



## **A Guide to the Suitability of Elastomeric Seal Materials for use in Radioactive Material Transport Packages**

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### **1. INTRODUCTION**

- 1.1 Elastomeric seals are a frequently favoured method of sealing Radioactive Material Transport (RMT) packages. The sealing technology has been proven for many years in a wide range of industrial applications. The requirements of the RMT package applications, however, are significantly different from those commonly found in other industries.
- 1.2 This guide outlines the Regulatory performance requirements placed on an RMT package sealing system by TS-R-1 [1], and then summarises the material, environment and geometry characteristics of elastomeric seals relevant to RMT applications. Tables in the guide list typical material properties for a range of elastomeric materials commonly used in RMT packages.

### **2. SEAL PERFORMANCE REQUIREMENTS FOR RMT APPLICATIONS**

#### General Considerations

- 2.1 The performance requirements for RMT packages are laid down in a number of National and International Regulations which are based on the IAEA Regulations for the safe transport of Radioactive Material (TS-R-1), [1].
- 2.2 The performance requirements for RMT packages identified in this guide relate to those hazards due to the radioactive contents. If a package contents have other, non radioactive, hazardous properties then other requirements may also apply.
- 2.3 The guide considers primarily O-ring seal geometry, but the discussion is also applicable to seals with non-circular cross-sections.

#### Temperature Requirements

- 2.4 The temperature requirements for the package sealing system are derived from: the environment and material requirements specified in TS-R-1, the effects of the contents, the effects of solar radiation, and the effects of the thermal testing required by TS-R-1 for the package type. The latter three effects only affect the high temperature performance requirements of the seal. The atmospheric and material temperature ranges for the package types identified in TS-R-1 are listed in Table 1.

#### Pressure Requirements

- 2.5 During their normal operating cycle the seals of RMT Packages will see a range of temperature/ pressure combinations. The package seals must be designed manufactured and maintained to withstand the most onerous of those temperature/pressure requirements as prescribed in TS-R-1.
- 2.6 The pressure capability requirements in TS-R-1 are intended to address the effects of altitude change during transport, and the effects of external pressure due to immersion following an accident. Other processes which will affect the pressure in a package are: thermal expansion and contraction of the contents, changes in vapour pressure of the contents, chemical and radiochemical changes in the contents.
- 2.7 The designer of a package with a twin elastomeric sealing system should also be aware of the possibility of high pressure arising in the interspace between those seals, due to thermal expansion of fluids trapped in that interspace.
- 2.8 It is usual that, for Type B(U), Type B(M) and Type C packages (not containing special form material) used in the U.K. a pre-despatch leak test of the seals is carried out before each movement. In some circumstances this leak test may be carried out at a pressure higher than the Maximum Normal Operating Pressure (M.N.O.P) of the package. The package designer should consider the effect of this pressure on the seals.
- 2.9 The minimum pressure capability requirements of the various types of packages identified in TS-R-1 are listed in Table 2. All pressures quoted in Table 2 are gauge pressures.

### Sealing Performance Requirements

- 2.10 The allowable leak rates for the various types of package are specified in TS-R-1 [1] in terms of the allowable activity release. Thus for each package design it is necessary to derive allowable liquid, gaseous and particulate leak rates from a study of the quantity and mobility of the active contents. However the Advisory Material for the IAEA Regulations for the Safe Transport of Radioactive Material, TS-G-1.1 [2], gives guidance on maximum gaseous leak test standards for Type B(U), Type B(M), and Type C packages as follows:
- a) For packages carrying liquids or gases a gaseous leak tightness standard of  $10^{-8}$  Pa m<sup>3</sup>/s at a pressure differential of  $10^5$  Pa is acceptable.
  - b) For packages carrying only solid contents a gaseous leak tightness standard of  $10^{-6}$  Pa m<sup>3</sup>/s at a pressure differential of  $10^5$  Pa is acceptable.

### Environmental Resistance Requirements

- 2.11 Paragraph 613 of TS-R-1 [1] states that :  
“ The materials of the packaging and any components or structures shall be physically and chemically compatible with each other, and with the radioactive contents. Account shall be taken of their behaviour under irradiation.”
- 2.12 In addition to the requirements in 2.11, consideration should be given to the operating environment of the seals, including where and how they are stored prior to use, which could also have an ageing effect on them.

## 3. CONSIDERATION OF THE FACTORS AFFECTING SEAL PERFORMANCE

### Basic Elastomer Compound

- 3.1 There are three basic elastomer types which are common in RMT applications, namely, Fluorocarbon (Viton), Ethylene Propylene Rubber (EPDM), and Silicone Rubber. Within these three basic types there are a number of different elastomers which are sometimes referred to by the generic common name. During the manufacturing process the basic elastomers are compounded with additives which may affect their colour, hardness, chemical stability, and thermal performance. For each elastomer there can be several hundred different commercially available compounds. Thus it is difficult to quote an all encompassing set of properties for a particular elastomer.
- 3.2 The properties quoted in this guide therefore, are typical minimum ranges for the particular elastomer. It is possible that specific compounds of an elastomer could perform outside of the ranges quoted. If, however, a designer claims properties outside of the ranges quoted herein, the relevant Competent Authority may insist on a demonstration of the performance of the compound by testing in an environment representative of that which the seal would experience in the package.
- 3.3 The designer should also be aware that the continued availability of a particular compound cannot always be assured.

### Hardness

- 3.4 Elastomer seal hardness is usually expressed in terms of the Shore A durometer scale or Degrees (IRHD) scale. For most applications a Shore A durometer hardness 70 to 80 is appropriate. However in low-pressure applications, in which the seals are not pressure activated, a lower hardness seal may be appropriate, at the cost of poor abrasion resistance.

### Tensile strength

- 3.5 The tensile strength of a seal is not usually directly related to its sealing performance. This property is, however, used as a quality check to ensure manufacturing consistency. A measure of the tensile strength of sample seals during the course of an endurance test can also be a useful indication of seal degradation.

## Compression and Compression Set

### Seal Compression

- 3.6 The performance of a seal is directly related to the amount by which the seal is compressed. This is especially important in low-pressure applications, in which the seal compression is the predominant activator of the seal.

- 3.7 Whilst it remains elastic, the load required to compress a Seal is proportional to the percentage compression, and thus high percentage compressions require robust package structures to apply the compressive force.
- 3.8 The compressed volume of a seal is squeezed into the seal groove. However thermal expansion and swelling of the seal can cause it to further expand in its groove and, if there is insufficient free space in the groove, failure can occur.
- 3.9 The amount of initial compression is therefore a compromise between achieving the required sealing performance, and avoiding excessive "gland fill" (the percentage of the groove which the seal occupies).
- 3.10 As a general guide the maximum recommended initial seal compression, expressed as cross section height reduction/original cross section height, is 16% for dynamic applications and 30% for static applications. Gland fill should be between 60% and 85% and never greater than 90% [3].

#### Compression Set

- 3.11 When the load is removed from a previously compressed seal, it doesn't always recover its full pre-compressed cross-section height. The amount by which it remains compressed is called the compression set.
- 3.12 The compression set is defined as the percent of deflection by which the elastomer fails to recover, after a fixed time under a specific initial compression and temperature. If the compression set is 0 % the seal fully recovers its original cross-sectional diameter. If the compression set is 100 % the seal does not recover any of its compression when unloaded.
- 3.13 One may also find, in some sources, compression set defined as a percentage of seal original cross-section.
- 3.14 Increased compression set leads to a reduction in the compression load on the seal, and also a to reduction in the low pressure sealing performance.
- 3.15 Compression set can be enhanced by a number of factors, including irradiation and lengthy exposure to high temperatures.

#### Permeation

- 3.16 The total leakage of a sealing system that incorporates elastomer seals is derived from two components, by-pass leakage which goes around the seal, and permeation which goes through the seal.
- 3.18 The permeation leakage of a sealing system depends on
  - The seal material
  - The temperature
  - The gas or combination of gases permeating.
  - The seal compression
  - The driving pressure
  - The seal geometry
- 3.17 As well as being a potential source of activity release, permeation can be a cause of overestimating the seal leakage rate during compliance testing, particularly if a low molecular weight gas such as helium is used as the test medium.
- 3.18 Because of the range of factors affecting permeability the figures quoted in this guide should only be used as an indication of relative permeability of the basic elastomer.
- 3.19 Ideally the designer should determine permeability data for the compression, temperature and gases appropriate to the design. However, as a general guide, the permeation rate increases as the molecular weight of the gas decreases, and rates determined for hydrogen can be considered as pessimistic for all other gases.
- 3.20 Permeation through the seals need only be considered for designs of packages that are intended to contain radioactive gases.

#### Thermal Effects

##### The Effects of High Temperatures.

- 3.23 High temperatures can affect elastomers in a number of ways as follows:
  - At high temperatures the compound will soften. This is significant in high-pressure applications because the softened seal may not be able to resist extrusion in the same way it did at room temperature.
  - There will be slower, time and temperature dependant, irreversible, chemical changes in the seal.

- 3.24 These latter chemical changes can cause an increase in compression set, and changes in the tensile strength of the seal. Because the rate of chemical change is temperature dependent, seals degrade faster at higher temperatures. However the limited duration of the higher temperature exposure may be such that the extent of chemical change, and subsequent physical degradation, are acceptable for the particular application. The upper temperature limits given in this guide cover long term exposure.

#### Low Temperature Performance

- 3.25 Exposures to low temperatures can cause reversible physical and chemical changes in elastomers. In particular, as the Glass Transition Temperature is reached the molecular chains in the elastomer cross-link and it takes on a plastic rather than an elastic nature.
- 3.26 Another temperature that is often quoted in the literature is the Brittle Transition Temperature. Below this temperature the elastomer is brittle, and will shatter if given a hard impact.
- 3.27 A third temperature that is quoted in seal performance statistics is the TR-10. Temperature. This temperature is determined by stretching a test piece at room temperature and then cooling it to a sufficiently low temperature such that it doesn't retract when the stretching force is released. With the stretching force removed the temperature is increased at a uniform rate. The temperature at which the test piece has retracted by 10% is the TR10 temperature. The method of determining TR temperatures is given in ISO 2921:1997.
- 3.28 A fourth criterion which has been used for determining the minimum functional temperature is that temperature at which the torsional modulus of the elastomer, as measured using the Gehman test, is equal to 70 MPa. ISO 1432:1998 describes the method of applying the Gehman test.
- 3.29 The minimum functional temperatures quoted in this guide have, where possible, been obtained from the reports of tests of simulated RMT package sealing systems.
- 3.30 In certain circumstances some sealing performance may be demonstrated at temperatures below the minimum quoted in this guide. However, any such claims can only be fully justified by test results obtained using representative seal groove geometry with the production seal material in contact with the appropriate medium to be sealed.
- 3.31 It has been shown that many seal materials that have been exposed to temperatures below the Glass Transition Temperature recover their sealing performance when the temperature is subsequently raised. In these circumstances it may be possible to show that, due to other mitigating effects, the integrity of the overall containment system is maintained at the low temperature. These potential mitigating effects include:
- Reduction of the internal pressure in the package at the low temperature, and hence the force driving a leak is reduced.
  - The condition of the contents of the package is such (e.g. indispersible solids or frozen aqueous solutions) that at the low temperature the inelastic elastomer seal and other components of the sealing system will still prevent leakage of the contents.

#### Thermal Expansion and Contraction

- 3.32 The coefficient of thermal expansion of an elastomer seal is invariably significantly greater than that of its metallic housing. Thus as a seal is cooled below ambient temperature, it shrinks volumetrically relative to its housing, and some of the original compression is lost. This can have an adverse effect on the sealing performance. A designer should, therefore, ensure that the designed seal compression is sufficient to accommodate the shrinkage of the seal on cooling.
- 3.33 Thermal expansion of the seal will increase the seal compression, and in low pressure applications, this will improve the sealing performance. In high-pressure applications, in which extrusion of the seal is an important factor in the sealing performance, there is a potential for a thermally expanded seal, which has lost some of its tensile strength, to be less effective than a cooler seal. The package designer should be aware of the need to demonstrate seal performance at the most adverse combination of temperature and pressure predicted for the package.
- 3.34 Thermal expansion of the seal can also result in overfilling of the seal housing. This can cause excessive stresses in the seal and lead to premature failure. The designer should, therefore, ensure that the seal housing has been designed with sufficient void space to allow for any differential thermal expansion.

#### The Joule Effect

- 3.35 An unloaded rubber strip when heated will expand in line with the coefficient of thermal expansion for that rubber. However conversely, and perversely, if that same rubber strip is loaded and stretched prior to heating, it will contract and pull the load.

- 3.36 This phenomenon is known as the **Joule Effect**. It is important in radial applications in which a seal is required to be in contact with a moving shaft. If the seal is smaller than the shaft and stretched over it, the frictional heating of the seal will cause it to contract and failure will occur. In such applications it is necessary, therefore, to design the seal to be 1% to 3% larger than the shaft and to restrict the outside diameter of the seal housing to ensure that the seal is compressed onto the shaft. Similarly in high temperature static face seal applications, the seal should be designed so that it is not stretched when it is installed in the housing.

#### Irradiation

- 3.37 Irradiation of elastomer seals can result in increased compression set, and hence a reduction in sealing performance. The resistance of a seal to irradiation depends on the seal material and the environment it is in. The figures of radiation induced compression set given in Table 3 of this guide are for seals in favourable environments at room temperature when subjected to a dose of  $10^5$  Gy. Whilst the figures cannot be applied to a particular RMT application, they can be used to rank the relative irradiation resistance of the seal materials.
- 3.38 In RMT package designs that will carry high dose contents it is preferable to locate any elastomeric containment seals outside of the radiation shield. If the package contents are mobile (gas, liquid, or finely divided solids) it will also be necessary to provide containment inside the shielding, to prevent the contents migrating to areas of reduced shielding thickness.

#### Pressure

- 3.39 Elastomer seals achieve their sealing performance in one of two ways. The primary sealing mechanism, which is more prevalent at low pressures, is by compressing the seal against the seal groove surfaces so that it fills any inconsistencies in these surfaces, and presents a “land” of contact which is difficult for the fluid to penetrate. This method of sealing is illustrated in Figure 1.
- 3.40 The secondary sealing mechanism is more prevalent at high pressures, and it is sometimes referred to as pressure energised sealing. In this mechanism the pressure forces the seal to the outside face of the seal groove and the seal tends to extrude into any gap between the sealing faces, as shown in Figure 2.
- 3.41 The transition between the primary and secondary sealing mechanism is dependant on a number of factors, including the seal groove geometry, seal hardness, and coefficient of friction between the seal and its housing. It is difficult to predict which mechanism is prevalent for any particular RMT package design, and both mechanisms may be present at some time during the packages operating cycle. In these circumstances a compromise is needed between a soft seal compound which is more resistant to low pressures and a harder seal compound which will resist the tendency to be extruded by high pressures. It is important, therefore, that a designer has tested the effectiveness of his package sealing system at all pressures it will experience during its operating life.

#### Housing Design

- 3.42 The design and manufacture of the seal housing is as important in achieving an adequate sealing performance as the selection and sizing of the seal. The designer of an RMT package should consider the following factors relating to the seal housing:
- Are the dimensions appropriate to allow for thermal expansion of the seal, whilst still retaining sufficient seal compression at the lowest operating temperatures.
  - Have the dimensions recommended in national or international standards been used for standard sized seals.
  - Do the manufacturing drawings or instructions call for removal of all sharp edges around the seal housing.
  - Is the housing rigid enough to withstand the loads imposed on it without excessive elastic or plastic distortion.
  - Is the housing material appropriate to resist the effects of any corrosive materials in the package or it's operating environment.

#### Chemical Environment

- 3.43 Elastomeric materials may be susceptible to chemical attack by chemical compounds that they come in contact with. These compounds can come from within the RMT package itself, or from the operating environment.
- 3.44 Different elastomer materials are vulnerable to damage by different chemical compounds. The compounds that are most damaging to the seal materials reviewed in this guide are identified in the properties table.

- 3.45 In addition to chemical degradation and the thermal and radiation effects described elsewhere in this guide, all elastomers are degraded to a greater or lesser extent by exposure to sunlight, or artificially produced ultra-violet light. This degradation is most significant in the storage of seals as described in section 3.48.

#### Damage

- 3.46 The integrity of RMT package seals is frequently demonstrated with as-new seals and seal housings. There is, however a potential for seal housings to be both elastically and plastically deformed during the Regulatory impact and thermal tests. Such deformation can significantly reduce the effectiveness of the seal.
- 3.47 The designer should determine how such damage affects the seal performance.

### Storage, Inspection, and Maintenance

#### Storage Conditions

- 3.48 As stated in section 3.45 elastomers are susceptible to degradation by chemical compounds in the environment, and by exposure to light. It is important therefore, that the operators and maintainers of RMT packages store spare seals in appropriate conditions. The following conditions are suggested for achieving maximum seal shelf life [3].
- Maximum ambient temperature 49 °C.
  - Exclude air, i.e. vacuum pack if possible
  - Exclude all chemical contaminants
  - Exclude light
  - Exclude ozone generating electrical devices from the vicinity of the stored seals.
- 3.49 It is usually found that optimum storage conditions can be achieved by placing the seal in a sealed plastic bag within an outer cardboard container.
- 3.50 Even with the precautions described above an elastomeric seal will have a finite seal life. The seal manufacturers will recommend a shelf life for their products.

#### Seal Lubrication

- 3.51 There are a number of proprietary seal lubricants that can be used to ease the first installation of a seal into its housing, thus minimising the risk of damage to the seal. However, the practice of regularly lubricating the seals on a package before closure should be avoided. The reason for this is that a lubricant can mask a gaseous leak path that, if the lubricant dries out during the journey, will allow activity to be released from the package.

#### Inspection and Maintenance

- 3.52 Once a seal has been fitted to an RMT package, continuing conformance with the approved design parameters can only be achieved by a regular programme of seal inspection and maintenance. It is generally accepted that the only rectification process applicable to a damaged seal is replacement, with a seal to the original approved specification. The maintenance regime should, therefore include provision of a stock of replacement seals, which are maintained within their shelf life, at locations which allow timely seal replacement.

## 4 FINITE ELEMENT ANALYSIS OF SEALS

- 4.1 In recent years there have been significant advances, particularly in the automotive industry, in the prediction of elastomeric seal performance using finite element methods.
- 4.2 For such analyses a numerical model of the seal's performance is created from basic test data determined by physical experiments. It can be shown that there is a good correlation between the performance predicted by the numerical model and the test data from which it was derived.
- 4.3 However, the performance of a seal in an RMT package application depends on numerous factors, such as irradiation, compression set and thermal degradation. These factors are rarely represented in basic tests and are thus not represented in the numerical model based on those tests.
- 4.4 As outlined elsewhere in this paper the properties of elastomeric materials are strongly temperature dependent, and seals in RMT applications have to be able to perform effectively over a wide temperature range. A numerical seal model will typically only be valid for a narrow temperature range.
- 4.5 From the foregoing it can be seen that, whilst numerical analysis of seals is possible, there are many uncertainties to be accounted. It is, therefore, recommended that such analyses are validated by physical

tests using representative seal and groove geometry, and the temperature and pressure profiles predicted for the package design.

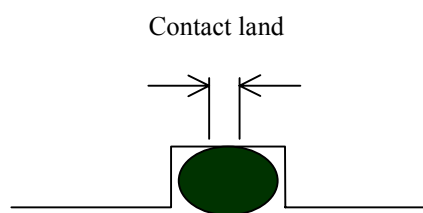
- 4.6 Designers of RMT packages should not, however, be discouraged from exploring the use of such numerical analyses. It is not inconceivable that, given sufficient time and resources, the methods can be developed to become a true representation of elastomeric seal performance in RMT applications.

## 5 MATERIAL PROPERTY TABLE

- 5.1 The data contained in Table 3 have been obtained from a number of sources, which are referenced in section 6.
- 5.2 The data relates to typical compounds of the basic elastomer material. Experience has proved that whilst extended property ranges can be achieved with “special” compounds of the material, it is difficult to maintain a secure supply of such compounds, and RMT package operators may frequently be obliged to reassess their packages for sealing performance using more readily available compounds.
- 5.3 Where possible the data has been taken from sources relevant to RMT package operations. The temperature operating ranges quoted are those which could be claimed for RMT packages without further, application-specific, testing, and are applicable to long term exposure conditions. Further information on the thermal performance of a range of RMT package seal materials can be found in [4] and [5].
- 5.4 The properties quoted in the table have often been obtained in laboratory test conditions and it is difficult to relate many of the properties to particular RMT applications. However the data contained in the table can be used to rank the suitability of the elastomers concerned.

## 6 REFERENCES

- [1] International Atomic Energy Agency Regulations for the Safe Transport of Radioactive Material, 1996 Edition (Revised), TS-R-1.
- [2] International Atomic Energy Agency Advisory Material for the IAEA Regulations for the Safe Transport of Radioactive Material (1996 Edition), TS-G-1.1. Draft February 2002.
- [3] Parker O-Ring Handbook, 2001 Edition, Parker Hannifin Corporation.
- [4] Effect of ageing on the low temperature performance of elastomeric seals, S.G. Burnay, J. Cook, and N. Evans. AEA Technology Plc, March 1998
- [5] Performance Testing of Elastomeric Seal Materials Under Low and High Temperature Conditions: Final Report, D.R. Bronowski, Sandia National Laboratories. June 2000.



**Figure 1 – Low Pressure Sealing Mechanism**



**Figure 2 – Pressure Energised Sealing**

Table 1- RMT Package Temperature Requirements

Package Type (Including Fissile Derivatives)	Ambient Temperature Range	Component Temperature Range
Excepted Package IP1	By air –40°C to +55°C Other modes – not specified	Not Specified
IP2	By air –40°C to +55°C Other modes – not specified except packages containing fissile material – 40°C to +38°C	Not Specified
IP3	By air – 40°C to +55°C Other modes - not specified except packages containing fissile material – 40°C to +38°C	- 40°C to + 70°C
Type A	By air – 40°C to + 55°C Other modes – not specified except packages containing fissile material – 40°C to +38°C	- 40°C to + 70°C
Type B (U)	By air – 40°C to + 55°C. Other modes – 40°C to +38°C	- 40°C to + 70°C
Type B (M)	By air – 40°C to + 55°C Other modes as approved by the competent authorities	As approved by the competent Authorities
Type C	- 40°C to +55°C	- 40°C to + 70°C
INF Cargo by sea	As package type requirements except that the INF Code recognises a maximum ambient hold temperature of 55 °C	

Table 2 – RMT Package Pressure Requirements

Package Type	Internal Pressure Capacity Requirement	External Pressure Capacity Requirement
Excepted Package IP1, IP2	Air – M.N.O.P. + 95 kPa. Other modes – not specified	Not specified
Types IP3 and A	Air – M.N.O.P. + 95 kPa Other modes – M.N.O.P. + 40 kPa	Not specified
Packages containing >0.1 kg Uranium Hexafluoride <sup>1</sup>	1.38 MPa (Multilateral Approval) 2.76 MPa (Unilateral Approval) <sup>1</sup>	<sup>1</sup>
Types B(U) and B(M) carrying not more than 10 <sup>5</sup> A <sub>2</sub>	Air – M.N.O.P. + 95 kPa Other modes – M.N.O.P. + 40kPa Allowable maximum M.N.O.P. = 700 kPa <sup>2</sup>	150 kPa
Types B(U) and B (M) Carrying more than 10 <sup>5</sup> A <sub>2</sub> and all Type C	Air – M.N.O.P. + 95 kPa Other modes – M.N.O.P. + 40 kPa. Allowable maximum M.N.O.P. = 700 kPa <sup>2</sup>	2 MPa.

1. Packages carrying > 0.1 kg of Uranium Hexafluoride also have to meet the IP, Type A, B, or C specific requirements as appropriate.
2. For type B(M) packages the 700 kPa maximum M.N.O.P. limit may be exceeded if approved by the Competent Authorities of the countries through which the package is transported



Table 3 – Elastomer Properties

Property	Rubber Compound				
	Fluorocarbon	Silicone	Ethylene propylene (-diene)	Fluorosilicone	Nitrile
Compression set at 10 <sup>5</sup> Gy exposure % [3]	66.7	20	28.6	67.6	24.3
Hydrogen permeability cm <sup>3</sup> cm/cm <sup>2</sup> sec.bar [3]	160 x 10 <sup>-8</sup> at 93 °C	1570-2070 x 10 <sup>-8</sup> at 93 °C	187-544 x 10 <sup>-8</sup> at 93 °C	N/A	98.8-330 x 10 <sup>-8</sup> at 121 °C
Coefficient of thermal expansion above low temp limit m/m/°C [3]	1.62 x 10 <sup>-4</sup>	1.8 x 10 <sup>-4</sup>	1.6 x 10 <sup>-4</sup>	8.1 x 10 <sup>-4</sup>	1.1 x 10 <sup>-4</sup>
Long-term high temperature limit °C [3]	204	204	177	204	100 (49 in water)
Long-term low temperature limit °C [3]	-20	-54 (-37 [5])	-40	-73	-34
Chemical incompatibility	Glycol base brake fluids, ammonia gas, amines, alkalis, superheated steam, low molecular weight organic acids (formic and acetic acids)	Superheated steam over 121 °C, Acids and alkalis, low molecular weight chlorinated hydrocarbons, aromatic mineral oils Hydrocarbon based fuel Aromatic hydrocarbons	Mineral oil products	As silicone rubber but the long-term high temperature limit reduces to 175 °C in air.	Fuels of high aromatic content, aromatic hydrocarbons, chlorinated hydrocarbons, polar solvents (ketone, acetone, acetic acid, ethylene-ester), strong acids, glycol based brake fluids, ozone.