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EXPLOSIVE DECOMPRESSION AND OTHER O-RING RELATED ISSUES FOR TURBOMACHINERY SERVICE- SOME USER GUIDANCE

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ABSTRACT

Flexible sealing elements, typically elastomeric O-rings are commonly used to contain fluids within pressurized cavities of turbomachinery at the interfaces between adjoining components. All too often the only selection criteria applied for these sealing element is chemical resistance and a check that the service conditions are within the published temperature limits for the material being considered. This seemingly simplistic selection process can be complicated when the fluid in question, comprised of numerous constituents that dictate several different elastomeric materials, would normally be the optimal selection. Furthermore in the case of duties where the fluid (typically gas) pressure is elevated, some additional considerations also become more prominent due to explosive decompression (ED) damage that can occur during rapid depressurization events in the pressurized system. Despite the effects of ED being well documented, there is still a relative lack of understanding regarding what makes a sealing device “ED resistant” and why.

This tutorial goes through the composition of flexible sealing element materials and how they compare with a more widely understood engineering material; steel. It also focuses on sizing issues and international standards and how they are applied in given applications. Thermal considerations will also be addressed and an appreciation of the methods used to test such materials will be covered. In addition to ED topics being fully addressed there will also be other issues covered such as storage and longevity, modulus, strength, hardness, elongation, compression set, and stress relaxation. Lastly, although this tutorial focuses mainly on O-rings it can equally be applied to any elastomeric sealing material used in the turbomachinery industry.

INTRODUCTION

Equipment and devices that are used to generate or contain fluid pressure all require their contents to be adequately sealed or allowed to flow through defined regions. Given that these items all comprise of numerous separate, manufactured components requires that sealing devices are employed to ensure interfaces between adjacent parts cannot allow the pressurized fluid to escape. Due to the diverse nature of pressure containing machinery, these sealing devices are needed to adopt many different forms produced in a wide variety of materials. In the case of most turbomachinery the seals have to be compliant with the profile of the irregular shaped parts and also accommodate both the manufacturing tolerance and surface textures of the interconnecting components. These conflicting requirements make elastomeric (elastomer) components ideally suited for turbomachinery duties since they are compliant and can easily be adapted to seal otherwise non-conformal surfaces. One of the most widely adopted forms for elastomeric sealing devices is circular cross section chord that is often produced in solid annular ring format, commonly referred to as O-rings (see figure 1). In contrast to the flexibility and versatility of elastomeric devices used for sealing turbomachinery is that there are a number of issues mainly related to the temperature extremes and high pressures often encountered with such equipment. Although it is possible to apply most of the topics discussed in this paper to any type of elastomeric sealing device, we will focus mainly on the O-ring, as it is the most common type of elastomeric sealing device.

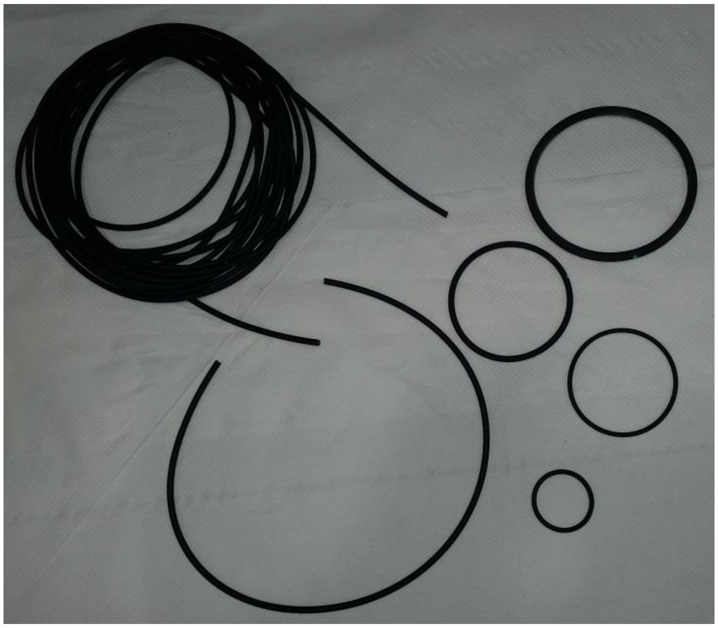


Figure 1- Circular cross section chord, a selection of different cross sections and different inside diameter O-rings.

When O-rings, or any elastomeric sealing elements, are being considered for a given duty it is usually on the basis of chemical compatibility, temperature resistance and ED resistance when high pressure gases are being sealed. Given that a significant number of turbomachinery applications demanding whereby materials are pushed to their limits, a great deal of care must be taken to ensure that material properties are not merely compared but also understood. In the case of elastomeric components used for arduous duties, the influence of operating conditions and property variance with temperature and pressure cycles is an essential aspect of turbomachinery design that is often overlooked. In addition this tutorial looks at how test data can be scrutinized to enable future success.

TYPICAL APPLICATIONS

Before looking at elastomer engineering, we should perhaps look at situations with which we are far more familiar such as centrifugal and reciprocating compressors. Although these machines vary in design, each function by adding energy to a gas medium resulting in a pressure and temperature rise. While pressure differentials exist throughout these units, O-ring selection should not be a cut and paste operation. Rather it is important to understand key aspects, i.e., where the critical sealing locations are, what the consequences and severity of a seal failure would be, what gas that particular area will experience, and the extent of maintenance involved with field seal change-outs.

Centrifugal compressors transfer energy into a gas through one or more rotating impellers. Pressures within these units can be upwards of 1,000 bar (14,500 psi) with temperatures near 260ºC (500ºF). Depending on the machine’s size, maximum continuous operating speeds can surpass 20,000 RPM. Centrifugal compressors give a relatively steady flow while operated on the performance map but can have surge or choke conditions that could affect compressor output. While the pressure differentials near rotating components are kept separate using various labyrinth seals, stationary components make use of O-rings.

Not all O-rings are meant for the same purpose and thus carry varying levels of importance. Figure 2 is cut away view of a standard straight-thru centrifugal compressor. An O-ring seal between the bearing housing and head keeps oil from leaking out of the assembly (shown by **A**). If this seal were to break, the unit would drip oil onto the baseplate. Despite the seal breaking, the unit would still run without issue. This may be a good example of a low level importance seal.

Another area of usage would be on hydraulic fit thrust discs or couplings. These parts are assembled by pressurizing the cavity between the part and shaft, thereby expanding the part and allowing it to slip into position. The O-ring seals this pressure in, and any leakage would result in mis-assembly.

O-rings are also used as cordage when an internal assembly is horizontally-split in order to restrict recycle between impeller stages; leakage past these elements would result in a minor drop in efficiency and pressure (head) (shown by **B**). In a back-to-back unit, the O-ring around the bundle division wall serves this same purpose. While internal recycle is more pronounced, leakage past the seal does not necessarily warrant a shutdown. Bundle seals directly inboard of the inlets also serve to limit internal recycle (shown by **C**).

The first example of a more critical seal is the area between the case and heads (shown by **D**). This interface represents the last line of defense to keep internal process gas contained. Leakage past this seal would allow process gas to release into the atmosphere, exposing plant personnel to potentially dangerous fumes or explosion hazards.

Dry gas seals are the dynamic shaft end seal of choice for today's centrifugal compressors. They seal the pressure boundary ends allowing the shaft ends to penetrate outside the pressure boundary without allowing process gas to evacuate the unit. Although the rotor portion of the seals are dynamic, their outer static housing interfaces with the static compressor head. This interface generally utilizes a series of O-rings (shown by **E**). Low pressure seals will use the same O-ring materials and design as typical bundle components, with high-pressure seals containing spring-energized, or "C" type, seals in their place to give proper sealing contact in extreme conditions. In either leakage case, the machine would require an immediate shutdown in order to investigate the issue and remedy any process gas being released into the atmosphere.

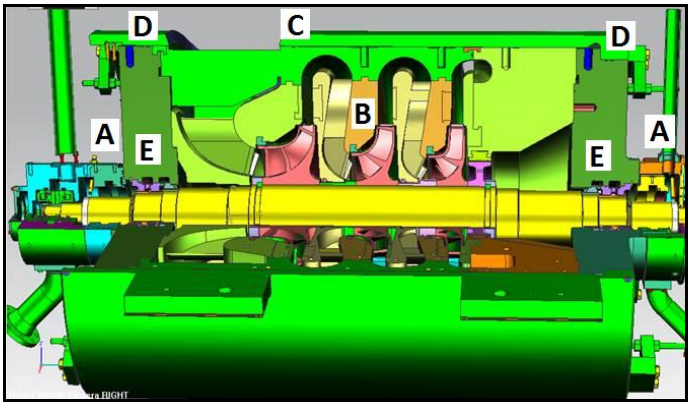


Figure 2- A typical centrifugal compressor cut-away view.

Reciprocating compressors operate by compressing a fixed volume of gas through the use of a piston and crankshaft. Pressures can reach 827 bar (12,000 psi) and 177 ºC (350ºF). Though reciprocating units are machines that push lower volumes of gas, they excel in high ratio services, changing capacity, and are used in applications where variable flow rates are needed. Pressures within the cylinder are dynamic and constantly load/unload both the metal and elastomeric components which affects service life.

Figure 3 is representative of a standard reciprocating compressor cross section, where the process gas is contained within the cylinder. In this class of machinery the important sealing locations include the main interface at the cylinder and heads (outer and inner, shown by **A**) and the valve covers (shown by **B)**. The heads each have one O-ring land milled into them that seat against the cylinder. While there are several valve covers, each has an O-ring that seats against the cylinder as well. In both cases, these O-rings act as a barrier between the process gas and atmosphere. Should any of these seals fail, process gas may be released to the outside. Standard unit startup procedures involve a manual sniffer walk-around of the unit.

Because of the dynamic pressures that occur in a reciprocating compressor, O-rings tend to have shorter life spans. Valve cover O-rings, for instance, can have a 3-5 year service life before needing to be changed out under ideal circumstances. For most designs, valve cover O-ring access renders them simpler to replace, than inner head seals which may require longer outages.

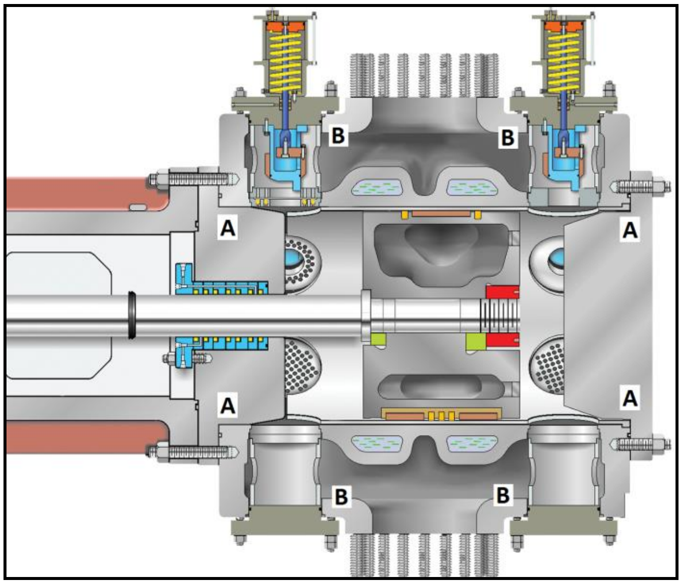


Figure 3- A typical reciprocating compressor cross section.

HOW STEEL AND ELASTOMERS DIFFER

Before looking at the relatively little known aspects of elastomer engineering, we should perhaps look at another textbook situation. Let's consider a pressure boundary that has to contain gas at a pressure of 70bar (1,000psi) and a moderate temperature of 24^{O}C (75^{O}F) and has a nominal diameter of around 1,000mm (40inch). Using ASME VIII, certain factors would be applied that would normally contribute to make the boundary "safe".

For example, we would apply the appropriate design rules for the selected material and this would dictate that the thickness would be 29.5mm (1.16in). Given that the vessel must have openings for the gas to enter and exit, we would then design fittings that would be flanged so we would adopt pressure vessel code rules to make sure that the flanges were also “safe”.

Adopting ASME VIII Div1 Appendix 2 rules would mean that the flange thickness was around 38mm (1.5inch). Having designed the pressure vessel out of steel, we were a little surprised to find that an elastomeric 3.2mm (0.125in) O-ring has been selected to seal the flange! We have therefore gone from proving why we need to use steel materials, rigid and strong enough for the tallest buildings and most robust bridges, to a piece of elastomer that can be readily deformed by hand. Surely this cannot be right? ·

When properties between steel and elastomers are compared the differences appear to be vast. As forces are applied to any material they deform and the comparison between undeformed and deformed conditions can be evaluated as strain measurements. In the case of steel this deformation is typically around 1% before the material fails, but in the case of elastomers it is often over 100%. Similarly as increased loads are applied, the stresses at which failure occurs are of a different magnitude. In the case of steels it can be well over 500MPa (73ksi) whereas elastomers fail at around 10MPa (1.5ksi). The difference in the stress strain characteristics are shown in figure 4.

Another marked difference between steel and elastomers relates to the composition. Most materials used for engineering components are manufactured to specific standards whereby the chemical composition and material properties have to be met in order for the material to conform to contractual and engineering requirements. In the case of elastomers there are no standards that cover the exact composition or properties of elastomers, therefore it is up to the user to select materials based upon their own judgment. The selection process is often impaired by proprietary branded materials are often given trade names that can further confuse comparative studies. In contrast, when it comes to steels, there are standards that dictate both composition and minimum property requirements, simplifying the selection process. These marked differences are the primary reason users of elastomeric components should pay far more attention to elastomeric properties and characteristics rather than just focusing on temperature limits and simplistic chemical compatibility checks.

O-RINGS

O-rings are probably the most common elastomeric sealing device. They are devices that comprise of a circular cross section that is formed or molded in the shape of a ring or toroid. Several standards exist relating to the sizes of O-rings. These

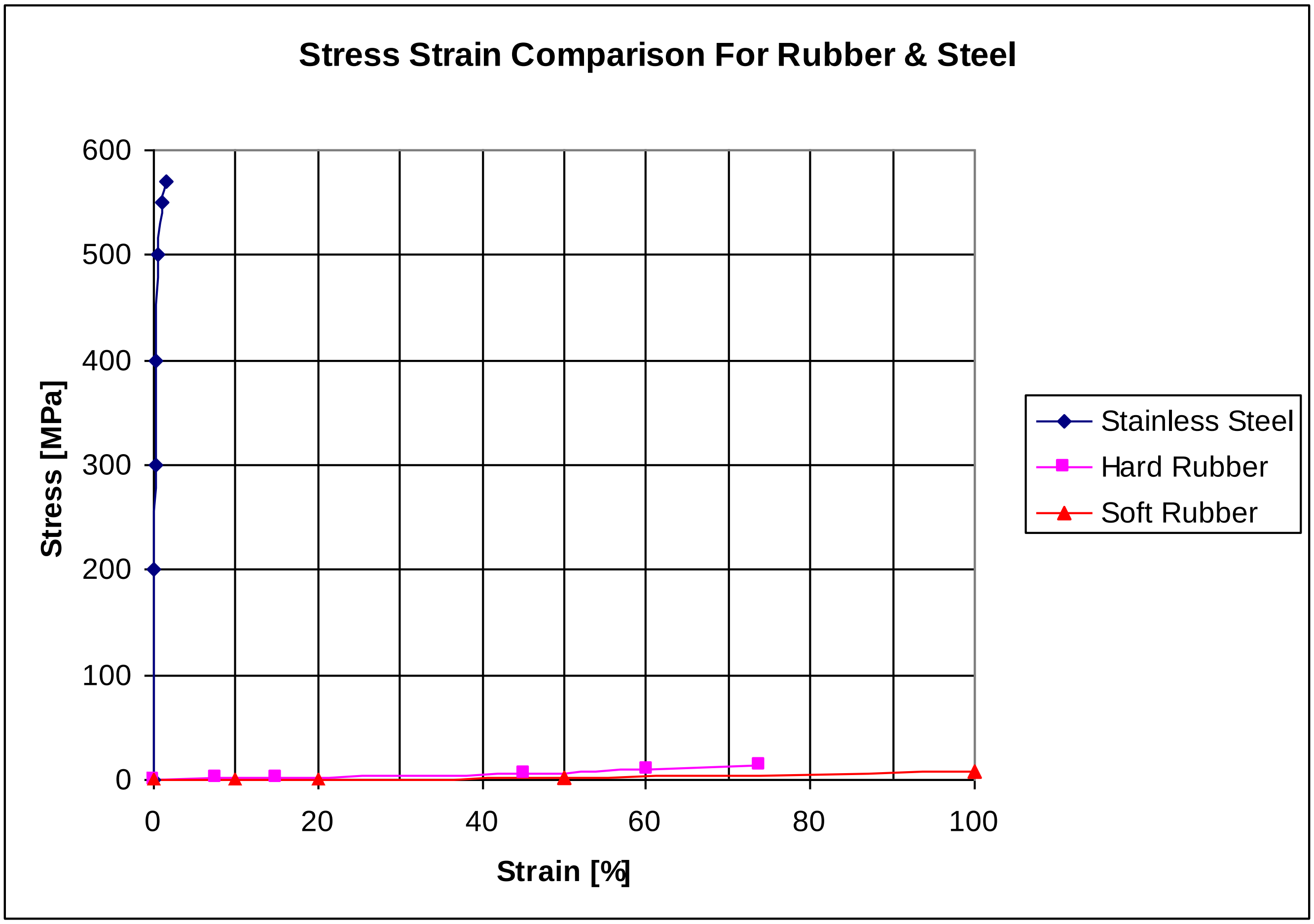


Figure 4- Stress-strain tensile relationship comparison between some typical elastomers and stainless steel.

tend to have a set number of sizes for the cross sectional rings together with a series of inside diameters spanning between lower and upper limits.

Standardizing the circular cross-section diameter enables standard groove geometry adoption, such that the correct amount of squeeze can be applied to any given O-ring to enable functionality as a sealing device. Although O-rings are commonly fitted to circular components, the flexibility of the material enables them to be pressed into irregular profiles provided the groove-like features are able to constrain the material. Similarly, the fact that they can be stretched enables them to be quite easily fitted over the top of components that are of a far larger diameter than the basic size of the O-ring. The elasticity or resilience of the material then allows it to recover its original shape once it has passed over the larger component. These versatile characteristics are all contributing factors that make O-rings so popular for sealing duties. Figure 5 shows a typical O-ring and the most typical groove profiles. This data is available in numerous international standards, however certain materials, most notably FFKM, require groove geometry that differs from such standards. Similarly, a consequence of the flexibility of O-rings allows them to be used in all types of sealing duties including situations where one of the standard groove profiles cannot be adopted. This proves why manufacturer's data should always be referenced.

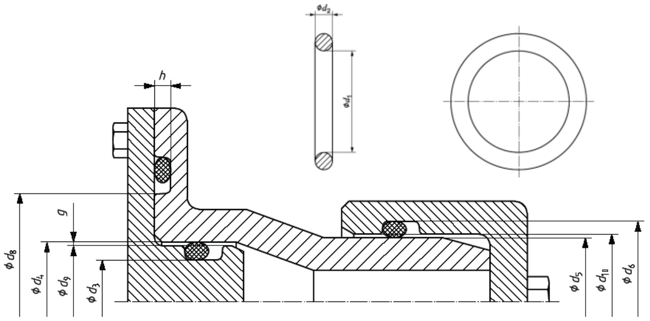


Figure 5- Extract from BS ISO 3601 showing an O-ring with d2 cross section and d1 inside diameter together with standard groove information[1].

In order to work correctly an O-ring has a certain amount of initial squeeze or compression applied to the circular section. In practice this is usually between 15- 20% for static applications, however, in certain situations it can be as low as 1% and as high as 30%. The initial squeeze provides a contact load on the surrounding housing and this is in effect the preload sealing force. The elastomeric material is incompressible at normal working temperatures and this, combined with its elastic modulus, enables it to deform as fluid pressure is applied to it. The pressure therefore deforms the O-ring, which in turn creates an interference stress between the seal and the groove that is always equal to the applied pressure plus the initial interference or preload stress. In most circumstances if the initial interference stress is maintained, the O-ring will be able to function as a sealing device over a wide range of pressure and temperature (see figure 6). When O-rings are deemed to have failed it is generally a consequence of this initial force being lost. Such occurrences are brought about by movement of the surrounding parts (i.e. distortion), extrusion of the O-ring or a change in the properties of the elastomer itself due to chemical attack, swelling, shrinkage, or aging effects.

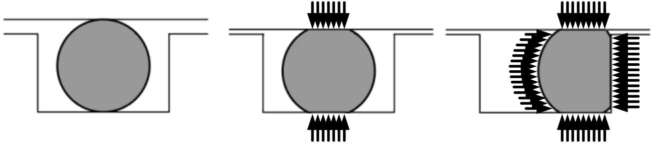


Figure 6- Loads on O-rings and groove. Left- No Squeeze (Uncompressed); Center- Initial Squeeze (Compressed); Right- Fluid Pressure & Squeeze

Because the O-ring continuously deforms under the action of pressure, the groove into which it is fitted acts as a constraint and support for the O-ring. In general terms, the cross-sectional area of the rectangular groove tends to be about 15% larger than the maximum cross section of the O-ring under ambient conditions. However, the co-efficient of thermal expansion of elastomers is far greater than that of most other engineering materials (i.e. steel) so the additional groove volume is necessary to accommodate any increase in temperature or expansion of the O-ring. The following table highlights the amount of expansion normally associated with a typical elastomer material.

Table 1- Thermal expansion of different materials

	cm/cm/Deg C	in/in/Deg F
Natural Rubber	15 x10-5	83 x10-6
Butyl	15 x10-5	83 x10-6
Chloroprene	13.7 x10-5	76 x10-6
Nitrile	11.2 x10-5	62 x10-6
Fluorocarbon	16.2 x10-5	90 x10-6
Perfluoroelastomers	46 x10-5	260 x10-6
Silicone	18.5 x10-5	103 x10-6
Typical Plastic	7.2 x10-5	40 x10-6
Carbon Steel	12 x10-6	6.7 x10-6
Stainless Steel	17 x10-6	9.4 x10-6

ELASTOMERS

Before looking at the characteristics and properties that make elastomers suitable or limited for high pressure gas duties, we must first understand something about the nature of elastomers and how it can be used in engineering components. Rubber in its natural form is a resin that is harvested from trees as latex, a white sticky material that seeps out of certain trees when their bark is cut. This product contains isoprene polymers with minor other constituents, plus water. This raw material is then refined and processed into natural rubber that exhibits very high elasticity and resilience and is extremely waterproof. While this may seem ideal, the reality is that as a sealing material it has limited temperature range and is also prone to rapid ageing. The limitations of natural rubber brought about the development of synthetic elastomeric materials that have been around for almost a century.

There are over a dozen different material groups for elastomer materials, but several standards attempt to categorize these into different groups. In each material group there are thousands of different elastomeric compounds available that are all in some way different to one another, thereby dictating that they can be used in a wide variety of applications. In general, most of the material groups are given abbreviations that identify the materials and are covered by numerous different international standards (see table 2). Irrespective of the different material types, there are several characteristics that are common throughout elastomeric materials.

Table 2- ASTM 1418/ISO 1629 Abbreviations

Elastomer Type	Abbreviation	Group[1]
Chloroprene	CR	R
Ethylene Propylene	EPM	M
Ethylene Propylene Diene	EPDM	M
Fluorocarbon	FKM	M
Fluorosilicone	FMQ,FVMQ,FSR	Q
Nitrile (Acrylonitrile Butadiene)	NBR	R
Nitrile (Hydrogenated)	HNBR	R
Perfluoroelastomers	FFKM	M
Silicone	MFQ	Q
Tetrafluoroethylene Propylene Copolymer	FEPM,TFE/P	M
1) Polymer chain/group M- Polymethylene chain Q- Silicone and oxygen chain R- Diene chain		

Regardless of type, most elastomers consist of a long chain of molecules that contain a repeating monomer pattern. In the case of nitrile materials, these molecules are predominantly hydrogen and carbon. In fluorocarbon polymers the equivalent chain has additions of fluorine. It is in effect, these long chains that give elastomers the ability to stretch to many times their original length.

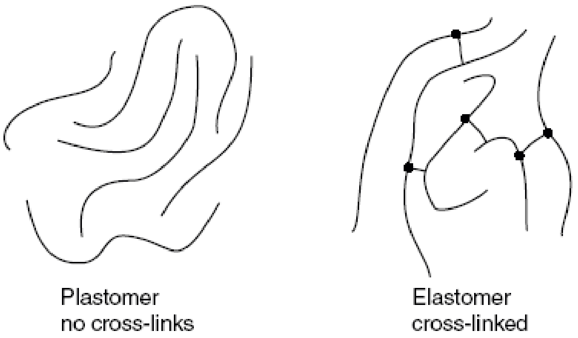
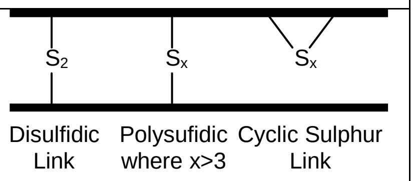
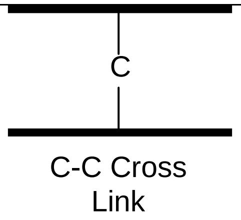
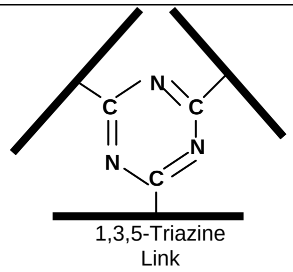
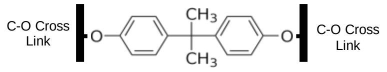
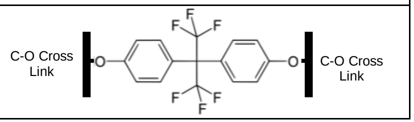


Figure 7- Shows the base material (left) prior to processing. Cross-linking (right) provides improved properties[2].

Polymer chains on their own would be relatively weak. In order to increase the strength of elastomeric materials, these separate polymer chains need to be cross-linked at various sites within the chain. To achieve the cross-linking process (see figure 7) certain agents are added to the base material mixture to encourage activation sites, enabling cross-linking to occur during the curing process where heat and pressure are added to the material, such that the chemical bonds between the polymer chains are produced. Typical curing agents may be sulfur, triazine, peroxide, or bisphenol (see table 3).

Table 3- Typical cure systems for common elastomeric materials[3]

Cure Systems	Material	
Sulfur	NBR, EPDM.	
Peroxide	NBR, EPDM, FKM or FFKM	
Triazine	FKM or FFKM.	
Bisphenol A	FKM or FFKM.	
Bisphenol AF	FKM or FFKM.	

In addition to curing agents, there are several other substances that can be added to the polymer base material that will greatly affect the properties of any given material. The additives to the base material gums or resin are usually categorized as either curing agents, fillers or processing aids. These constituents, plus the ratios in which they are mixed, are not the only factors that influence material characteristics since molding techniques, temperature, time and power consumption will all influence properties. In general, the process of producing a typical elastomer component consists of the mixing, a milling process, the pre-forming, and finally the molding of the component into its finished form. In certain instances there are additional post-processing techniques that are adopted to further refine the material properties. Table 4 summarizes the more common components that are added to the base elastomer compound together with their influence on the finished material.

Table 4- Elastomeric O-ring additives and their influence on the finished material[3]l.

Compound Constituent	Primary Influence
Base Polymer	Chemical Resistance
Bulking Fillers (Carbon Blacks, Non-Black Materials) Curatives (Vulcanizing Agents)	Physical Properties
Plasticizer, Softeners Antidegradant (Antioxidents, Antiozonants, Protective Waxes)	Temperature Properties
Activator or Retarders Peptizers, Lubricants, Release Agents and Tackifiers	Processing Aids
Pigments	Cosmetic/Color

Probably the most common elastomeric sealing material used in the oil and gas turbomachinery industry is the fluorine-based fluoroelastomer (FKM). This material has a wide variety of trade names associated with it. Many people fail to appreciate that within the FKM family there are five different sub-groups, each of which have been formulated to provide specific characteristics required for certain duties. In the case of certain FKM producers, not only do they offer all five material groups, but they have numerous different compounds within each grouping, meaning there are a wide number of different material compounds available from the same supplier. When this rationale is rolled out to all of the other FKM manufacturers, it can be appreciated how there are literally hundreds of different FKM materials commercially available. The following figure summarizes some of the different grades of FKM.

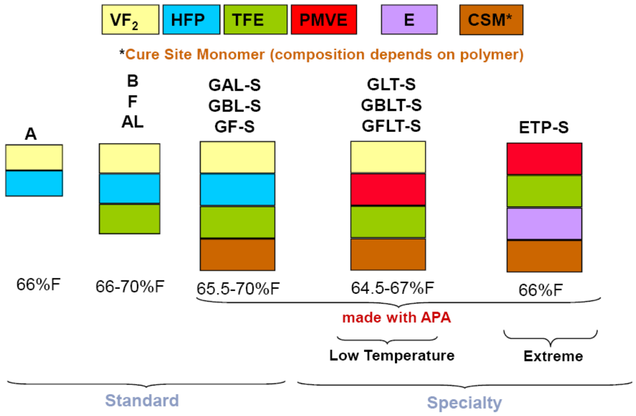


Figure 8- FKM material sub-groups[4]

Figure 8 shows that since the introduction of the original FKM compound (A) that other FKM materials were developed mainly as a consequence of specific customer requirements. FKM A had excellent resistance to oils and hydrocarbon mixtures over a reasonable temperature range whereas FKM B materials improved ageing and flexibility with better chemical resistance. The G series of materials further widened the temperature range and chemical resistance. The F materials were developed to withstand newer fuel additives that were particular problems for A and B materials. The ETP range of FKMs further extended chemical resistance particularly for high pH chemical that were known to attack the other FKM materials.

The phrase 'not all FKMs are equal', can therefore be more readily understood when the above is taken into consideration. However, in addition to this the actual amount of base polymer (fluorine) can vary greatly from manufacturer to manufacturer. In recent times fluorine materials have become increasingly scarce. In an effort to produce materials more economically certain producers of FKM have replaced fluorine content with low grade fillers or bulking agents significantly affecting the material properties. Most high grade FKM materials contain approximately 65% to over 70% of base material. The significance of this is to highlight the need to be fully aware of what is being specified and used on their critical applications. The same logic can be equally applicable to all of the other base materials such as nitriles and perfluoroelastomers.

EXPLOSIVE DECOMPRESSION

Explosive decompression (ED) occurs to elastomers when gases are absorbed into the material through pressure and is retained within the material until the system is depressurized. The retained gases then expand rapidly causing blistering and mechanical damage to the material (see figure 9). The extent to which this damage occurs is dependant upon a number of factors, such as the sealed pressure, the decompression rate, the gas itself, and the properties of the material. Explosive decompression, also known as rapid gas decompression (RGD) is largely related to the materials' tear strength. This dictates the materials ability to resist cracks from regions that are highly stressed during the decompression process. The pockets of trapped gas induce stress within the material void, which is essentially a stress riser. The applied pressure tends to put the material into tension which causes tearing to occur. Elastomers with high tensile strength, high tear strength and high modulus tend to resist such damage more readily than the so-called lesser materials. It should however, be pointed out that the high strength characteristics are at the expense of flexibility and resilience.

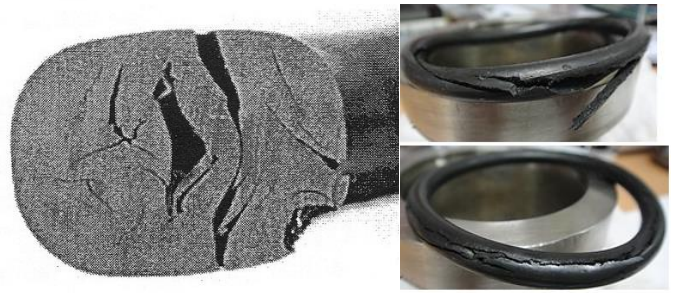


Figure 9- Typical ED damage internal (left) and external (right).

Explosive decompression is probably the most important material characteristic when specifying elastomers for high pressure gas duty, therefore many individual oil and gas related organizations have developed their own ED assessment and test procedures[5,6]. In addition to this there are also ED test methods that are published by independent standards organizations[7,8,9]. The following list summarizes such test but this list is by no means exhaustive and hence additional standards may apply in some organizations or within certain business sectors or geographical areas.

TOTAL GS PVV 142 [5]
Shell DODEP 02.01B.03.02[6]
NORSOK M-CR-710[7]
ISO 23936[8]
Health and Safety Executive (UK)[9]

Most ED tests comprise of repeatedly pressurizing and depressurizing a test piece, using a given gas composition over a certain number of cycles. At the end of the test sequence, the test piece is then examined externally in a variety of ways before the O-ring is cut up into sections for further examination. The extent of the damage, or lack thereof, is then established and rated. A 0 rating would mean that there were no cracks or defects and the maximum rating of 5 would signify that the cut section condition was severely damaged.

In certain instances the actual defects can be measured using optical magnification and an associated measuring device. However, most of the inspection is done with the naked eye. Once the rating of each cut section is established, the condition is deemed such that the specimen has either passed or failed the ED test. Given that the test specimen is sectioned, the test is actually destructive, meaning that the specimen cannot be used in service after the test. This means that on certain critical duties, the test is conducted on additional parts produced just for test purposes, thereby meaning that several of the items produced in any one given batch will be an indication as to the integrity of the remainder of the batch put into service. In other words, the test is a damage assessment technique on selected samples or specimens.

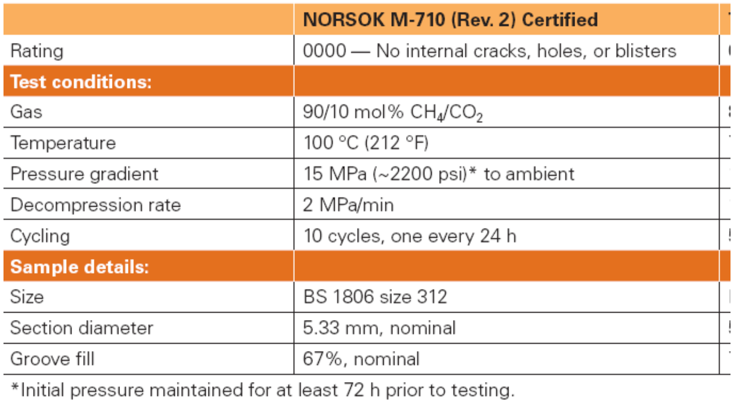
What would appear to be a perfectly acceptable method of assessing an O-ring's resistance to explosive decompression, the testing does have certain limitations. Given that the consequences of elastomeric failure in high pressure gas applications can cause serious incidents, seal designers and equipment manufacturers need to be fully aware of all the issues surrounding explosive decompression resistance of elastomers.

ISSUES ASSOCIATED WITH ED TESTING AND ACCEPTANCE

The first issue to look at relates to the actual test conditions themselves. Typically they can be conducted at different pressures and temperatures and are held over different periods of time. Clearly the exposure time to high pressure will influence how much gas permeates into the material. Similarly, the number of times that the pressurization and depressurization cycle is repeated will influence the damage together with the actual depressurization rate. There‘s also nothing specifying how many times the test is repeated before a given material or component is deemed as having passed or failed the ED requirement. It's imperative that the designers compare the actual test procedure with their actual application details.

The next thing to consider is the gas itself, because different gases are adopted for different test specifications. Tests can be conducted on air, carbon dioxide or mixtures of methane and carbon dioxide, plus some specific tests use impurities such as hydrogen sulphide in the test gas composition. In general, gas solubility and rate of diffusion for each elastomer material differ for different carbon dioxide and hydrocarbon combinations.

A great deal of testing for ED resistance is done on O-rings. While it may seem surprising, there is no set O-ring size or section stated in most test procedures. Therefore, it is important for the designer to know what size O-ring is being tested. A small cross section O-ring (100 series) has a much smaller surface area exposed to the gas than a larger cross section O-ring (say a 300 series). Similarly there is usually nothing that specifies the amount of squeeze imposed upon the O-ring during the test, or even the width of the groove, i.e. how much the O-ring fills a given groove. Because both of these factors will dictate the area exposed to the gas during testing, it suggests that groove design is an important feature. It should also be noted that the groove will not only support and constrain the O-rings but also dictate the defamation during testing (see figure 10). Similarly in the case of other elastomeric seal designs and cross sections like flat gasket, T-sections or rectangular sections, even greater care must be taken when establishing the seal test requirements.



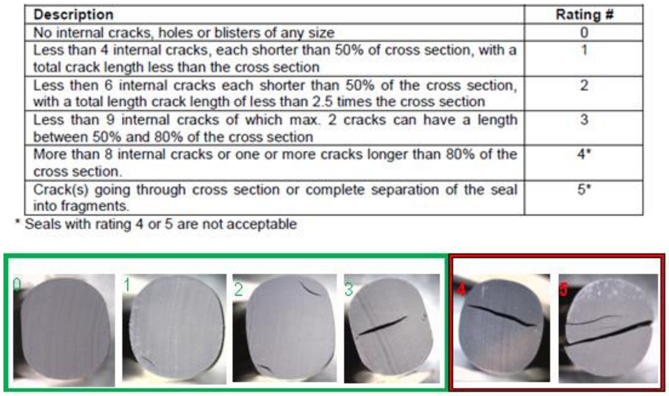
	NORSOK M-710 (Rev. 2) Certified
Rating	0000 — No internal cracks, holes, or blisters
Test conditions:	
Gas	90/10 mol% CH_4/CO_2
Temperature	100 °C (212 °F)
Pressure gradient	15 MPa (~2200 psi)* to ambient
Decompression rate	2 MPa/min
Cycling	10 cycles, one every 24 h
Sample details:	
Size	BS 1806 size 312
Section diameter	5.33 mm, nominal
Groove fill	67%, nominal

*Initial pressure maintained for at least 72 h prior to testing.

Figure 10- Extract from manufacturer's literature[10] showing how test methods for the same material can vary.

Probably the most surprising aspect of the test is that it does not actually assess the test specimen's ability to seal effectively. In ED tests the O-ring is actually pressurized from both sides, whereas in service an O-ring is used to separate a high-pressure medium from a low-pressure medium. Pressure is only applied to one side of the sealing device. Given that this is probably the whole purpose of conducting the test, it seems strange that the most widely accepted method of assessing an O-ring's suitability for ED resistance completely neglects its ability to seal.

Finally, there is the actual 'ED' rating itself. As previously stated the damage rating system is a numerical ranking ranging from 0 to 5 (see figure 11). As also mentioned, this relates to the condition of the material contained within a cut section where 4 cuts are usually done on any one test specimen. The position of the cut and also the manner in which the material is divided can sometimes have a direct influence on the material itself and hence great care should be taken to ensure that the cutting process during the sectioning of a specimen does not incur any additional damage that might be mistaken for damage sustained during the test itself. Probably the most alarming aspect of the rating system relates to the amount of damage sustained on an O-ring before it has deemed to have failed the test. As stated rating are 0 to 5 where only a 4 or 5 signifies that an O-ring has failed, however in normal engineering terms there is significant damage to O-rings that have consistent 3, or passing, ratings all around (see figure 12).



Description	Rating #
No internal cracks, holes or blisters of any size	0
Less than 4 internal cracks, each shorter than 50% of cross section, with a total crack length less than the cross section	1
Less then 6 internal cracks each shorter than 50% of the cross section, with a total length crack length of less than 2.5 times the cross section	2
Less than 9 internal cracks of which max. 2 cracks can have a length between 50% and 80% of the cross section	3
More than 8 internal cracks or one or more cracks longer than 80% of the cross section.	4*
Crack(s) going through cross section or complete separation of the seal into fragments.	5*

* Seals with rating 4 or 5 are not acceptable

Figure 11- Norsok ED 0-5 Damage Rating (1-3 Pass & 4-5 Fail)[3]

Three O-rings are shown in figure 12 where each has been cut into four sections, examined for damage and assigned a rating. The ratings were then grouped into a 4-digit overall rating. Provided that none have a 4 or 5 rating, then the O-ring will pass the ED test. The O-ring to the left has a perfect 0000 overall rating, whereas the one on the right has failed because of the 4 condition on one of the cuts. In the center is an O-ring with a 3233 overall rating. This is a pass, however much of it is in a worse condition than the failed O-ring on the right and is in nowhere near as good condition as the O-ring on the left. However, the manufacturer may simply elect to state that is has passed the ED test. This illustrates why it is important to not only select O-rings that are ED-resistant but also to establish the actual rating.

Figure 12- Example showing test rating results for three O-rings.

As stated previously there are several international standards (Norsok M-710, ISO 23936) and independent standards (TOTAL GS PVV 142, Shell DODEP 02.01B.03.02) that cover ED testing that all differ from one another. Given that there are such a wide number of test parameters and variables associated with ED resistance, it is recommended to ensure that the test method adopted is one that closely matches the service conditions.

OTHER PROPERTIES & TESTS

In addition to ED there are a number of other properties that influence the suitability of O-rings for high duty turbomachinery applications. There are a several other tests undertaken on elastomers and O-rings, in particular. Without a full knowledge of what these tests are and their significance with regard to sealing components, it is difficult to completely assess the suitability of a given seal type and the material of construction for arduous duties. This section looks at some of the more common tests undertaken on elastomeric O-rings and their significance on the sealing functions and ability.

Although not strictly a material property another pressure induced issue is extrusion. This occurs when the O-ring material is deformed by pressure and displaced into an extrusion gap on the low-pressure side of the groove (see figure 13). The extrusion gap can be due to the necessity to have a working clearance between adjoining parts or because the surrounding structure has deformed under load, causing the gap to open during service. In any event the problem is caused when the O-ring is no longer constrained within the confines of the groove.

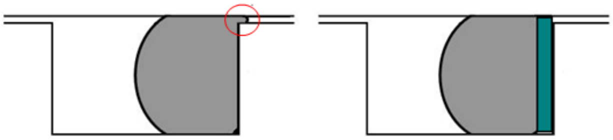


Figure 13- O-ring extrusion (left) and how it can be avoided with the use of back up rings (right)

Extrusion is generally far better understood than ED and most O-ring manufacturers provide tables that display pressure limits for different hardness and O-ring sizes at varying clearance gaps. In general high tensile strength, high tear strength and high modulus tend to resist extrusion better than softer materials although the problem is complicated at temperature extremes. In situations where large extrusion gaps cannot be avoided, the problem can sometimes be overcome with the use of backup rings that effectively close off the extrusion gap (see figure 13). Backup rings tend to be made out of much stiffer and deformation-resistant materials such as filled PTFE or other engineering plastics. Figure 14 shows how O-rings can be used at pressures far higher than 100bar (1,500psi) provided that clearances are kept to a minimum. However, it does not detail the influence of temperature and how ED limits and depressurization rates need to be factored into the design.

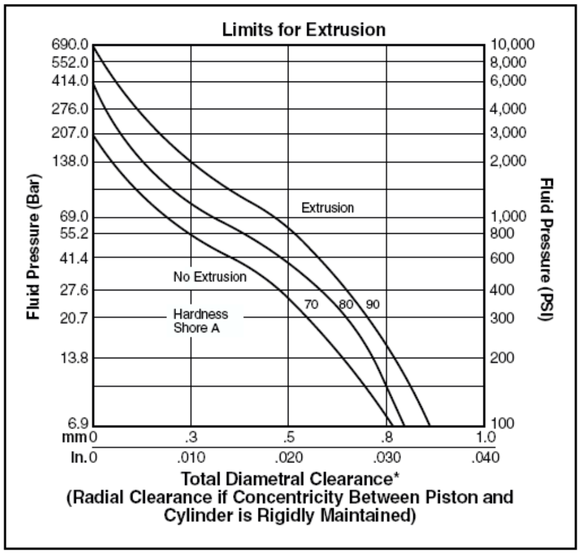


Figure 14- o-ring pressure limit dependence on clearances[2]

TENSILE STRENGTH

In general most elastomeric materials can be stretched to well over 100% of their original length. This means they are usually able to deform far more than the components they are sealing. For instance, a 'typical' steel would not be able to elongate by more than 1% of its original size without failing, thereby dictating that an elastomeric sealing element used within the same assembly would never reach the point at which its tensile strength limits are attained. Generally speaking, what is of greater interest is how the tensile strength and elongation changes with exposure to fluids and temperature. Like with most materials, a higher tensile strength value is generally more desirable than a lower value (see figure 15). However, most of the tensile tests that are conducted are done at room temperature, not service temperatures. Great care must be taken when operating conditions approach the upper or lower temperature limits for the material.

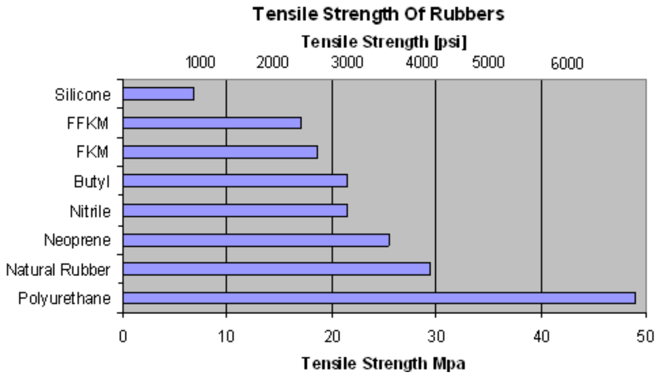


Figure 15- Tensile strength for typical O-ring materials.

HARDNESS

Hardness is probably the most widely used property to determine the suitability of an elastomer in a given application. As a rule of thumb, high hardness elastomers are used for high-pressure duties and lower hardness materials are used for lower temperature duties. Softer materials used for low temperatures often have hardness values of around 50 - 60 Shore A at room temperature, but since the hardness increases as the temperature reduces, the hardness value at the cryogenic operating temperature is often more like 70 - 75 Shore A. As a rule, high-pressure duties have O-rings with hardness values of 90-95 Shore A. Hardness testing is a non-destructive test that can be done using 'portable' equipment (see figure 16). Because high hardness is closely linked to strength and modulus, a portable check to verify hardness is probably the easiest method to determine suitability for high duty service.

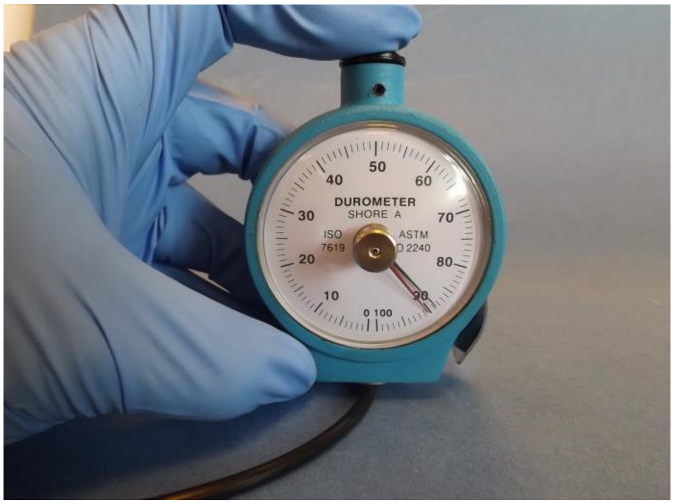


Figure 16- Portable elastomer hardness testing device.

MODULUS

The modulus as defined for an elastomer differs to that of steel's since it is actually the tensile stress at a specified elongation. The modulus, or modulus of elasticity or Youngs modulus, of a steel is the slope of a stress strain curve. The latter is normally the linear proportion of the stress strain curve, whereas an elastomer exhibits a non-linear stress strain curve, making it impractical to treat both types of material in the same manner.

Modulus has a significant effect on the performance of an elastomer since most high-pressure applications require tough materials. Low pressure applications require a more compliant and resilient material. In addition, modulus is generally confused with hardness. Although the two may have some correlation, they are not directly related to one another. Most low duty applications have O-rings with a hardness between 70- 75 Shore A and a 100% modulus of 5- 8 MPa (0.7 and 1.1ksi). In contrast a high duty O-ring used for turbomachinery and dry gas seals would have a hardness of 90- 95 Shore A with a 100% modulus of 15- 25 MPa (2.2 and 3.6ksi).

COMPRESSION SET

Compression set is a measure of the material elasticity after prolonged compression. The compression set 'property' is expressed as a percentage whereby an O-ring is compressed to 75% of its original section, and tested at a given temperature over a period of time and then allowed time to recover. The compression set is a measure of how much the seal has not recovered, thereby dictating that a percentage of 100% means that the seal has not recovered at all, or it is the same shape as when it was tested, and a value of 0% means that it has fully recovered to its original size (see figure 17). ASTM D395 and ISO 815 are the main test standards used for compression set testing of O-rings. It follows that O-rings with lower compression set values are able to seal better than those with higher values. Temperature has a great influence on matters since as temperature increases the degree of thermal and chemical attack also increases, thus reducing the ability of an elastomer to recover to its original condition.

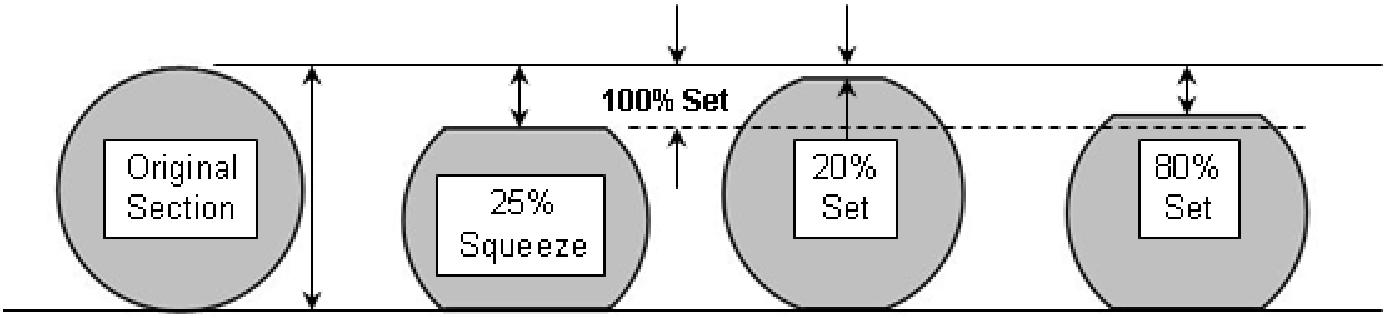


Figure 17- Illustration of compression set test conditions (left to right) O-ring section prior to test, O-ring in its test condition, O-ring after test showing 20% set, and O-ring after test showing 80% set.

There are three main test methods outlined in the standards where the three compression set test methods can be summarized as follows:-

Method A

The sample is compressed to 75% of its original height and then heated over a period of time. Once the period of testing is complete the fixture is removed from the oven and the test piece is removed while it is hot and allowed to cool over a 30 minute period before measuring.

Method B

This uses exactly the same procedure as *Method A* but, once the heating cycle is complete the fixture is removed and allowed to cool at room temperature before removing a test sample.

Method C

The third method again uses the same set up, however, the test fixture is disassembled while hot and the sample is allowed to recover at the test temperature before being removed from the oven.

Although all these test methods may appear to be similar there are subtle differences, all of which affect the results. Table 5 summarizes the different compression test methods and the effect on results.

Table 5- Comparison of tests conducted on the same O-ring using different compression set methods[11]

Test Regime	ISO Method A	ISO Method B	ISO Method C
Duration/Temperature	72 hours/200^{O}C	72 hours/200^{O}C	72 hours/200^{O}C
% Compression Set	24.1	69.0	13.8

Ideally an engineer would look at all of the compression set test results to establish whether a given elastomer was suitable for a duty, however all too often only one result is provided and it is important to find out what results are stated. The first method outlined above is probably the most widely adopted within the industry, however, the second method is closer to how an O-ring would operate in most applications. The third method would be more appropriate when some sort of polymer degradation would be expected, possibly due to chemical attack. Similarly the latter method would probably give the better results and the second method the worst results. However, that is not to say that they do not provide insight into actual elastomer behavior. Compression set is an important property especially when temperature cycling is encountered during the process. In most instances, the compression set test is only conducted over one thermal cycle. Similarly, there is no pressure test requirement aspect to the procedure, which makes it difficult to know the consequences of the sealing ability.

COMPRESSION STRESS RELAXATION

This term is often confused with compression set. Elastomers are materials that can be both an elastic solid and a viscous liquid, or viscoelastic. This means that a constant deformation of an elastomer can lead to internal structural and molecular changes, which in turn can affect the stress within the material under constant load. Typically when an elastomer is compressed, energy is stored within the material and there is an associated reaction or sealing force with the surrounding components. Over time the stored energy within the material will decrease and hence preload is reduced and sealing ability will reduce.

TEMPERATURE

The importance of understanding the influence of temperature cannot be understated. This not only affects thermal expansion, which is an order of magnitude greater than most steels, but also the material properties. In particular what needs to be appreciated is that most published test results relate to properties at room temperature and that the same property at conditions approaching the temperature limit for a given material may be as little as 50% that of the published condition. In general most elastomers harden significantly at low cryogenic temperatures and soften as temperature increases. This is shown in Figure 18 where hardness variation with temperature is shown. The modulus and tensile and tear strength will also have similar variations. On the left of figure 17 there is some similar data for compression set for different O-ring materials where significant variations are evident.

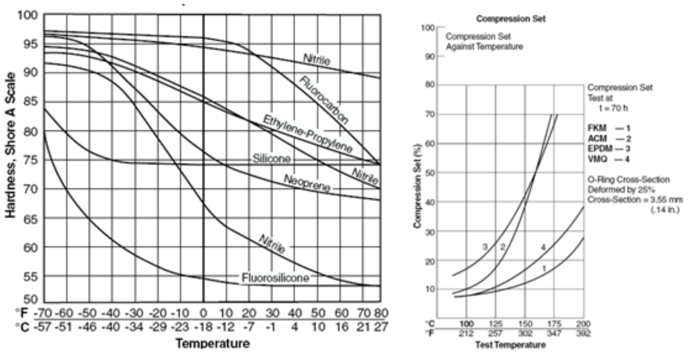


Figure 18- Diagrams showing how hardness (left) and compression set (right) properties cause temperature variation[2]

Most manufacturers produce tables or charts to demonstrate temperature limits for O-ring materials and some even provide additional margins at either end of the range to further assist application engineers (see Figure 18). These margins often account for the fact that the manufacturer in question has several different grades of the same material but could also be an indicator that certain materials may still be used under specific conditions. In any event, Figure 19 shows there are no real absolutes when it comes to specifying an O-ring and the importance of knowing exactly what operating conditions exist for any given application.

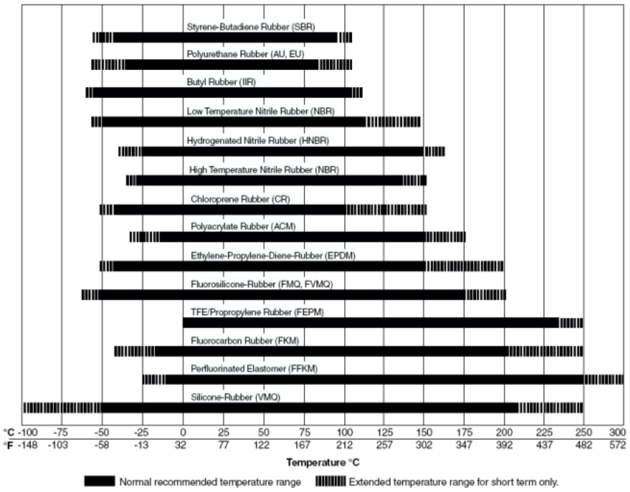


Figure 19- Temperature limits for typical O-ring materials[2]

In situations where the elastomeric material proposed for a given duty is likely to be exposed to temperature within 10% of its limits then additional guidance should be sought from the manufacturer to verify its suitability for service.

Lastly, it's important to note that exposure time adversely affects seal life, particularly at temperatures approaching upper service limits. Figure 20 shows this dependence where the 1,000 hour life temperature closely approximates the upper temperature limit and the marked increase in slope (at the LHS) at short exposure times does indicate that temperature over specified limits are possible.

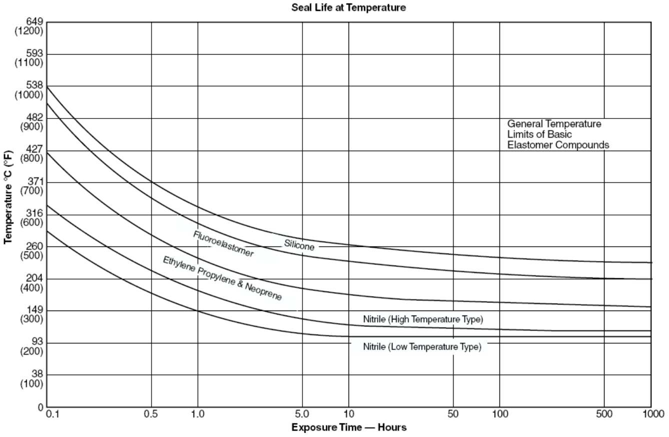


Figure 20- Graph showing how temperature exposure time influence o ring materials[2]

STORAGE AND INSPECTION

When most engineering materials are stored, there will be little change in properties provided they are adequately protected. In this respect, O-rings are no different. In the case of steel storage in a clean, dry, well-lit environment at ambient temperature, the material could be stored for years without any deterioration in properties. Although similar logic can be applied to most elastomers, additional steps need to be taken to ensure that the material properties are maintained. The main things to note are that elastomers tend to age harden and they are subject to ozone depletion plus other time dependent factors that tend to reduce material properties. Degradation varies for different material types and there are standards that recognize this by establishing storage periods for different materials[12]. Figure 21 shows the different groupings where group B contain mostly nitrile and chloroprene materials (NBR, HNBR, CR etc.) and group C contain fluorine based materials (FKM, FFKM, FEPM etc.). This document also assumes that certain storage requirements are being observed like temperature, light, humidity etc.).

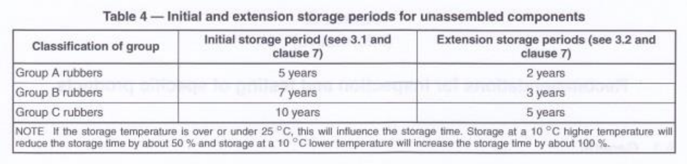


Table 4 — Initial and extension storage periods for unassembled components

Classification of group	Initial storage period (see 3.1 and clause 7)	Extension storage periods (see 3.2 and clause 7)
Group A rubbers	5 years	2 years
Group B rubbers	7 years	3 years
Group C rubbers	10 years	5 years
NOTE If the storage temperature is over or under 25 °C, this will influence the storage time. Storage at a 10 °C higher temperature will reduce the storage time by about 50 % and storage at a 10 °C lower temperature will increase the storage time by about 100 %.		

Figure 21- Extract from BS 2230 showing storage periods for different elastomeric materials[12]

What also needs to be appreciated is that the storage periods relate to unassembled components and hence these limits need to be adjusted when O-rings are placed into components and stored. In this situation, it is important to know about the origins of O-rings that are put into service. The following illustrates the 'life' of a standard O-ring.

Cure date- The date that the O-ring was manufactured.

Storage- The time that the O-ring is on the manufacturer's shelf.

Purchase date- The date at which it arrives at the equipment manufacturers.

Assembly date- The date that it forms part of the equipment.

Stand time- This is the period between the equipment arriving on site and being put into service.

Service life- Time since the machine is first used.

It can therefore be appreciated how an O-ring can have aged considerably prior to being put into service. The best method to determine suitability for O-rings used in critical service is not only to ensure that they are stored in airtight and opaque containers but also that the cure date and batch details are known for each item. Similarly equipment assembly records should cross reference these O-ring details so that traceability of stored assemblies can be determined for evaluation prior to equipment being put into service. In situations where O-rings have been fitted into assemblies that are then stored for long periods (over 24 months) the traceability of the O-ring should be retained so that the storage life can be identified and compared with standards(12). It is also advisable to verify the integrity of all O-rings when they have been stored in the assembled format for periods in excess of 60 months.

Thus far only properties have been discussed, but in the case of O-rings that are intended for use on turbomachinery and other high duty applications it is important to check the condition of O-rings and the manufacturer details before they are put into service. In the case of ED where gases permeate into an O-ring through the surface exposed to pressure, it is essential to check for surface imperfections since these are the sites where gas is most likely to enter the material. Several standards exist such as BS ISO 3601-3 that provides extensive details on how to check for defects together with acceptable limits for imperfections (see figure 22). It's important to consider that testing is usually conducted on otherwise ideal samples that have thoroughly been checked prior to testing. However, once O-rings are produced commercially there is a possibility that production methods will result in defects.

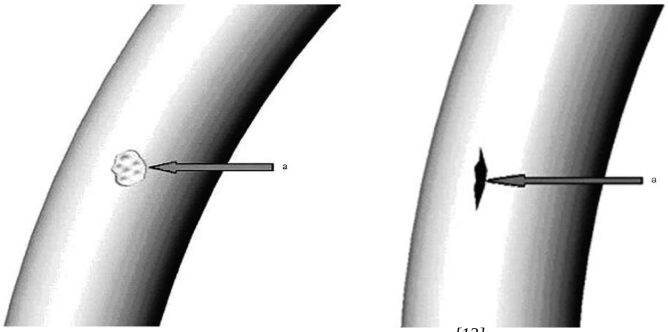


Figure 22- Imperfections found on O-rings[13]

DESIGNING FOR DECOMPRESSION

The American Petroleum Institute (API) provides guidelines for O-ring selection in rapid decompression scenarios (API 617 7th edition, section 2.2.1.13 & API 617 8th edition, section 4.5.1.15 & API 618 5th edition, section 6.15.1.14). End users and contractors are encouraged to provide the compressor OEMs with the most accurate gas analysis available for all operating conditions. Flagging instances that could meet ED conditions in the design phase is the first step to avoiding it in the field. Higher mole weight gases such as CO_2 are more prone to exhibiting this behavior. Pressure also plays a role. Through estimates, it has been found that reciprocating units begin to see the effects of ED when discharge pressures near 41- 48 bar (600- 700 psi); centrifugal machines have been observed with issues over 82 bar (1,200 psi). Higher temperatures support this behavior, but pressure remains the critical player.

With proper input and careful design and operation, ED can be avoided. ED damage (such as that shown in figure 23) is related to pressure, temperature, depressurization rates, O-ring material and hardness and partial pressure of CO_2 Any O-ring that is porous allowing gas to enter into the materials interior can be exposed to the right conditions for ED, but as long as the depressurization rate is kept low enough, no damage will occur. In other words, ED is the turbomachinery equivalent to the Bends/Decompression Sickness observed in deep sea diving. In applications where ED is not a concern unit blown down rates of 50 psi/sec may be common, whereas in applications where ED is expected these rates should be set as low as possible (under 8 psi/sec). In some scenarios such at an emergency shutdown (ESD) it may be impossible to adhere to depressurization rates low enough to accommodate ED prevention.

Figure 23 – The process of ED damage begins with visible bubbling of the O-ring (left) that eventually tears (right). Suggest making this two separate figures.

O-ring material selection and hardness are important factors to preclude ED. Choosing materials with greater than 85 durometer is a general key component. O-ring manufacturers have also been formulating products that specifically have resistance to ED. Another alternative to traditional O-rings is PTFE (Polytetrafluoroethylene), a thermoplastic material that is not permeable to gas. However because PTFE lacks elasticity, there will always be some amount of leakage until the unit is at pressure and temperature. To solve this, spring-energized, or “C” type, PTFE glass-filled seals have been used, though these are typically reserved for gas seals and bundle O-rings (see Figure 23). The gaskets seal at low pressures under the force provided by the spring, and the operating pressures provide the force past startup [14]. The designer must be aware that using these harder materials may result in difficulties during Hydro testing. These harder materials are less forgiving and do not conform to machining marks as well as the softer materials would.

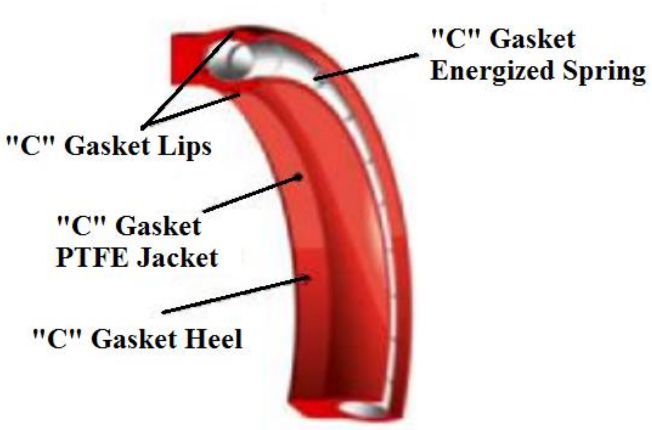


Figure 23 – Example of PTFE C Type, spring energized seals.

Looking past changing the O-ring material, another option would be to add another O-ring groove to the area in question. An extra O-ring would allow for another area of pressure breakdown should the first seal fail. This would help protect the interface from seeing the full depressurization rate. If used on a centrifugal compressor unit head, adequate axial space is needed to fit this and should be accounted for early in the design phase. Reciprocating unit heads follow the same rule, except the lands would be added radially. In addition, back-up rings on both sides of the O-ring in question is also known to help limit the swelling of the seal.

Because ED occurs during shutdown, it cannot be emphasized enough that proper performance monitoring be used on startups. Manual sniffer walk-arounds can be invaluable to detect process leaks before the unit gets to full pressure. Centrifugal compressors could have a number of affected O-rings that would need data to prove which was damaged without opening the unit. For example, the aerodynamic performance curves can give beneficial information in this regard. Internal leakage, caused by a damaged division wall O-ring or split gap cordage, would show up as lowered head and efficiency, a higher work input and reduced surge capacity.

A process leak could show up in a couple ways. If the process in question results in net product output, then the mass flow can be examined for any trend in shortcomings between machine starts. If this type of info is not accounted for, maybe in a refrigeration loop or reinjection line, performance curves could shift if the leak is large enough. For instance, an inlet head leak on a centrifugal compressor would shift all curves down and to the left because the flow being measured going into the compressor is higher than what is actually leaving it. Typical performance maps have inlet flow as the x-axis. A discharge head leak would not affect the power curve but lower the head/efficiency curves. However these types of differences can be minute and difficult to notice, whereas a sniffer will work in any case.

CONCLUSIONS

This document provides insight to encourage more detailed evaluations when choosing elastomers for high-pressure duties often encountered in turbomachinery. It highlights some of the most relevant issues and how test data and material properties need to be taken into consideration in order to identify the optimum elastomeric seal material for a given duty. In this respect the reader should be aware of the following guides that are stated:

Make sure that the full gas composition is known (together with any variations).

Identify all known operating conditions and not just minimums/maximums.

Make sure that pressure and temperatures are correctly paired for cyclic duties.

At elevated temperatures the elastic strength of elastomers is significantly reduced and at sub zero temperatures elastomers are brittle.

How much specific property/test data is available for the exact material grades under consideration is there.

Explosive decompression potential becomes significant for service pressures of about 40bar (580 psi) or higher.

If explosive decompression is suspected then an assessment should be made to determine under what conditions and at what rate the sealed system can decompress.

In conditions where pressure differential is high, damage can occur to elastomer seals after just one single decompression cycle.

Actual seal failure is most likely to become evident following start-up after the damaging system depressurization. Therefore, it is vital to monitor these machines carefully on each startup to look for anomalies that could indicate a seal failure.

Many high-pressure and temperature applications are sealed with O-rings and other similar elastomeric seals. With proper design, operation and preventative maintenance ED can be avoided resulting in highly reliable profitable machinery

NOMENCLATURE

ED = Explosive Decompression
RGD = Rapid Gas Decompression (European term)

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