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Elastomeric seals for rapid gas decompression applications in high-pressure services

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Elastomeric seals for rapid gas decompression applications in high-pressure services

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Seal damage and observed gas leaks to atmosphere caused by Rapid Gas Decompression (also known as Explosive Decompression) in elastomeric seals have been reported in many types of equipment in the oil and gas industry. These failures have had costly financial, safety and environmental implications for the operators and equipment suppliers.

The aim of this document is to:

- provide designers, specifying engineers and operational managers with a systematic approach towards the prevention of decompression damage in elastomeric seals;
- provide technical purchasing managers with advice on functional specifications for equipment and materials;
- advise the oil and gas industry on methods and procedures available to protect against decompression damage;
- make production engineers aware of operating scenarios where damage may have occurred even though its effects are hidden; and
- widen the knowledge and understanding of rapid gas decompression and raise awareness in the industry in general.

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HSE BOOKS

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EXECUTIVE SUMMARY

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The seal failure process due to rapid gas decompression is extremely complex. It depends on many variables that interact, including the seal material, groove design, gas composition, system pressure and temperature. Failure is also highly location dependent within the seal section, with certain locations failing prematurely due to the magnitude of the pressure differential and the local stress field. This document puts forward short guidelines for the following scenarios

(i) when determining whether rapid gas decompression is relevant
(ii) when selecting seals for a new high pressure gas application
(iii) when specifying seals for competing operational requirements, such as high pressure, rapid gas decompression, fluid exposure, high and low temperatures
(iv) when assessing the decompression resistance of the seals in an existing system
(v) when carrying out equipment maintenance
(vi) during site or equipment inspection to detect potential rapid gas decompression problems
(vii) when investigating whether rapid decompression is the cause of a failed seal

Within this document, the major factors determining decompression damage to elastomeric seals are discussed, and common explosive decompression test protocols together with the predictive modelling procedures used in industry are commented on. This document is not intended as a stand-alone design, diagnostic or qualification tool. Expert / consultant advice is always recommended for critical applications. **Figures are included for illustrating the principles of rapid decompression resistance and sealing only, not for design use**.

The information sources for these guideline notes are published literature, selected MODES Project findings and field knowledge/experience from the current project sponsors. Several journals and conference papers that have been used as reference material are also listed in Section 10.

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1. INTRODUCTION

This document is one of the outputs of a joint industry project, to provide practical guidance in the use of elastomeric seals for rapid gas decompression in high pressure applications. Much of the material information and sealing knowledge within this work has been derived from the MODES "Modelling of Decompressions in Elastomeric Systems" programme run by BHR Group with support from HSE, several major operators, and seal manufacturers. MODES continues to advance knowledge on rapid gas decompression, and to develop a methodology to predict seal damage for oil and gas and other industrial applications.

This document puts forward a systematic approach towards minimising rapid gas decompression problems, highlights the important points to be considered and includes relevant technical information as reference for designers, specifying and purchasing departments and field engineers.

For the non-expert, recommendations from reputable seal suppliers are extremely useful. Such companies should be able to provide a list of relevant and successful installation case histories, along with test data, design calculations and other application details for one or two cases.

1.1 DEFINITION OF ELASTOMERS

Elastomers are defined by their ability to be stretched easily to high extensions and then rapidly reverse back to shape when the stress is released. The major constituents of a typical elastomer compound are long chain molecules known as the base polymer, which provide the basic chemical and physical characteristics. A small amount of free space (termed 'free volume') exists between the long chain molecules. This allows for movement of the molecules more or less independently of one another. It is this characteristic that allows elastomeric components to deform and change shape. Crosslinks formed within the closely-packed molecular network during the vulcanising or curing process influence the reversibility of elastomers. Some nomenclature of generic elastomer types, commonly used in rapid decompression applications in the oil and gas industry, are shown in table 1 with further details in Section 5.1 and table 5. The naming convention used for base polymer types in this document follows ASTM D1418-06.

Table 1 Commercially available rapid decompression resistant elastomers

Designation	*Elastomer type*
NBR Nitrile	Acrylonitrile-butadiene
HNBR	Hydrogenated acrylonitrile-butadiene
FKM-3	Fluorocarbon terpolymer of fluorinated vinyl ether and vinylidene fluoride
FKM-4	Fluorocarbon tetrapolymer of propylene and vinylidene fluoride
FEPM or FCM (TFEP)	Tetrafluoroethylene-propylene copolymer
FFKM	Perfluoro elastomer

Many different sub grades exist depending on polymer make up, cure site chemistry and molecular weight. Formulations and compounds can also change as new research is conducted. For more information on the tradenames please refer to table 5

It is important that the characteristics of the final product are known by the end user, as much can change depending on how the base polymer is processed and compounded. In this document examples of physical characteristics are shown for elastomers classified by their generic polymer backbone. It is the author’s intention that the readers of this document do not use this information for any design calculations or make any assumption about the physical and chemical properties of specific commercial compounds based on the generic information contained here in. It is recommended that the vendor’s data sheets are consulted and if needed additional test results for the specific product be obtained.

1.2 DEFINITION OF RAPID DECOMPRESSION

Damage to elastomeric seals due to rapid decompression is a familiar problem in the oil & gas industry and other high pressure gas applications. It has been reported in all types of fluid handling devices, including valves, blow out preventers and even car air conditioning systems. However, due to the flexibility and resilience of elastomers, its ability to self-energise, and to compensate for housing tolerances, relative component movements, surface textures and scratches, elastomer is still the first choice of sealing material for many equipment used in the oil and gas industry.

Rapid decompression is commonly known as explosive decompression (ED), an operational condition during which the applied system pressure is quickly released, resulting in the expansion of absorbed gas damaging elastomeric seals (Section 3.1). However, the prefix “explosive” can be misleading, since decompression damage can occur even when pressure is let down gradually over many hours (Section 3.2.1). Within this document, the condition will therefore be referred to as “rapid” rather than “explosive”.

1.3 SCOPE OF THIS DOCUMENT

The cause of rapid gas decompression damage in elastomeric seals is well established (Section 3). High strength elastomers, well supported at the operational temperature (Section 5) are known to be most resistant to rapid decompression. However, the quantitative prediction of the resistance of individual seals for individual applications is very complex. Major seal and housing design parameters determining rapid gas decompression resistance are discussed in this document (Section 6), along with seal material consideration. For example, the strength of elastomers can be substantially affected by many other factors including high and low temperature, swell and chemical attack (Section 4).

Extrusion is another major failure mechanism for elastomeric seals used in high pressure application. This is specifically covered (Section 5.2.1) and the characteristics of this type of failure distinguished from rapid decompression (Section 2.7). Effective methods to mitigate extrusion have also been provided. (Section 6.6).

Five major industry explosive decompression test protocols together with the finite element analysis modelling procedure developed during the MODES project are commented on (Section 7), and the specific requirements for performing material tests to assess decompression resistance of elastomeric seals are highlighted (Section 8).

Where no suitable elastomeric seals are found for a rapid decompression application, sprung PTFE seals should be considered. Polytetrafluoroethylene (PTFE) is classified as plastic, with low resilience and elasticity. It does not normally suffer from rapid decompression damage because of its higher strength (over 100MPa) than elastomers (usually well below 50MPa). However, very different design rules are applicable to sprung PTFE seals for providing resilience, elasticity and to control creep / leakage. These rules are outside the scope of this document.

1.4 STRUCTURE OF GUIDELINES

The structure of this guideline document is illustrated in Figure 1. Section 2 is the key section for providing practical guidance and a functional approach to this area of technology. Sections 3-6 explain relevant technical factors to be considered for rapid gas decompression applications. Sections 7, 8 and 9 provide advice for selecting and specifying seal function tests, predictive modelling and material tests. Section 10 lists relevant references, which are sources of further information and Section 11 is a glossary explaining items peculiar to elastomer seals and rapid gas decompression.

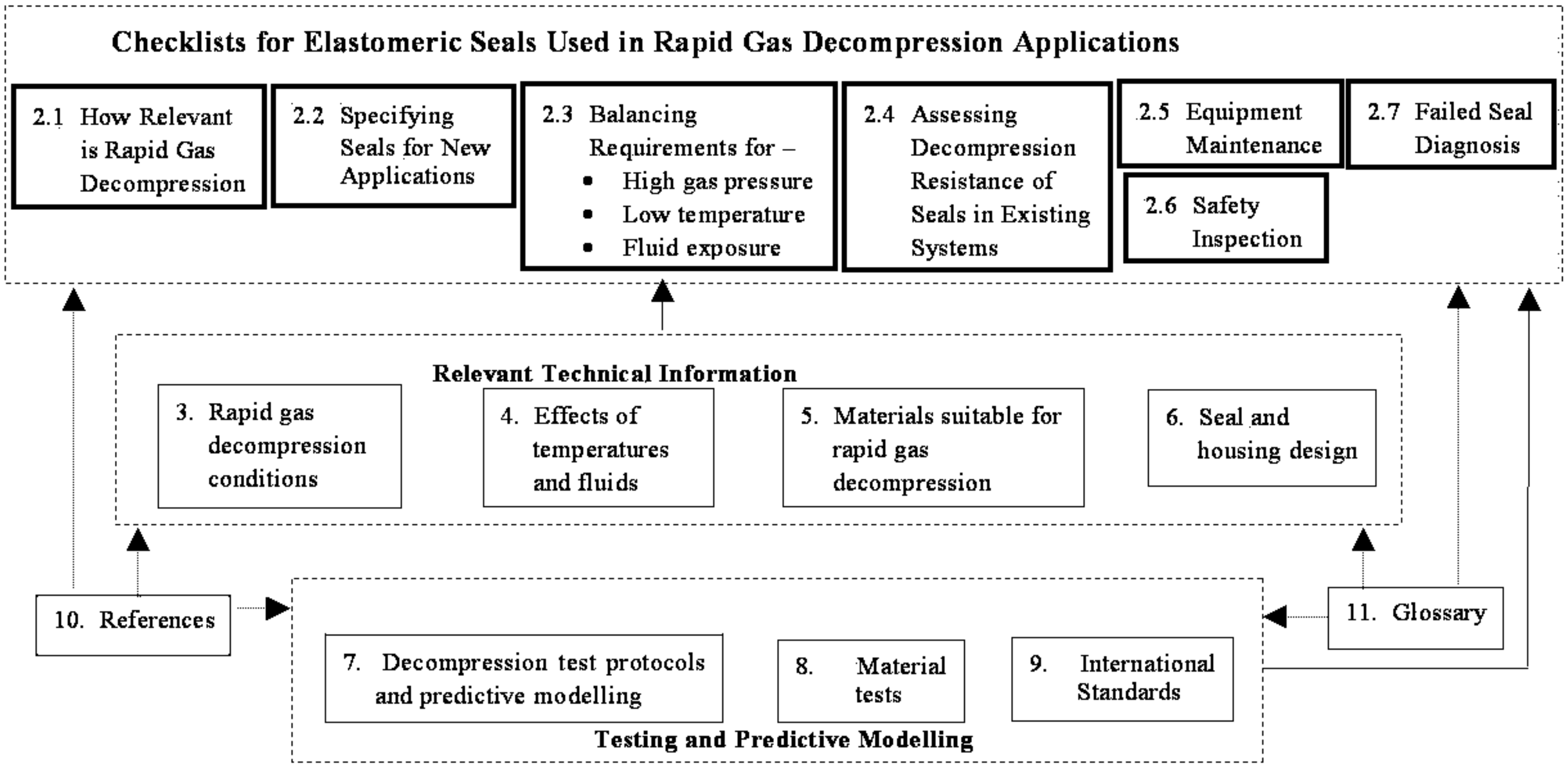


Figure 1 Structure of guidelines

2. CHECKLISTS FOR ELASTOMERIC SEALS USED IN RAPID GAS DECOMPRESSION APPLICATIONS

2.1 HOW RELEVANT IS RAPID GAS DECOMPRESSION

Many design and field engineers have heard of rapid gas decompression or explosive decompression, and would like to enquire whether it is relevant for their application. Section 3.1 provides a concise description of the failure mechanism of rapid decompression condition, and the following is a quick check list for establishing the relevance:

(i) Rapid decompression is generally applicable to a “dry” gas application when the system fluid is mostly gas (section 3.5).

(ii) It is a particular threat to elastomers because of their relatively lower elastic strength.

(iii) It potentially becomes significant for service pressures of about 35bar (510 psi) or higher.

(iv) It is most common at elevated temperatures when the elastic strength of elastomers has been significantly reduced (section 4.1), or at sub zero temperatures when the elastomers are brittle (section 4.2.2).

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

(vi) The prefix “explosive” can be misleading, since decompression damage can occur even when pressure is let down gradually over many hours (Section 3.2.1).

(vii) Seal failure is most likely to become evident after a system depressurization (decompression), or during the following start-up

2.2 SPECIFYING SEALS FOR NEW HIGH PRESSURE APPLICATION

For engineers specifying for a given oilfield or gas facility, it is necessary to take a number of steps to avoid damage of elastomer seals in high pressure gas. The following list serves as an "aide memoire" to assist the process of seal specification.

(i) Identify high pressure "dry" gas services, e.g. gas lift, gas injection, gas processing etc.

(ii) Establish the operational and transient conditions, including the normal operational temperature and pressure, the maximum and minimum transient temperatures and pressures, the temperature and pressure of the elastomeric seals at the start of decompression, the total number of decompression cycles in operation and possible reverse pressures during shut down.

(iii) Check that you have considered item (ii) for the *full life* of the facility. Some well compositions change with its production age.

(iv) Specify high quality 80/90 IRHD elastomeric seals from reputable seal suppliers. If the gas pressure is higher than 35 bar (510 psi), consider the use of decompression-resistant seal materials (Section 5.1). If the gas pressure is higher than 120 bar (1740 psi), decompression tests or predictive modelling may be required to validate the application (Section 7). For some primary sealing applications elastomeric seals may not be capable of performing under the arduous environment. In this case alternate materials such as sprung PTFE or metal seals may need to be specified. This design / specification process is outside the scope of this document.

(v) Limit seal section size for elastomeric seals exposed to gas decompression (Section 6), ≤5.33 mm is normally recommended.

(vi) Specify the use of anti-extrusion devices, e.g. PTFE or PEEK back-up rings (Sections 6.5 – 6.6)

(vii) Increase groove fill (close to 90%) and make use of rigid anti-extrusion rings on <u>both</u> sides if necessary. However, volumetric expansion due to temperature and swell must also be considered to avoid overfilling the groove (Sections 4.3, 5.7 and 6.4)

(viii) If the application has other critical requirements, such as extreme temperatures (>100ºC, or below 10ºC), chemical injection etc., a compromise has to be achieved. Refer to Section 2.3 and 4 for further information, but advice from seal experts is recommended in such situations. In addition to this advice the end user organisation may have field experience. Check if the operating conditions are similar between the current application and previous experience.

(ix) For specifying elastomeric seals for equipment such as rotary compressors, use a relief valve instead of burst-discs to limit pressure, so that pressure can be vented more progressively (Section 4.4)

(x) Ensure suitable protocols are in place for material trace ability and quality control. Be aware of the possibility of inadvertent material and size substitutions in the field. By maintaining these protocols the end users can gain valuable reliability data to feed back into specification and design.

(xi) Finally, when pressure tests are performed on new equipment, use liquid tests if possible. Otherwise, high gas pressure should only be maintained for a very short period of time and as close to room temperature as possible. This is to ensure that the seals inside the equipment will not become saturated with high pressure gas and the elastomer seals have the highest tensile strength before depressurisation.

2.3 BALANCING REQUIREMENTS FOR HIGH GAS PRESSURE AS WELL AS LOW TEMPERATURE OR FLUID EXPOSURE

For complex applications where the strength of the seal materials can be affected by elevated temperatures or exposure to aggressive fluids, expert advice should be sought. The following provides a systematic approach for design engineers to assess the application with the seal expert to deduce the optimum solution. In addition to the information in this document, end user organisations may have collected field service reliability data for elastomeric seals. This should also be used to guide the specification process.

(i) Read through Section 4 which provides details on the various important factors to be considered.

(ii) Establish the operational conditions such as the normal operational temperature and pressure, the temperature and pressure of the elastomeric seals at the start of decompression, and the total number of decompression cycles in operation. Then define the transient conditions, including the maximum and minimum transient temperatures and pressures, and possible reverse pressures during shut down

(iii) Identify the primary and secondary fluids involved in the applications. Primary fluids are the fluids that exist in a significant proportion (> 10% for hydrocarbons, > 5% for carbon dioxide and hydrogen sulphide) and those chemicals continuously injected into the system, which normally include corrosion inhibitors. Secondary fluids are the fluids that exist in a small proportion and those chemicals periodically injected into the system only.

(iv) Specify minimum seal size, high groove fill and anti-extrusion devices to increase seal decompression resistance (Section 6). However, volumetric expansion due to temperature and swell must also be considered to avoid overfilling the groove (Sections 4.3, 5.7 and 6.4)

(v) Softer seals are normally used for low temperature (<0ºC) applications. However, for rapid gas decompression applications 80/90 IRHD elastomeric seals should be used even if the low temperature requirement exists.

(vi) Make a list of elastomers that would be suitable for the normal operational conditions and the primary fluids. If no elastomer is expected to be suitable, an alternative such as sprung PTFE seals or other technologies should be considered and/or the operational requirements of the facility has to be reduced, e.g. valves situated in cold weather for extended periods require trace heating and lagging.

(vii) Review the list of elastomers for suitability in the transient conditions and secondary fluids. Very likely, a compromise has to be made to balance the different requirements. Choose the elastomer that is suitable for the normal operational conditions and primary fluids, and perform fairly well in the transient conditions or secondary fluids, then specify decompression tests or predictive modelling to validate the application (Section 7).

(viii) In summary, the compliance with the normal operational conditions and primary fluids are likely to be more critical than that with the transient conditions and secondary fluids, e.g. a continuous low temperature requirement of < -40ºC combined with gas decompression needs sprung PTFE; whereas transient low temperature can typically be sealed using normal decompression resistant grade elastomers.

(ix) Reconsider items (iv) to (viii) if necessary to achieve the optimum seal-housing specification.

2.4 ASSESSING DECOMPRESSION RESISTANCE OF SEALS IN EXISTING SYSTEMS

Within the installed life of equipment, its operational conditions and the fluids it handles can change for a variety of reasons and engineers are often faced with the task of re-qualification. The list below is provided to assist engineers performing such duty.

(i) Specify the new system requirements in detail, including the normal operational temperature and pressure, the maximum and minimum transient temperatures and pressures, the temperature and pressure of the elastomeric seals at the start of decompression, the total number of decompression cycles in operation and possible reverse pressures during shut down

(ii) Identify the material of the existing seal and therefore its hardness, tensile and fatigue properties (Section 5), from installation records, from store inventory records etc. If the seal records cannot be traced, tests have to be performed to identify the seal material. These include hardness (section 9.6), solvent (methanol) swell and Dynamic Mechanical Thermal Spectrometer tests (Section 4.2.4)

(iii) Find out the dimensions of all the seals and housings, and calculate the groove fill. Smaller seals (≤ 5.33 mm) and high groove fill (close to 90%), have better decompression resistance. (Section 6). However, volumetric expansion due to temperature and swell must also be considered to avoid overfilling the groove (Sections 4.3, 5.7 and 6.4)

(iv) Check that high quality 80/90 IRHD elastomeric seals from reputable seal suppliers are being used. If the gas pressure is higher than 35 bar (510 psi), decompression-resistant seal materials should be used (Section 5.1).

(v) Check that there are sufficient anti-extrusion devices for the proposed high pressure application, refer to Sections 5.2 and 6.6 for additional information.

(vi) The introduction of extreme temperatures or new chemicals need to be reviewed to confirm that they are within the functional envelop of the existing seals (Section 4 and Table 3 & 4), to confirm no new risks arise.

(vii) If the gas pressure is higher than 120 bar (1740 psi), decompression tests or predictive modelling (Section 7) may be required to confirm the decompression resistance of the existing seals.

2.5 EQUIPMENT MAINTENANCE

During scheduled equipment maintenance programmes, operators need to decide whether elastomeric seals need to be replaced, and maintenance engineers need to take special precautions to avoid damaging the installed elastomeric seals unnecessarily. The following is a list of advice for general maintenance procedures.

(i) Elastomeric seals do not normally need routine maintenance.

(ii) It is generally advised that elastomeric seals should not be released/removed from the their housings unless they are to be replaced.

(iii) For scheduled preventative maintenance programmes of equipment, gas system pressure should be released as slow as possible, at temperature as close to room temperature as possible to avoid inducing rapid decompression conditions.

(iv) Equipment maintenance contractors should be informed that the equipment is specified for rapid decompression. They should be given the original polymer seal specification, together with other operational conditions such as fluid composition, temperature and pressure.

(v) Check that there is no elastomeric seal debris inside the equipment, if so this should be reported and the suitability of the original seal material and specification should be reassessed (Section 2.4).

(vi) Make a close visual inspection of the area around installed seals, noting whether leakage was evident or signs that it had occurred in the past.

(vii) Elastomeric seals have limited life due to long term ageing and/or number of decompression cycles. Therefore elastomeric seals should be replaced when the equipment is disconnected from service for routine equipment maintenance, if the age of the elastomer seals will be over the manufacturer’s recommended life for the next scheduled maintenance.

(viii) When elastomeric seals are to be replaced, ensure that the material specification of the replacement seals satisfies the operational rapid decompression, fluid compatible, temperature and pressure conditions, and the replacement seals are from newly produced batches, and have been stored in sealed bags. Some elastomeric seals can be aged substantially in air after years of storage even at room temperature, also avoid ultra violet radiation and atmospheres high in oxygen.

(ix) When equipment (e.g. valves, pumps, compressors, etc.) is replaced by a stored unit, it is important to check the storage time, and compare it with the seal manufacturers’ recommended storage time.

(x) When elastomeric seals are being replaced, ensure that the required back-up rings are replaced as well, as back-up rings are critical parts against extrusion, and for maintaining high groove fill.

(xi) If pressure tests are performed on the replacement equipment, use liquid if possible. Otherwise high gas pressure should be maintained for as short period of time as possible and as close to room temperature as possible. This is to ensure that the seals inside the equipment will not be saturated with high pressure gas and the elastomer seals have the highest tensile strength before depressurisation.

2.6 SAFETY INSPECTION

When safety inspections are being carried out on site, without dismantling equipment, it is difficult to detect potential elastomeric seal decompression problems. Records review is therefore important. This includes identifying equipment that can be subjected to rapid gas decompression, and check the following:

(i) The specifications of the original seals, operational conditions such as fluid composition, temperature and pressure are traceable, and passed onto maintenance team before scheduled maintenance.
(ii) The record of seal replacement is up to date.
(iii) Inventories of the elastomeric seals required for rapid gas decompression systems are of the required quality and specification.
(iv) The number of rapid decompression cycles occurred is no more than that recommended by the equipment supplier.
(v) Facilities (such as trace heating and lagging for valves situated in cold weather) for lowering the operational requirement of the equipment are being maintained properly.
(vi) A close visual inspection of the area around installed seals, noting whether leakage is evident or signs that it had occurred in the past.

2.7 FAILED SEAL DIAGNOSIS

The possible causes of seal fracture in high pressure gas service are rapid decompression, extrusion, installation damage, low temperature embrittlement and groove overfill at high temperature.

Failed seal diagnosis/analysis is the job of a seal expert. However, it is most useful if field/maintenance engineers can collect all the forensic information available as subtle differences aiding diagnosis can be lost by inattention to detail. The procedures for collecting useful information are listed below. Based on the results from these procedures a seal expert can often identify the causes of the failed seals. Also be aware that different seals installed in different parts of equipment can fail due to different causes.

Failed Seal Diagnosis Checklist

(i) Remove the elastomeric seal from its housing carefully, clearly mark the high pressure side, record the installation orientation of the seal (i.e. flange or piston or rod) and the housing dimensions. Also collect the anti-extrusion devices if they are present. Take photographs of the seal in situ if possible.

(ii) Immediately after disassembly, record any blisters (Section 3.6) which appear on the surface of the seal. The presence of blisters, especially those that deflate after removal, is an indicator of rapid decompression damage.

(iii) If possible try to measure the main dimensions of the seal (outer diameter, inner diameter and cross section). If the equipment is easily available the material hardness can be instructive on the type of material and if swell or ageing has had an effect. This property may change with time if due to dissolved gas.

(iv) Collect the operational history of the failed seals such as pressure and temperature cycles, composition of gas mixture, chemical injection etc. Also identify the hardness and material of the failed seal from installation records, or store inventory records etc

(v) If the seal material type cannot be traced from records:

- Measure the hardness of the seal
- Identify the seal material by solvent (methanol) swell and Dynamic Mechanical Thermal Spectrometer Tests, see section 4.2.4

(vi) If the minimum operational temperature of the seal is less than 10ºC higher than the glass transition temperature of the elastomer, the risk of low temperature embrittlement cannot be eliminated. (Section 4.2)

(vii) Measure the dimensions of the used seals and compare it with the original seal specification:

- If the failed seals are significantly smaller than their sectional dimension specification in all directions, and have external damage, this can indicate extrusion damage (Section 5.2.1).
- If the failed seals are larger than their specification in all dimensions, the used seal can have been swollen by either liquid adsorption, or internal blisters and cracks (Section 3.6).
- If the seals have been excessively stretched (>5%), they are more likely to fail at low temperature (Section 4.2).

(viii) Check and record the dimensions of the housing and groove fill:

- If the diametral clearance is big, see Section 5.2.1, and no anti-extrusion devices are present, the risk of extrusion damage is high.
- If the housing on the low pressure side has round corners, there are no anti-extrusion devices and the used seals have external damage on the low pressure side, in particular at the corners, this can indicate extrusion damage.
- If there is no chamfer to ease installation, i.e. the seal has to be installed over sharp corners, and the used seal has external damage at their corners, this can indicate installation damage
- If the seal is highly constrained, e.g. 90% groove fill, the risk of rapid decompression damage decreases, but the risk of extrusion or thermal expansion damage increase
- If the groove fill is below 80%, the risk of extrusion or thermal expansion damage reduces, but the risk of rapid decompression damage significantly increases.

(ix) Make internal and external examinations under a microscope of all the failed seals to study:

- location of cracks or fractures.
- orientation of cracks or fractures, are fatigue rings visible ? (Section 3.3)
  internal cracks are very often found in seals damaged by rapid decompression, and the orientations of most cracks will be along the direction of installation squeeze (Section 3.6).
- approximate number and size of cracks
  the internal examination can be carried out by following the Norsok Standard (section 7.4)
- location of any extrusion flash (on the high or low pressure side ?) - if the extrusion flash is located on the high pressure side, this can indicate rapid decompression damage.

(x) Refer to Table 4 to check the operational envelope of the seal.

3. RAPID GAS DECOMPRESSION CONDITIONS

3.1 FAILURE MECHANISM

Decompression failure of a seal results from the following sequence of events :

- Elastomeric seals contain voids and rigid inclusions that are produced during manufacture.
- Fluids in contact with elastomer surfaces are absorbed into the material.
- The absorbed gas diffuses into the bulk of the elastomer until fully saturated.
- At high pressure, the absorbed gas is in the compressed state.
- When external pressure is suddenly reduced, the compressed gas nucleates at the voids.
- The compressed gas expands within the elastomers, and the voids inflate leading to high tensile stresses or strains in the void walls.
- If the tensile void wall stress or strain is higher than the strength of the elastomer or the elongation at break, cracks initiate and propagate [Briscoe 1994].
- In multiple decompression applications cracks can form and grow at stresses well below the tensile strength, or at strains below elongation at break, if the number of decompression cycles is higher than the number of fatigue cycles to failure at the void wall stress or strain. As shown in Figure 2, the material can fail as low as 50% strain after hundreds of decompression cycles.

3.2 OPERATIONAL PRESSURE

Gas decompression damage generally increases with pressure. The threshold pressure above which damage occurs is linked to :

(i) the gas combination, e.g. above 50 bar (725 psi) in methane, or lower in carbon dioxide
(ii) the hardness of the rubber, e.g. 17.5 bar (250 psi) for 50 IRHD material, 34.5 bar (500 psi) for 90 IRHD material

The effect of pressure increase on void inflation tends to be more obvious at high pressures. For example, increasing operational pressure from 150 bar (2200 psi) to 170 bar (2500 psi) would cause catastrophic seal failure in a single cycle decompression for the material shown in Figure 2. Whilst increasing operational pressure from 80 bar (1160 psi) to 100 bar (1450 psi) would reduce the number of safe decompression cycles from 740 cycles to 240 cycles.

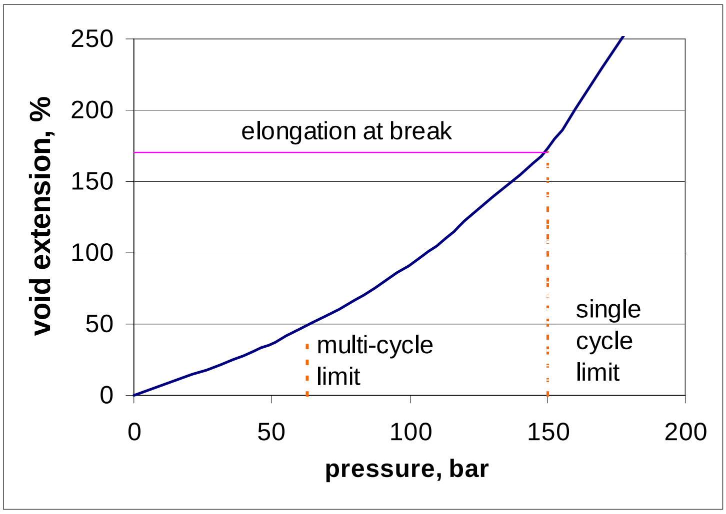


Figure 2 Void strains versus gas pressures for a sample elastomer

3.2.1 Decompression time

The dependence of damage on decompression time tends to be more significant at high temperatures and in seals with an open groove arrangement, where there is unrestricted access for absorbed gas to diffuse out quickly. A 30 minutes decompression can cause as much damage as an instantaneous decompression for a 5.33 mm section O-ring. For significantly longer decompression times, as shown in Figure 3, large reductions in decompression damage have been seen. The internal and external pressure differential will then be significant reduced, resulting in the void extension falls below the safe elongation at break (170% in Figure 3) after 15 hours.

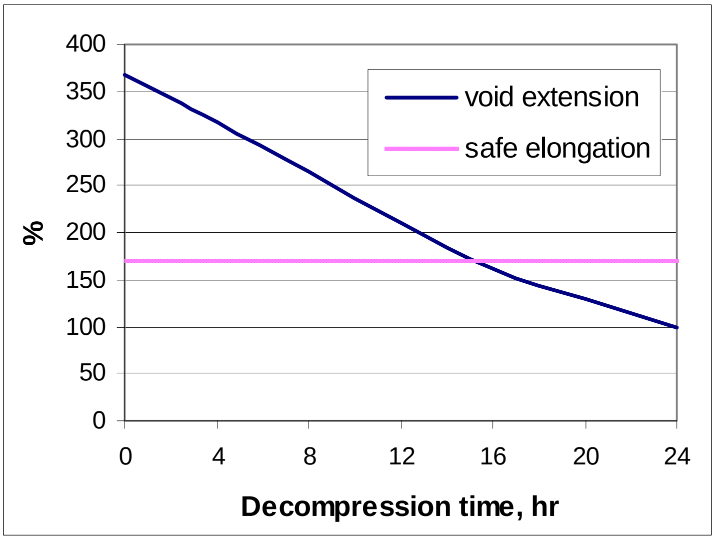


Figure 3 Effect of decompression time on void extension at the centre of a 5.33 mm section O-ring, for a sample elastomer

3.3 DECOMPRESSION CYCLES

Elastomeric seals in service can be subjected to a number of decompression cycles. It has been noted that when carrying out rapid gas decompression tests, there can be no apparent damage to a seal after a single decompression, but after several more cycles damage is evident. When the fracture surfaces of the cracks from the test seals are studied under a microscope, ring markings as shown in Figure 4 are visible. This is clear evidence of the occurrence of fatigue, thereby indicating that fatigue is a major mechanism of failure for decompression cycling [Edmond 2003].

During decompression cycling, the actual pressure drop is important, for example a pressure drop from 150 bar (2200 psi) to 50 bar (725 psi) is likely to be more damaging then a pressure drop from 200 bar (2900 psi) to 150 bar (2200 psi).

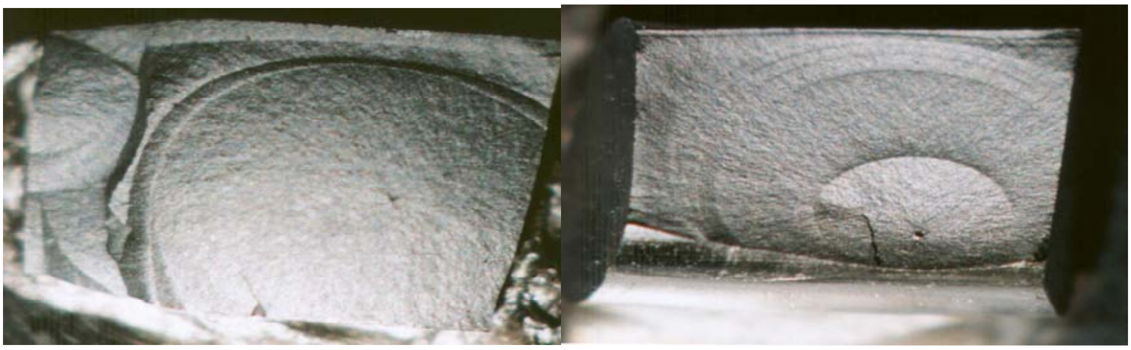


Figure 4 Fracture surfaces of rapid gas decompression damaged seals

3.4 COMPOSITION OF GAS MIXTURE

The resistance of seals to rapid decompression varies with the composition of the operational gas mixtures. Gas solubility and rate of diffusion for each elastomer material differ for different carbon dioxide and hydrocarbon combinations, as shown in Figures 5 and 6. The effect of temperature on diffusivity and solubility will be discussed in Section 4.1. Gases with high solubility and low rate of diffusion in elastomers are likely to cause most damage to elastomeric seals during rapid decompression.

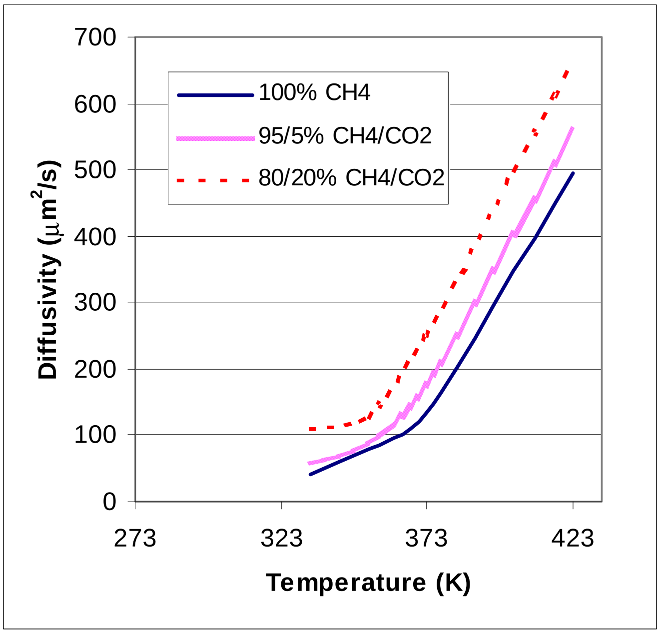


Figure 5 Diffusivity variation with temperature, for a specific FEPM material

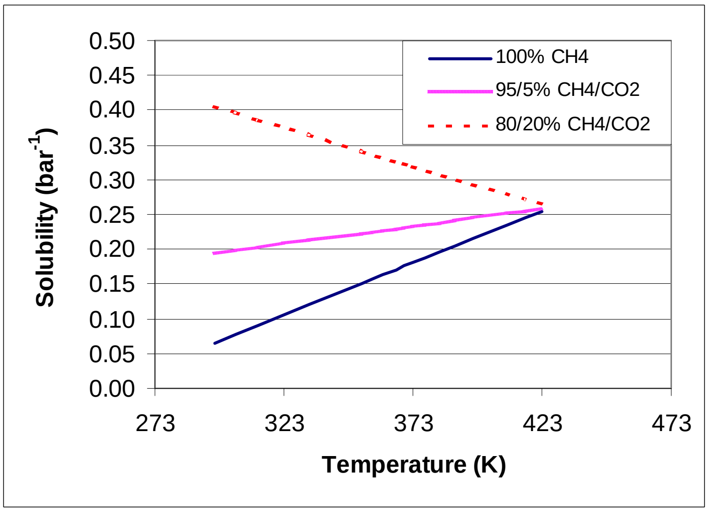


Figure 6 Solubility variations with temperature, for a specific HNBR material

At ambient temperature (10-40ºC), the tensile properties of fluorocarbon and nitrile greatly weakened when saturated with carbon dioxide [George 1997]. Therefore, an elastomeric seal in a high carbon dioxide concentration media at ambient temperatures is at a higher risk of suffering from rapid decompression seal damage than in low carbon dioxide concentration media. At temperature increases, the effect of carbon dioxide on the strength of materials becomes less significant.

3.4.1 The presence of hydrogen sulphide (H_2S)

Hydrogen sulphide is a chemically aggressive gas. It can chemically attack some elastomers, causing seal degradation. It has a relatively limited effect on rapid gas decompression resistance when compared with long term seal ageing. Some elastomer seals can be embrittled or weakened (i.e. lower elongation at break) over time due to ageing, resulting in the reduction of safe operational rapid decompression gas pressure, as shown in Figure 7. This assumes that seals are likely to remain undamaged when the ratio, void extension over safe elongation, is below 1.

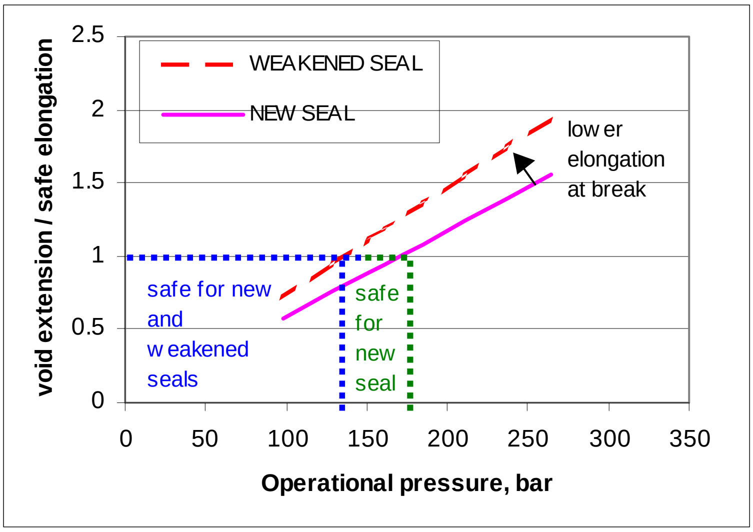


Figure 7 Theoretical example of the effect that reduced elongation at break may have on the safe decompression pressures

However recently published work by [Martin et al 2006] showed a slight improvement of RGD damage resitance after ageing o-rings in sour gas for 80 days. The tensile testing on exposed samples showed little sign of ageing, which may indicate other complex factors being at work in the RGD damage process.

FKM materials in general are used only for H_2S concentration below 2000ppm [James Walker]. No higher than 5% H_2S depending on temperature can be recommended for saturated HNBR materials, in which H_2S attack occurs predominantly to the Acrylonitrile (ACN) group. Therefore, low ACN compounds have better resistance to those with a high ACN content. ACN content is varied in commercial products from 18% to 48%, where it is generally quoted that “high” ACN refers to a content around 40% or higher, “medium” and “low” ACN contents correspond to around 30% and 20% respectively. FEPM based compounds are widely recognised as being resistant to systems containing high level (5-30%) of H_2S. However, FEPM tends to have lower decompression resistance than FKM or HNBR materials. Therefore, the selection of elastomer materials will depend on the exact H_2S content in service (Table 4).

It must also be remembered that for hydrogen sulphide service, there is often the presence of other chemical species, e.g. amine corrosion inhibitors, which may themselves cause chemical degradation to the elastomers (Section 4.5.2).

3.5 GAS AND LIQUID MIXTURE

There is limited documentation available on the effect of rapid decompression in gas/liquid mixtures. However, some rough estimates can be made based on theories from physical chemistry.

When an elastomer is exposed to gas, gas dissolves on to its surface. This process is highly pressure dependent until the densities of gases approach the liquid range. According to Henry's law, for a perfect gas, gas concentration (c) on the elastomer surface is directly proportional to pressure (p):

$$c = s\,p$$

where s is the solubility coefficient in bar^{-1}

In gas mixtures, the concentration (c_i) of constituent 'i' absorbed at the surface of the polymer is directly proportional to its partial pressure (p_i)

$$c_i = s\,p_i$$

The partial pressure (p_i) is determined by Dalton's Law, being expressed in terms of the molar fraction (m_i) of constituent 'i' and the total pressure (p)

$$p_i = \frac{m_i}{m_1 + m_2 + m_3 + \ldots\ldots + m_i + \ldots\ldots}\,p$$

The partial pressure of gas in a gas and liquid mixture can be treated similarly,

$$p_{gas} = \frac{m_{gas}}{m_{gas} + m_{liquid}}\,p$$

For example in Table 2, the partial pressure of a gas (methane) in a gas/liquid mixture at 100 bar with the specified composition, is only 68 bar (68% of 100 bar) due to the presence of 10% volume of liquid and water in the mixture.

Table 2 Gas molar percentage calculation based on volume percentages of a gas/liquid mixture at 100 bar

Constituent	*Molecular mass*	*Density at 100 bar*	*Volume %*	*Mass %*	*Molar %*
methane	16	0.0676	90	43.4	68.0
heptane	100.2	0.68	5	24.3	6.1
cyclo-hexane	84.16	0.779	2	11.1	3.3
toluene	92.14	0.865	1	6.2	1.7
water	18	1.05	2	15.0	20.9

Where Molar % and Mass % are calculated from :

$$Molar\% = \frac{\dfrac{Mass\ \%_i}{molecular\ mass_i}}{\dfrac{Mass\ \%_1}{molecular\ mass_1} + \dfrac{Mass\ \%_2}{molecular\ mass_2} + \ldots\ldots.}$$

$$Mass\% = \frac{density_i \times Volume\%_i}{density_1 \times Volume\%_1 + density_2 \times Volume\%_2 + \ldots\ldots}$$

3.6 CRACK AND FRACTURE SURFACE

Decompression damaged elastomeric seals can have blisters or bubbles appear on their surface, particularly when the seals are newly disassembled from the groove/housing and especially on the open groove side where the seal is free to expand in its housing (see Figure 8). After the seal has been removed from its housing for a long time, these blisters may deflate and leave no visible damage. However, in most cases cutting a seal through a blister can reveal an internal crack in the section where a void has expanded, as shown in Figure 9.

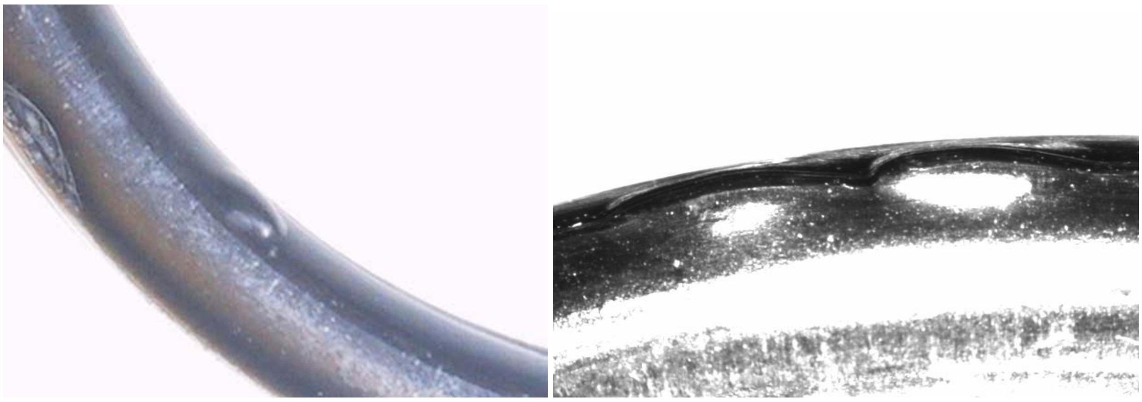


Figure 8 Blisters appear after rapid decompression

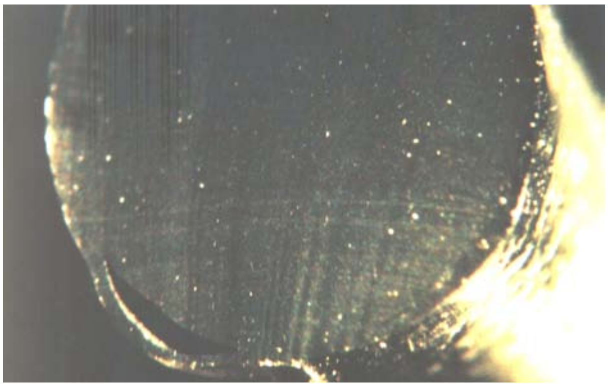


Figure 9 The internal crack under a blister

Cracks caused by rapid gas decompression are most likely to be initiated internally, and will be along the direction of the installation squeeze, as shown in Figures 10a and 10b.

There are 2 major types of fracture surface for rapid decompression damaged seals

(i) Some materials fail rapidly when the failure point is reached. These seals are likely to have relatively fewer internal cracks, but the cracks tend to be long (Figure 10b).

(ii) Some materials fail gradually over a range of pressure. These seals are likely to have a larger number of smaller cracks (Figure 10a).

Figure 10 Sections of damaged seals after rapid gas decompression
(a) with multiple cracks, (b) with a single crack

Internal cracks can also be caused by excessive thermal expansion, liquid swell, or high stresses at low temperatures when the material is brittle. Figure 11 shows the section of a seal fractured at very high temperature (above 225°C, 690 bar/10000 psi, 12.5% initial squeeze and 66% groove fill cold) in an all liquid media. The seal, weakened by high temperature and swell, expanded in the direction perpendicular to initial squeeze. The resulting cracks are very similar to those caused by rapid decompression.

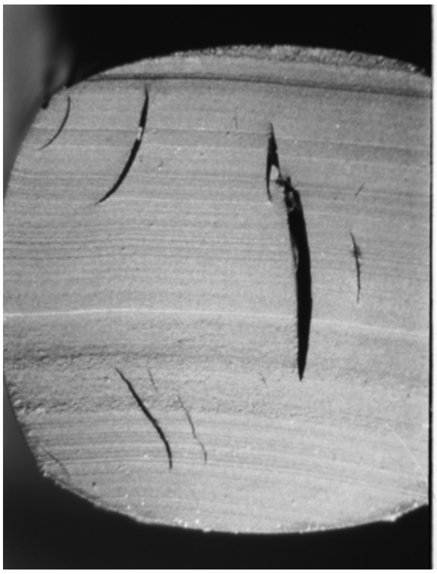


Figure 11 Section of a seal damaged by excessive thermal expansion

Figure 12 shows the section of a seal fractured by high stresses at low temperature. The 10 to 20 small internal cracks are located at the inner diameter of the seal where it was subjected to high stresses. The cracks found in brittle seals tend to be multi-directional.

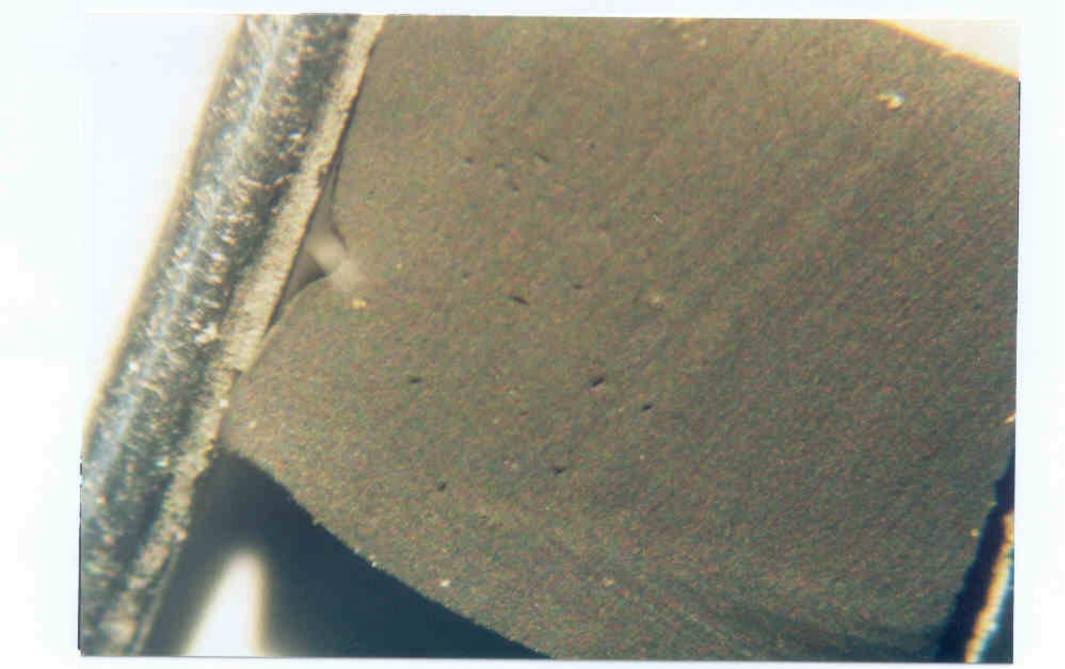


Figure 12 Section of a seal damaged by high local stresses when brittle, due to low temperature

4 EFFECTS OF TEMPERATURE AND FLUIDS

A list of some commercially available rapid decompression-resistant elastomers is detailed in Table 5 of Section 5.1. However, seal selection in high pressure gas systems is often a compromise between :-

(i) rapid decompression resistance,
(ii) temperature range
(iii) chemical resistance (e.g. methanol, corrosion inhibitors).

4.1 HIGH TEMPERATURE

It must be emphasised that physical properties do not align with chemical resistance properties. There are elastomers with excellent chemical resistance up to, circa 200ºC but their physical properties (e.g. tensile strength) can be significantly reduced even at a much lower temperatures, e.g. 100ºC. It is therefore important to select decompression-resistant seals based on material properties at the temperature of gas decompression. Figure 13 illustrates how the tensile strength and elongation at break of a particular 70 IRHD (International Rubber Hardness Degree) nitrile may decrease from 20ºC to 125ºC.

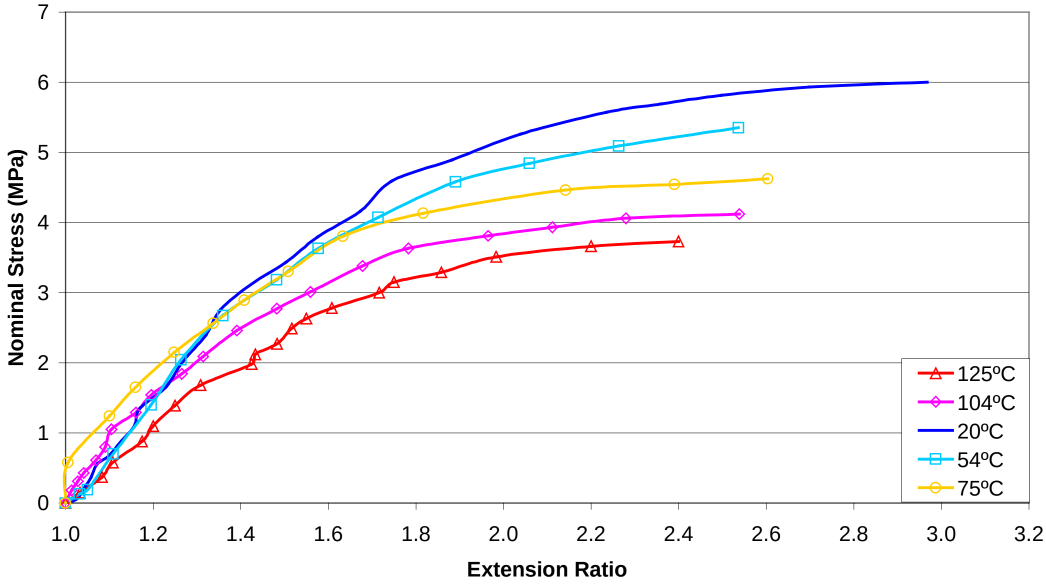


Figure 13 Change in tensile properties with temperature, for a specific 70 IRHD nitrile material

The gas permeation properties of elastomers (Section 5.4) also strongly depend on temperature. The effect of decompression time as described in Section 3.2.1 is therefore greater at high temperature when diffusion is fast. In general, diffusion of gases in elastomers may be regarded as a thermally activated process [van Amerongen 1964], expressed by an equation of the Arrhenius type:

$$D = D_o \exp(-E_D/RT)$$

Where D_o and E_D are constants for the particular gas and polymer.

The temperature dependence of gas solubility in elastomers is more complex. With gases such as helium, hydrogen and nitrogen, solubilities increase with increasing temperatures. For gases having larger molecules such as carbon dioxide and the lower hydrocarbons, the reverse is true [Ho 2001]. Graphs of solubility and diffusivity against temperature of specific elastomers have been included in Section 3.4.

Recent publication [Embury 2004] suggests that the benefits of reducing the out-gassing time is less significant than those achieved by returning the seal to a lower temperature / high strength state as rapidly as possible after depressurising.

4.2 LOW TEMPERATURE

Low temperature can be continuous due to regional weather conditions e.g. Siberia, Alaska, and local “wind chill”, or transient during blow-down condition when the gas system pressure is rapidly released. Stretch in seals which may be subjected to low temperatures, below 0ºC, must not exceed 5% of the internal diameter after installation, because high stretch can easily cause fracture when the seal becomes brittle at low temperatures. Another problem caused by high stretch is that it causes a reduction in cross section, which is of particular concern at low temperatures where the cross section size has already been reduced as a result of thermal contraction.

4.2.1 Operational temperature of the seal

Rapid decompression resistant elastomeric seal materials are commercially available, but the materials with the highest decompression resistance are not capable of very low temperatures, e.g. -40°C. In some cases, elastomeric seals are surrounded by large sections of steel (Figure 14), and are therefore likely to be less affected by transient low temperatures due to the thermal inertia of the mass of metal. However, calculations are required to justify this.

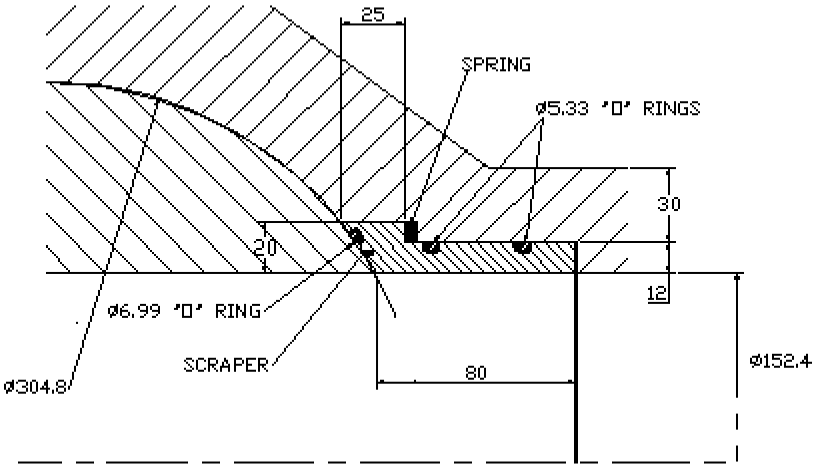


Figure 14 Typical ball valve seal arrangement

The calculation example, summarised in Figure 15 uses a 6 inch ball valve with a primary elastomeric seal (as shown in Figure 14), operating in an outside temperature of 10-15ºC, and insulated with a coating that has a heat transfer coefficient of 10W/m^2/K. The service gas is methane at 50ºC operational condition, but this can reduce to –40ºC during blow down. Thermal transfer models show that the seals would only be down to –30ºC after 10 minutes, and approaching –40ºC after 15 minutes (Figure 15). Therefore, the lowest operational temperature for the seals can be specified based on the length of blow down period.

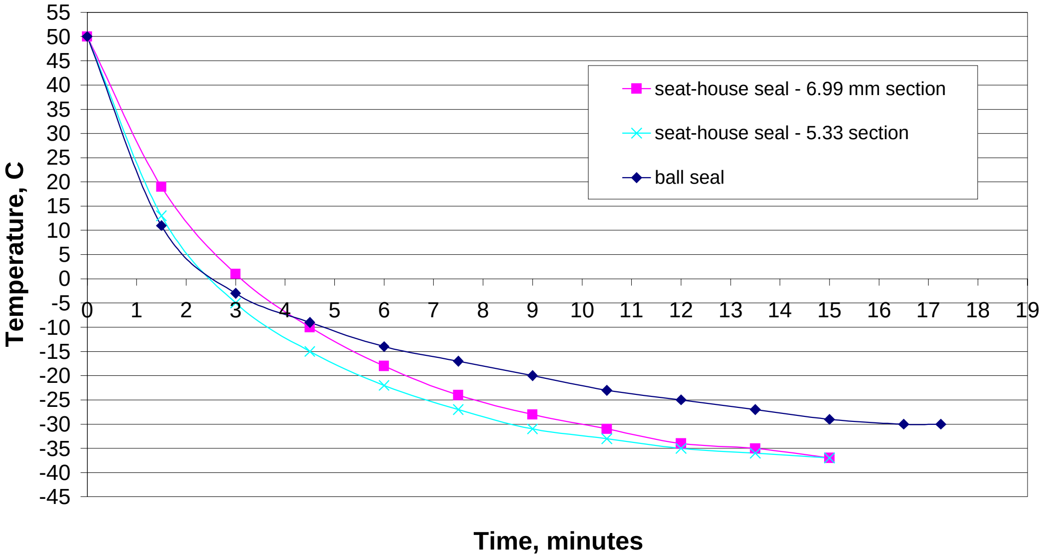


Figure 15 Example of seal temperature reduction in a ball valve during blow down

In extreme conditions, components equipped with decompression-resistant elastomeric seals must be equipped with heating devices to ensure that the seals remain above glass transition temperature at all time.

4.2.2 Glass transition temperature (T_g)

As the temperature of an elastomer is lowered to the region near its glass transition temperature, the material begins to lose its rubbery properties. It becomes progressively less able to seal, and leakage may occur both as a result of stiffening and the reduction in volume associated with T_g. The T_g and methanol mass uptake of some commonly used materials are listed in Table 3 below:

Table 3 The glass transition temperature and methanol mass uptake of some common elastomers

Elastomer Type	*Glass transition temperature Typical values (DMTS) [°C]*	*Mass increase in solvent at 23ºC, [%]*
FKM-1	-4	40
FKM-2	0	13
FKM-3	-20	55
FKM-3 low temp	-30	1
EPDM	-40	3
Low Nitrile	-30	5
High Nitrile	-10	10
Hydrogenated Nitrile	-10	6
FEPM	+15	1
FQM – Silicone	-80	-

These standard solvent (methanol) uptake values can vary by ±5%, depending on the other constituents of the elastomer formulation, such as fillers, plasticisers, stabilisers etc. The numerous Viton® grades are included to show how wide the range can be and therefore how improtant it is to get information that is specific to the final compound of use.

4.2.3 Shift of glass transition temperature at high pressure

When elastomers are subjected to high pressure, its free volume can be reduced. This manifests itself as a T_g shift, at a rate of approximately 1ºC/1.8ºF per 52bar / 750psi of applied pressure [James Walker]. As a result, the low temperature flexibility of the elastomers will be reduced, and the elastomers become brittle at higher temperatures.

An example of this behaviour would be an elastomer with a low temperature limit of –20ºC used at 1,000 bar (15,000psi).

At 1000 bar (15,000 psi), the T_g shift equates to : $\frac{15{,}000\,psi}{750\,psi} = 20^{\circ}\mathrm{C}$

Therefore, the new low temperature limit for the material at 1000bar = -20ºC + 20ºC = 0ºC

4.2.4 Determination of glass transition temperature

Glass transition temperature can be measured by Gabo Eplexor Dynamic Mechanical Thermal Spectrometer (DMTS) Tests. In a DMTS test, sinusoidal force is applied to a test sample, and the resulting strain, which will also be sinusoidal at the same frequency, but out of phase, is measured. The complex dynamic modulus E*, which is made up of a dynamic modulus E' and a loss modulus E" can therefore be measured.

$$E^* = E' + iE'' = \frac{\sigma^*}{\varepsilon^*}$$

and σ^* leads ε^* by a loss angle δ. Therefore,

$$\tan\delta = \frac{E''}{E'}$$

At a transition point such as T_g or the melting temperature, T_m, a peak in loss angle (Figure 16a) or loss modulus (Figure 16b) will be detected in the oscillatory experiment.

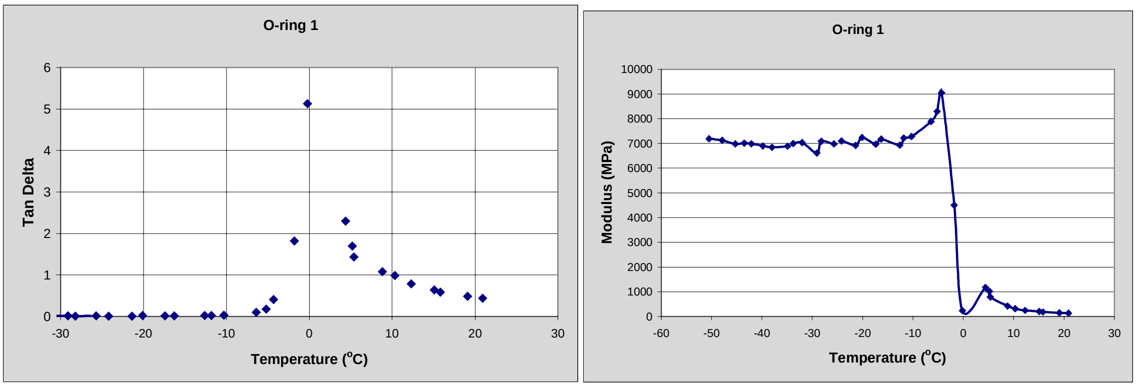


Figure 16 Property peak at the glass transition temperature: (a) loss angle (b) loss modulus

4.2.5 Determination of low temperature elastomer characteristics

There are several test procedures that are used to define low temperature characteristics of elastomers, but there does not seem to be much correlation among them.

Temperature Retraction Test

Temperature Retraction (TR) test results are easily reproducible, commonly quoted and used by seal manufacturers as the means of indicating the low temperature capability of an elastomeric compression seal. The temperature retraction test, ASTM D1329, is carried out by elongating a specimen usually to 250%, freezing it in the elongated condition to a non-elastic state and then allowing it to retract freely whilst raising the temperature at a uniform rate. A full retraction curve is shown in Figure 17. However the temperatures most commonly quoted are those corresponding to 10% (TR10), 30%(TR30), 70%(TR70) and 90%(TR90) retraction.

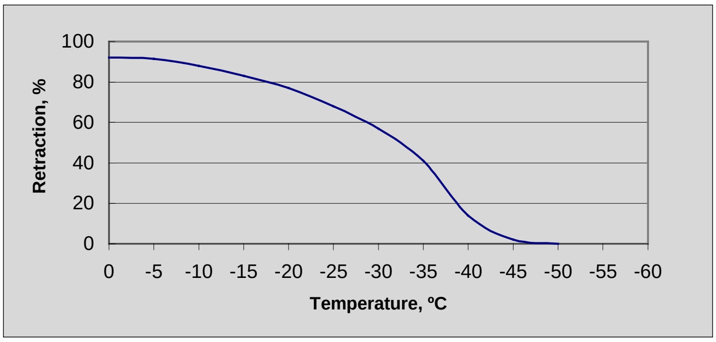


Figure 17 An example of a retraction curve for a low temperature, rapid decompression resistant elastomer

Torsion Modulus

BS903 Part A13 specifies a static procedure, known as the Gehman test, for determining the relative stiffness characteristics of vulcanized or thermoplastic rubbers over a temperature range from room temperature to approximately –150ºC. The Gehman apparatus is used to measure the torsion modulus by twisting a strip of rubber at room temperature and at several reduced temperatures to generate a temperature-modulus curve. The torsional modulus of the test piece at any temperature is proportional to the quantity

$$\frac{180-\alpha}{\alpha}$$

where α is the angle of twist, in degrees, of the test piece.

The relative modulus (RM) at any temperature is the ratio of the torsional modulus at that temperature to the torsional modulus at 23ºC. Results are usually quoted as the temperatures at which the modulus is 2, 5, 10 or 100 times the value at room temperature.

The RM value in general does not provide a meaningful guide to the performance of elastomers at low temperature. Therefore, some manufacturers quote the temperature at which the modulus increases to a predetermined high value which equates with the loss of technically useful flexibility. For example, some give a T_{70} value – i.e. the temperature at which the torsional modulus increases to 70MPa.

Brittle Point

The temperature at which the material becomes brittle (i) in a slow bending test; or (ii) in an impact test – BS 903 A25; ASTM D746 is sometimes included in the data sheets provided by seal manufacturers. However, in applications, sealing can seldom be accomplished 10ºC above the Brittle Point. The value is therefore not very useful for indicating elastomer performance.

4.3 THERMAL EXPANSION

Some consideration should also be given to high and low temperature applications from the point of view of expansion of the elastomer. The volumetric expansion coefficient of elastomers range from 40 x 10^{-5} per ^{o}C for nitrile rubbers to 80 x 10^{-5} per $^{\circ}$C for silicone rubbers, compared with 3 x 10^{-5} per $^{\circ}$C for mild steel. Care must therefore be exercised to ensure that the volume of the elastomer does not exceed the groove volume at high temperature and the linear interference/squeeze does not reduce to zero at low temperature. Thermal expansion calculations should be carried out to assess the potential groove tolerance variations required.

4.4 ELASTOMERIC SECONDARY SEALS

Elastomeric rings are also used as secondary seals for rotary dynamic seals (e.g. dry gas seals) in equipment such as rotary compressors in gas production installations. The primary function of the secondary seal is to help the spring-loaded rotary face maintain close axial proximity to its counterface, the design separation is only a few micrometres [HSE 2000/070]. These secondary seals can also suffer from rapid decompression damage, for which PTFE-based materials are an effective solution. However, the flexure mode of elastomeric seals is more tolerant of solids build-up, which is sometimes difficult to eliminate and is the most common cause of secondary seal failure. Therefore whenever possible, elastomeric seals are used.

The acceptable upper limit on temperature of the gas in a rotary sealing system is normally determined by the thermal compatibility or by the extrusion resistance of the secondary seals (elastomer or PTFE). If the compressor discharge temperature is too high, then gas may be tapped from an intermediate stage at a lower temperature.

The low temperature limits for rotary sealing systems are however commonly set by the dew point, freezing or solidification point of any liquid or vapour present.

When using elastomeric seals in equipment such as rotary compressors, avoid using burst-discs to limit pressure. A relief valve vents pressure more progressively and this can reduce the risk of decompression damage.

4.5 FLUIDS

Some materials swell when in contact with certain types of service gases and liquids, e.g. Ethylene propylene diene (EPDM) in methane. It is important to select a rapid decompression resistant elastomer that will not swell excessively in the fluids to which it can be exposed. For existing operations, it is essential to keep detailed records of elastomer formula changes.

4.5.1 Methanol injection

Methanol injection is a common practice, to dissolve methane hydrates. Some fluorocarbons can have excessive swell (as much as 40%) and lose physical strength due to methanol uptake, especially at low temperatures, e.g. 4ºC to 23ºC.

However, small concentrations of water, 2 to 5%, negate this effect. It is advisable to avoid pure methanol, and the opening or closing of valves during and straight after methanol injection. The time period for methanol injection should also be limited, so that the elastomeric seals will not become fully saturated with methanol. Calculations would be required to justify this. Some rapid decompression resistant elastomeric seal materials are compatible with methanol, e.g. HNBR and FEPM (Table 3 and Section 4.2.2). Other materials can be acceptable for short periods of time, e.g. Fluorocarbon Terpolymers (i.e. Viton® B types) and Tetrapolymers.

4.5.2 Chemical injection

Compatibility of seal materials with specific chemicals is typically confirmed by testing, and must include the full range of tensile properties as well as volume swell, mass uptake and hardness change. With the exception of amine based corrosion inhibitors, most other production chemicals have little effect on seal materials once diluted in produced or injected fluids

The effects of amine based corrosion inhibitors on elastomers are very temperature dependent, but not dependent on concentration as a few ppm is sufficient to cause degradation [NACE 1G286]. FKM should only be used at temperatures below 90ºC. HNBR is more resistant to amine types, but only FEPM can be used for potassium carbonates (Table 4).

Table 4 Example of operational envelop and chemical resistance of some commonly used elastomers

	Temperature, [°C]			*Decompression Pressure [bar]*	*H_2S [ppm]*	*Pure methanol*	*Corrosion inhibitors*
	*Temperature range suggested by supplier.**		*Safe decompression temperature @ Decompression pressure*				
80-90 IRHD Low ACN NBR - nitrile	-30	70	70	50	10	resistant	Fair at their high temperature limits for dilute inhibitors
80-90 IRHD High ACN NBR - nitrile	-15	100	50 100	100 50	6-10	resistant	
Low temperature HNBR	-40	90	90	138	5×10^5	resistant	resistant
HNBR	-20	120	55 75 100 120	280 190 130 100	5×10^5	resistant	resistant
FKM - 3	-5	170	70 100 150	200 140 100	2000	high swell	Fair at <90°C for dilute inhibitors
FKM - 4	-25	150	120 100	345 380	2000	resistant	
FEPM	30	200	120	345	5×10^5 - 3×10^6	resistant	resistant
FFKM special decompression grade	-20	327 max 200 Typical	66	140	5×10^5 - 3×10^6	resistant	resistant

** Lower Limit not based on T_g. High limit will depend on acceptable ageing in system. Special compounding can shift limits and improve chemical resistance. Always check manufacturer's advice, in-house field experience and if in doubt conduct testing for the specific commercial compound (not generic elastomer type). RGD resistance assumes 15% squeeze, high groove fill (close to 90%). Values depend on the compounding and processing and are only included as an example. They are also subject to revision as product formulation can change.*
[Sources: Grove, Derham 2003, DuPont Elastomers, James Walker, Greene Tweed]

If the gas pressure is higher than 35 bar (510 psi), specific "decompression-resistant" materials are advisable, unless prior knowledge exists within the organisation of a different threshold proven by field experience. Commercial decompression resistant grades normally have a hardness value at or above 85 IRHD. However, the reverse is not true – a lot of the 85 IRHD commercially available elastomer seals are not "decompression-resistant". It is therefore important to specify a "decompression-resistant" formulation from reputable seal suppliers.

5 MATERIALS SUITABLE FOR RAPID GAS DECOMPRESSION

Elastomeric materials play an important role in fluid sealing, with certain uniquely valuable physical properties. However, elastomer also has its limitations. Therefore, when selecting an elastomer material for a seal, a list of its properties needed to be assessed [Müller 1998]. For rapid gas decompression, further material criteria need to be fulfilled. This section details these additional material requirement.

5.1 UNIAXIAL AND BIAXIAL STRENGTH AND EXTENSION

Seals of good quality medium to high acrylonitrile (NBR) with hardness 80 to 90 IRHD (International Rubber Hardness Degree) have been used in moderate conditions at temperatures < 100ºC and pressures < 50 bar (725 psi).

When specifying materials it is worthwhile using a reputable supplier as they are more likely to produce quality product with the following important features:

- No surface imperfections, such as foreign materials or flow marks.(This can be difficult to achieve with certain polymers due to the processing viscosity being very high).
- The quality of mixing between the filler and the polymer should be well controlled and of a high standard. This will minimise the possibility of filler agglomerates or contamination acting as stress raisers.
- The cure is carefully controlled. This will keep to a minimum the size and distribution of voids created by the gaseous by-product of curing (methane in the case of HNBR).
- Elongation to break above 100% at ambient temperature.
- Uniaxial tensile strength in excess of 10 MPa at ambient temperature.

Table 5 Commercially available rapid decompression resistant elastomers

Designation	***Elastomer type***	***Commercial Tradenames***
HNBR	Hydrogenated nitrile	Therban®, Thornac®, Zetpol®
FKM	Fluoro rubber of the polymethylene type See types below	Dai-El®, Fluorel®, Technoflon®, Viton® (A Type 1, B / GF Type 2, GFLT Type 3)
FKM-1	Dipolymer of hexafluoropropylene and vinylidene	
FKM-2	Terpolymer of tetrafluoroethylene and vinylidene fluoride and hexafluoropropylene	
FKM-3	Fluorocarbon terpolymer	
FKM-4	Fluorocarbon tetrapolymer	
FEPM /FCM/ TFEP	Tetrafluoroethylene-propylene copolymer	Aflas®
FFKM	Perfluoro Elastomer	Chemraz®, Kalrez®, Perfluor®, Simriz®

The compounding and processing of the final product will strongly influence the performance of the seal. The advice of seal manufacturers should be sought when specifying material for decompression resistance.

In more extreme environments, specific “decompression-resistant” materials should be used. There is a choice of elastomer materials on the market with “decompression-resistant” grades. Their hardness is normally at or above 85 IRHD (Table 4). However, the reverse is not true – a lot of the 85 IRHD commercially available FKM, HNBR and FEPM seals are not “decompression-resistant”. It is therefore important to specify a “decompression-resistant” formulation from reputable seal suppliers.

Good quality 80 to 90 IRHD Ethylene propylene diene (EPDM) seals have decompression resistance comparable to NBR. However, they are incompatible with hydrocarbons (e.g. methane) and therefore are rarely used in the oil and gas industry.

Equi-biaxial stress-strain characteristic of elastomers can be obtained by the inflation of a circular rubber sheet clamped round its circumference, after the manner of a bursting test. The strain in the sheet is of course not uniform over its surface, but it is very nearly uniform over a region near the centre of the sheet. The measurement of the extension ratio in the plane of the sheet can be used to calculate the equivalent compressive strain in the corresponding uniaxial compression [Treloar 1975].

5.2 HARDNESS

Increasing the hardness of an elastomeric seal normally increases its rapid gas decompression resistance. For example, medium to high acrylonitrile elastomers are often recommended for gas services where the operational temperature is below 100ºC, and pressure is below 50 bar (725 psi). However, the hardness of a seal is also limited by other operational conditions, such as :

(i) low temperature - e.g. when the amount of reinforcing filler is reduced in the formulation of a 75A fluoroelastomer to 60A, the glass transition temperature of the elastomer can be lowered by 3-4ºC.

(ii) difficulty in installation - harder seals will require higher assembly force, and will not be able to stretch easily over metal parts.

(iii) tolerances of the metal components - in oilfield applications, casings have diametral size tolerances of +1.00%/-0.5%. For design and manufacturing economy, a single seal assembly is preferred to cover the entire range of tolerances for a given casing size.

5.2.1 High pressure seal extrusion

When elastomers are subjected to high pressure, especially at high temperatures, they behave like very viscous fluids and will be forced into the clearance gap of the housing’s low pressure side. This action is known as extrusion. The extruded volume of elastomer is physically removed when the clearance gap closes, resulting in a smaller seal for each pressure cycle, until eventually seal failure occurs. Figure 18 shows extrusion damaged seals.

Figure 18 Typical peeling damage to O-ring caused by extrusion

Extrusion failure will depend on the pressure, the size of the clearance gaps, the temperature, the radius in the corners of the groove and the hardness of the material. Figure 19 gives the maximum allowable clearance for given pressures and hardness, when back-up rings are not fitted, using standard Nitrile at less than 60°C. As temperature increases, elastomers tend to soften and therefore become more prone to extrusion.

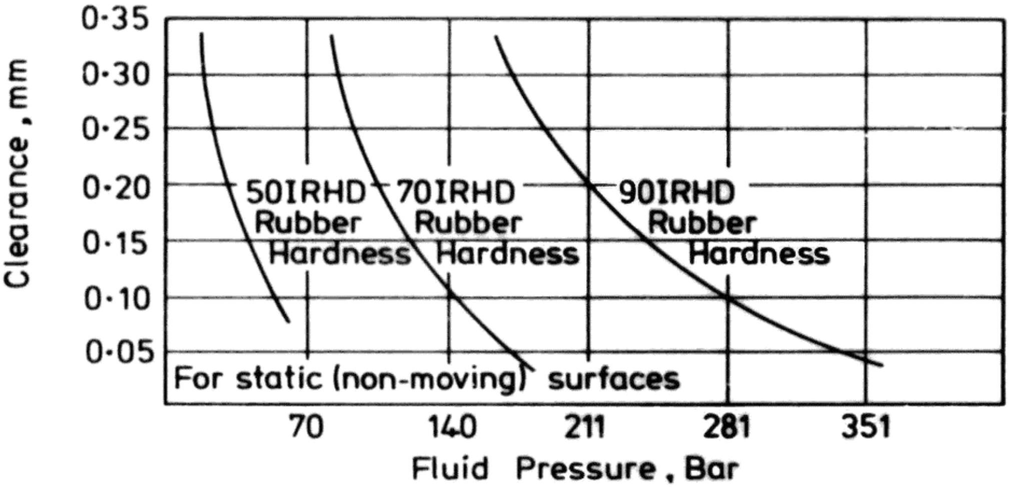


Figure 19 Typical recommended housing clearance for different O-ring hardness

5.3 FATIGUE

The presence of classical fatigue ‘rings’ on seals subjected to rapid decompression cycling (Figure 4) has established that fatigue is a major failure mechanism in elastomeric seals subjected to multiple decompressions. The failure initiates from voids present in the material from the manufacturing process, and fatigue samples that have failed at a lower number of cycles have larger void sizes than those that last for more cycles. For cases where the failure initiation point is an inclusion rather than a void, a large inclusion will behave as if it were a smaller void.

Fatigue tests on un-notched dumbbell samples (BS 903 Part A type 1) at 2 minutes per cycle, a minimum of five samples per strain level, help to provide good prediction of decompression cycling failure. The spread of results within each test strain however can be very wide. The five samples of some decompression-resistant materials tested at room temperature to a specific strain can either fail on the 1st cycle or last for the whole 100 cycles. Refer to Section 8.2 for further guidance in the test procedure.

As the strain level decreases, more fatigue cycles will be completed before failure occurs, as shown in Figure 20. This is why as the system gas pressure decreases and voids inflate less, the more rapid decompression cycles will be completed without seal failure. At elevated temperatures, fatigue failure occurs at lower strain levels, therefore rapid decompression cycling results in seal fracture at lower gas pressures. The range of strain levels between failure on the first cycle and no failure during fatigue tests is larger at the elevated temperature, this is because the material is softer and will extend further for the same applied load at the elevated temperature.

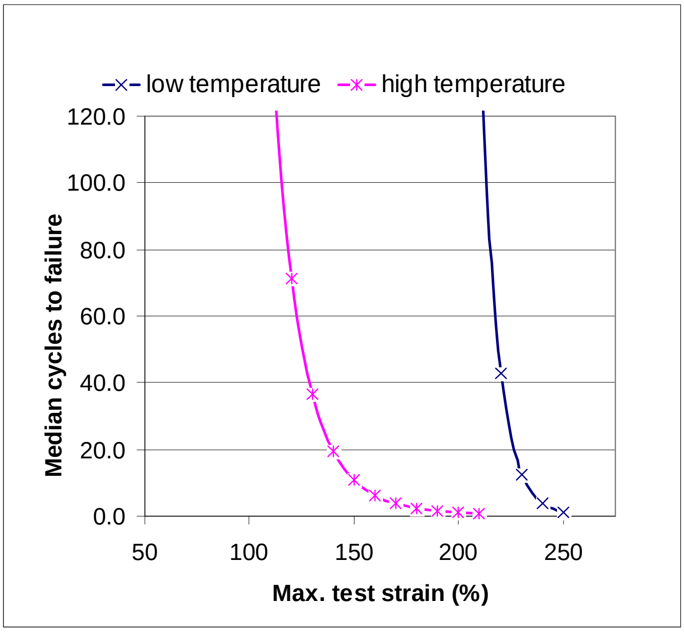


Figure 20 Cycles to failure against test strain from fatigue tests for a specific elastomer

5.4 GAS PERMEAITON

During rapid decompression, an elastomer/gas combination with a high solubility and a low diffusion coefficient is most prone to elastomeric seal fracture. This is because under such conditions a large volume of absorbed gas will stay within the elastomer for a longer time during rapid decompression.

Based on Fick's 1st Law of Diffusion, the gas flow (J_x) in the x direction is proportional to the concentration gradient ($\partial c/\partial t$) in the same direction.

$$J_x = -DA\frac{\partial c}{\partial x}$$

Where D is the diffusion coefficient, A is the cross-sectional area, and c is the gas concentration in the elastomer.

Permeation (P) is the amount of gas passing *through* an elastomer of unit thickness, per second, per unit area, and at a unit pressure difference. It is related to D and s by the following equation:

$$P = D \bullet s$$

The values of P, D and s are all highly dependant on temperature as discussed in Section 4.1. Therefore, permeation tests (Section 8.1) must be performed at the operational temperatures.

5.5 MATERIAL VARIABILITY

There is significant inherent variability in elastomer material properties. A statistical analysis completed by BHR Group on the quality control data of 3 elastomer materials supplied by 2 seal manufacturers showed that the physical properties of elastomers are extremely variable, up to ±40%. Figure 21 shows the frequency distribution comparison of stress at 50% strain between two materials. It is recommended that variability of physical properties should not be higher than 30% at the 95% confidence level [Routh 1998].

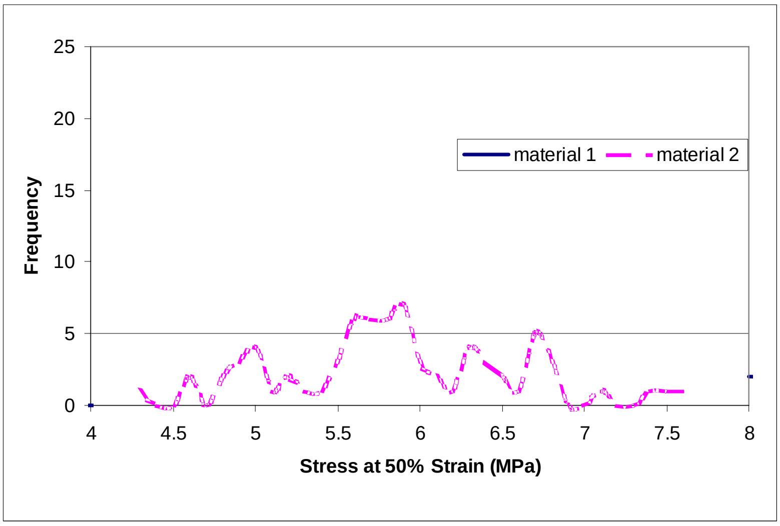


Figure 21 Frequency distribution of stress at 50% strain for two elastomers

5.6 VOID AND DEFECT DISTRIBUTION

Voids and rigid inclusions within the elastomer matrix of elastomeric seals are considered a major contributing factor to failure under rapid decompression conditions. The number of larger voids and rigid inclusions (>20 µm) is generally far less than the number of smaller voids and rigid inclusions. However, they are considered potentially very important for decompression resistance, as void inflation is likely to start at much lower gas pressure in the larger voids and rigid inclusions. Larger section seals also contained larger voids. It is recommended that elastomeric seals used in high-pressure service should not have voids and/or rigid inclusions larger than 10 µm [Routh 1999].

5.7 VOLUMETRIC EXPANSION

When a seal is exposed to an elevated temperature or a rapid decompression, it will increase in volume to as much as 20%, see Figure 22. In high groove fill applications detailed in Section 6.4, as the seal expands, more of the surface area will be in contact with the housing, resulting in higher compressive forces from the housing. This force can, in a marginal case, restrict void inflation and improve the rapid decompression resistance of the seal [Routh 1999].

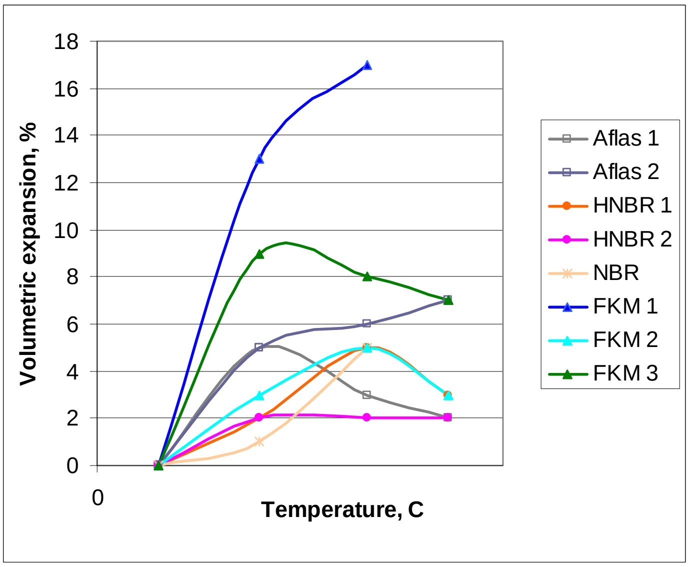


Figure 22 Volumetric expansion of some decompression-resistant elastomers

5.8 COMPRESSION SET

Any mechanically loaded elastomeric seal will exhibit time dependent relaxation in the long term. If the seal is subsequently unloaded, the elastomer will recover towards its original shape to an extent defined by chemical and physical degradation. Such relaxation and recovery phenomena are determined primarily by the visco-elastic nature of elastomers and by the chemical reactions that occur between the material and the environment. Some of the “decompression-resistant” materials have high compression set, this particularly needs to be taken into consideration for applications involving very low temperature (< -10ºC) conditions.

The other parameter that will determine the robustness of an elastomeric seal is the retained sealing force or resilience of the seal. This is a similar property to compression set but gives more information about the performance of the sealing material over time. When specifying a material for application in a system that will experience multiple decompression and recompression events it is important that the material will retain sufficient sealing force during re-pressurisation. This is when a seal is most likely to leak. At high pressure the fluid exerts a force on the seal and therefore increases the sealing force. At low pressure it is the materials rubbery character that provides the sealing force. Another aspect of resilient materials is the ability to seal even with multiple cracks in the material. The retention of sealing force ensures that leakage paths along cracks remain closed or of sufficiently small clearance to allow re-pressurisation. The materials that tend to show this feature can also benefit from high elongation at break and are therefore more robust when fitting the seal over an obstruction.

6. SEAL AND HOUSING DESIGN

BS1806 gives standard sizes of O-rings in imperial units whilst metric O-rings are covered by BS4518. The two Standards also recommend dimensions and surface finishes for housings of standard O-rings. However, to improve the rapid decompression resistance of seals, the housing dimensions are often different from the Standards. A complete sealing system performs best during rapid gas decompression with:

- Seal section diameter as small as possible, (5.33 mm or lower)
- Initial squeeze as low as practicable, 10-15%
- Close to 90% groove fill
- The use of rigid anti-extrusion rings on both sides

However, volumetric expansion due to temperature and swell must also be considered to avoid overfilling the groove (Sections 4.3, 5.7 and 6.4)

6.1 SEAL GEOMETRY

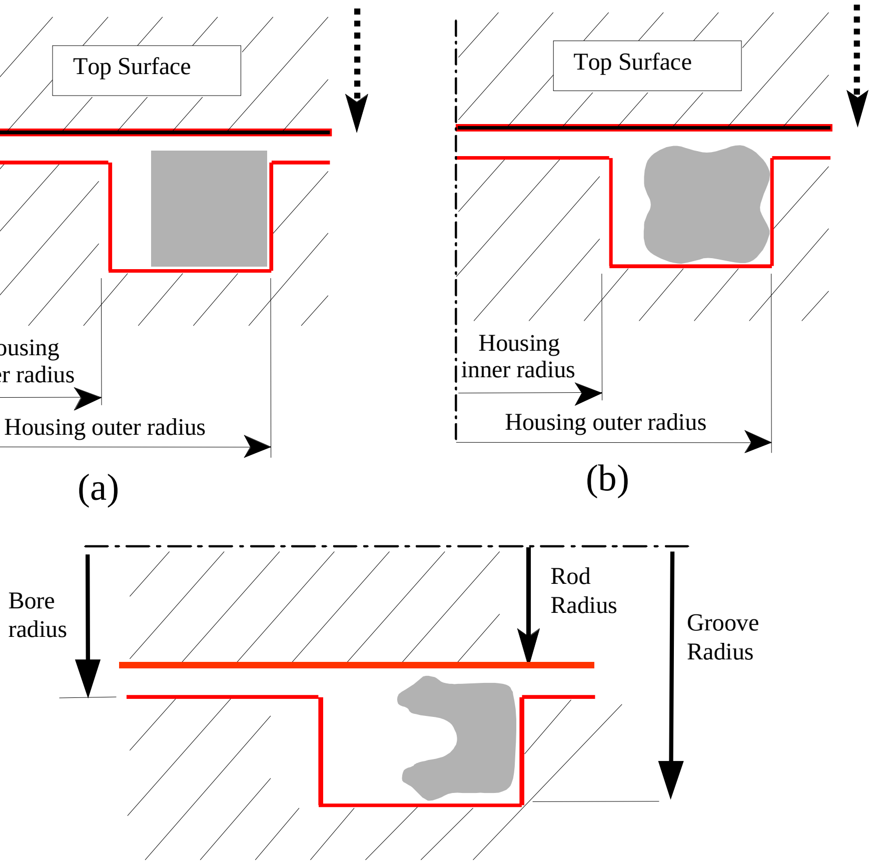
6.1.1 Section size

Elastomeric seals with cross section ≤ 5.33 mm made from gas decompression-resistant materials can perform well over a wide range of decompression conditions. Seals with cross-section greater than or equal to 10 mm generally perform badly, irrespective of elastomer material employed. For “ large” seals, either redesign incorporating smaller elastomeric seals, or the use of sprung PTFE seals should be considered for critical applications.

6.1.2 Section shape

O-ring is the most commonly used elastomeric seal geometry. Other seal section shapes used include square, X (Quad) or U rings, (Figure 23). Square and X goemetries are used to prevent seals twisting in their grooves. The design rules for square and X rings to improve rapid decompression resistance are the same as those listed above for O-rings.

X and U rings are also used to provide more flexure to accommodate wide tolerance in housings. U rings are uni-directional, they need to be used in pairs for application where the pressure differential across the seal can reverse. A suitable design of back-up ring inside the inner bore of the two U-ring lips is recommended for rapid decompression application to support the lips and increase groove fill. Additional care during assembly is also required to ensure the proper installation of U-rings.



(a)

(b)

(c)

Figure 23 Alternative seal designs before closing housing, (a) square ring, (b) X ring, (c) U ring

6.2 INITIAL SQUEEZE

Elastomeric seals such as O-rings are compressed (squeezed) perpendicular to the direction of fluid pressure-drop (Figure 24) to provide initial sealing before fluid pressurisation. 10 to 15% squeeze in O-rings is generally recommended for rapid decompression applications, with a squeeze closer to 15% being required for very small section (such as 1.87, 2.62 mm) seals to compensate for housing tolerances (section 6.5).

High initial compression (squeeze) increases sealing contact stress, but it also increases the tensile stress inside an elastomeric seal in the perpendicular direction, especially in seals that have significant volumetric expansion after rapid gas decompression. This is because seal expansion in the circumferential direction will be very limited, leaving all seal expansion in the direction of fluid pressure action. It is therefore not desirable to have initial compression (squeeze) significantly higher than 15%.

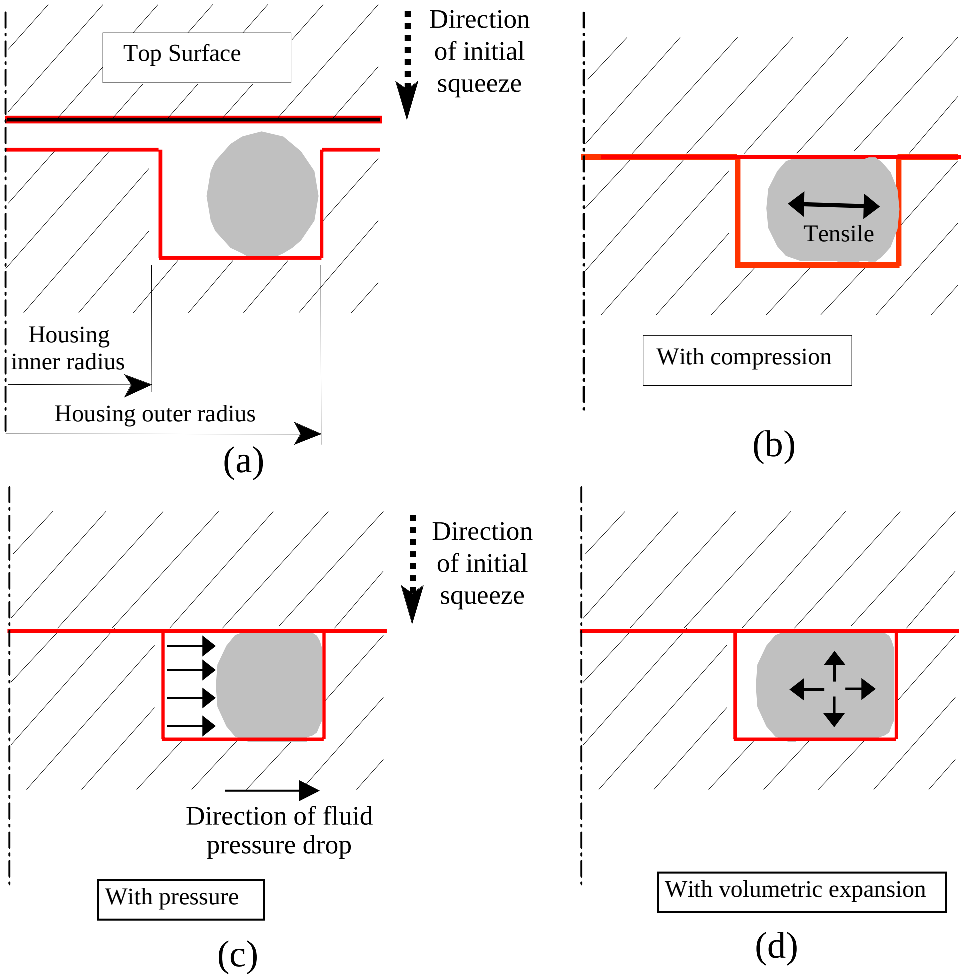


Figure 24 O-ring distortion (a) before closing housing, (b) with compression, (c) with fluid pressure, (d) with volumetric expansion

As fluid pressure acts on one side of an elastomeric seal, the fluid pressure is transmitted more or less uniformly throughout the seal – and enhances the preload at the sealing interfaces. Thus:

Sealing contact stress thus increases automatically such that (approximately) :

- Sealing contact stress = system pressure + initial interference stress

A sealing condition is maintained as long as :

- Maximum sealing contact stress > system pressure

For calculating initial squeeze in critical applications where temperature, tolerance or eccentricity variations are a problem, the O-ring cord section tolerance must also be considered, as detailed in Section 6.5.

6.3 SEAL STRETCH

High hoop stretch (> 5%) should be avoided for high or low temperature applications. It can result in rapid deterioration of certain elastomers such as nitrile, particularly if service approaches their high temperature limits. It can also easily fracture brittle seals (see Figure 12) at low temperature and reduce cross section size and therefore seal compression.

6.4 GROOVE FILL

High groove fill reduces rapid decompression damage in seals by increasing the compressive stress field. If the compressive stress field surrounding a void is greater than the applied pressure differential, the void cannot inflate. These can be achieved in equipment with standard grooves, by inserting rigid back-up rings (PTFE or PEEK) on either or both the high and low pressure sides. However, high initial compression and groove fill can cause stress cracking due to high strains. An ideal case would be standard compression (15%) and high groove fill (close to 90%), but volumetric expansion due to temperature and service fluid swell must be considered to avoid groove overfill in service, and/or increased friction (torque) in valves and other semi-dynamic applications.

Some materials can expand by as much as 20% during depressurisation, as discussed in Section 5.7, even under moderate pressure regimes. This magnitude of gross volumetric expansion can significantly improve rapid decompression resistance in 85% groove fill applications, even for the high temperature and high pressure cases. However, no improvements in rapid decompression resistance have been found with the same gross volumetric expansion in the standard 70% groove. This indicates that groove fill during depressurisation, at the service temperature is required to be close to 100% to suppress void inflation.

6.5 SEAL AND HOUSING TOLERANCES

Shaft eccentricity and excessive extrusion gaps are limiting factors in high pressure applications. Tolerances should therefore always be within those quoted in the relevant standard for the seal type to be used. Figure 25 shows the O-ring compression (interference) variations possible within the imperial standard BS1806, taking account of permissible groove and seal tolerances.

For optimum seal operation and life, tolerances should be as tight as economically achievable for a given component, with the purpose of minimising eccentricity or misalignment of sealed surfaces, and reducing extrusion gap to a minimum for pressurised seals. It is quite feasible to use elastomeric seals with system pressures in the range of several hundred bar, with attention to rapid decompression resistance and elimination of seal extrusion.

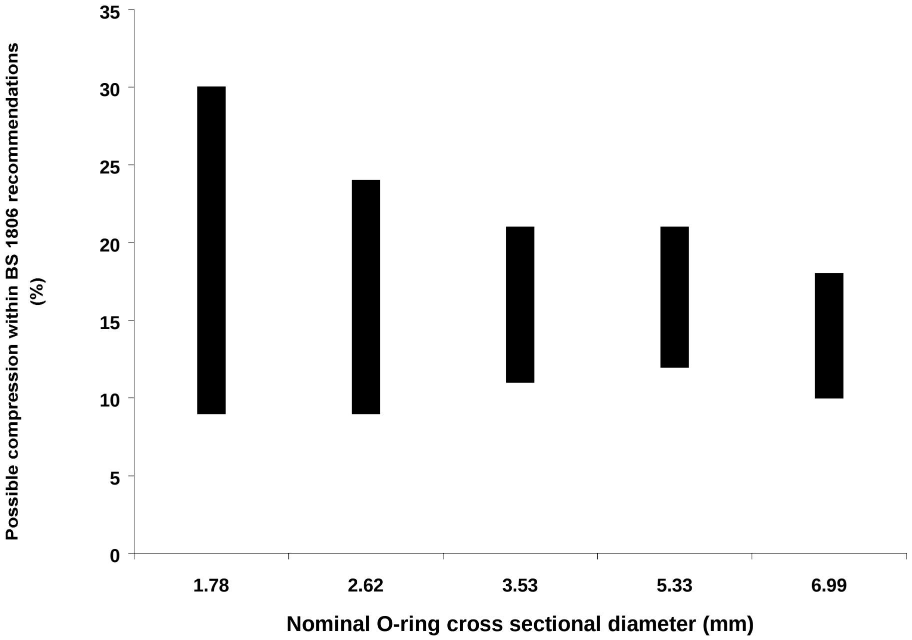


Figure 25 Possible O-ring compression variation within BS recommendations

6.6 EXTRUSION CONTROLS

6.6.1 Back-up rings for elastomeric seals

Standardised back-up rings are normally available for standard O-ring sizes, (Figure 26a). It may however require a longer groove than standard, depending on groove fill. They are made of material harder than the O-ring material, but softer than the metal work. Usually plastic, they can also be a soft metal. Spiral back-up rings can be used to ease fitting into a groove. These are less reliable with fluctuating pressure or high pressures (> 350 bar / 5100 psi), and need an inside diameter greater than 3 mm for machining purposes. Single turn back-up rings or those from harder materials, e.g. Polyether Ether Ketone (PEEK), need relatively close tolerances, therefore can be difficult to assemble.

An elastomer T-ring has a pair of back-up rings as standard, (Figure 26b). The back-up ring, on the low pressure side, is being pushed against the extrusion gap as pressure increases. It therefore does not require an interference during assembly. As radial loading of the back-up ring varies directly with fluid pressure, seal friction is kept to a minimum during the low pressure part of the pressure cycle in a dynamic application. It also has better resistance to seal rolling and spiral failure. However, it has lower contact stress at the locator, particularly at low temperatures (below 0^oC).

One disadvantage of using back-up rings is that there is more than one component and, parts may get lost or fitted wrongly.

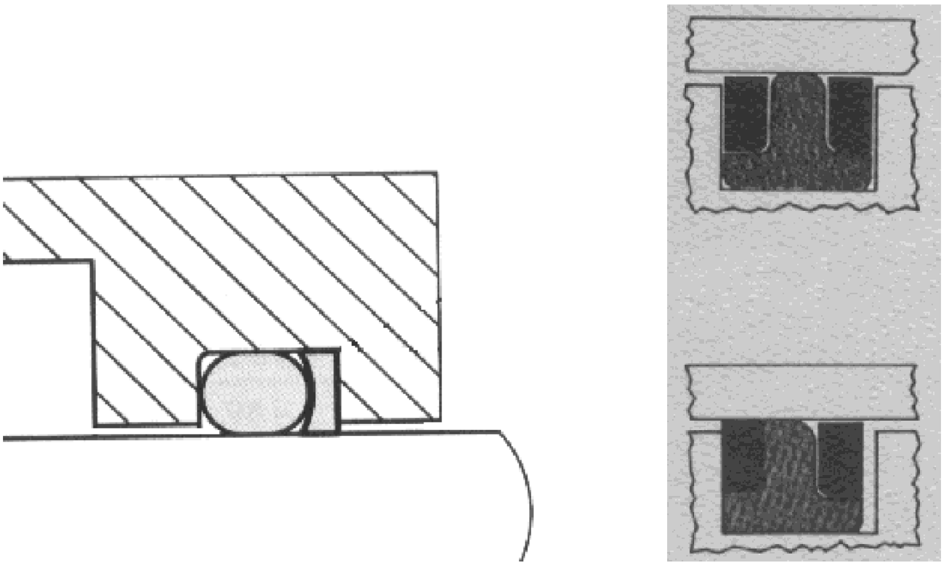


Figure 26 (a) an O-ring with its back-up ring, (b) a T-ring with its back-up rings

6.6.2 Integral anti-extrusion devices – fabric or metal Reinforced elastomeric seals

This type of elastomeric seal has wire mesh anti-extrusion elements made from compressed stainless steel wire (Figure 27a) or fabric material at the atmospheric side, which are directly energised by the elastomer material (Figure 27b). The use of fabric material is however limited by the thermal, chemical and mechanical resistance of the fabric, and metal reinforced seals cannot be as easily stretched as an elastomeric seal. Depending on the bonding between the fibre/metal wires and elastomer, it can generate more sites for initial void expansion in rapid decompression application.

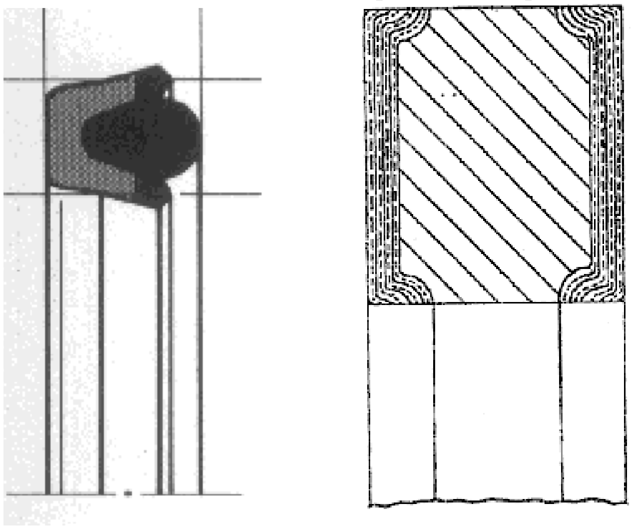


Figure 27 (a) Steel-mesh reinforced elastomeric seal,
(b) Fabric reinforced elastomeric seal

6.6.3 Integral anti-extrusion devices – Coil spring reinforced elastometric seals

This design has a pair of coil spring moulded into a elastomeric seal, (Figure 28). The seal design is in some ways an extension of the T-seal principle. It is double acting, therefore cannot be installed in the wrong way. The most common applications are as casing and tubing hanger seals on wellheads. However, there may be problems in the flow of the elastomer material round the spring during moulding, creating initiation points for void expansion in rapid decompression application, therefore they are not normally used.

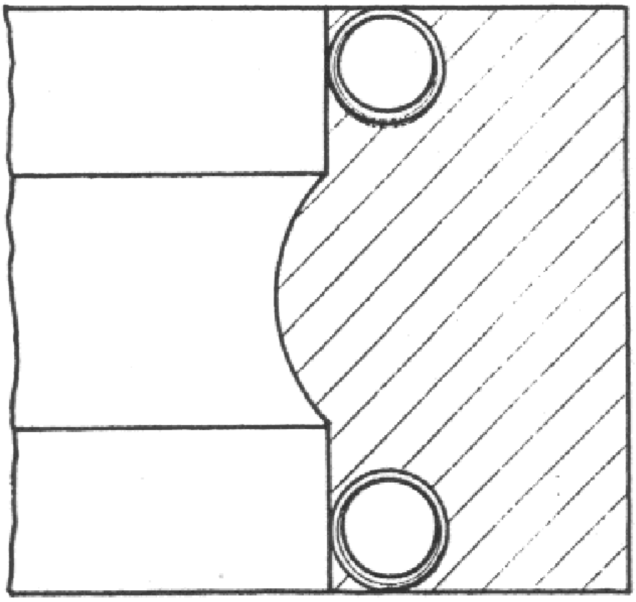


Figure 28 Coil spring reinforced seal

7. DECOMPRESSION TEST PROTOCOLS AND PREDICTIVE MODELLING

7.1 SPECIFYING DECOMPRESSION TESTS

Various oil companies and national standards organizations have developed test protocols or modelling methods aimed at defining elastomeric seal performance during rapid decompression in high pressure gas duty. Each test or modelling method has its strengths and weakness. In selecting a test standard or modelling method for a particular application, the end-user must aim to get as close to the final working conditions as possible. Test environment, housing geometry, seal geometry and cyclic conditions must all be replicated.

Five test specifications and one modelling method have been quoted in the industry. Table 6 summarizes test conditions specified in these standards, which are :

i) NACE TM0192-2003 “Evaluating Elastomeric Materials in Carbon Dioxide Decompression Environments”

ii) NACE TM0297-2002 “Effects of High-Temperature, High-Pressure Carbon Dioxide Decompression on Elastomeric Materials”

iii) SHELL test procedure, as described by [Cox 1985]

iv) TOTAL GS PVV 142 Appendix 8 “Elastomer “O”-Ring Seals Explosion Decompression Type Testing Procedure

v) NORSOK M-CR-710 Rev. 2 2001 “Qualification of Non-metallic Sealing Materials and Manufacturers”

vi) BHR Group Modelling of Decompressions in Elastomeric Systems (MODES) Consortium, 2003, “EDView Version 3.0”.

The NACE standards are for high CO_2 environment. They are intended only to be a means of initial material evaluation and comparison, not for providing any direct correlation with service performance. The SHELL and TOTAL test procedures are specially prepared for evaluating seals in valves. The NORSOK and BHR Group methodology are based on research work carried out on decompression of seals in general. Predictive modelling would be most cost effective when seals in a wide range of conditions needed to be specified, or when the application involves a large number of decompression cycles.

When selecting / specifying a decompression test standard, it is important to specify the following parameters based on the application. Some standards do not include parameters as follows, some allow end-users to choose from a list of several values.

Exposure period –	This is to ensure test seals are fully saturated with the test gas before decompression.
Test conditions between cycles-	Seals can perform differently depending on the duration and temperature between cycles
With or without inspection between cycles -	Face seal arrangement is normally used if inspection between cycles is required.
Dismantle procedures -	The test seals needed to be fully degassed before dismantling, so any blister/cracks recorded are not a result of the pre-mature removal of housing constraints during dismantling only.

Then carry out Internal and external crack inspections

7.2 DECOMPRESSION TEST RESULTS

O-rings of different elastomers can be rated differently using the different test or modelling specifications. The performance of the elastomer is subject to many operational factors, some of wqhich are:

7.2.1 Testing environment, including the composition of the medium, pressure and temperature

The environment can significantly affect the material strength of elastomers. For example, the presence of high concentrations of carbon dioxide can significantly reduce the strength and elongation at break of many fluorocarbons from ambient to 80ºC. The effect of carbon dioxide on nitrile or at high temperature is less significant.

7.2.2 The design of the housing, and the level of seal constraint

High groove fill, in the region of 85% or over can improve rapid decompression resistance. However this can be difficult to achieve in operation without overfilling the groove, particularly for spigot seals when taking into account the tolerance of O-rings, thermal expansion and fluid swell. The materials that tend to expand more during rapid decompression will be most benefited by high groove fill.

A higher than normal (>15%) compression without significant increase in groove fill will, however, induce and increase risk of premature seal failure (section 6.2).

7.2.3 The geometry of the seal

As far as possible, the seals used in standard testing or modelling should have cross-section dimensions that are representative of those used in the application. Larger section seals are prone to cracking as a result of larger void sizes and slower diffusion.

The overall seal diameter is of less significance to rapid decompression resistance.

7.2.4 Cyclical effects

In multiple decompression tests, the time and temperature maintained at ambient pressure between cycles, and the method of dismantling seals for inspection can significantly influence results.

Table 6 Seal decompression test conditions

TEST STANDARDS	***NACE***		***NORSOK***
	Ambient Temperature	***High –Temperature, High Pressure***	***High-Temperature, High Pressure***
TEST/ MODELLING	TEST	TEST	TEST
MEDIA	CO_2	CO_2	CO_2, 10:90 CO_2:CH_4, 3:97 CO_2:CH_4
TEMPERATURE (^oC)	room temp (20-30)	50, 100, 120, 150 170 or 230	100, 150 or 200
PRESSURE (bar)	52	70, 170, 280 or 380	150, 200 or 300
SEAL TYPE	O-ring	O-ring	O-ring
NUMBER OF SPECIMENS	3	6	3
SECTION (mm)	5.33	5.33	5.33
ID (mm)	37.47	37.47	37.47
EXPOSURE PERIOD (hours)	24	24	72
DECOMP RATE	≤ 1min	70 bar/min	20 – 40 bar/min
CONSTRAINTS	free	free or constrained (to be specified by end-user)	20% compression
CYCLES	1	Minimum 1, the hold period to be agreed with end-users	10, a hold period of 1 hour at ambient pressure at the end of each cycle while maintaining the test temperature
DISMANTLE	removed as soon as ambient pressure achieved		removed after 24 +4/0 hours at ambient pressure
INSPECTION	internal and external, measure : hardness, cross section diameter, tensile strength, elongation at break, tensile modulus (at 25, 50 and 100% elongation)		internal and external, 10 × magnification

Table 6 continued Seal decompression test conditions

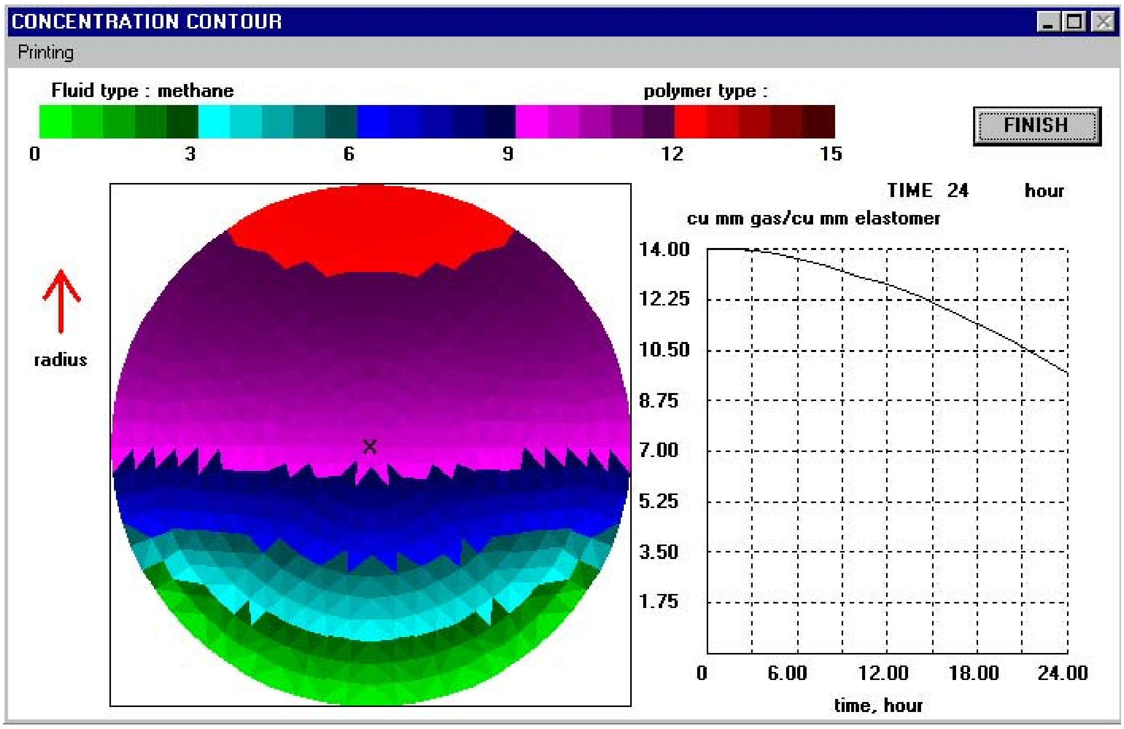
STANDARDS	***Organisations***		
	TOTAL	***SHELL*** (Cox 1985)	***BHR Group (MODES)***
TEST / MODELING	TEST	TEST	MODELLING
MEDIA	20:80 CO_2:CH_4	CO_2, CH_4, North Sea hydrocarbon gas At least 5% Co_2	20:80 CO_2:CH4, 5:95 CO_2:CH_4, CH_4
TEMPERATURE (^oC)	75	100	23, 75, 100, 150
PRESSURE (bar)	190	138 minimum	User specified up to 500
SEAL / HOUSING TYPE	O-rings as flange seals	O-rings as flange seals	O-ring
NUMBER OF SPECIMENS	5	Not specified	Not applicable
SECTION (mm)	largest in valve, min 5mm	5.33	3.53, 5.33, 6.99, 10
ID (mm)	> 40.64	50.165	not specified
EXPOSURE PERIOD (hours)	48	72	assumed fully saturated
DECOMP RATE	max 90 sec.	Instantaneous	Instantaneous – 24 hour
CONSTRAINTS	5% - 15% compression	14% compression/open ID, 14% comp 83% groove fill	7%, 15%, 25% compression 70% or 85% groove fill
CYCLES	5	20	User specified to 1000
DISMENTLE	removed from the test vessel within 3 hours	Not specified	Not applicable
INSPECTION	external, 10 & 20 × magnification. measure: hardness, weight, density, cross section and internal diameter, tensile strength, elongation & tensile modulus at 100% elongation	internal & external measure: hardness, seal dimensions, tensile properties (strength, elongation)	Void wall strain vs elongation at break from fatigue tests Measure : void size, permeation, fatigue, tensile properties (strength, elongation)

7.3 SPECIFYING PREDICTIVE COMPUTER MODELLING

Predictive computer modelling for rapid decompression of elastomeric seals can incorporate three stages of analysis. They are:

(i) transient gas diffusion
(ii) stress distribution inside the seal within its housing
(iii) inflation of a void within the material.

The transient gas diffusion modelling stage of the analysis uses data generated from permeation tests to determine the concentration gradient within the seal following a decompression (see Figure 29). From this, the gas pressure remaining at any point within the seal section can be calculated.



Fluid type : methane

polymer type :

TIME 24 hour

Figure 29 Transient gas diffusion predicted by computer modelling

The second stage in the modelling process calculates the seal installation stress (Figure 30), using the actual seal and groove dimensions, and stress-strain material data at the start of decompression. This is to take into account factors such as initial squeeze, seal section size and groove fill.

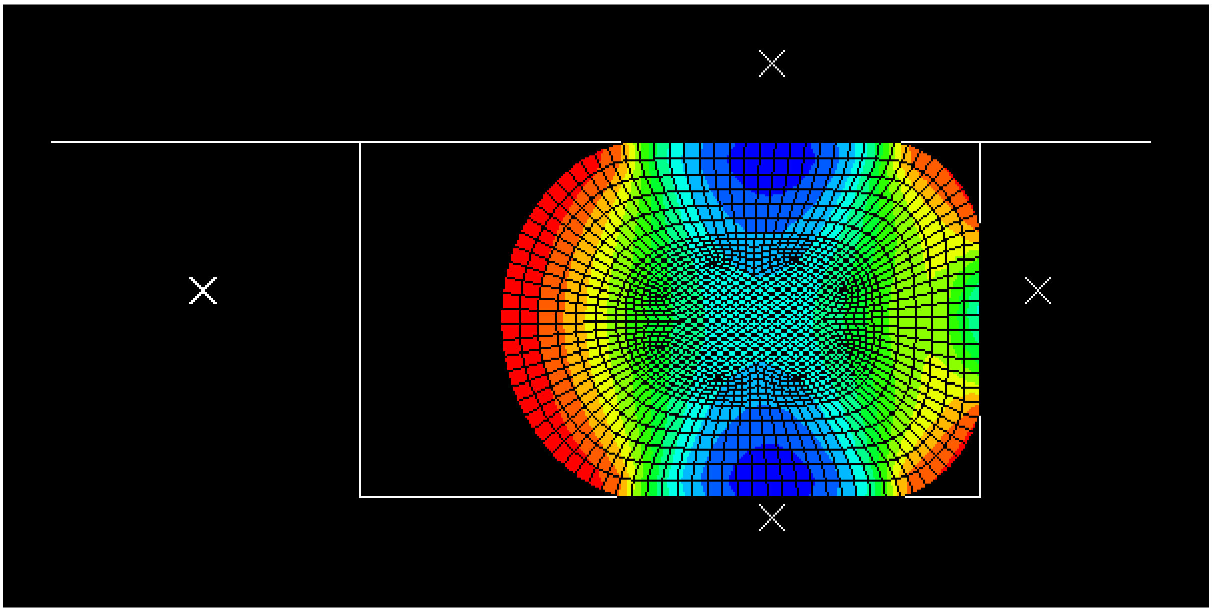


Figure 30 O-ring stress analysis

For the final modelling stage - void inflation analysis (Figure 31), samples of unused seals needed to be sectioned and subjected to microscopic examination to determine the maximum size of voids present in the O-rings. The 'worst case' decompression conditions (temperature, pressure, decompression time) is then modelled, to determine the maximum strain generated within the material during decompression conditions, and therefore the likely decompression performance limit of the seal in operation, such as the shortest safe decompression time, or the maximum number of safe decompressions.

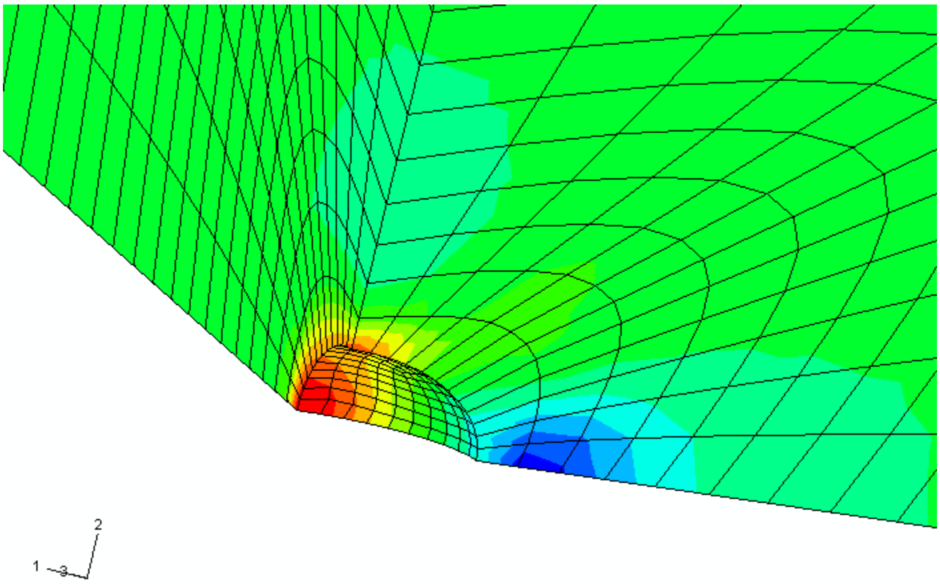


Figure 31 Void inflation analysis

7.4 FAILURE CRITERIA

The two NACE standards do not specify failure criteria. The failure criterion for the TOTAL specification is ‘no external cracks’, for the SHELL specification it is more qualitative e.g. ‘no significant cracking’. For BHR Group specification, it is void wall strain less than elongation at break from fatigue tests, which represents the initiation of any internal or external cracks.

NORSK standard has an internal inspection rating method commonly used in the oil and gas industry. Test seals are cut into 4 equal quadrants as shown in Figure 32 and each section is rated as Table 7. Seals with rating 4 or 5 are classified as not acceptable.

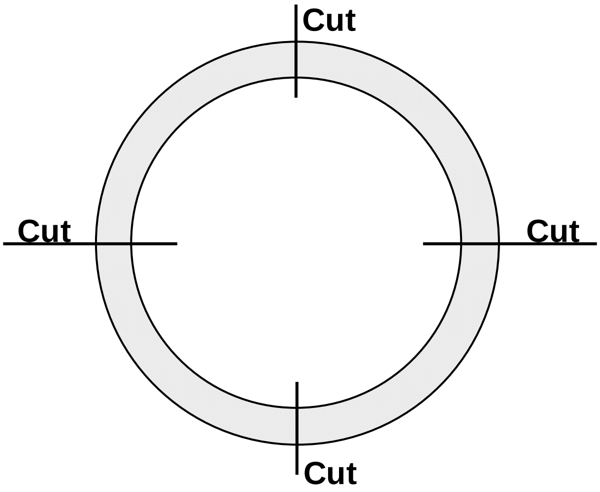


Figure 32 Sectioning of test O-rings into quadrants

Table 7 Description of rating number system

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 than 6 internal cracks, each shorter than 50% of the cross section, with a total 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

8. MATERIAL TESTS

8.1 SPECIFYING GAS PERMEATION TESTS

BS 903 : Part A30 : 1996 is the Standard test procedures for gas permeation. However, it aims to obtain the gas permeation rate through elastomers at a small pressure differential, and measurements are taken in the steady state only, therefore the solubility and the diffusion rate cannot be determined. Permeation tests performed to establish the decompression performance of elastomers include measurements at the initial state, so that the solubility and the diffusion rate can be derived (Section 5.4).

The diffusion rate (D) of the gas within an elastomer is important for estimating decompression damage and calculating the minimum time required for performing decompression tests, whereas the solubility, (the amount of gas dissolved in the elastomers), determines the extent of the potential problem. Both properties vary widely with gas, elastomer formulation, pressure and temperature. Both values can be calculated from test results, the time lag (τ) and the gradient of the graph shown in Figure 33, obtained by performing permeation tests on sheet samples.

$$D = \frac{h^2}{6\tau}$$ where h is the thickness of the test sheet

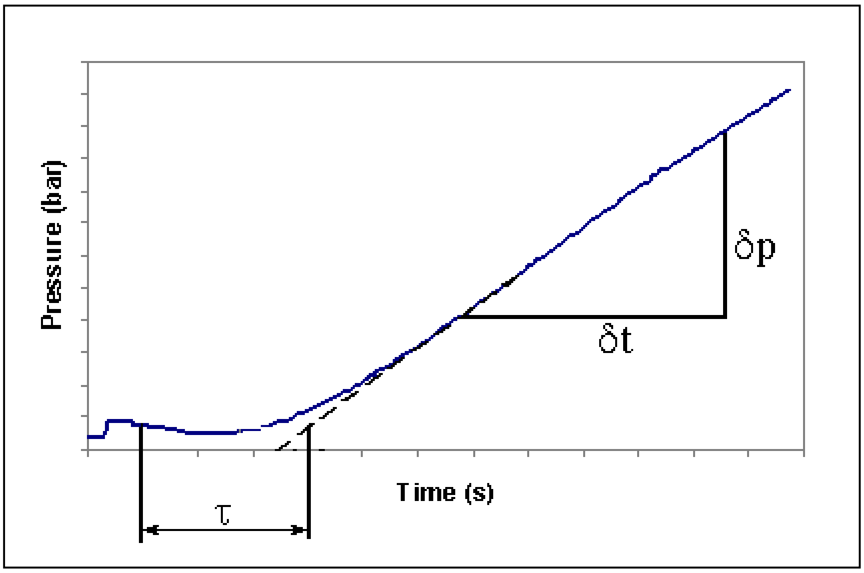


Figure 33: Pressure increase with time on the low pressure side of a gas permeation test

The schematic diagram of a typical permeation testing facility, which uses an elastomer sheet of 2 mm thickness, carefully sealed in position is shown in Figure 34.

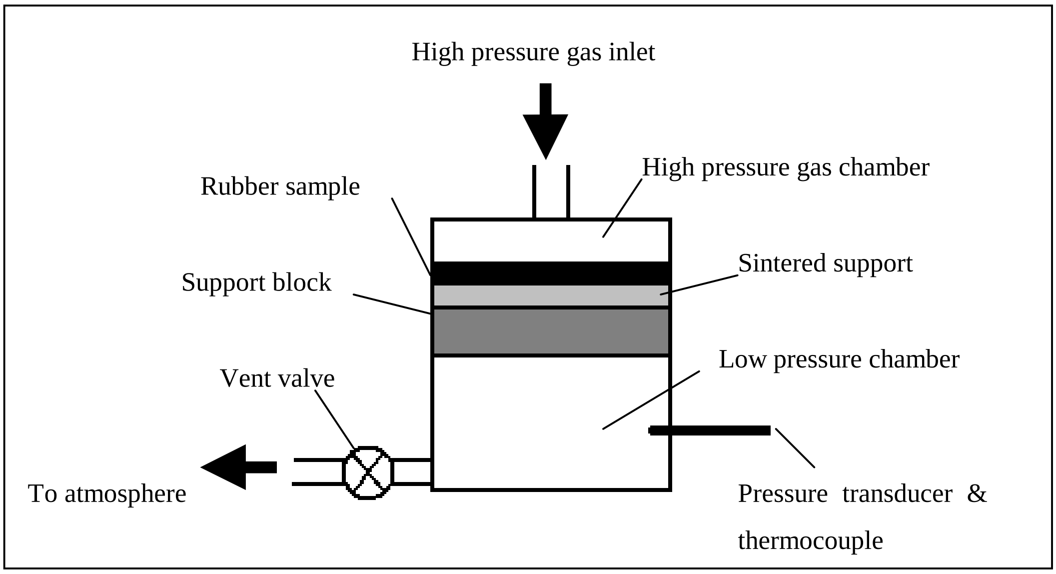


Figure 34 Diagram of a permeation rig

Gas permeation test specifications [Edmond 2001] need to include:

- A new sample for each test condition. Using a sample for testing several pressures during one test cannot be justified.
- Test duration long enough for a steady state pressure rise to be achieved (Figure 35). With typical engineering elastomers used for high pressure gas test, periods of 12 hours plus are required.
- Detail data analysis. As the Permeation Coefficient, Diffusion Coefficient and Solubility are dependent variables calculated from the data; any errors at the original data stage are greatly increased during the calculation of the coefficients.

When performed correctly, the results obtained provide good agreement with practical observations of testing and degassing of seals in operational equipment.

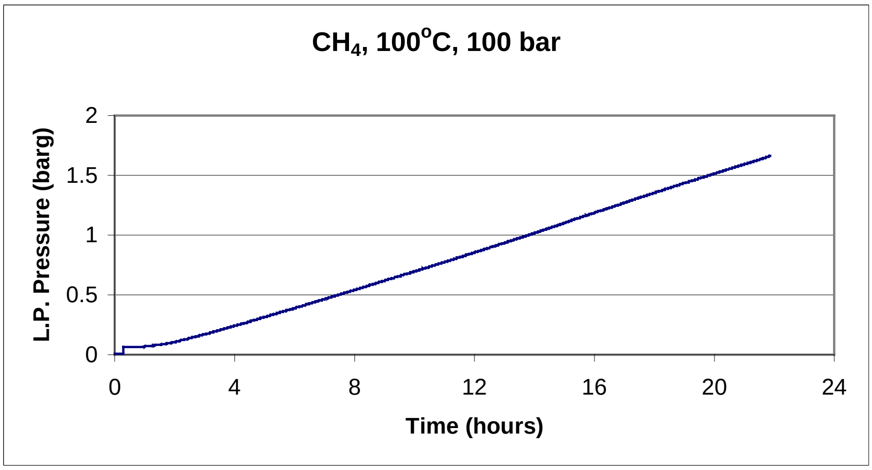


Figure 35: Example of pressure increase on the low pressure side at a steady state

8.2 SPECIFYING FATIGUE TESTS

The aim of fatigue tests is to characterise the multiple decompression performance of elastomers knowing that a seal can have no apparent damage after a single decompression, but become damaged after several more cycles. Figure 36 shows the type of results to be obtained from the tests, and Section 5.3 has provided information on how the fatigue tests should be performed.

In general, specify the fatigue tests to:

(i) be carried out at the operational temperature of the seal

(ii) have a standard tensile tests performed at the operational temperature to determine the elongation at break.

(iii) start with strain level at the elongation at break

(iv) reduce the strain levels in steps of 5% which appear to be most effective. Too large steps in some materials will result in only 2 data points, failure on the first cycle and no failure, with no intermediate numbers of cycles to failure. However, due to the variability in materials, the effectiveness of very small strain steps is limited, as the spread of results within each test strain can be very wide.

(v) Determine the maximum and minimum number of cycles to failure as well as the medium number of cycles to failure.

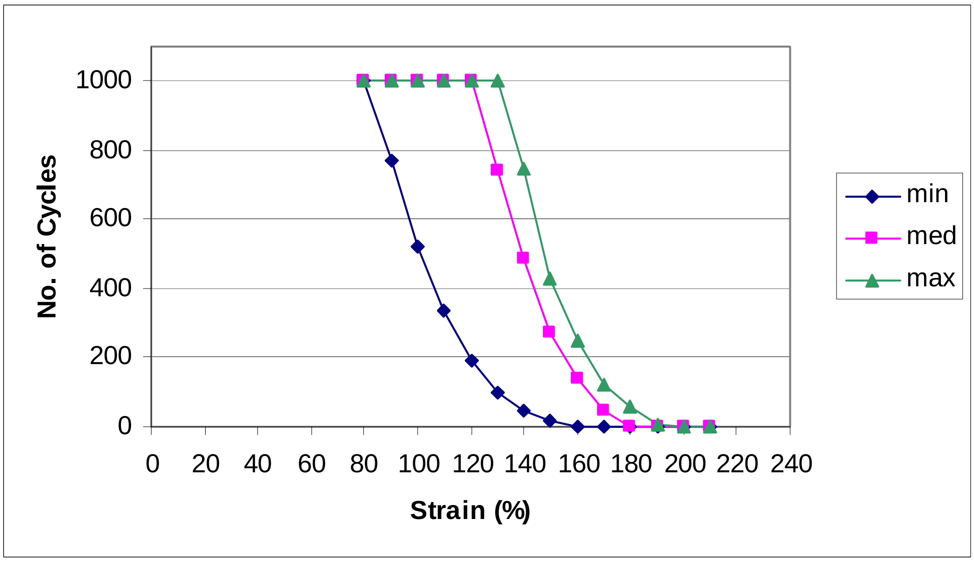


Figure 36 Cycles to failure variation with strain in a fatigue test

9. RELEVANT STANDARDS

9.1 O-RING AND HOUSING DIMENSIONS

BS 1806 : 1989,	Specification for dimensions of toroidal sealing rings (O-rings) and their housings (inch series)
BS 4518 : 1982,	Specification for metric dimensions of toroidal sealing rings (O-rings) and their housings
ISO 3601-1:2002	Fluid power systems – O-rings – Part 1: Inside diameters, cross-sections, tolerances and size identification code

9.2 NOMENCLATURE

ISO 1629 : 1995	Rubber and latices - Nomenclature
ASTM D1418-06	Standard Practice for Rubber and Rubber Latices - Nomenclature

9.3 SEAL DECOMPRESSION

NACE TM0192-2003	Evaluating Elastomeric Materials in Carbon Dioxide Decompression Environments
NACE TM0297-2002	Effects of High-Temperature, High-Pressure Carbon Dioxide Decompression on Elastomeric Materials
TOTAL GS PVV 142	Appendix 8 “Elastomer “O”-Ring Seals Explosion Decompression Type Testing Procedure
NORSOK M-CR-710 Rev. 2 2001	Qualification of Non-metallic Sealing Materials and Manufacturers

9.4 TENSILE AND COMPRESSION PROPERTIES

BS 903 : Part A2 : 1995, ISO 37 : 1994	Physical testing of rubber – Method for determination of tensile stress-strain properties
ASTM D412 – 98a (2000) e1	Standard test methods for vulcanized rubber and thermoplastic elastomers - tension
ASTM D1414-94 (2003)	Standard test methods for rubber O-rings
BS ISO 7743 : 2004	Rubber, vulcanized or thermoplastic - Determination of compression stress-strain properties

9.5 FATIGUE

BS903 Part A51 : 1986, ISO 6943 : 1984	Methods of testing vulcanized rubber - Determination of resistance to tension fatigue.

9.6 HARDNESS

BS 903 : Part A26 : 1995	Physical testing of rubber – Method for determination of hardness (hardness between 10 IRHD and 100 IRHD)
ISO 48 : 1994	Rubber, Vulcanized or Thermoplastic – Determination of hardness (hardness between 10 IRHD to 100 IRHD)
ASTM D1415 – 88 (2004)	Standard test method for rubber property – International hardness
ASTM D2240 – 04e1	Standard test method for rubber property – Durometer hardness

9.7 LOW TEMPERATURE FLEXIBILITY

BS 903 – A29 : 1997, ISO 2921 : 1997	Physical testing of rubber. Determination of low-temperature characteristics. Temperature-retraction procedure (TR test)
ASTM D1329 – 02	Standard test method for evaluating rubber property – Retraction at Low Temperatures
BS 903 Part A13: 1990 or ISO 1432 : 1998	Physical testing of rubber – Method of determination of stiffness at low temperature (Gehman test)
ASTM D1053 – 92a (2001) e1	Standard test methods for rubber property – stiffening at low temperatures flexible polymers and coated fabrics
BS 903 Part A25 : 1992, ISO 812 : 1991	Physical testing of rubber. Determination of low-temperature brittleness
ASTM D746-04	Standard test method for brittleness temperature of plastics and elastomers by impact
ASTM D2137 – 94 (2000)	Standard test methods for rubber property – brittleness point of flexible polymers and coated fabrics

9.8 GAS PERMEATION

BS 903 : Part A30 : 1996 or ISO 2782 : 1995	Physical testing of rubber – Determination of permeability of gases

9.9 LIQUID UPTAKE

BS 903 : Part A16 : 1997 or ISO 1817 : 1999	Rubber, vulanized – Determination of the effect of liquids
ASTM D471 – 98e2	Standard test method for rubber property – Effect of liquids

9.10 HYDROGEN SULPHIDE

NACE TM0187-2003	Evaluating elastomeric materials in sour gas environments
ASTM D297 – 93(2002)e2	Standard Test Methods for Rubber Products - Chemical Analysis

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James Walker Sealing Guide for the Oil & Gas Industry

11. GLOSSARY

Terms	***Description***
Absorbed gas	Gases dissolved into the elastomer surfaces and then penetrated into the elastomer molecular matrix.
Ageing	Elastomers react with oxygen, hydrocarbon and/or other media, causing permanent change in material properties. The process is normally most severe at high temperatures.
Anti-extrusion device	A separate (see backup ring) or integral device used with an elastomer seal to prevent extrusion of the seal.
Backup ring	A ring of relatively hard and tough material placed in the gland between the elastomeric seal and groove side walls, to prevent extrusion of the seal.
Curing	A thermo-setting reaction involving the use of heat and pressure, resulting in greatly increased strength and elasticity of rubber-like materials
Diffusivity	The rate at which a liquid or gas moving through an elastomer molecular matrix due to concentration differential
DMTS	Dynamic Mechanical Thermal Spectrometer
Dry gas	Natural gas composed mainly of methane with only minor amounts of ethane, propane and butane and little or no heavier hydrocarbon in the gasoline range.
EPDM	Ethylene propylene diene rubber, an elastomer base polymer
Fatigue	Crack growth caused by repetitive/cyclic deformation (loading).
Fatigue rings	Ring marking on fracture surface due to crack growth as a result of energy release fatigue
FEPM (TFEP)	Tetrafluoroethylene-propylene copolymer, an elastomer base polymer
FFKM	Perfluoroelastomer, an elastomer base polymer
Filler	Constituents of a typical elastomer compound to increase the mechanical properties of the elastomer. The most widely used filler is carbon black
FKM	Fluorocarbon, an elastomer base polymer

Terms	***Description***
Gehman test	A test procedure to measure torsion modulus, specified by BS903 Part A13
Glass transition temperature	The temperature at which the transition from the elastomeric to the glassy state occurs
Groove fill	% of the volume of seal in the groove housing the elastomer seal
High ACN NBR	A high acrylonitrile content NBR (a copolymer of butadiene and acrylonitrile), an elastomer base polymer
HNBR	Hydrogenated nitrile, an elastomer base polymer
Housing	A groove in the metal work into which an elastomer seal is inserted.
Installation damage	The damage of seal on assembly attributes to poor assembly technique, poor working environment or bad housing design.
IRHD	International rubber hardness degree, ISO 48 : 1994
Loss angle	The phase angle by which an imposed cyclic stress leads the resulting cyclic strain.
Loss modulus	The part of the modulus measured out of phase from the imposed cyclic stress, when stress to strain ratio for a material is treated as a complex quantity.
NACE	The National Association of Corrosion Engineers
NORSOK	Norwegian Centre for Ecological Agriculture
PEEK	Polyether Ether Ketone, a thermoplastic material
Permeation	The process for which liquids or gases under pressure pass through an elastomer matrix by diffuion and solution
Plasticiser	Chemical additives, such as mineral oils and waxes, to decrease stiffness, improve low temperature properties, aid mixing and moulding of elastomer components.
Predictive modelling	The use of computer modelling to predict material, component or system performance
PTFE	Polytetrafluorethylene, a thermoplastic material
Rigid inclusions	Foreign particles trapped in an elastomer matrix during the manufacturing process
Saturation	The maximum amount of fluid being absorbed in an elastomer matrix

Terms	***Description***
Seal stretch	The inner diameter of an elastomer seal is less than the diameter of the metal part it has to be located onto. The seal is therefore stretched on its inner diameter.
Solubility	The volume of gas at standard temperature and pressure dissolved in unit volume of elastomer at 1 atmosphere of gas pressure.
Squeeze	Also called interference, [(Seal cross-section diameter) – (seal-housing recess height)], each measured normal to the direction of fluid pressure drop across seal
Stabiliser	An additive that is used to help prevent an elastomeric matrix from breaking down due to exposure to adverse environments.
Swell	Significant increase in the volume of elastomers due to the absorption of fluids.
temperature retraction	After freezing to a state of reduced elasticity at a lower temperature, the percentage of the stretched length of an elastomeric specimen being released at the specified temperature.
Tensile (elastic) modulus	Defined as the stress value divided by the relative change of length (elongation). It is not a constant for elastomeric materials.
Thermal expansion / contraction	The increase and decrease in the volume of materials due to increase and decrease of temperature respectively. Thermal expansion / contraction of elastomers can be 10 times as high as that of metals.
Thermoplastic rubbers	Plastics that can be softened by heating and return to their original state on cooling
Viscoelastic	Having some of the characteristics of both viscous flow and perfect elasticity, e.g. strains are recoverable, but only over a period of time, and the stress-strain curve is sensitive to strain rate and the loading history.
Void	Microscopic “holes” in an elastomer matrix created during manufacturing process
Volumetric expansion	The increase in volume, which is approximately 3 times linear expansion
Vulcanising	See Curing
μm	Micro-metre (10^{-6} m)

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