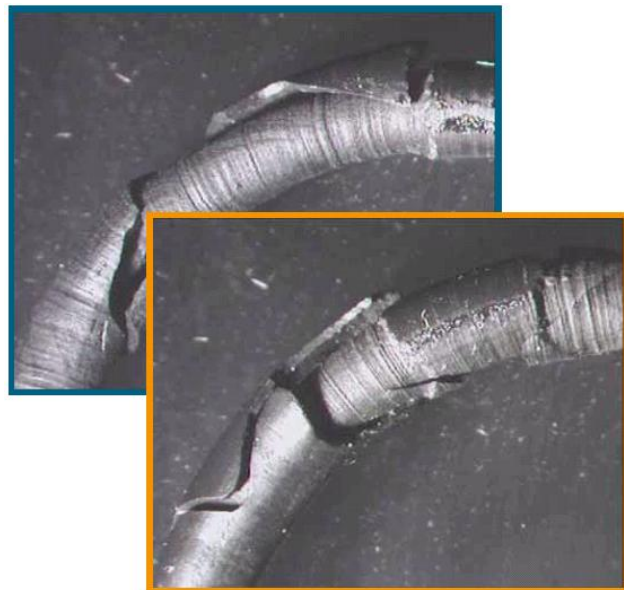


Figure 25

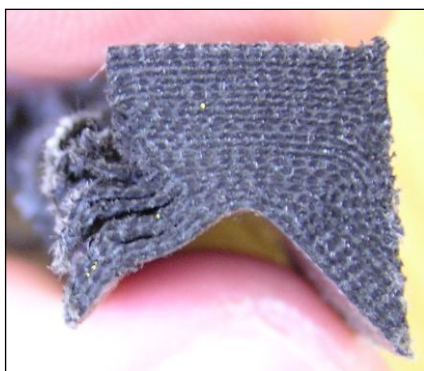


Figure 24

Shaving is normally associated with a continuous or pulsing application of pressure and most often occurs with o-rings. Here the seal is forced into a clearance and with time literally unwinds into that clearance. Any sharp housing edges at the clearance will cause extrusion damage to be initiated more easily and thereafter cause the rate of extrusion to be higher than when acceptable radii are present.

Influencing factors which affect the likelihood of failure mode are the following:

- System interactions
- Hardware details
- Material properties

System interactions

Each system has unique characteristic such as temperature, pressure, process fluid, and vibrations. The system characteristic can influence the performance of the elastomeric seal. Excessive temperature (high or low temperature) and/or pressure can cause the elastomer to soften facilitating the extrusion. Similarly the process fluid can permeate into the elastomer and act as a Plasticiser causing the elastomer to soften and flow more easily into the extrusion gap. Vibrations could lead to the “chewing” and removal of the extruded material.

The relative motion within the system can also increase the likelihood of extrusion damage. Dynamic applications, particularly those with axial-reciprocating displacement can force the elastomer to become wedged in the clearance gap.

Hardware details

The groove dimensions can impact the occurrence of extrusion damage. Large extrusion gaps facilitate the wedging of the elastomer into the gap. Furthermore, hardware with varying extrusion gaps can cause problems. In piston/cylinder assemblies where pressurisation of the system can close extrusion gaps there is more likelihood of forcing the elastomer into the gap. Variations in the extrusion gaps can be introduced with eccentricities or misalignment in the system.

Undersized grooves also increase the likelihood of forcing the elastomer out of the extrusion gap. Oversized or thermally expanded seals can also cause this effect. Sharper cornered extrusion gaps will likely cut the skin of the o-ring initiating shaving.

Material properties

Material hardness influences its conformance to the groove, and tendency to suffer extrusion damage. A material with high compression set will conform at a faster rate, and move to an area of low pressure such as the extrusion gap.

In general, failure mode occurs with one or more of the following conditions:

1. Excessive clearances
2. High pressure
3. Material too soft
4. Degradation (swelling, softening, shrinking, cracking, etc.) of the material by system fluid/circumstances
5. Irregular clearance gaps caused by eccentricity
6. Increase in clearance gaps due to excessive system pressure. e.g. ballooning of cylinder bore
7. Improper size (too large) seal installed causing groove overfill

Recommendations for optimising performance

Suggested solutions to the causes of failure mode listed above are:

1. Decrease clearance by reducing machining tolerances.
2. Use back-up rings.
3. Check seal material compatibility with system fluid/circumstances.
4. Increase rigidity of metal components.
5. Replace current seal with a harder seal.
6. Break sharp edges of gland to a minimum radius 0,2mm.
7. Insure installation of proper size seal.
8. Use alternative seal profile.

3.7 Spiral twist / Rolling

Spiral twist failure is particularly associated with O-rings and is often found on lip seals and to a lesser degree on rod seals. This type of failure is caused when the seal diameter (against the cylinder wall) and rolls at the same time at other points.

Failure mode

The resultant twisting of the O-ring as the sealed device is cycled causes the seal to develop cuts (usually at a 45° angle) on the surface of the seal. You will see the typical damage.

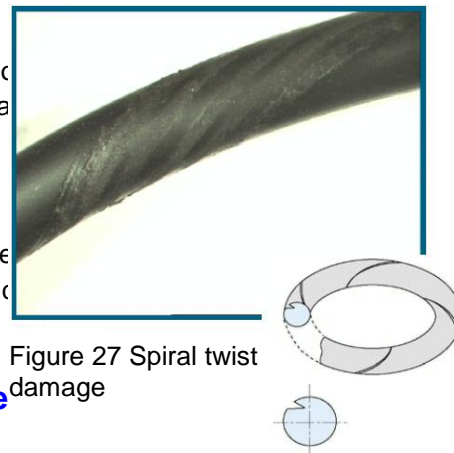


Figure 27 Spiral twist damage

Influencing factors which affect the likelihood of failure mode

- Installation
- Eccentricity or lay-down in the system

Installation

Often times a lubricant is used at installation to help slide the elastomer over the length of the rod. This is done to reduce the friction between the components and reduce the likelihood of spiral twisting of the O-ring. Lack of, or inconsistent coating can fix the elastomer and initiate rolling.

Eccentricity or lay-down in the system

In systems with eccentricity or lay-down there is the possibility that half of the circumference of an elastomer is more compressed than the other half. The over-compressed area acts as a hinge, thereby fixing the elastomer in one area, whilst allowing movement 180° away. The reduced compression in the lightly loaded area will initiate spiral twisting. This is particularly damaging in reciprocating applications where the elastomer is forced to travel the whole length of stroke.

In general, spiral twist failure occurs with one or more of the following conditions:

1. Over-compression of part of the elastomer
2. Dynamic movement of the elastomer particularly in reciprocating applications
3. Installation of elastomer over shaft
4. Small O-ring cross section to diameter ratio

Recommendations for optimising performance

Suggested solutions to the causes of Failure Mode listed above are:

1. Improve surface finish of sealed assembly at dynamic interface (Cylinder Bore, Piston Rod).
2. Check for out-of-round components (Cylinder Bores especially).
3. Provide proper lubrication. Consider the use of internally lubricated O-rings.
4. Replace with a harder, more rigid O-ring.
5. Increase the cross section to diameter ratio
6. Consider use of alternate seal shapes, for example X-rings, D-seals or T-seals

3.8 Installation and/or Port damage

Parts of a seal can be subject to shearing during installation or when a spool or rod moves in a bore broken by cross-drilled port(s). The squeezed seal returns to its original cross section as it enters the port and is sheared as it leaves the drilled area.

Failure mode

Typically, this traversing damage is noticed at initial pressurisation and/or introduction of fluid into the system. Leakage occurs immediately due to the lack of sealing surface. Upon removal of the seal, typical damage appears to be a missing elliptical section with a sharp leading edge. The deeper centre section typically has some 'V' shape tears. The trailing edge is generally rougher than the leading, sharply sheared section.



Figure 28 Skive damage due to traversing port



Influencing factor which affects the likelihood of failure mode is the following:

Installation damage

Installation damage

Many seal failures can be attributed directly to incorrect installation. In spite of its simple appearance, the seal is a precision device requiring care during installation. Seals should not be forced over sharp edges, threads, slits, bores, glands, splines, etc. Such sharp edges must be removed or covered. Fitting aids assist assembly and thus avoid sharp edges.



Figure 29 Seal damaged by connection holes



Figure 30 Close-up of damage

To avoid this, connection holes should be repositioned. If repositioning is not possible, an internal chamfer is recommended. The optimal solution is the relief of the bore around the complete circumference (with chamfers on both sides) which allows the seal to return to its original cross section before being compressed again.

In general, failure mode occurs with one or more of the following conditions:

1. There are sharp corners on mating metal components such as the seal gland or threads over which the seal must pass during assembly.
2. Insufficient lead-in chamfer.
3. Blind grooves in multi-port valves.
4. Oversize seal on piston seal application.

5. Undersize seal on rod application.
6. Seal twisted/pinched during installation.
7. Seal not properly lubricated before installation.
8. Seal dirty upon installation.
9. Seal gland and/or other surfaces over which seal must pass during assembly contaminated with metal particles.

Recommendations for optimising performance

Suggested solutions to the causes of failure mode listed above are:

1. Break all sharp edges on metal components.
2. Provide a 15 to 20° lead-in chamfer.
3. Check all components for cleanliness before installation.
4. Tape the threads over which the seal will pass.
5. Use a seal lubricant.
6. Check seal to ensure correct size and material.
7. To prevent damaging of seals during assembly, chamfers are necessary on all leading edges. All edges must be free from burrs and sharp edges bevelled.

3.9 Chemical degradation

Chemical Degradation occurs when fluid that has permeated the elastomer interacts with it and degrades the physical properties ultimately causing failure. Chemical degradation occurs with the making or breaking of molecular bonds in one of the following ways:

- 1) Scission of the backbone structure
- 2) Scission of the cross-links
- 3) Creation of new cross-links

Failure mode

Chemical degradation is usually identified via the failure mode. Commonly observed failure modes are:

- Blistering/Bubbling
- Softening/ Compression Set
- Swelling
- Polymerisation/Hardening



Figure 31 Polymerisation of process fluid



Figure 32 Blistering/ bubbling damage on exposed surface

Influencing factors which affect the likelihood of chemical degradation are the following:

- Scission of bonds
- Creation of bonds
- Temperature
- Pressure

Scission of bonds

Swelling results when the medium permeates into the elastomer and causes scission of the molecular structure, either to the backbone, cross-links or both. The severed bonds move away from what was previously a tightly packed arrangement.

Swelling caused by pure medium permeation is sometimes confused with that caused by chemical degradation. If the elastomer is allowed to “dry-out” and returns to its original dimensions, it is likely no molecular bonds were severed; this is reversible swelling. In contrast, if the swelling is irreversible and the elastomer remains permanently swollen after being removed from the medium, it is likely scission of bonds has occurred.

Swelling caused by chemical degradation can lead to problems associated with excessive volume fill such as extrusion and dynamic hang up.

Softening/ compression set can occur when the permeated fluid breaks the cross-links or the backbone of the elastomer. Cross-link scission reduces the resilience of the material and allows softening, whilst, for example,

ozone will break the weak double bonds in an NBR molecular chain backbone, not the peroxide cured cross-links. This type of softening can also lead to the loss of tensile strength, and reduction of elongation at break.

Although scission to the backbone or cross-links is caused by different chemical mechanisms, the net result is similar. The bonds become more mobile and can rearrange to pack together until molecular mobility is lost. This causes a loss of resilience and a high degree of compression set is often observed. Compression set reduces the ability of the elastomer to react and the loss of elastomeric properties.

Creation of bonds

Degradation of the elastomer by the creation of bonds can occur in a variety of ways, two such being polymerisation and hardening. In both of these cases permeation of the sealed medium into the elastomer results in bond creation, but the bonds created in polymerisation can be independent of the elastomeric structure, while hardening usually involves the creation of bonds between either the backbone or cross-links (or both) either with or by the permeated medium.

Polymerisation manifests itself by the creation of hardened material underneath the skin of the elastomer as the medium changes phase from a liquid to a solid. These inclusions can tear and disintegrate the material resulting in leakage paths at the seal surface or internal tears which lead to reduced sealing force and ultimately seal failure.

On the other hand, hardening occurs when new bonds are formed either with or by the permeated medium and the cross-linking agents. These new bonds reduce the resilience and elastomeric physical properties of the elastomer making it less responsive.

In some cases the creation of bonds between the medium and the elastomer cross-links can even cause scission of the original bonds between the cross-links and the elastomer backbone structure, resulting in softening and increased compression set.

Temperature

Unless the sealing fluid and the elastomer material have very poor compatibility, chemical degradation occurs over a period of time as the sealing medium permeates into the elastomer and interacts with it chemically.

The rate at which an elastomer experiences the chemical degradation is dictated by the Arrhenius Equation:

$$k = Ae^{-E_a/RT}$$

Where: k = the rate constant of the chemical reaction
 A = Constant Factor – Arrhenius constant for the reaction
 E_a = Activation Energy – Threshold of energy for the reaction to take place
 T = Temperature (Kelvin) – Absolute

Pressure

Regardless the hardness or density of the material, some amount of medium will permeate into the elastomer. High pressure can act as a driving force, thereby pushing medium into the elastomer. If chain scission occurs, the pressure can accelerate conformance to the hardware. Subsequently, when pressure is removed or lowered, blow-by failure can occur.

In general, chemical degradation occurs with one or more of the following conditions:

1. The energy in the system activates or maintains chemical reactions, to either make or break bonds. This is typically in the form of excessive temperature.
2. The sealing fluid is an easily polymerising fluid such as styrene or acrylic acid.
3. The density of the elastomer is low, or highly permeable to the sealed medium.
4. The backbone structure, Plasticiser, filler and/or cross-links of the elastomer is susceptible to chemical attack by the sealed fluid.

Recommendations for optimising performance

Suggested solutions to the causes of chemical degradation listed above are:

1. Reduce the permeability of the elastomeric material when sealing highly polymerising fluids
2. Verify the fluid is compatible with the elastomer backbone structure, Plasticiser, filler and/or cross-links
3. When possible reduce temperature in the sealing system below levels where reactions occur.
4. Consider the use of a barrier fluid to isolate the elastomers from the aggressive fluid

3.10 Compression fracture

Compression fracture occurs when the over compression of the seal section induces both tension and compression. The elastomer “barrels” to compensate for the stresses and strains. When the elastomer can no longer counterbalance the compressive stresses internal tears form.

The barrelling phenomenon is explained by the Poisson’s ratio:

$$\nu = - \epsilon_x / \epsilon_y$$

Where: ϵ_x = Strain perpendicular to the applied load or tension
 ϵ_y = Strain axial to the applied load or tension

Internal tears reduce the sealing force that the elastomer can provide and ultimately can extend through the bulk of the elastomer thus creating a leak path.

Failure mode

Compression fracture is sometimes not noticed until inspection of the cross section. The inner substrate typically has one or multiple sharp tears. These tears follow the contours of stress, and sometimes resemble sections of an onion skin. The tears are typically sharp with curves close to the elastomer edges. Tearing is perpendicular to the compressive surfaces.

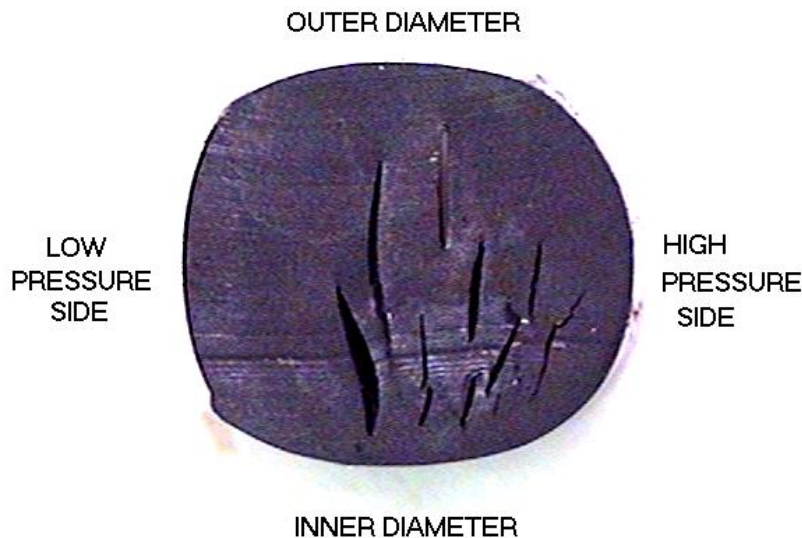


Figure 33 Internal tears of fracture O-ring

Influencing factors which affect the likelihood of compression fracture are the following:

- Compressive loads
- Temperature / Thermal expansion
- Volumetric fill
- Surface finish
- Rapid gas decompression (RGD)

Compressive loads

As previously mentioned high compressive loads lead to equally high levels of strain. Typically these loads are thought only to be applied once by the hardware, however sudden radial movements can also induce stresses and strains causing compressive fracture. Consider the sudden side loading of a sleeve o-ring in a mixer seal application. This could result in a compression fraction on only a section of the elastomer.

Temperature / Thermal expansion

High temperatures typically reduce the physical properties of elastomers. This can reduce the allowable level of stress and strain the elastomer can withstand before experiencing compression fraction.

Elastomers have higher coefficients thermal expansion (CTE) on an order of magnitude greater than that of the mating hardware. Larger CTE's coupled with large temperature differentials could in effect "reduce" the groove size, while "increasing" the size of the elastomer. This would again increase the elastomer's stresses and strains, potentially leading to compression fracture.

Volumetric fill

Low volume fill results in the high pressure side of a radial seal to be unsupported. This results in the elastomer straining along the high pressure side of the groove. By increasing the volume fill all sides of the elastomer are in compression, and are "supported".

Surface finish

The finish on the surfaces applying the compressive force can also influence the occurrence of compression fracture. Consider a rod seal with poor surface finish mating hardware. The elastomer would experience a greater friction along the sealing surface, and would not easily slide over the surface asperities. Each surface asperity creates a normal force, thus increasing the apparent compressive force.

Rapid gas decompression

When in service, the process fluid acts as another compressive force. When Rapid Gas Decompression (RGD) occurs this compressive force pulls off. The elastomer reacts by straining, thus creating a stress/strain situation which could give rise to compression fracture.

In general, compression fracture occurs with one or more of the following conditions:

1. The initial compression caused by the hardware induces high strain
2. High temperature are found in the system
3. Initial Volume fill is too low
4. The surface finish of the compression surfaces is poor
5. The system is exposed to RGD

Recommendations for optimising performance

Suggested solutions to the causes of compression fracture listed above are:

1. Reduce the initial compression
2. Reduce the temperature in the system
3. Reduce the width of the groove
4. Improve surface finish conditions of the hardware
5. Control the pressure losses in the system to a level below which RGD occurs

3.11 Dieseling / Air entrapment

Dieseling is a term that is used to describe what happens when a pocket of air/oil mist self ignites. It can occur when the rise in pressure is fast enough to cause a significant rise in temperature and hence ignition occurs.

In any closed system, whether static or dynamic, although this is most often encountered in reciprocating applications, a small proportion of air may become trapped which, if adjacent to a seal, can cause severe seal damage. Additionally, air which is entrained in a hydrocarbon fluid in a rapidly cycling dynamic application may become exceedingly dangerous if no automatic venting is available or if compression is rapid. If one considers that in 10 litres of hydraulic oil at 20 MPa (3000 psi) and 10°C it is possible to dissolve approximately 200 litres of air, some indication of the magnitude of the risk will be apparent.

Seal failure can occur in two ways – either by rapid gas (air) decompression ([see section 2.2](#)) or by dieseling.

Figure 34 shows a schematic of a typical case, an inclined cylinder where air may become trapped adjacent to the piston seal (and the gland seal).

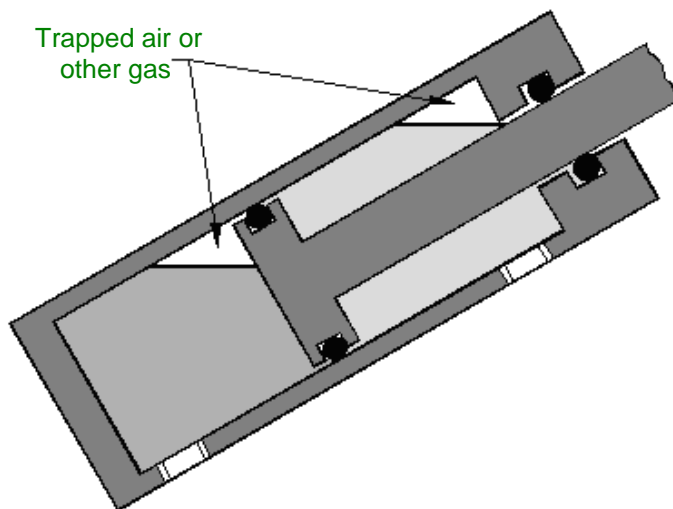


Figure 34 Schematic showing trapped air in inclined cylinder

Failure mode

When ignition happens in the area of the seal it can cause severe localised damage and even burning, or melting of plastic components, see Figure 35. Evidence of burning such as carbonization is typically present on the plastic and elastomers, metallic components may show Localised blueing.



Figure 35 Catastrophic seal failure caused by dieseling

On a lesser scale air entrainment may cause delamination of the fabric plies in a double acting piston seal as shown in Figure 36.



Figure 36 Air entrainment causing fabric delamination on a piston seal

Influencing factors which affect the likelihood of dieseling are the following:

- Improper venting
- Dissolved gas
- Process fluid

Improper venting

While centrifugal systems also require proper venting, they typically do not see rapidly changing pressure cycles as do reciprocating assemblies. Improper venting of these systems can allow trapped gas to build up. The introduction of temperature and pressure, combined with the reduction of volume can cause the gas to reach the ignition temperature.

Dissolved gas

In systems where the hydraulic or barrier fluid is introduced under high pressure it is usual for a pressurized gas blanket to be used. This can cause the blanketing gas to dissolve into the liquid. Settling of the hydraulic/ barrier fluid or increasing the temperature can cause the gas to separate potentially leading to dieseling.

Process fluid

The auto-ignition temperature is the minimum temperature required to ignite a gas or vapour in air without a spark or flame. This explains why dieseling may occur in the same equipment using one fluid but not with another.

In general, dieseling occurs with one or both of the following conditions:

1. Air / gas entrapment due to pressurising or improper venting
2. Process fluid has a low auto-ignition temperature and/or allows air to dissolve easily

Recommendations for optimising performance

1. Minimize the presence of air in the system.
2. Provide venting
3. Use single-acting seals where appropriate
4. Consider using a bladder to separate pressurising air and fluid

3.12 Short stroke failure

Short stroke failure occurs in reciprocating applications when there is insufficient transport of lubricant along the entire contact area of the seal. In this situation the sealing elements towards the low pressure side can run dry.

Failure mode

As a result of dry running, abrasive wear occurs and abraded particles of the seal material are dragged towards the forward sealing edge where they may act as a grinding paste reducing seal life or create an uneven contact area ultimately resulting in leakage.



Figure 38 Effect of lubrication starvation



Figure 37 Short-stroke failure

Influencing factors which affect the likelihood of failure mode are the following:

- Lubrication
- Stroke length

Lubrication

For all dynamic seals it is essential that all contact faces are suitably lubricated. In multi-lip reciprocating applications this lubrication is effected by the relative movement of the rod or cylinder across the seal.

Stroke length

A short stroke in this context refers to the distance travelled as a ratio of overall stack depth. It is ironic that for more arduous high pressure applications the tendency has been, and to some extent still is, to increase the number of sealing rings and therefore the depth of the stack.

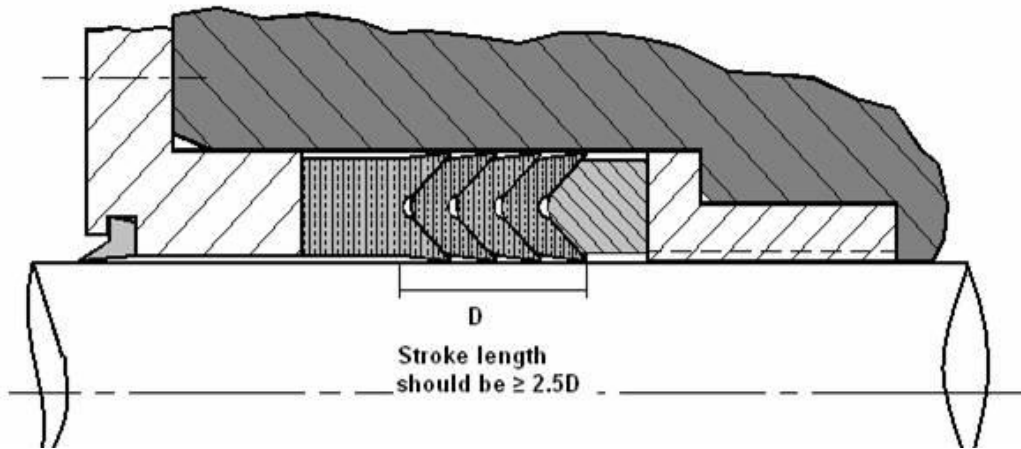


Figure 39 Schematic showing stroke/stack depth ratio

In general, short stroke failure occurs with one or more of the following conditions:

1. Lubrication to the sealing surface is inadequate
2. Excessive force is placed on the sealing surface

Recommendations for optimising performance

1. Ensure a minimum stroke length of 2.5 times the stack depth to provide lubrication to all contact lips
2. Use shallow seals, even single element (unit) seals, as multi-lip packings can reduce seal life and cause premature failure.

3.13 Pressure trapping

Pressure trapping can develop in the annular clearance between two double-acting reciprocating seals whereby inter-seal pressures many times system pressure can build up.

Failure mode

Evidence of pressure trapping on failed seals are signs of extrusion into the applied pressure (i.e. the 'wrong' direction) and damage to the nominal high pressure side of the seal as can be seen in typical cases shown in Figures 40 and 41. This may cause seal failure, delamination, system lock-up or, in the most extreme cases metal work fracture.



Figure 41 Seal damage caused by inter-seal build up



Figure 40 Seal damage caused by inter-seal build up

Influencing factors which affect the likelihood of failure mode are the following:

Double-acting seal design

O-rings and other types of squeeze seal perform as double-acting seals and Figure 42 shows a typical arrangement where an opposed pair of such seals can lead to pressure trapping.

This type of sealing arrangement on multiple reversals can act as a pump causing inter-seal cavity pressure to build up due to viscous drag past the unenergised seal. The effect of this is that both seals become permanently energized resulting in higher friction and wear, an increased tendency for extrusion damage, piston seizure, catastrophic seal failure and potentially metalwork fracture.

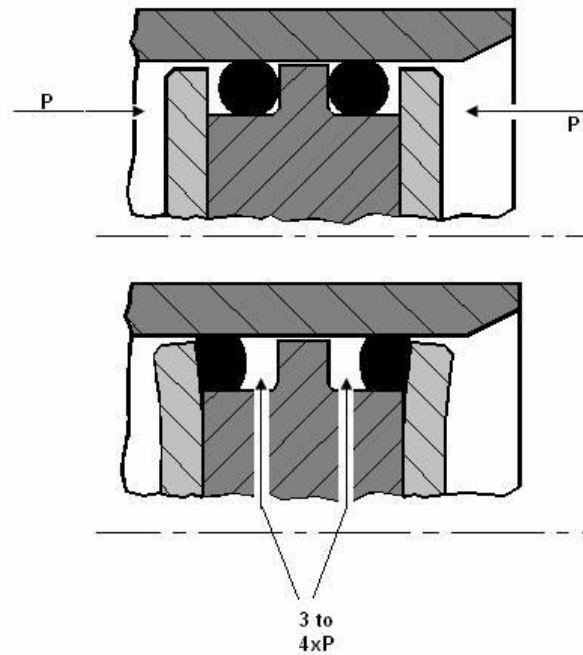


Figure 42 Schematic showing inter-seal pressure

In general, failure mode occurs under the following condition:

1. Pairs of double-acting seals are used in a reciprocating application.

Recommendations for optimising performance

1. Two double-acting seals should never be used in series.
2. If opposed seals are necessary then it is essential that at least one of them is a true single-acting seal in order that any inter-seal pressure build-up is automatically vented.

3.14 Bunching

The term bunching describes an application effect that causes both compression and tension in different areas of a seal simultaneously.

Failure mode

Bunching is typically characterized by the kinking of one or multiple areas along the elastomer. The driving area can show some signs of compression, while the area behind it may appear stretched; this area is prone to tensile fracture. The area before the compressed section is pushed and *bunched* thereby causing a kink in the elastomer.



Figure 43

Influencing factors which affect the likelihood of bunching are the following:

- Relative rotary motion
- Eccentricity / Lay down
- Chemical interaction

Relative rotary motion

Unlike spiral twist, which is closely associated with axial displacement, bunching is encountered on slow rotary applications, especially if subject to reversals such as in swivels, or where seal assembly requires the use of threaded gland nuts. With such relative motion there is a high level of linear drag, which causes part of the seal to be pushed or bunched up circumferentially, leading to other parts being stretched. This again causes reduction in seal section in places, with the potential for seal leakage.

Eccentricity / Lay down

As previously discussed in [section 3.7 Spiral Twist Failure](#), over-compression fixes the elastomer while allowing movement 180° away. In rotary applications the compressed area drives the movement of the elastomer while the adjacent area is held in tension. Ultimately this can cause deformation or tensile fracture of the seal.

Chemical interaction

Breaking of the backbone or cross-links can have a negative effect on the tensile properties of the elastomer. Swelling associated with chemical interaction can subject the elastomer to increased squeeze. The combination of these can create compression/tension which differs from the original design intention.

In general, bunching occurs with one or more of the following conditions:

1. Over compression caused by system or chemical interactions
2. Rotary or swivel motion is present in the system
3. High friction limits elastomers motion
4. Small cross section to seal diameter ratio

Recommendations for optimising performance

1. Lubrication of the seal surfaces on assembly or the use of low friction seals such as rubber or spring energised PTFE seals.
2. The introduction of reinforcement into elastomeric seals can give increased stiffness which resists the bunching effect.
3. The use of a larger cross section can also give increased stiffness which resists the bunching effect.

3.15 Wear and fatigue

When wear of an elastomer seal occurs, material is removed from the seal, by the abrasive action of the seal against a contacting element. The contacting element may be the seal housing, a dynamic mating face, or abrasive media passing across the seal surface. In high pressure situations the 'abrasive' media, may appear to be quite benign, such as a pressurised fluid, but at high pressure and velocity can remove seal material.

Failure mode

Removal of material from the seal obviously changes the dimensions and geometry of the seal which results in changes to the contact area. In turn, this can accelerate wear reduce sealing force and release debris into the system, which may further affect lubrication, ultimately resulting in leakage

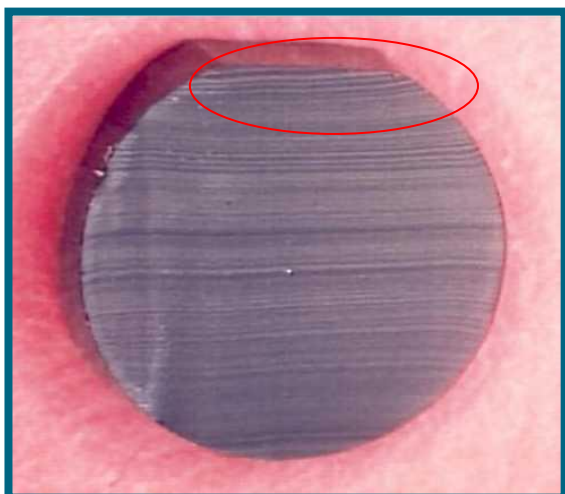


Figure 45 O-Ring Wear © Bernhard Richter, O-Ring Prüflabor
Richter GmbH, Großbottwar, Germany,
www.o-ring-prueflabor.de



Figure 44 Uneven wear of a lip seal

Influencing factors which affect the likelihood of failure mode are the following:

- Velocity
- Lubricant
- Seal elastomer type
- Surface finish
- Contamination
- Temperature
- Diesel effect

Velocity

Lubricated dynamic seals ride on a film of lubricant between the seal lip and the moving surface. The fluid is drawn under by relative movement of seal and mating face and is known as hydrodynamic drag. Friction will depend upon the thickness of this film, which will be squeezed to a minimum when velocity decreases, resulting in no drag. Frictional force will increase, increasing wear. Extremely high velocity can also result in loss of the hydrodynamic film and in turn increase wear.

Lubricant

It may not always be possible to select the ideal lubricant for the seal, if for example the media being transported is also acting as the seal lubricant. If it is, the seal material and operating conditions must be compatible with the fluid.

Seal elastomer type

Different elastomer types and grades within these types all exhibit varying degrees of resistance to abrasive wear. It is very important to select the appropriate material and grade if the seal is expected to withstand dynamic operating conditions as well as the chemical and thermal environment.

Elastomer types such as HNBR demonstrate good resistance to abrasive wear, and careful use of reinforcing fillers can enhance abrasion resistance of many elastomers, as can the inclusion of self lubricating components such as PTFE and graphite.

Swelling of the elastomer by the lubricating media can increase the tendency for abrasive loss, by reducing the modulus and tear strength of the material. In some cases it can also reduce the friction by providing a source of lubricant from within the material. It is important that correct elastomer grade selection is made and the supplier is aware of as much of the operating conditions and media as possible.

Surface finish

The aim of all types of surface finish processes is to provide a surface which minimizes seal wear. Surface finish is usually expressed in Ra values, which is average roughness in microns (μm). Typical recommended values are as follows:

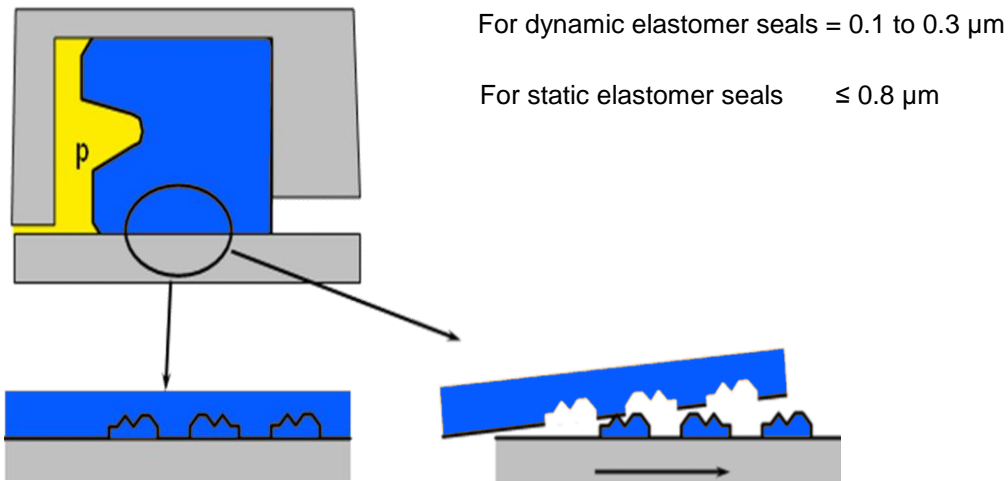


Figure 46 Wear

The recommendations of the seal supplier should always be followed for the type selected. It should be noted that very smooth (less than 0.1 μm) finishes are not normally recommended as they can result in unstable fluid film conditions.

Contamination

Contamination within the system can occur due to inadequate cleaning of parts before assembly and /or due to operational debris from the seal and bearings, with levels of contamination more intensive around the seal area than in the system generally. The effect is manifested by scoring in the direction of the motion. The extent and probability of damage will depend upon seal material and contaminant type, shape and size.

Contaminants may also lodge under the sealing element allowing a leak path and may not only damage the seal but also any contacting faces, changing their surface roughness and accelerating wear further.

Temperature

Increased temperature, brought about by either operational conditions or friction, can cause dimensional changes to the seal, changing mating face characteristics and changing the properties of the elastomer making it more prone to abrasion.

In general, failure mode occurs with one or more of the following conditions:

1. The velocity of the lubricating fluid film is sufficient to cause wear
2. The elastomer is incompatible with either the lubricant or sealing fluid
3. The surface finish of the hardware is poor
4. Contamination in the sealing fluid or lubricant
5. Excessive temperature due to friction

Recommendations for optimising performance

1. Select the appropriate elastomer type and grade for the operating conditions.
2. Ensure that the seal does not operate outside its design conditions
3. Ensure contacting surfaces are of the correct surface finish.
4. Ensure any lubrication is of the correct type for the conditions and elastomers used and that hydrodynamic films are maintained by correct control of speed and lubrication.
5. Ensure all good fitting and operational practice is maintained to avoid the introduction and generation of contaminants

3.16 Volume change

Swell is the result of fluid absorption by an elastomer and is generally reversible. The magnitude of the effect varies with the fluid, the elastomer and the temperature. Also it reflects the readiness with which the elastomer and liquid mix and is related to a property known as the solubility parameter. For more information see [Annex 4.6](#).

Failure mode

The effect of high swell is generally to degrade physical properties, such as tensile strength, and can give rise to seal damage due to extrusion between adjacent metal parts. However, lower levels of swell can have the beneficial effect of increasing or maintaining seal contact stress.

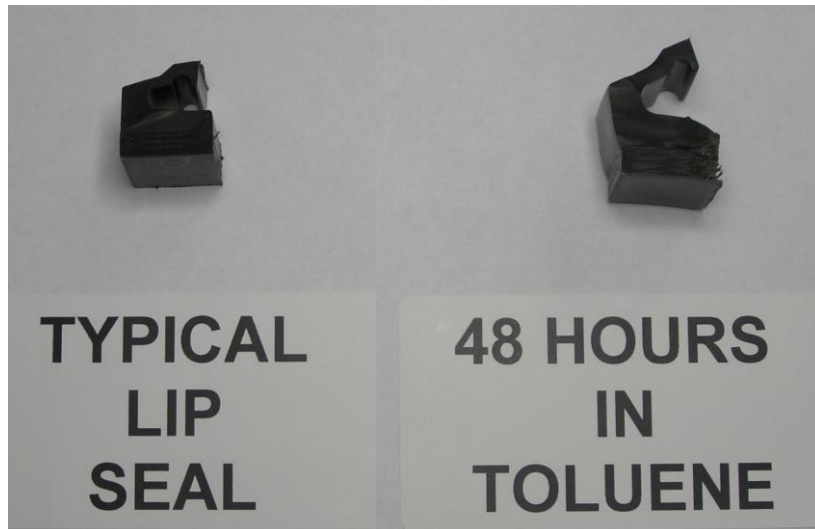


Figure 47 Volume swell

Shrinkage can also occur as a result of constituents of the elastomer (such as plasticisers, process aids, protective systems etc) being extracted by the contact media. This can cause loss of interference, increase of hardness, system contamination, and a reduction in the ageing resistance of the elastomer.

Further information on this subject can be found in ISO/TR7620 'Rubber Material – Chemical Resistance'.

Influencing factors which affect the likelihood of failure mode are the following:

- Volume to area ratio
- Contact area
- Grade of polymer
- Crosslink density
- Proportion of filler
- Temperature
- Concentration
- Pressure
- Surface finish of elastomer

Volume to area ratio

The greater the surface area the quicker the elastomer reaches equilibrium swell (or shrinkage).

Contact area

The greater the proportion of the seal in contact with the medium, the quicker the elastomer reaches equilibrium. For example, a flat flange gasket will reach equilibrium slower than an O-ring (in fact a flat flange gasket may never reach equilibrium).

Grade of polymer

Different grades exist within each generic polymer group, which may behave differently in a given medium.

Crosslink density

Generally a higher cross-link density will result in less swell. For example Nitrile compounds with the same acrylonitrile content and levels of filler but different cross-link densities may exhibit differing levels of swell in a given fluid.

Proportion of filler

The higher the filler to polymer ratio the lower the swell.

Temperature

The higher the temperature the faster the rate of change and overall effect.

Concentration

Some fluids cause high levels of swell. Higher concentrations of these fluids will increase the amount of swell. In complex mixtures, consisting of various fluid types, solubility parameter has a significant influence on swell. For more information reference [Annex 4.6](#).

Pressure

Increasing pressure usually increases the rate of swell. However, in very high pressure systems equilibrium swell can be reduced due to molecular compaction.

Surface finish of elastomer

The rougher the surface finish the greater the area in contact with the medium, and higher the rate of swell.

In general, failure mode occurs with one or more of the following conditions:

1. Loss of physical properties
2. Seal extrusion
3. Overfill of the seal housing/groove
4. In extreme cases, fracture of the metal hardware

Recommendations for optimising performance

Correct elastomer selection for a given set of operating conditions will minimize the risk of failure. It is important to inform your seal supplier of the contact media, concentration and temperature along with any other factors (such as high system pressures) which may influence performance. From this information the end-user should be supplied with a suitable elastomer for the application.

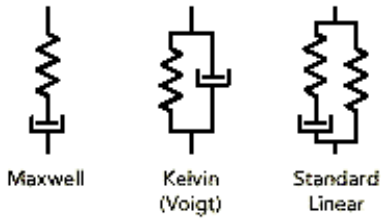
1. Select the appropriate elastomer type and grade for the operating conditions
2. Ensure any swell will be accounted for in the design of the seal housing/groove

4 Annex

4.1 Compression set / Stress relaxation

Stress relaxation

Elastomers are visco-elastic in nature. When deformed initially, some energy is dissipated (viscous shown by the dashpot) but most is stored (elastic shown by the spring) in the elastomer. For sealing purposes the elastic component of this response is most important. An applied stress induces a corresponding strain which generates a contact stress or sealing force. Over time the polymer chains and entanglements within the elastomer will rearrange, and filler to filler interactions will be changed. This dissipates more of the stored energy, and a corresponding loss of sealing force occurs. The rearrangement is known as physical stress relaxation. The process of chain flow and entanglement movement is



reversible when strain is removed from the system. Because the seal is constrained the stress can not be removed from the system and therefore the relaxation will not be reversed.

Temperature cycling makes this problem worse because as the polymer is heated it expands and flows under the resulting higher compression. When cooled it retracts evenly from the deformed shape so applied stress on the seal decreases and the corresponding sealing force is also lost, resulting in leakage.

Temperature

Elastomeric materials used in seals all have varying levels of thermal growth from low levels of 100 $\mu\text{m}/\text{m}/^\circ\text{C}$ for NBR materials to 250 $\mu\text{m}/\text{m}/^\circ\text{C}$ for FFKM materials. This growth is due to the macro Brownian motion. If the groove, which houses the seal has insufficient volume to contain the expanded seal at temperature then a set can occur between the wide walls and the elastomer caused by the stress generated from thermal growth. [Figure 2](#) shows the squared off section resulting from excessive gland fill.

Table 49 shows the effect of temperature on the amount of compression set for two different FFKM elastomers over the same time frame. Even between FFKM's properties and thermal growths resulting in varying levels of compression set.

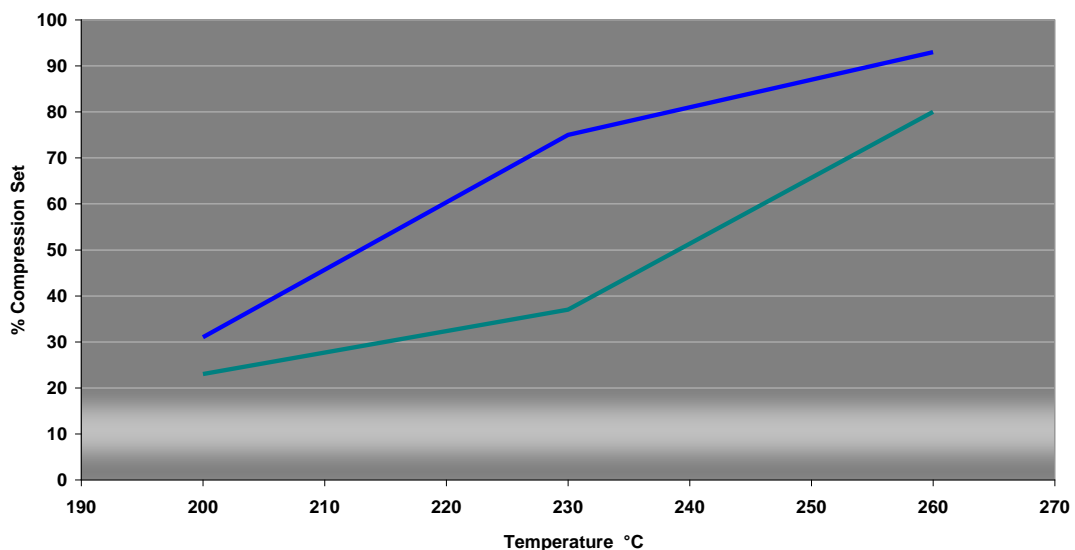


Figure 49 Compression set after 70 hours at temperature

Material

Physical properties of the material, as well as the back bone structure and type of curing can influence the amount of compression set seen in the elastomer. Weak bonds such as those found between sulphur atoms, a common crosslink in NBR and EPDM can yield very poor compression set values compared to the stronger bonds created

using peroxide or triazine bonds. The strong bonds and high rigidity structure found in triazine cured high temperature capable perfluoroelastomers FFKMs give very good compression set, around 20%, at temperatures where carbon and hydrogen based elastomers such as NBR and EPDM have achieved 100% set.

Chemical compatibility

If no reactions/interactions occur between the seal and the media being sealed then compression set in the media is often much better than that in air. An example is the difference in compression set of a sulphur cured NBR compound in air and oil as shown below, where the values in the aerospace oils are much lower than those in air.

70 Shore A NBR Compression Set @ 25% Deflection		
70 Hrs. @ 275°F, In Air, % of Original Deflection, O-Ring	D1414	76
70 Hrs. @ 275°F, In Air, % of Original Deflection, Button	D395	38
70 Hrs. @ 275°F, In AMS-3020, % of Original Deflection, O-Ring	D1414	35
70 Hrs. @ 275°F, In AMS-3020, % of Original Deflection, Button	D395	25
70 Hrs. @ 275°F, In MIL-H-83282, % of Original Deflection, O-Ring	D1414	44
70 Hrs. @ 275°F, In MIL-H-83282, % of Original Deflection, Button	D395	35

Figure 50 Shore A NBR Compression Set @ 25% Deflection

Time

The rule of Arrhenius, which describes the rate of chemical reactions with temperature and time, is often used to determine the long term compression set capabilities of a material by increasing temperature the scope of this use is beyond this discussion, however many papers have been written on the subject.

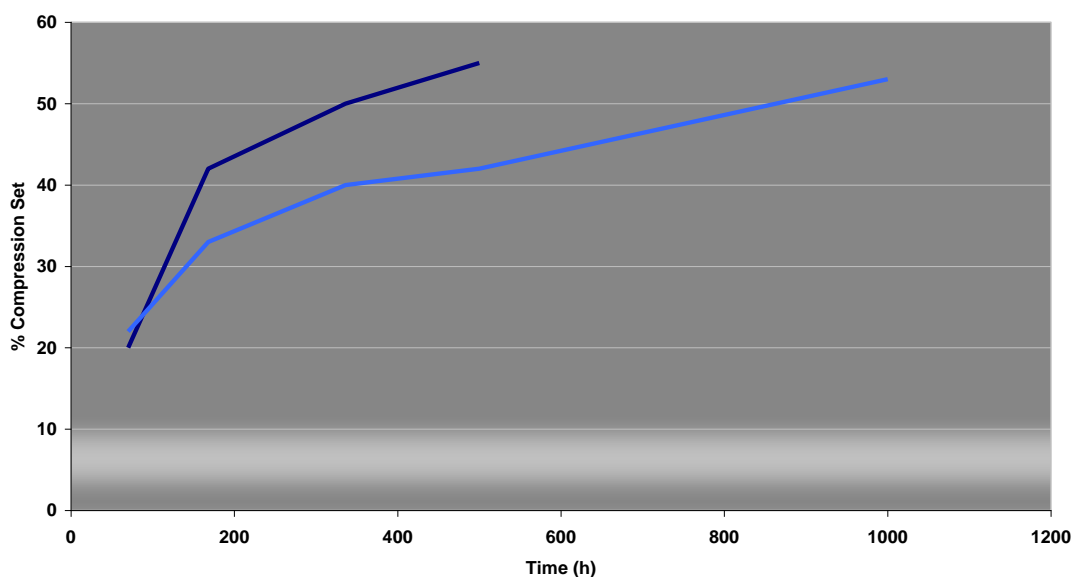


Figure 51 Long term compression set evaluation of two FFKM materials

4.2 Rapid gas decompression (RGD)

Industry RGD standards

These standards may not agree on specific test conditions, but in general terms they follow the same principle.

Standard	No. Cycles	Test Media	Temp °C	Pressure MPa	Exposure Period	Pressure release	Measure
NACE TM 0192-2003	1	CO ₂	25	5.2	24 H	decompression <1min	Changes to: visual appearance, x-sectional diameter, hardness, tensile props
NACE TM 0297-1997 (R2008)	1 minimum #	CO ₂	50 100 120 150 175 200	07 17 28 38	24 H	7MPa/min	Changes to: visual appearance, x-sectional diameter, hardness, tensile props
NORSOK M-710 Rev 2 Oct 2001 ANNEX B	10	3/97, 10/90, 100/0 CO ₂ /CH ₄	100, 150, 200	10,15,30	72 H	2-4 MPa/min	Visual appearance rating 0-5 (4+5 = fail)
TOTAL GS EP PVV 142 APPENDIX 8	5	20/80 CO ₂ /CH ₄	75	19	48 H	decompression <90secs	Changes to: weight, density, visual appearance, x-sectional diameter, hardness, tensile props
DODEP 02.01B.03.02 minimums of	5 minimum	As NACE TM 0297-1997(R2008) or NORSOK M-710 Rev 2 Oct 2001 Annex B or Approved Manufacturer's testing procedure					
		5% CO ₂	70	14	48 H	7MPa/min	Visual appearance rating 1 or 2

= 1 minimum but at request of customer can be multiple cycles

Figure 52 Industry standard tests

- Test specimens are first examined and mass, hardness, cross-sectional diameter, tensile properties etc recorded.
- They are then pressurised at a specified temperature in either Sweet, Sour or pure CO₂ gases, and left to 'soak' to allow complete saturation to occur.
- Decompression is then carried out by reducing the gas pressure at a specified rate while maintaining a constant test temperature.
- After a given hold period at ambient pressure, re-pressurisation is carried out.
- This is then held at test pressure for a set time before the decompression cycle is repeated for a fixed number of cycles.
- Specimens are then retrieved and re-examined.

4.3 Low temperature effects

Some common laboratory test methods for measuring the low temperature properties of elastomers

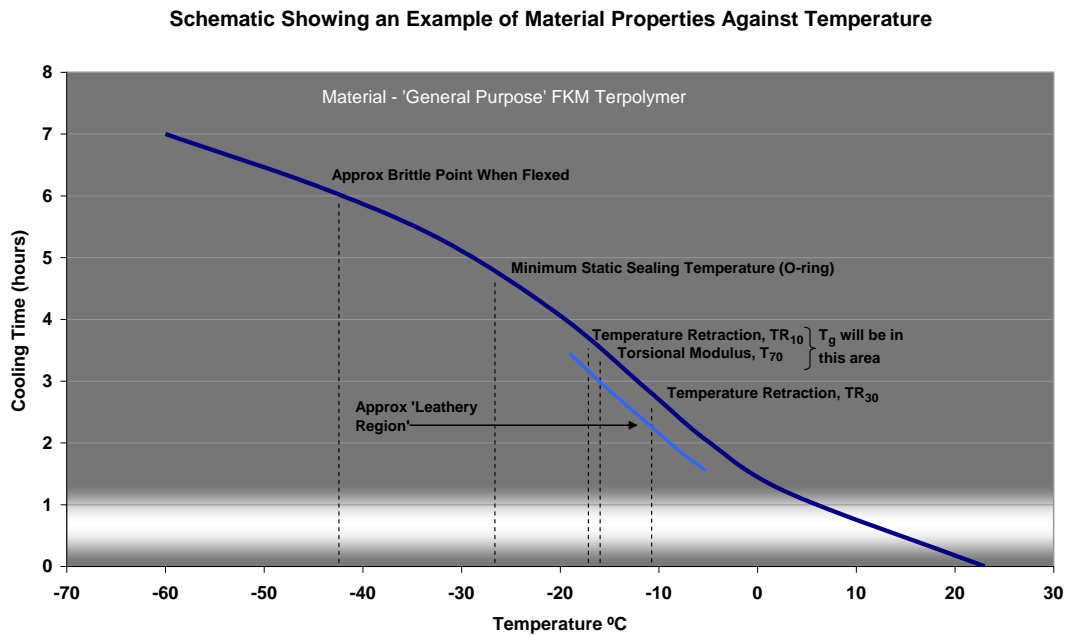


Figure 53 Material properties versus temperature

A. Temperature retraction ISO2921/ASTMD1329/BS ISO2921:2005

Essentially this stretches the sample by typically 25% and 'freezes' it in position using an alcohol bath cooled with solid carbon dioxide (dry ice) to -70°C (other temperatures can be specified depending on the cooling media). The specimen is then allowed to retract freely while the temperature is raised at a uniform rate. Its ability to recover is measured as a temperature at a given percentage. The temperature to recover by 10% (TR_{10}) is often used to establish the minimum operating temperature of an elastomer. Normally the percent recovery is recorded every minute against temperature, and the results plotted on a graph. It is worth noting that the elastic modulus of an elastomer may influence the results independently of its low temperature properties.

B. Gehman torsional modulus ISO1432/ASTM1053/BS903 A13

Small samples cut from sheet are placed in a carousel holder and immersed in an alcohol bath cooled as above. They are conditioned at the test temperature before being twisted using a calibrated wire, which after a simple calculation gives the torsional modulus. The temperature at which a torsional modulus of 70MPa (T_{70}) is achieved has also been used to set a value for the minimum operating temperature of an elastomer. The absolute torsional modulus of a given material may to some extent influence the result. A minimum operating temperature can also be estimated by finding at which point a given ratio of torsional moduli between room temperature and a lower temperature is reached. This may in some circumstances be a more reliable option.

C. Dynamic mechanical thermal analysis (DMTA or DMA)

A small sample of elastomer is flexed and properties such as modulus and damping are measured over a range of temperatures at fixed frequencies. Elastic (E') and viscous (E'') moduli are recorded along with a ratio of these, $\text{Tan}\delta$. From these data, an assessment of T_g and 'Brittle Onset Temperature' can be made.

D. Differential scanning calorimetry (DSC)

DSC measures the heat flow associated with transitions in materials as a function of time and temperature. Basically DSC measures heat flow into or out of a sample as it is heated, cooled or held at a set temperature. This technique can provide a wide range of data including T_g.

E. Bend brittle test (eg. DTD 458: 1948)

This somewhat crude test locates an elastomer sample between two jaws connected via a helical screw. After conditioning at the specified temperature in a cooled alcohol bath, the jaws are screwed together by a predetermined amount which subsequently flexes the sample which is then examined for splits or cracks. Obviously, this is not a measure of elasticity and merely measures brittleness at a given temperature.

F. Compression stress relaxometer BS ISO 3384:2005

Perhaps the most representative laboratory evaluation of potential sealing performance is the measurement of residual sealing force at a given temperature. This is possible via a Compression Stress Relaxometer. An elastomer button is compressed in a specially designed jig, and the residual sealing force in Newtons is measured by momentarily placing the jig in a CSR unit. The jigs complete with sample under a preset level of compression can be placed in an environmental chamber to condition the sample for specified periods of time at a given temperature. By this means, the residual sealing force at this temperature can be measured. It should be noted that BS ISO 3384 does not specify a procedure for testing at low temperatures stating 'the methods [described] have been used for low temperature testing but their reliability under these conditions is not proven'.

Measurement of actual sealing performance of o-rings at low temperatures

The O-ring low temperature seal test quoted by some seal manufacturers was first reported in 1991. Values were for a 10% squeeze of a lubricated '214' size O-ring under 1.38 MPa (200psi) of nitrogen. The seal was energised and then the temperature was reduced slowly until leakage was measured. The value obtained was 13°C below the TR₁₀ temperature for low temperature FKM. The 2003 report was under similar conditions but the squeeze was increased to 19%. Using this modified test the difference to TR₁₀ was now 15°C. The 1991 evaluation proved that the increased squeeze would have this effect.

It is worth noting however, that this often quoted 15°C offset is actually the failure temperature and not a safe working temperature. This work was conducted on certain FKM polymers but, interestingly, this sealing at 10°C to 15°C below TR₁₀ is quoted for compounds using other, non-fluorocarbon polymers by some suppliers.

The claims of working 15°C below TR₁₀ are only theoretically applicable if the seal is of the same size, lubricated in the same way and pressurised with nitrogen at 200psi prior to reduction in temperature. In reality few seals would be pressurised before the temperature was reduced.

A report by Sandia Laboratories studied the failure temperatures of selected elastomer O-rings by pressurising after the seal had been conditioned at the test temperature. As would be expected, the failure temperatures were significantly higher.

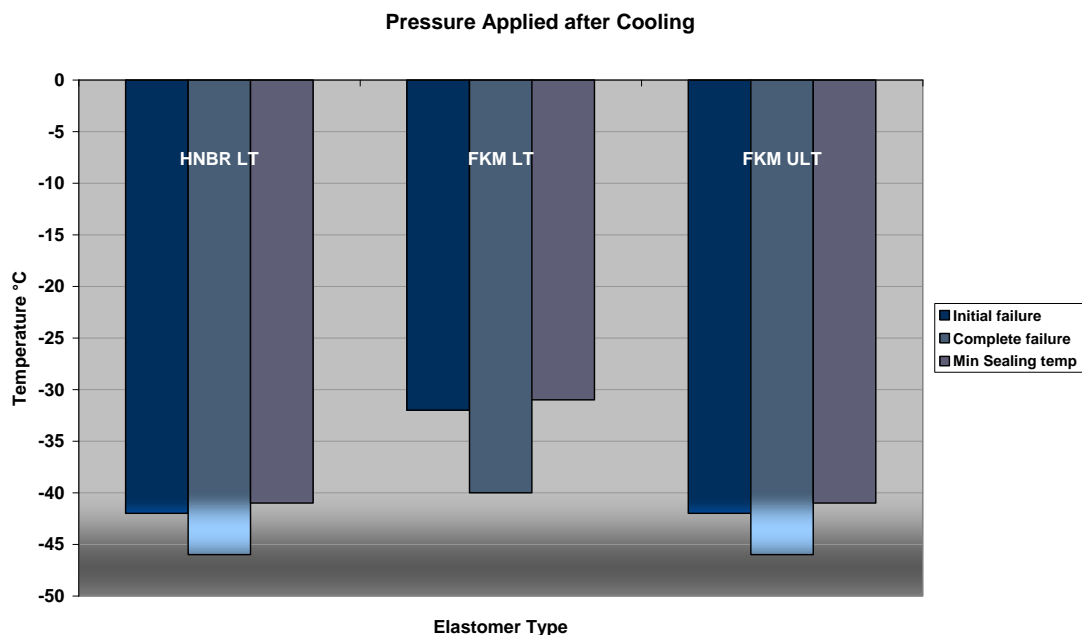


Figure 54 Pressure applied after cooling

Laboratory assessment of low temperature behaviour and comparison with leak test results

The same 3 compounds were evaluated for low temperature performance using Gehman Torsional Modulus, Temperature Retraction and Dynamic Mechanical Analysis (DMA). These test methods and associated test procedures were described earlier.

Illustrative examples to show the different low temperature values given by different tests:			
	HNBR LT	FKM LT	FKM ULT
Temperature Retraction, TR ₁₀	-36°C	-31°C	-40°C
Torsional Modulus, T ₇₀	-40°C	-31°C	-40°C
Tg (established by DMA*)	-31.7°C	-18.8°C	-27.3°C
Brittle Onset Temperature, (established by DMA*)	-45.8°C	-36.0°C	-45.6°C
Min. sealing temp (pressurised before temp. drop)	-53°C	-54°C	-55°C
Min sealing temp (pressurised to 5 MPa at test temperature)	Data not yet available	-31°C	-41°C
Min sealing temp (pressurised to 10 MPa at test temperature)	-41°C	-31°C	-41°C
Min sealing temp (pressurised to 17.5 MPa at test temperature)	Data not yet available	-40°C	-45°C

Figure 55 Low temperature sealing limits for various tests

Temperature retraction TR_{10} values are normally close to those of Gehman torsional modulus T_{70} . In this particular data set, the Gehman T_{70} temperatures align well with the leakage temperatures obtained when the temperature was reduced without system pressure. This is more reflective of 'real life' applications. The T_g 's obtained by DMA had little relevance, however there may be a link between 'Brittle Onset Temperature' and the minimum temperature a static elastomer O-ring can be made to seal when pressurised after reaching its operating temperature.

Based on some findings, there appears to be a temperature down to which static O-rings will seal at pressures of at least up to 17.25 MPa (2500 psi), which is sometimes referred to as '*Full Sealability*'. These data suggest this to be represented by the temperature at which a Gehman value of T_{70} , or a Temperature Retraction value of TR_{10} is achieved. If the tests suggest different temperatures, select the lower of the two.

Immediately below this, the elastomer becomes very 'leathery' and unresponsive. If the system is pressurised first, the O-rings will seal at much lower temperatures. This is however not so representative of the majority of applications. Different elastomers will have varying distances between the onset of increasing stiffness, and brittleness. It has been suggested that static O-rings will seal at 15°C below the TR_{10} value. Under certain conditions this could be the case, though Fig. 15 puts the differences between 15 to 23°C dependent upon material. It has been referred to as the region of '*Conditional Sealability*', where factors such as level of squeeze, volume fill, lubrication and system pressure will have a profound influence on the effectiveness of a seal.

4.4 Thermal cycling / Thermal expansion and contraction

Plasticiser

Plasticisers must be chosen with care as those which provide the best low temperature properties may be lost as volatiles when the elastomer is subjected to high temperatures.

Figure 56 shows the comparative volatile loss of five plasticisers at 180°C (chosen because it is the maximum operating temperature suggested by at least one manufacturer) and 10phr (parts per hundred rubber) loading.

Figure 57 compares their subsequent low temperature properties to those achieved before ageing.

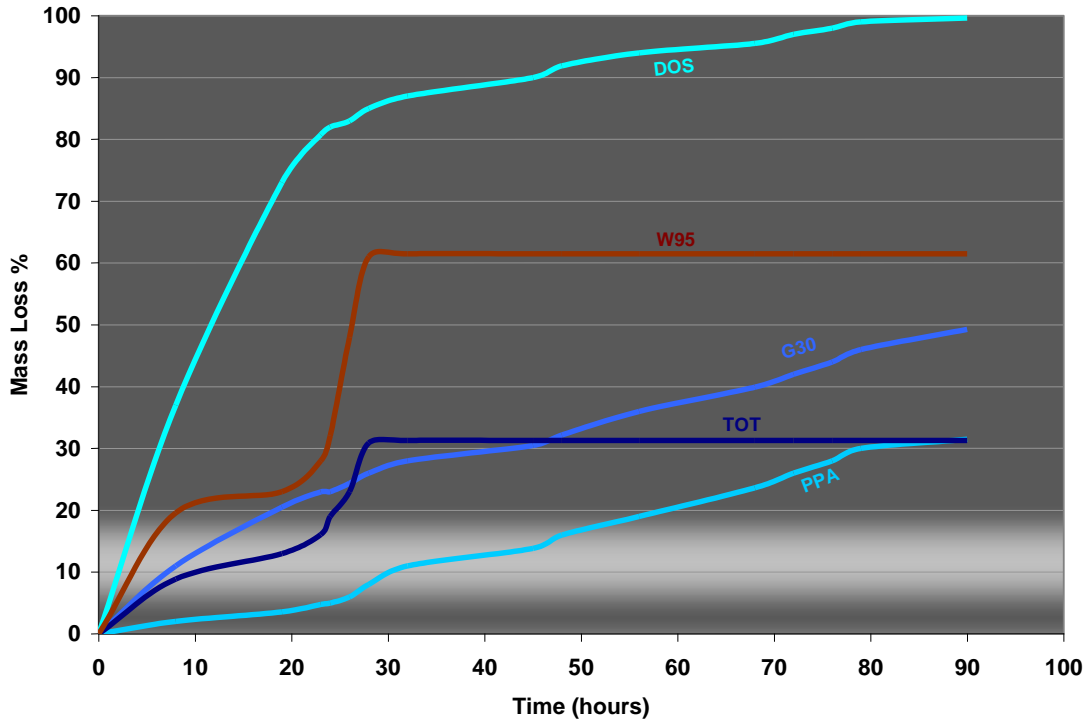


Figure 56 Volatile loss at maximum operating temperature of 180°C

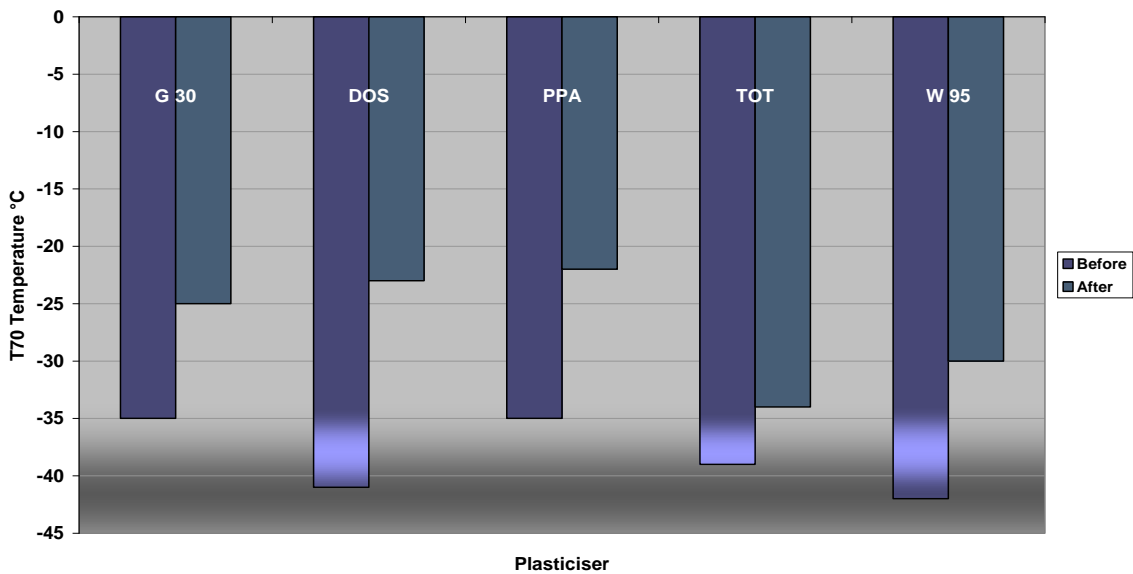


Figure 57 Changes in Gehman T70 Modulus after ageing for 72 hours at 180°C

It can be seen that any gain in the flexibility at low temperatures through the selective use of plasticisers in HNBR (or NBR), may be reduced or negated by the possibility of volatile loss at higher temperatures. Plasticiser loss can also lead to increased compression set at high temperatures

4.5 High temperature effects

Most elastomers, after being subjected to excessive high temperature or prolonged exposure to high temperature, will exhibit increased cross-link density and ultimate embrittlement.

An increase in the cross-link density will cause a reduction in elongation and elastic properties and therefore sealing performance. There may be an increase in modulus, hardness and tensile strength (initially), followed by a fall in strength, before gross degradation occurs. Embrittlement can lead to cracking in the radial and/or axial direction thereby creating leak paths. See pictures below:



Figure 58



Figure 59

Natural, butyl, and silicone rubbers are notable exceptions, where softening and tackiness can occur.

Reversion

When an elastomeric item is cured, it goes through a soft tacky stage to a tough stage where the elastomer is fully cross-linked. In the case of some elastomer compounds using sulphur based cure systems, if heat is applied after the optimum cure state is reached, the elastomer can exhibit what is commonly known as reversion. Once the elastomer has begun to revert, many of its desirable physical properties are lost.

Reversion of rubber can occur during the use of elastomer items; when they are flexed resulting in internal heat generation, subjected to frictional heating or used in high temperature environments. This occurs in large tires, rotary and sliding seals.

Reversion occurs most commonly in sulphur cured natural rubber and its synthetic alternative polyisoprene, which also have a greater tendency to revert than other general purpose elastomers, such as styrene-butadiene, and polybutadiene.

Compound additives can reduce the risks and severity of reversion and many synthetic elastomers using alternative cure chemistry have been developed. These elastomers, although excellent for reversion resistance, can have high heat build up properties, or are high cost materials which preclude their use in certain areas.

4.6 Volume change

Swell is the result of fluid absorption by an elastomer and generally is reversible. The magnitude of the effect varies with the fluid, the elastomer and the temperature. Also it reflects the readiness with which the elastomer and liquid mix, i.e. the relative magnitude of the solubility parameters of the two components. The solubility parameter is a thermodynamic property which is related to the energy of attraction between molecules, thus if the fluid has a solubility parameter (δ) close to (normally within $1.5 \text{ cal}^{1/2} / \text{cm}^{-3/2}$) that of the polymer, it will be absorbed. As the difference between the values increases, the likelihood of the elastomer swelling will decrease. The distance between the values necessary for the elastomer to resist swelling varies, with the viscosity of the fluid being the major factor. Low viscosity fluids adversely affect the rubber at wider values (typically $2.0 \text{ cal}^{1/2} / \text{cm}^{-3/2}$). These units can also be referred to as 'Hildebrands' following the work of Professor Joel Hildebrand and his subsequent development of solubility theory.

The overall solubility parameter of mixed fluids can change due to the interactive effects of the molecules, this means that fluids which individually are 'safe' to use with a given elastomer can when mixed, give high levels of swell. A good example is fuel and methanol with nitrile rubber, where individually these liquids give levels of volume swell of approximately 15% and 8% respectively with a 'high' nitrile NBR. When mixed the level of volume swell can increase to 30% due to the solubility parameter of the mixture becoming close to that of the polymer.

SI units for solubility parameters are $\text{MPa}^{1/2}$, which are approximately twice the Hildebrand value.

5 Storage and handling of elastomeric seals

These guidelines make use of the relevant sections of:

BS ISO 2230: 2002. Rubber Products - Guidelines for storage

BS 4F 68: 2002 - Controlled storage for vulcanised rubbers.

Damage resulting from poor storage and handling procedures can be manifested in the following ways:

A. Accelerated oxidative degradation

Oxidative aging will occur slowly over time whenever a rubber is in direct contact with oxygen or ultraviolet radiation from the sun. Oxidisation will lead to chain scission, so weakening the material by lowering the molecular weight, and cracks start to grow in the regions affected.

Being stored at too high a temperature and the presence of certain metals or other contaminants can accelerate the oxidative process.

B. Ozone degradation

Ozone is formed when oxygen molecules absorb the sun's radiation, split into free radicals and recombine with other oxygen radicals to form a triatomic molecule of oxygen, O₃. It is a powerful oxidizing agent which attacks any unsaturated bonds within the polymer, leading to chain scission. This causes the polymer to lose its strength and, cracks will form from the surface at right angles to the strain, under strains of only 1%.

The kinetics of this reaction are increased as temperature is raised above 25°C or when the rubber is in contact with catalytic metals/contaminants.

C. Hydrolysis

Hydrolysis is technically a chemical reaction with water but the reaction is so slow that it is only when there is an acid or alkali present to act as a catalyst that much concern is necessary. Hydrolysis is of particular importance to Fluorocarbons and Nitriles but is also relevant to other elastomer types.

D. Swelling

Any liquid or vapour introduced by humidity or contaminants, given enough time will diffuse into and be absorbed within the polymer, forcing the macromolecules apart and causing the elastomer to swell. This increase in molecular separation results in a reduction in the secondary bonding forces, making the material softer. An elastomer's susceptibility to swelling depends on the similarity of the chemical structure between the solvent and rubber. The greater the similarity the more likely the elastomer will swell. Temperature will also affect swelling and a higher temperature will increase the rate at which the solvent is dissolved.

E. U.V degradation

U.V light is absorbed by rubbers removing an electron from a specific atom converting it into a positively charged ion. There is then a rearrangement of atoms at this point and either chain scission or cross linking will occur leading to either a loss of strength or hardening and cracking.

F. Low temperature embrittlement

When rubbers are stored in cold conditions the temperature of the rubber may fall below its glass transition point, T_g when it will become glassy and brittle. Its toughness is lost and any deformation incurred while in this state will be plastic and permanent. Providing the rubber is not damaged whilst cold, embrittlement is fully reversible by warming the rubber to a temperature above its T_g.

G. Chemical degradation

Chemicals can attack double bonds in the rubber molecular structure causing chain scission and new chemical bonds to be formed which harden the material. Chemicals can also cause/exacerbate swell and hydrolysis.

Factors affecting the likelihood of deterioration during storage and handling:

H. Packaging

Contact with light, U.V, oxygen, ozone or other contaminants that cause hydrolysis or chemical degradation, such as oil/grease/water vapour etc can be prevented by enclosing rubber products in individually sealed, clean, black, dry, and preservative free packages in an atmosphere of less than 65% humidity. Packaging should be completed as soon as is practical after the final vulcanisation processes so that this protection is in place before any contact can occur.

Polyethylene, polyethylene coated Kraft paper and aluminium foil would make good packaging materials but PVC film or film containing plasticisers should not be used.

I. Induced stresses

Induced stresses as a result of deformation during storage will accelerate the degradation processes. Therefore components should not be stored in a deformed, twisted or highly loaded state.

Where it is not possible to store components in a free state, large rings for example, they should be coiled into three equal superimposing loops to avoid twisting, and laid flat. They should not be hung on hooks.

J. Storage conditions

If storage rooms are:

1. clean
2. dry
3. $\leq 25^{\circ}\text{C}$
4. relative humidity of $\leq 70\%$ for most rubbers and $\leq 65\%$ if polyurethanes are being stored,
5. free from sources of heat such as boilers & radiators
6. free from strong artificial light or sunlight
7. free from sources of ozone such as high voltage electrical equipment, powerful lamps and any equipment that may generate sparks or electrical discharges.

then the probability of any detrimental changes occurring to the rubber during storage is greatly reduced.

If storage temperature is routinely below 15°C , care should be taken to allow products to warm through thoroughly before they are put into service.

In all cases, rubber products should be used in correct age rotation

Susceptibility

In terms of general storage, vulcanised rubbers are classified into 3 groups, according to their susceptibility to deterioration.

Group	Rubber	Acronym
A	Natural Rubber	NR
A	Butadiene Rubbers	BR
A	Synthetic isoprene Rubbers	IR
A	Styrene butadiene Rubbers	SBR
A	Polyester and Polyether Urethane rubbers	AU/EU
B	Acrylonitrile Butadiene rubbers	NBR
B	Carboxylated and Hydrogenated NBR	XNBR/HNBR
B	Polyacrylic rubbers	ACM
B	Chloroprene Rubbers	CR
B	Isobutylene Isoprene rubbers	IIR
B	Halogenated IIR	BIIR/CIIR
C	Chlorosulphonated Polyethylene	CSM
C	EthylenePropylene/Diene rubbers	EPR/EPDM
C	Fluorocarbon Rubbers	FKM/FFKM
C	Silicone Rubbers	MQ/FMQ/PMQ/VMQ/PVMQ

Figure 60 Rubber family susceptibility to deterioration

Providing the storage conditions described earlier are adhered to, the above materials can be stored for an initial period, after which they should be assessed, examined or tested as appropriate, following which they may be stored for a further extended period as follows:

	Initial Period Yrs	Extended Period Yrs
Group A Rubbers	5	+2
Group B Rubbers	7	+3
Group C Rubbers	10	+5

Health and safety

For all health and safety aspects of storage, handling and use, always refer to health and safety data sheets, which all reputable seal suppliers will provide.

6 Glossary of sealing terms

The terms included in this Glossary are related to elastomeric and polymeric seals and their applications.

A

abrasive wear - Wear occurring by the mechanical action of suspended abrasives or by abrasives that crystallize on the atmospheric side of the seal.

ANSI - American National Standards Institute.

air entrapment - Refer to [Dieseling / Air Entrapment section 3.11](#).

air side - That side of an elastomeric shaft seal which in normal use faces away from the fluid being sealed.

anti-extrusion ring - A close clearance ring installed on the low pressure side of a seal, in order to prevent extrusion of the sealing material.

anti-rotation device - A device such as a key or pin, used to prevent rotation of one component relative to an adjacent component in a seal assembly.

ASME - American Society of Mechanical Engineers.

asperities - Imperfections or surface irregularities that result from the formulations or ingredients used in elastomeric seals.

B

back-up ring - See *anti-extrusion ring*.

bi-rotational seal - A rotary shaft seal which will seal regardless of the direction of shaft rotation.

blister - A raised surface or bubble that forms on the surface of a seal.

boundary lubrication - A condition of lubrication where the seal is in solid contact though separated by surface films.

breakaway torque - See *starting torque*.

bunching - Refer to [Bunching section 3.14](#).

bypass leakage – Leakage resulting from loss of sealing force or contact.

C

carbonisation - Oxidation of a hydrocarbon resulting in the formation of a carbonaceous residue.

cartridge seal - A completely self-contained unit, including sealing elements, gland, sleeve, etc., which is pre-assembled and pre-set before installation.

cascade seals - Seals which are staged or arranged in series with regulated pressure between adjacent pairs.

cavitation - A condition in which vapour or gas bubbles occur locally in liquids, normally in an area where pressure decreases or temperature changes abruptly. The subsequent collapse of the bubbles causes high local impact pressure, which can contribute to equipment wear and reduced seal life.

checking – See *cracking*.

coefficient of friction - The coefficient of friction is a number which represents the friction between two surfaces. The ratio of the resultant force over the applied force.

coil spring - A type of spring which is formed from wire wrapped in a helix commonly used as the tension spring in a rotary shaft lip seal.

compression fracture - Refer to [Compression Fracture section 3.10](#).

compression set - is often quoted as a percentage reduction of the initial squeeze deformation of the seal and is calculated by the following equation:

$$CS = \left(\frac{h_0 - h_2}{h_0 - h_1} \right) \times 100$$

Refer to [Compression Set section 3.1](#).

concentricity - A measurement made comparing the run out of the seal chamber bore or gland register in reference to the shaft.

coolant - A liquid from an external source circulated through a heat exchanger or some other piece of equipment to remove heat.

cracking -- Axial cracks on the lip contact surface of elastomeric seals

cross-link – bonds which form interlinks within a polymer structure producing a three dimensional elastic matrix.

cross-link density – a measure of the relative number of cross-links within an elastomer.

crystallising fluid – A fluid which is in the process of forming solids or which may form solids due to dehydration or chemical reaction.

curing – a thermosetting reaction involving the use of heat and pressure, to form cross-links in elastomer materials, resulting in increased strength and resilience

D

dieseling - Refer to [Dieseling/ Air Entrapment section 3.11.](#)

differential pressure - A difference in pressure between two points in a seal system.

dimensional stability - The ability to retain manufactured shape and size after having experienced the combination of operating stresses and temperatures..

dry-running - Running without liquid present between the sealing surfaces.

durometer reading - An index used for measuring the relative hardness of elastomers.

dynamic seal - A seal which is designed to slide or move relative to other components to allow for movement of the flexible element.

E

elastomer - A natural or synthetic rubber from which seal components such as O-rings, bellows, and gaskets are made.

emission - A release of the sealed fluid to the environment.

erosion - Abrasive wear of a surface by small particles in a gas, vapour, or liquid, or droplets of liquid in a gas or vapour flowing across the surface.

explosive decompression (ED) - Refer to [Rapid Gas Decompression section 3.2.](#)

extender – any ingredient added to a polymer compound to reduce cost with out enhancing the physical properties (cf *filler*)

extrusion - Displacement of part of a seal such as an O-ring into a gap under the action of fluid pressure or relative movement. Refer to [Extrusion/ Nibbling/ Shaving Damage section 3.6.](#)

extrusion gap - The clearance on the low-pressure side between components which confine an elastomeric seal.

extrusion ring - See *anti-extrusion ring*.

F

FFKM – See *perfluoroelastomer*

filler – Constituents of an elastomer compound incorporated to increase the mechanical properties (cf *extender*)

film thickness - The distance separating the two surfaces by means of a contact fluid.

FKM / FPM – See *fluoroelastomer*.

flash - Thin extensions on the elastomeric portion of a seal formed by extrusion of the elastomer at the parting lines in the mould cavity.

flashing - A rapid change in fluid state, from liquid to gaseous. In a dynamic seal, this can occur when fluid pressure is reduced below the fluid's vapour pressure because of a pressure drop across the seal.

flexible members - That portion of a seal containing springs or bellows.

flexibly mounted - A design technique for installing a resilient seal component so that it may compensate for slight irregularities due to alignment or pressures, thereby extending seal life.

fluid film - A film of liquid or gas separating the surfaces generated by hydrostatic and/or hydrodynamic lubrication.

full fluid film lubrication - A condition of lubrication in which the surfaces are completely separated by a liquid or gas film.

fluid side - That side of the seal which, in normal use, faces toward the fluid being sealed.

fluorocarbon - A general class of compounds containing fluorine and carbon such as PTFE and fluoroelastomers.

fluoroelastomer - A fluorocarbon elastomer commonly used as a seal in high temperature and/or corrosive service. Material is a saturated polymer in which hydrogen atoms have been replaced with fluorine. The designations FKM and FPM are synonymous.

flush - A fluid which is introduced in close proximity to the seal, used typically for cooling and lubricating the seal.

fretting - A type of wear that occurs due to the rubbing motion of a seal against its counter face.

G

gasket - A device made of several deformable materials used between two surfaces to prevent leakage. Usually the two surfaces are not in relative motion.

gland plate - A pressure retaining end plate to a seal chamber. Also called a gland or an end plate.

H

hang-up - Failure of components to move axially along the shaft under the applied mechanical and hydraulic forces.

housing - A rigid structure which supports and locates the seal.

housing bore - The cylindrical surface inside the seal chamber.

hydrodynamic lubrication - Fluid film lubrication in which the pressure in the fluid film is generated by relative motion of the seal. This can be either in a circumferential or axial direction.

hydrolysis - Refer to Volume Change [Annex 4.6.](#)

L

leakage rate - The volume or mass of fluid passing through a seal over a given length of time.

liquid film – See *fluid film*.

M

mechanical seal – A seal for rotating shafts whereby a stationary primary seal face bears against the face of a rotating mating seal ring mounted to a shaft. Often they are fitted with elastomeric secondary static seals to optimise performance.

modulus of elasticity – The ratio of stress to strain in an elastic material when that material is being stretched.

N

nibbling - Refer to [Extrusion/ Nibbling/ Shaving Damage section 3.6.](#)

O

offset (*seal offset*) – A step in the seal surface caused by a mismatch of mould halves.

oil resistance - The measure of an elastomer's ability to withstand the deteriorating effect of oil upon its mechanical properties.

O-ring - An elastomeric seal ring with an O-shaped (circular) cross-section, which may be used as either a static or dynamic seal.

O-ring groove - The space in which an O-ring is inserted for sealing.

ozone resistance - The ability of a material to withstand the deteriorating effects of ozone (surface cracking).

P

perfluoroelastomer - A fully fluorinated fluorocarbon elastomer commonly used as a seal in high temperature and /or corrosive service. The designations FFKM and FFPM are synonymous.

pitting - Surface voids usually caused by mechanical erosion, chemical corrosion, or cavitation.

plasticiser- chemical additives such as mineral oils and waxes used to decrease stiffness, improve low temperature properties, or aid processing of elastomer compounds.

polymerising fluid – A fluid which is in the process of changing, or is capable of changing from one chemical composition to another with longer-chain components and different properties, becoming usually significantly more viscous and/or tacky.

porosity - Connected minute cavities in the seal material through which fluids or gases may pass or become trapped.

port damage – Refer to [Installation and/or Port Damage section 3.8.](#)

process fluid - Either a liquid or gas to be contained by a seal.

PTFE - Polytetrafluoroethylene, a semi-rigid fluoropolymer with excellent thermal and chemical resistance and a low coefficient of friction. PTFE may be compounded with fillers (such as molybdenum disulfide, graphite, pigments, and glass fibres) or otherwise modified to improve wear characteristics and other properties.

PV value - The product of sealed pressure and relative sliding velocity. PV is used to provide a measure of the severity of the service and may be related to seal life.

R

radial play - Movement perpendicular to the shaft.

rapid gas decompression (RGD) - Refer to [Rapid Gas Decompression section 3.2.](#)

resilience - The elastic property of a sealing material that provides the ability to maintain sealing pressure.

reversion - Refer to High Temperature Effects [Annex 4.5.](#)

rolling - Refer to [Spiral Twist/ Rolling section 3.7.](#)

run-out - Twice the distance which the centre of a shaft is displaced from the axis of rotation; i. e., twice the eccentricity. Also known as Full Indicator Movement (FIM).

S

scission – breaking of chemical bonds

seal assembly - A group of unitized detail parts which includes sealing surfaces, provisions for initial loading, and sealing mechanisms.

scission – breaking of chemical bonds

seal cavity pressure - The pressure acting on the seal assembly.

seal environment - The physical and chemical conditions to which the seal is subjected.

seal housing - A structure which supports and locates the seal.

secondary seal – A term used often for the static sealing device in a mechanical seal or other dynamic sealing assemblies.

shaft eccentricity - The radial distance which the geometric centre of the shaft cross section is displaced from the axis of shaft rotation.

shaft out-of-round - The deviation of the shaft cross section from a true circle.

shaft roughness - Those irregularities in the surface texture of a shaft, usually measured as roughness average, Ra.

shaft run out - Dynamic run out, twice the distance which the centre of a shaft cross section is displaced from the axis of rotation, i.e. twice the eccentricity.

shaft sleeve - A cylindrical component placed over the shaft to protect it from wear and corrosion.

shaving - Refer to [Extrusion/ Nibbling/ Shaving Damage section 3.6](#).

Shore hardness - The relative hardness of an elastomer measured by a Shore durometer instrument.

short stroke failure - Refer to [Short Stroke Failure section 3.12](#).

spiral twist - Refer to [Spiral Twist/ Rolling section 3.7](#).

squeeze – the amount of radial or axial compression applied to a sealing element when installed.

stick-slip - A friction phenomenon which can be described as a start-stop motion which sometimes results when one surface is being dragged across another. Normally it is associated with a non-lubricated or boundary-lubricated condition.

stress relaxation - Refer to [Compression Set /Stress relaxation section 3.1](#).

swelling – An increase in volume of an elastomeric seal due to an interaction with the contact fluid.

T

torque - The resistance to shaft rotation caused by a seal's frictional drag.

torsion modulus – The ratio of stress to strain in an elastic material when that material is being twisted.

tribology - The study of interacting surfaces in rubbing contact.

U

U-cup - A type of seal with a U-shaped cross section.

uni-rotational seal - A seal designed for applications having a single direction of shaft rotation.

V

vapour pressure - Pressure at a given temperature below which a liquid changes to a gas.

V-ring seal - A seal consisting of a ring or nested rings which are of V-shaped cross section.

W

wear rate - The amount of seal surface wearing away over a period of time.

7 Conversion factors

The International System of Units (Le Système International d'Unités, or SI units) was first adopted by the 11th General Conference of Weights and Measures in 1960. This list is not exhaustive, and more details of the SI system can be found in publications such as ISO 31, ISO 1000, DIN 1301, BS 5555, BS 5775.

7.1 SI units

Quantity	Unit name	Symbol	Expressed in terms of other SI units
Energy (work)	joule	J	$J = N.m = kg.m^2.s^{-2}$
Force	newton	N	$N = kg.m.s^{-2}$
Length	metre	m	
Mass	kilogram	kg	
Pressure	pascal	Pa	$Pa = N.m^{-2} = MN.mm^{-2}$
Power	watt	W	$W = kg.m^2.s^{-3}$
Temperature (thermodynamic)	kelvin	K	$K = ^\circ C + 273.15$
Time	second	s	

7.2 Multiples of SI units

The multiples are expressed by orders of magnitude, which are given as a prefix to the SI unit:

Prefix name	Prefix symbol	Factor by which the primary unit is multiplied
exa	E	10^{18} 1 000 000 000 000 000 000
peta	P	10^{15} 1 000 000 000 000 000
tera	T	10^{12} 1 000 000 000 000
giga	G	10^9 1 000 000 000
mega	M	10^6 1 000 000
kilo	k	10^3 1 000
hecto	h	10^2 100
deca	da	10^1 10
deci	d	10^{-1} 0.1
centi	c	10^{-2} 0.01
milli	m	10^{-3} 0.001
micro	μ	10^{-6} 0.000 001
nano	n	10^{-9} 0.000 000 001
pico	p	10^{-12} 0.000 000 000 001
femto	f	10^{-15} 0.000 000 000 000 001
atto	a	10^{-18} 0.000 000 000 000 000 001

As an example, the multiple unit MPa (megaPascal = 10^6 Pa) is often used when referring to pressure in fluid systems, such as those in the process industries.

7.3 Units of common usage in sealing terminology

The following list covers non-SI units which are used regularly in connection with sealing terminology, and gives equivalent conversions into SI units (and other units where appropriate). The list is in alphabetical order (for conversion factors for SI units, please refer to [Section 7.4](#)):

Unit	SI equivalent	Other non-SI unit equivalents				Various other units or conversions
		<i>bar</i>	<i>kp.cm⁻²</i>	<i>N.mm⁻²</i>	<i>psi</i>	
1 at	0.1013 MPa	1.013 bar	1.033 kp.cm ⁻²	0.1013 N.mm ⁻²	14.695 psi	
1 bar	0.1 MPa			0.10 N.mm ⁻²	14.504 psi	0.987 atmospheres
1 °C	-273.15 K					
1 °F						(°C x 1.8) + 32
1 ft (foot)	0.305 m					
1 in (inch)	0.025 m					
1 in ²	645.2 mm ²					
1 kgf	9.81 N					2.2046 lbf
1 kg/cm ²	0.098 MPa	0.981 bar	1 kp.cm ⁻²	0.098 N.mm ⁻²	14.223 psi	
1 N/mm ²	1 MPa	10.0 bar	10.197 kp.cm ⁻²	1 N.mm ⁻²	145.038 psi	
1 lb (pound)	4.45 N					0.4536 kp
1 lbf. ft	1.355 N.m					
1 lbf.in	0.113 N.m					
1 mm Hg	0.133322 kPa					
1 ppm	35.92 ^{-0.733} g.h ⁻¹					#
1 psi	6.895 kPa	0.0689 bar	0.0703 kp.cm ⁻²	0.00689 N.mm ⁻²		

This follows from the standard US field measurement technique, known as EPA Reference Method 21, which was introduced by the US Environmental Protection Agency (US EPA) for the monitoring of fugitive emissions in parts per million (ppm). This approach was established to provide a "go" / "no go" method (i.e. there is either a leak or no leak). While this is useful as a qualitative measure of emissions, ppm cannot be converted directly into quantitative units. Accordingly, the US EPA has developed a series of correlations for the prediction of mass flow rate. These resemble closely a later joint study in the USA by the Chemical Manufacturers Association (CMA) and the Society of Tribologists and Lubrication Engineers (STLE), in which bagging data were analysed to determine the following relationship:

$$\text{Leakage rate (lb.h}^{-1}\text{)} = 6.138 \times 10^{-5} \times (\text{SV})^{0.733}, \text{ where SV is the screening value in ppm}$$

When converted into metric units (453.6 g = 1 lb):

$$\text{Leakage rate (g.h}^{-1}\text{)} = 0.02784 \times (\text{SV})^{0.733}$$

7.4 Conversion factors (SI units)

Quantity	SI unit	Non-SI unit	Conversions
Acceleration	$\text{m}\cdot\text{s}^{-2}$	$\text{ft}\cdot\text{s}^{-2}$	$1 \text{ m}\cdot\text{s}^{-2} = 3.281 \text{ ft}\cdot\text{s}^{-2}$ $1 \text{ ft}\cdot\text{s}^{-2} = 0.305 \text{ m}\cdot\text{s}^{-2}$
	$9.806 \text{ m}\cdot\text{s}^{-2}$	$32.174 \text{ ft}\cdot\text{s}^{-2}$	= Standard acceleration of gravity
Area	ha (hectare)	acre	$1 \text{ ha} = 10,000 \text{ m}^2 = 2.471 \text{ acres} = 3.86 \times 10^{-3} \text{ mile}^2$ $1 \text{ acre} = 0.405 \text{ ha} = 4046.86 \text{ m}^2$
	m^2	ft^2	$1 \text{ m}^2 = 10.764 \text{ ft}^2$ $1 \text{ ft}^2 = 9.290 \times 10^{-2} \text{ m}^2$
	m^2	in^2	$1 \text{ m}^2 = 1.550 \times 10^3 \text{ in}^2$ $1 \text{ mm}^2 = 1.550 \times 10^{-3} \text{ in}^2$ $1 \text{ in}^2 = 6.452 \times 10^{-4} \text{ m}^2 = 645.2 \text{ mm}^2$
	m^2	mile^2	$1 \text{ m}^2 = 3.861 \times 10^{-7} \text{ mile}^2$ $1 \text{ mile}^2 = 2.589 \times 10^6 \text{ m}^2 = 259 \text{ ha}$
	m^2	yd^2	$1 \text{ m}^2 = 1.196 \text{ yd}^2$ $1 \text{ yd}^2 = 0.836 \text{ m}^2$
	Density	$\text{kg}\cdot\text{m}^{-3}$	$\text{lb}\cdot\text{ft}^{-3}$
	$\text{kg}\cdot\text{m}^{-3}$	$\text{lb}\cdot\text{gal}^{-1}$	$1 \text{ lb}\cdot\text{gal}^{-1} = 0.099 \text{ kg}\cdot\text{dm}^{-3}$
	$\text{kg}\cdot\text{m}^{-3}$	$\text{lb}\cdot\text{in}^{-3}$	$1 \text{ lb}\cdot\text{in}^{-3} = 27.679 \text{ g}\cdot\text{cm}^{-3}$
Energy (work)	J	Btu	$1 \text{ J} = 9.478 \times 10^{-4} \text{ Btu}$ $1 \text{ Btu} = 1.055 \times 10^3 \text{ J}$
	J	$\text{ft}\cdot\text{lbf}$	$1 \text{ J} = 0.738 \text{ ft}\cdot\text{lbf}$ $1 \text{ ft}\cdot\text{lbf} = 1.356 \text{ J}$
	J	kcal	$1 \text{ J} = 2.390 \times 10^{-4} \text{ kcal}$ $1 \text{ kcal} = 4.19 \times 10^3 \text{ J}$
	J	$\text{kgf}\cdot\text{m}$	$1 \text{ J} = 0.102 \text{ kgf}\cdot\text{m}$ $1 \text{ kgf}\cdot\text{m} = 9.810 \text{ J}$
	J	kWh	$1 \text{ J} = 2.778 \times 10^{-7} \text{ kWh}$ $1 \text{ kWh} = 3.6 \times 10^6 \text{ J}$
Force	N	kgf	$1 \text{ N} = 0.102 \text{ kgf}$ $1 \text{ kgf} = 9.81 \text{ N} = 2.205 \text{ lbf}$
	N	lbf	$1 \text{ N} = 0.225 \text{ lbf}$ $1 \text{ lbf} = 4.448 \text{ N}$
	N	tonf	$1 \text{ N} = 1.003 \times 10^{-4} \text{ tonf}$ $1 \text{ tonf} = 9964 \text{ N}$
Length	m	ft	$1 \text{ m} = 3.281 \text{ ft}$ $1 \text{ ft} = 0.305 \text{ m}$
	m	in (1")	$1 \text{ m} = 39.37 \text{ in}$ $1 \text{ in} = 0.025 \text{ m}$
	m	mile	$1 \text{ m} = 6.214 \times 10^{-4} \text{ mile}$ $1 \text{ mile} = 1.609 \times 10^3 \text{ m}$
	m	milli-inch ("thou")	$1 \text{ "thou"} = 25.4 \mu\text{m}$
	m	yd	$1 \text{ m} = 1.094 \text{ yd}$ $1 \text{ yd} = 0.914 \text{ m}$

Quantity	SI unit	Non-SI unit	Conversions
Mass	kg	cwt	1 kg = 1.968 x 10 ⁻² cwt 1 cwt = 50.802 kg
	kg	oz	1 kg = 35.274 oz 1 oz = 28.349 g
	kg	pound (lb)	1 kg = 2.203 lb 1 lb = 0.454 kg
	kg	ton	1 kg = 9.842 x 10 ⁻⁴ ton 1 ton = 1.016 x 10 ³ kg = 1.016 tonne 1 tonne (= 1 metric tonne) = 1000 kg
Moment of force (torque)	N.m	kgf.m	1 N.m = 0.102 kgf.m 1 kgf.m = 9.807 N.m
	N.m	ozf.in	1 N.m. = 141.612 ozf.in 1 ozf.in = 7061.55 μN.m
	N.m	lbf.ft	1 N.m = 0.738 lbf.ft 1 lbf.ft = 1.356 N.m
	N.m	lbf.in	1 N.m = 8.85 lbf.in 1 lbf.in = 0.113 N.m
	N.m	tonf.ft	1 kN.m = 0.329 tonf.ft 1 tonf.ft = 3.037 kN.m
Moment of inertia	kg.m ²	oz.in ²	1 kg.m ² = 5.464 x 10 ³ oz.in ² 1 oz.in ² = 1.829 x 10 ⁻⁵ kg.m ²
	kg.m ²	lb.ft ²	1 kg.m ² = 23.730 lb.ft ² 1 lb.ft ² = 0.042 kg.m ²
	kg.m ²	lb.in ²	1 kg.m ² = 3.417 x 10 ³ lb.in ² 1 lb.in ² = 2.926 x 10 ⁻⁴ kg.m ²
Power	W	ft.lbf.s ⁻¹	1 W = 0.738 ft.lbf.s ⁻¹ 1 ft.lbf.s ⁻¹ = 1.356 W
	W	hp	1 W = 1.341 x 10 ⁻³ hp 1 hp = 7.457 x 10 ² W
	W	kgf.m.s ⁻¹	1 W = 0.102 kgf.m.s ⁻¹ 1 kgf.m.s ⁻¹ = 9.81 W
Pressure	Pa	bar	10 ⁶ Pa = 1 MPa = 10 bar = 1 N.mm ⁻² 1 bar = 0.10 MPa = 14.504 psi
	Pa	ft H ₂ O (feet of water)	1 kPa = 0.335 ft H ₂ O 1 ft H ₂ O = 2.989 kPa
	Pa	in Hg (inch of mercury)	1 kPa = 0.295 in Hg 1 in Hg = 3.386 kPa
	Pa	kgf.m ⁻²	1 Pa = 0.102 kgf.m ⁻² 1 kgf.m ⁻² = 9.81 Pa
	Pa	kp.cm ⁻²	1 MPa = 10.194 kp.cm ⁻² 1 kp.cm ⁻² = 0.0981 MPa = 0.981 bar = 14.223 psi
	Pa	N.mm ⁻²	1 MPa = 1 N.mm ⁻² = 1 MN.m ⁻² = 10.197 kp.cm ⁻²
	Pa	lbf. ft ⁻²	1 kPa = 20.885 lbf. ft ⁻² 1 lbf. ft ⁻² = 47.880 Pa
	Pa	psi (lbf.in ⁻²)	1 Pa = 1.450 x 10 ⁻⁴ lbf.in ⁻² 1 lbf.in ⁻² = 6.895 kPa = 0.0703 kp.cm ⁻² = 0.0689 bar
	Pa	ton.in ⁻²	1 MPa = 6.477 x 10 ⁻² ton.in ⁻² 1 ton.in ⁻² = 15.44 MPa = 15.44 N.mm ⁻²
		1.013 x 10 ⁵ Pa	14.696 lbf.in ⁻²

Quantity	SI unit	Non-SI unit	Conversions
Rate of flow (volumetric)	$\text{m}^3 \cdot \text{s}^{-1}$	$\text{ft}^3 \cdot \text{s}^{-1}$ (cusec)	$1 \text{ m}^3 \cdot \text{s}^{-1} = 35.314 \text{ ft}^3 \cdot \text{s}^{-1}$ $1 \text{ ft}^3 \cdot \text{s}^{-1} = 0.028 \text{ m}^3 \cdot \text{s}^{-1} = 28.317 \text{ dm}^3 \cdot \text{s}^{-1}$
	$\text{m}^3 \cdot \text{s}^{-1}$	imperial gal.h ⁻¹	$1 \text{ m}^3 \cdot \text{s}^{-1} = 7.919 \times 10^5 \text{ imp gal} \cdot \text{h}^{-1}$ $1 \text{ imp gal} \cdot \text{h}^{-1} = 1.263 \times 10^{-6} \text{ m}^3 \cdot \text{s}^{-1} = 4.546 \text{ dm}^3 \cdot \text{h}^{-1}$
	$\text{m}^3 \cdot \text{s}^{-1}$	$\text{in}^3 \cdot \text{min}^{-1}$	$1 \text{ m}^3 \cdot \text{s}^{-1} = 3.661 \times 10^6 \text{ in}^3 \cdot \text{min}^{-1}$ $1 \text{ in}^3 \cdot \text{min}^{-1} = 2.731 \times 10^{-7} \text{ m}^3 \cdot \text{s}^{-1}$
	$\text{m}^3 \cdot \text{s}^{-1}$	US gal. min ⁻¹	$1 \text{ m}^3 \cdot \text{s}^{-1} = 1.585 \times 10^4 \text{ US gal} \cdot \text{min}^{-1}$ $1 \text{ US gal} \cdot \text{min}^{-1} = 6.309 \times 10^{-5} \text{ m}^3 \cdot \text{s}^{-1}$
Temperature	K	°C	$\text{K} = ^\circ\text{C} + 273.15$ $^\circ\text{C} = \text{K} - 273.15$
		°F	$^\circ\text{C} = (^\circ\text{F} - 32) \times 0.556$ $^\circ\text{F} = (^\circ\text{C} \times 1.8) + 32$
Velocity	$\text{m} \cdot \text{s}^{-1}$	$\text{ft} \cdot \text{s}^{-1}$	$1 \text{ m} \cdot \text{s}^{-1} = 3.281 \text{ ft} \cdot \text{s}^{-1}$ $1 \text{ ft} \cdot \text{s}^{-1} = 0.305 \text{ m} \cdot \text{s}^{-1}$
	$\text{m} \cdot \text{s}^{-1}$	km.h ⁻¹	$1 \text{ m} \cdot \text{s}^{-1} = 3.6 \text{ km} \cdot \text{h}^{-1}$ $1 \text{ km} \cdot \text{h}^{-1} = 0.278 \text{ m} \cdot \text{s}^{-1}$
	$\text{m} \cdot \text{s}^{-1}$	mile.h ⁻¹	$1 \text{ m} \cdot \text{s}^{-1} = 2.237 \text{ mile} \cdot \text{h}^{-1}$ $1 \text{ mile} \cdot \text{h}^{-1} = 0.447 \text{ m} \cdot \text{s}^{-1} = 1.467 \text{ ft} \cdot \text{s}^{-1}$
Viscosity (dynamic)	Pa.s	P (poise)	$1 \text{ Pa} \cdot \text{s} = 10 \text{ P}$ $1 \text{ P} = 0.1 \text{ Pa} \cdot \text{s}$
	Pa.s	lbf.s.ft ⁻²	$1 \text{ Pa} \cdot \text{s} = 2.089 \times 10^{-2} \text{ lbf} \cdot \text{s} \cdot \text{ft}^{-2}$ $1 \text{ lbf} \cdot \text{s} \cdot \text{ft}^{-2} = 47.880 \text{ Pa} \cdot \text{s}$
Viscosity (kinematic)	$\text{m}^2 \cdot \text{s}^{-1}$	$\text{ft}^2 \cdot \text{s}^{-1}$	$1 \text{ m}^2 \cdot \text{s}^{-1} = 10.764 \text{ ft}^2 \cdot \text{s}^{-1}$ $1 \text{ ft}^2 \cdot \text{s}^{-1} = 9.290 \times 10^{-2} \text{ m}^2 \cdot \text{s}^{-1}$
	$\text{m}^2 \cdot \text{s}^{-1}$	$\text{in}^2 \cdot \text{s}^{-1}$	$1 \text{ in}^2 \cdot \text{s}^{-1} = 6.452 \text{ cm}^2 \cdot \text{s}^{-1} = 645.16 \text{ cSt}$
	$\text{m}^2 \cdot \text{s}^{-1}$	St (stokes)	$1 \text{ m}^2 \cdot \text{s}^{-1} = 10^4 \text{ St}$ $1 \text{ St} = 10^{-4} \text{ m}^2 \cdot \text{s}^{-1}$
Volume (capacity)	m^3	ft^3	$1 \text{ m}^3 = 35.315 \text{ ft}^3$ $1 \text{ ft}^3 = 0.028 \text{ m}^3$
	m^3	imperial fl oz	$1 \text{ fl oz} = 28.413 \text{ cm}^3$
	m^3	imperial gal	$1 \text{ m}^3 = 2.199 \times 10^2 \text{ imp gal}$ $1 \text{ imp gal} = 4.546 \times 10^{-3} \text{ m}^3$
	m^3	imperial pt (pint)	$1 \text{ pt} = 0.568 \text{ dm}^3$
	m^3	in^3	$1 \text{ m}^3 = 6.102 \times 10^4 \text{ in}^3$ $1 \text{ in}^3 = 1.639 \times 10^{-5} \text{ m}^3$
	m^3	litre (L)	$1 \text{ L} = 10^{-3} \text{ m}^3 = 0.220 \text{ imp gal} = 0.264 \text{ US gal}$
	m^3	US gal	$1 \text{ m}^3 = 2.642 \times 10^2 \text{ US gal}$ $1 \text{ US gal} = 3.785 \times 10^{-3} \text{ m}^3$

8 References

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