Elastomer Characteristics

Information on the characteristics of the three elastomer seal materials evaluated for use in the 10-160B are taken from the Parker O-ring Handbook[1]; pages 2-5, 2-6, 2-9, and 2-28 through 2-31 are attached. As shown in the Handbook, these materials, ethylene propylene rubber, butyl rubber, and silicone rubber, have a heat resistance of 250°F or higher. Further, as discussed on pages 2-28 through 2-31, the temperature limits are conservative estimates of the maximum temperatures for 1,000 hours of continuous service. This indicates that these materials are suitable for cask seals under Normal Conditions of Transport (NCT).

Parker Figure 2-24 (page 2-30) shows that the seal life for silicone and ethylene propylene exceeds one hour at 400°F but does not provide information on butyl rubber. Additional information on butyl rubber seals is provided from the test report on the TRUPACT-II Package[2]; pages 5 through 9 & 23 are attached. Table 3-1 (page 23) shows that the butyl rubber seals maintain integrity for up to eight hours at 400°F. The Parker information combined with the TRUPACT-II information indicates that the selected elastomer materials are suitable for cask seals under Hypothetical Accident Conditions (HAC).

[1] Parker O-Ring Handbook, Parker Hannifin Corporation, Cleveland, OH, 2001

[2] Design Development and Certification Testing of the TRUPACT-II Package, Portemus Engineering, Puyallup, WA, October, 2002

Parker O-Ring Handbook 2001 Edition

Parker Accessories for O-ring Users

Sections

Parker Seals

WARNING

Failure, improper selection or improper use of the products and/or systems described herein or related items can cause death, personal injury or property damage.

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Heat resistance

- Up to 100°C (212°F) with shorter life @ 121°C (250°F).

Cold flexibility

- Depending on individual compound, between -34°C and -57°C (-30°F and -70°F).

Chemical resistance

- Aliphatic hydrocarbons (propane, butane, petroleum oil, mineral oil and grease, diesel fuel, fuel oils) vegetable and mineral oils and greases.
- HFA, HFB and HFC fluids.
- Dilute acids, alkali and salt solutions at low temperatures.
- Water (special compounds up to 100°C) (212°F).

Not compatible with:

- Fuels of high aromatic content (for flex fuels a special compound must be used).
- Aromatic hydrocarbons (benzene).
- Chlorinated hydrocarbons (trichlorethylene).
- Polar solvents (ketone, acetone, acetic acid, ethylene-ester).
- Strong acids.
- Brake fluid with glycol base.
- Ozone, weather and atmospheric aging.

2.2.2 Carboxylated Nitrile (XNBR)

Carboxylated Nitrile (XNBR) is a special type of nitrile polymer that exhibits enhanced tear and abrasion resistance. For this reason, XNBR based materials are often specified for dynamic applications such as rod seals and rod wipers.

Heat resistance

- Up to 100°C (212°F) with shorter life @ 121°C (250°F).

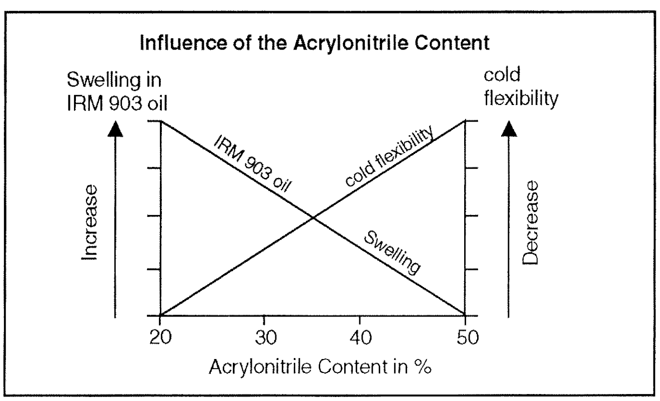

Figure 2-2: Influence of the Acrylonitrile Content

Cold flexibility

- Depending on individual compound, between -18°C and -48°C (0°F and -55°F).

Chemical resistance

- Aliphatic hydrocarbons (propane, butane, petroleum oil, mineral oil and grease, Diesel fuel, fuel oils) vegetable and mineral oils and greases.
- HFA, HFB and HFC fluids.
- Many diluted acids, alkali and salt solutions at low temperatures.
- Water (special compounds up to 100°C) (212°F).

Not compatible with:

- Fuels of high aromatic content (for flex fuels a special compound must be used).
- Aromatic hydrocarbons (benzene).
- Chlorinated hydrocarbons (trichlorethylene).
- Polar solvents (ketone, acetone, acetic acid, ethylene-ester).
- Strong acids.
- Brake fluid with glycol base.

2.2.3 Ethylene Acrylate (AEM)

Ethylene acrylate is a mixed polymer of ethylene and methyl acrylate with the addition of a small amount of carboxylated curing monomer. Ethylene acrylate rubber is not to be confused with ethyl acrylate rubber (ACM).

Heat resistance

- Up to 149°C (300°F) with shorter life up to 163°C (325°F).

Cold flexibility

- Between -29°C and -40°C (-20°F and -40°F).

Chemical resistance

- Ozone.
- Oxidizing media.
- Moderate resistance to mineral oils.

Not compatible with:

- Ketones.
- Fuels.
- Brake fluids.

2.2.4 Ethylene Propylene Rubber (EPM, EPDM)

EPM is a copolymer of ethylene and propylene. Ethylene-propylene-diene rubber (EPDM) is produced using a third monomer and is particularly useful when sealing phosphate-ester hydraulic fluids and in brake systems that use fluids having a glycol base.

Heat resistance

- Up to 150°C (302°F) (max. 204°C (400°F)) in water and/ or steam).

Cold flexibility

- Down to approximately -57°C (-70°F).

Chemical resistance

- Hot water and steam up to 149°C (300°F) with special compounds up to 204°C (400°F).
- Glycol based brake fluids up to 149°C (300°F).
- Many organic and inorganic acids.
- Cleaning agents, soda and potassium alkalis.
- Phosphate-ester based hydraulic fluids (HFD-R).
- Silicone oil and grease.
- Many polar solvents (alcohols, ketones, esters).
- Ozone, aging and weather resistant.

Not compatible with:

- Mineral oil products (oils, greases and fuels).

2.2.5 Butyl Rubber (IIR)

Butyl (isobutylene, isoprene rubber, IIR) is produced by many companies in different types and varies widely in isoprene content. Isoprene is necessary for proper vulcanization. Butyl has a very low permeability rate and good electrical properties.

Heat resistance

- Up to approximately 121°C (250°F).

Cold flexibility

- Down to approximately -59°C (-75°F).

Chemical resistance

- Hot water and steam up to 121°C (250°F).
- Brake fluids with glycol base.
- Many acids (see Fluid Compatibility Tables in Section VII).
- Salt solutions.
- Polar solvents, e.g. alcohols, ketones and esters.
- Poly-glycol based hydraulic fluids (HFC fluids) and phosphate-ester bases (HFD-R fluids).
- Silicone oil and grease.
- Ozone, aging and weather resistant.

Not compatible with:

- Mineral oil and grease.
- Fuels.
- Chlorinated hydrocarbons.

2.2.6 Butadiene Rubber (BR)

Polybutadiene (BR) is mostly used in combination with other rubbers to improve cold flexibility and wear resistance. BR is primarily used in the tire industry, for some drive belts and conveyor belts and is not suitable as a sealing compound.

2.2.7 Chlorobutyl Rubber (CIIR)

Chlorobutyl (CIIR) is produced by chlorinating butyl polymer. Its chlorine content is approximately 1.1% to 1.3%. Apart from the properties of butyl rubber (IIR), chlorobutyl (CIIR) shows improved compression set properties and can be compounded with other materials.

2.2.8 Chloroprene Rubber (CR)

Chloroprene was the first synthetic rubber developed commercially and exhibits generally good ozone, aging and chemical resistance. It has good mechanical properties over a wide temperature range.

Heat resistance

- Up to approximately 121°C (250°F).

Cold flexibility

- Down to approximately -40°C (-40°F).

Chemical resistance

- Paraffin base mineral oil with low DPI, e.g. ASTM oil No. 1.
- Silicone oil and grease.
- Water and water solvents at low temperatures.
- Refrigerants
- Ammonia
- Carbon dioxide
- Improved ozone, weathering and aging resistance compared with NBR.

Limited compatibility

- Naphthalene based mineral oil (IRM 902 and IRM 903 oils).
- Low molecular aliphatic hydrocarbons (propane, butane, fuel).
- Glycol based brake fluids.

Not compatible with:

- Aromatic hydrocarbons (benzene).
- Chlorinated hydrocarbons (trichloroethylene).
- Polar solvents (ketones, esters, ethers, acetones).

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Heat resistance

- Shortened lifetime up to approximately 177°C (350°F).

Cold flexibility

- Down to approximately -21°C (-5°F).

Chemical resistance

- Mineral oil (engine, gear box, ATF oil).
- Ozone, weather and aging resistance.

Not compatible with:

- Glycol based brake fluid.
- Aromatics and chlorinated hydrocarbons.
- Hot water, steam.
- Acids, alkalis, amines.

2.2.16 Polyurethane (AU, EU)

One must differentiate between polyester urethane (AU) and polyether urethane (EU). AU type urethanes exhibit better resistance to hydraulic fluids. Polyurethane elastomers, as a class, have excellent wear resistance, high tensile strength and high elasticity in comparison with any other elastomers. Permeability is good and comparable with butyl.

Heat resistance

- Up to approximately 82°C (180°F).

Cold flexibility

- Down to approximately -40°C (-40°F).

Chemical resistance

- Pure aliphatic hydrocarbons (propane, butane, fuel).
- Mineral oil and grease.
- Silicone oil and grease.
- Water up to 50°C (125°F) (EU type).
- Ozone and aging resistant.

Not compatible with:

- Ketones, esters, ethers, alcohols, glycols.
- Hot water, steam, alkalis, amines, acids.

2.2.17 Silicone Rubber (Q, MQ, VMQ, PVMQ)

The term silicone covers a large group of materials in which vinyl-methyl-silicone (VMQ) is often the central ingredient. Silicone elastomers as a group have relatively low tensile strength, poor tear and wear resistance. However, they have many useful properties as well. Silicones have good heat resistance up to 232°C (450°F), good cold flexibility down to -59°C (-75°F) and good ozone and weather resistance as well as good insulating and physiologically neutral properties.

Heat resistance

- Up to approximately 204°C (400°F) (special compounds up to 232°C (450°F).

Cold flexibility

- Down to approximately -59°C to -54°C (-75°F to -65°F) with special compounds down to -115°C (-175°F).

Chemical resistance

- Engine and transmission oil (e.g.: ASTM oil No.1).
- Animal and vegetable oil and grease.
- Brake fluid (non-petroleum base).
- Fire-resistant hydraulic fluid, HFD-R and HFD-S.
- High molecular weight chlorinated aromatic hydrocarbons (including flame-resistant insulators, and coolant for transformers).
- Moderate water resistance.
- Diluted salt solutions.
- Ozone, aging and weather resistant.

Not compatible with:

- Superheated water steam over 121°C (250°F).
- Acids and alkalis.
- Low molecular weight chlorinated hydrocarbons (trichloroethylene).
- Aromatic mineral oil.
- Hydrocarbon based fuels.
- Aromatic hydrocarbons (benzene, toluene).

2.2.18 Styrene-Butadiene (SBR)

SBR probably is better known under its old names Buna S and GRS (government rubber styrene.) SBR was first produced under government control between 1930 and 1950 as a replacement for natural rubber. The basic monomers are butadiene and styrene, with styrene content approximately 23.5%. About one third of the world output of SBR is used in tire production. SBR is mostly used in seals for non-mineral oil based brake fluid applications.

Heat resistance

- Up to approximately 107°C (225°F).

Cold flexibility

- Down to approximately -57°C (-70°F).

Compatible with

- Water, alcohol, glycol and certain ketones (acetone).
- Non-mineral oil based brake fluid.
- Silicone oil and grease.
- Diluted water solutions, weak acids.

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D. Seals used in meters or other devices that must be read through glass, a liquid, or plastic, must not discolor these materials and hinder vision.

Sound judgment, then, dictates that all fluids involved in an application be considered. Once this is done, it is a simple matter to check the Fluid Compatibility Tables in Section VII to find a compound suitable for use with all the media.

2.13.2 Temperature

Temperature ranges are often over-specified. For example, a torch or burner might reach temperatures of 400°C to 540°C (750°F to 1000°F). However, the tanks of gas being sealed may be located a good distance from this heat source and the actual ambient temperature at the seal might be as low as 121°C to 149°C (250°F to 300°F).

A specification for aircraft landing gear bearing seals might call out -54°C to 760°C (-65°F to 1400°F), yet the bearing grease to be sealed becomes so viscous at -54°C (-65°F) it cannot possibly leak out. At the high end, there is a time-temperature relationship in the landing rollout that allows rapid heat dissipation through the magnesium wheel housing on which the seals are mounted. This, combined with low thermal conductivity of the seal, limits heat input to the seal so that temperature may never exceed 71°C (160°F). As a result, a more realistic temperature range would be -34°C to 82°C (-30°F to 180°F). This can be handled by a good, industrial type nitrile compound as N0674-70.

Parker has applied a realistic temperature range with a margin of safety when setting the general operating temperature range for seal compounds. The maximum temperature recommendation for a compound is based on long term functional service. If it is subjected to this temperature continuously, it should perform reliably for 1,000 hours. Time at less than maximum temperature will extend life. Similarly, higher temperature will reduce it.

The high temperature limits assigned to compounds in Figure 2-21 are conservative estimates of the maximum temperature for 1,000 hours of continuous service in the media the compounds are most often used to seal. Since the top limit for any compound varies with the medium, the high temperature limit for many compounds is shown as a range rather than a single figure. This range may be reduced or extended in unusual fluids.

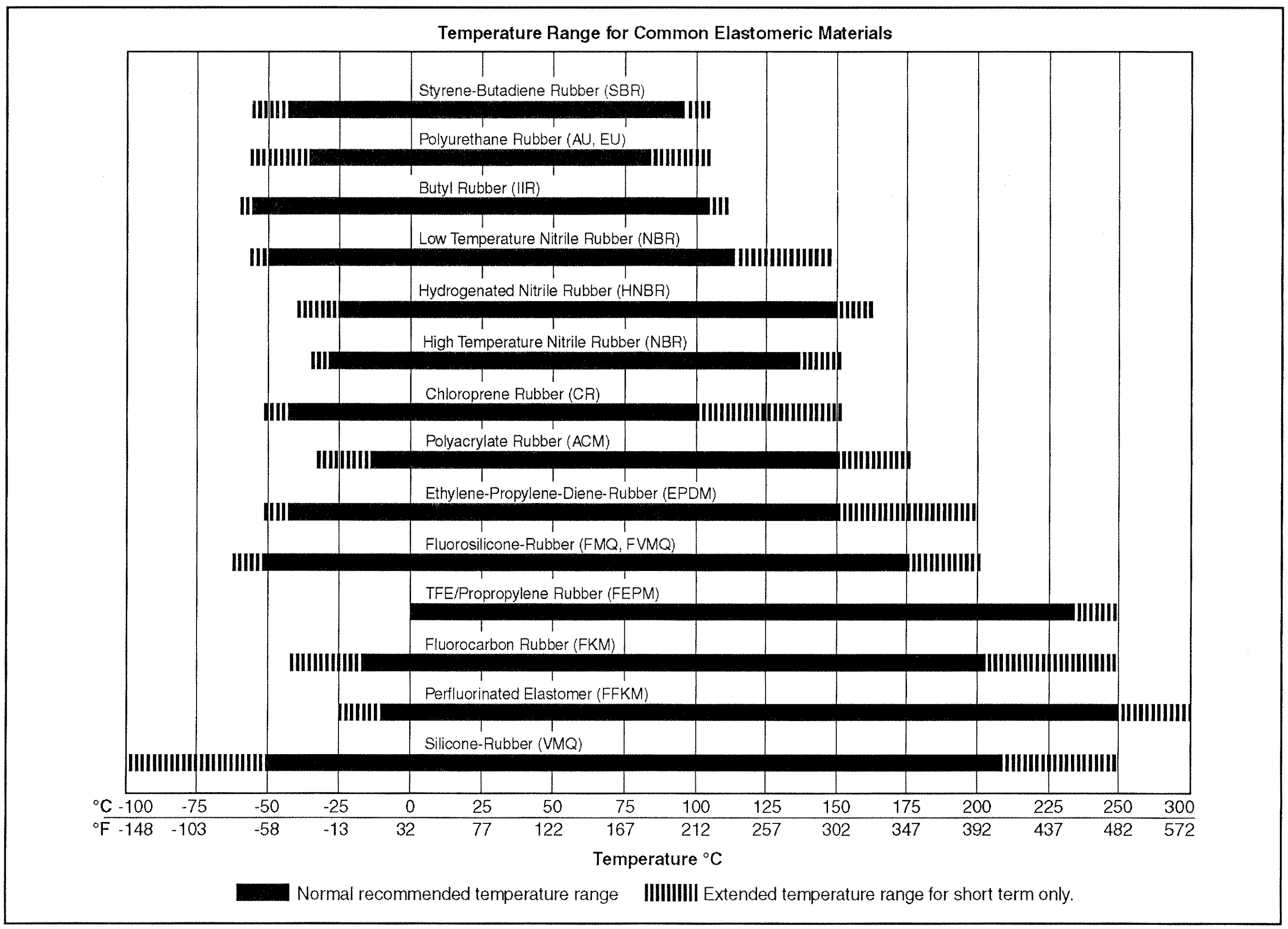

Figure 2-21: Temperature Capabilities of Principal Elastomers Employed in Seals

Since some fluids decompose at a temperature lower than the maximum temperature limit of the elastomer, the temperature limits of both the seal and the fluid must be considered in determining limits for a system.

Low temperature service ratings in the past have been based on values obtained by ASTM Test Methods D736 and D746. Currently, Method D2137 is in wide use. The present ASTM D2000 SAE 200 specification calls for the ASTM D2137 low temperature test. For O-rings and other compression seals, however, the TR-10 value per ASTM D1329 provides a better means of approximating the low temperature capability of an elastomer compression seal. The low temperature sealing limit is generally about 10°C (15°F) below the TR-10 value. This is the formula that has been used, with a few exceptions, to establish the recommended low temperature limits for Parker Seal Group compounds shown in Figure 2-21 and the Fluid Compatibility Tables in Section VII. This is the lowest temperature normally recommended for static seals. In dynamic use, or in static applications with pulsing pressure, sealing may not be accomplished below the TR-10 temperature, or approximately 10°C (15°F) higher than the low-limit recommendation in the Parker Handbook.

These recommendations are based on Parker tests. Some manufacturers use a less conservative method to arrive at low temperature recommendations, but similar compounds with the same TR-10 temperature would be expected to have the same actual low temperature limit regardless of catalog recommendations.

A few degrees may sometimes be gained by increasing the squeeze on the O-ring section, while insufficient squeeze may cause O-ring leakage before the recommended low temperature limit is reached.

The low temperature limit on an O-ring seal may be compromised if the seal is previously exposed to extra high temperature or a fluid that causes it to take a set, or to a fluid that causes the seal compound to shrink. Conversely, the limit may be lowered significantly if the fluid swells the compound. See Figure 2-22.

With decreasing temperature, elastomers shrink approximately ten times as much as surrounding metal parts. In a rod type assembly, whether static or dynamic, this effect causes the sealing element to hug the rod more firmly as the temperature goes down. Therefore, an O-ring may seal below the recommended low temperature limit when used as a rod type seal.

When excessive side loads are encountered on maximum tolerance rods or glands, and the pressure is in the low range, leakage may occur at temperatures 5°or 8°C (10°or 15°F) above the TR-10 value. It may be necessary to add as much as 22°C (40°F) to the low temperature shown in the tables for this type of service. See Figure 2-24.

2.13.3 Time

The three obvious "dimensions" in sealing are fluid, temperature, and pressure. The fourth dimension, equally important, but easily overlooked, is time.

Up to this point, temperature limits, both high and low, have been published at conventional short-term test temperatures. These have little bearing on actual long-term service of the seal in either static or dynamic applications. A comparison of the temperature limits of individual compounds in this guide with previous literature will reveal that for comparable materials the upper temperature limit is more conservatively expressed. The narrower temperature range does not imply that the compounds discussed are inferior to others. Rather, those high temperature values based on continuous seal reliability for 1,000 hours are being recommended.

As illustrated by the graph (Figure 2-24), short term or intermittent service at higher temperatures can be handled by these materials.

For example, an industrial nitrile (Buna-N) compound, N0674-70, is recommended to only 121°C (250°F), yet it is known to seal satisfactorily for five minutes at 538°C (1,000°F) and at 149°C (300°F) for 300 hours. Therefore, when the application requires a temperature higher than that recommended in the compound and fluid tables, check the temperature curve to determine if the total accumulated time at high temperature is within the maximum allowable

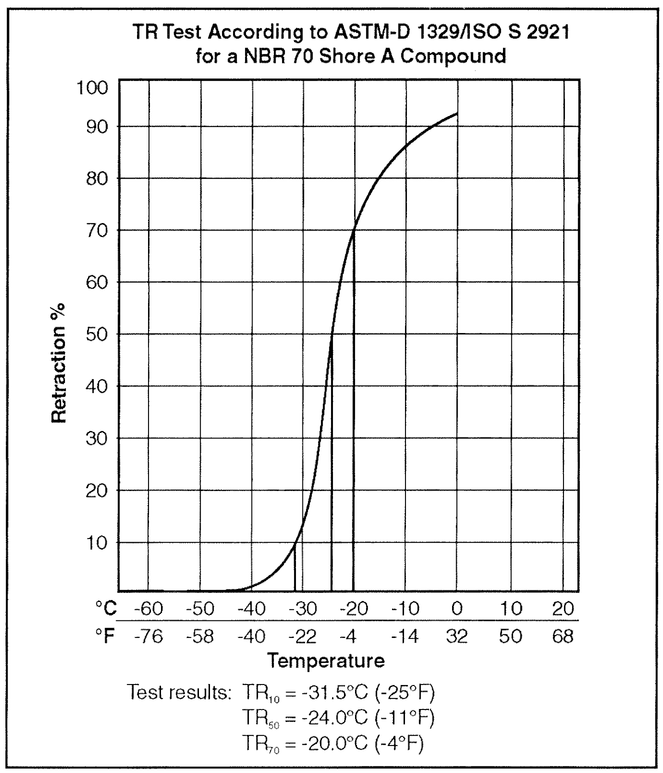

Figure 2-22: TR Test According to ASTM-D 1329/ISO S2921 for a NBR 70 Shore A Compound

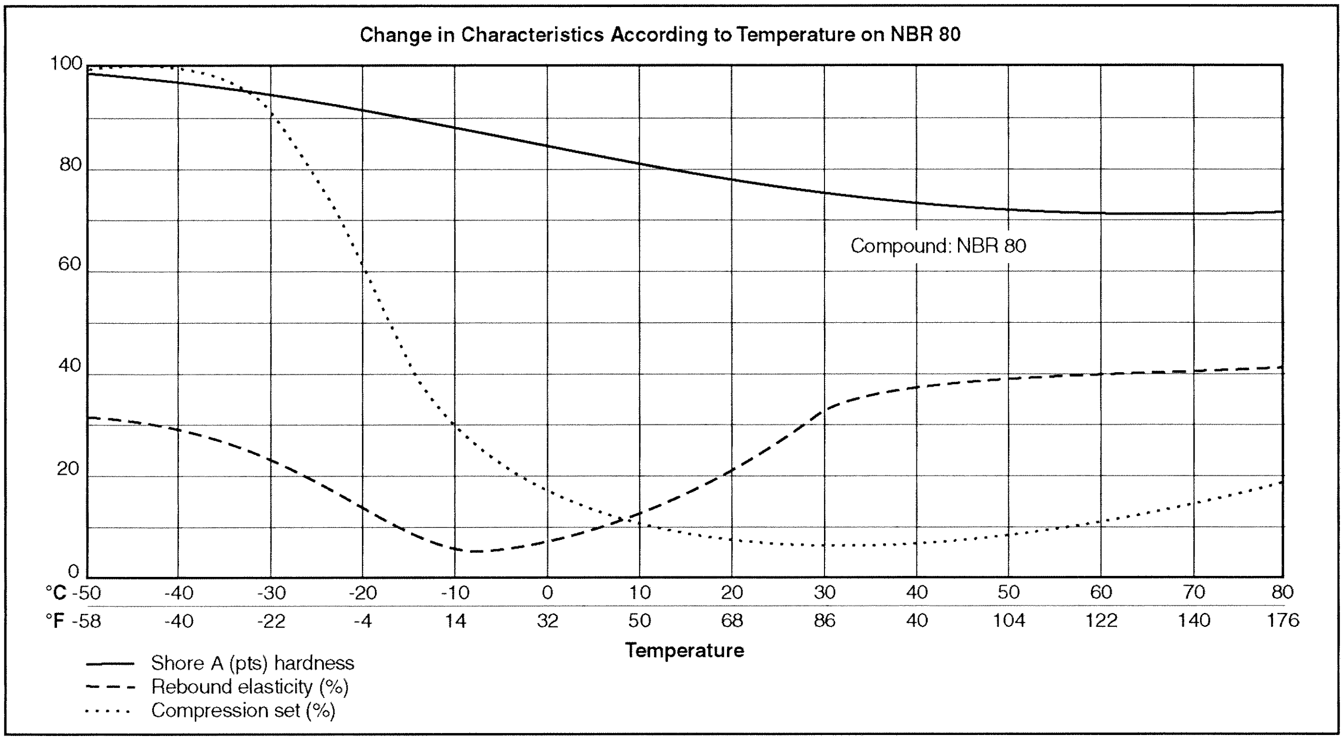

Figure 2-23: Change in Characteristics According to Temperature on NBR 80

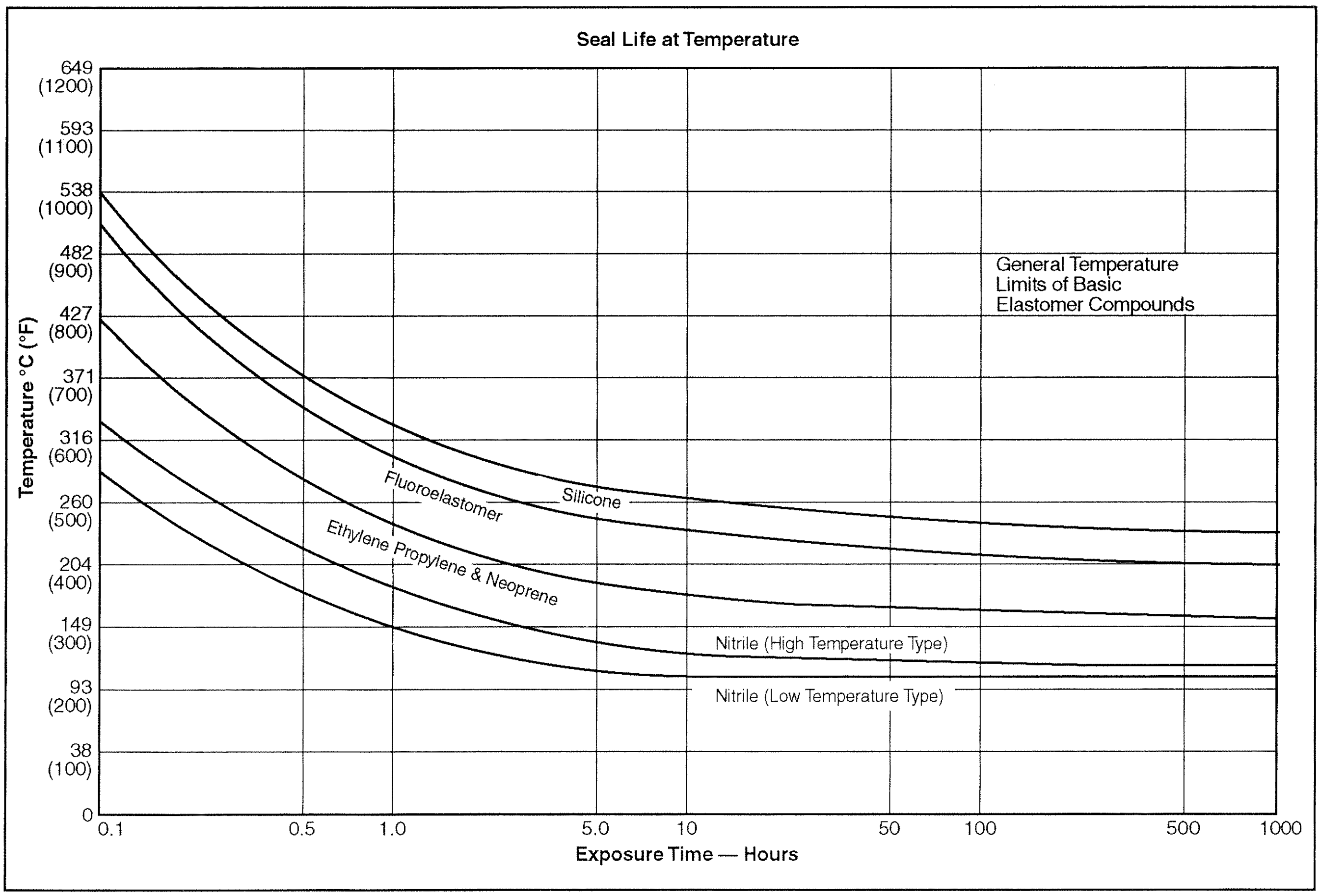

Figure 2-24: Seal Life at Temperature

limit. The sealing ability of a compound deteriorates with total accumulated time at temperature. The curves show the safe, cumulative time at a given temperature for specific elastomers used as static seals. For dynamic seal applications, temperatures as much as 14°C (25°F) below those indicated may be more realistic.

2.13.4 Pressure

The system operating pressure is always a consideration as it effects the choice of seal materials in several ways. First is hardness, as may be required to resist extrusion in dynamic designs or where there is a large gap between sealed members in static applications. Second is at-rest vs operating conditions and requirements for "leakless" at rest conditions which would suggest due consideration be given to the long-term compression set properties of a given material.

2.13.5 Mechanical Requirements

An important consideration in selecting the proper seal material should be the nature of its mechanical operation, i.e. reciprocating, oscillating, rotating, or static. How the seal functions will influence the limitations on each of the parameters (fluids, temperature, pressure, and time) previously discussed.

Static applications require little additional compound consideration. The prime requisite of a static seal compound is good compression set resistance.

Dynamic applications, due to movement, are more involved. All properties must approach the optimum in a dynamic seal compound, resilience to assure that the seal will remain in contact with the sealing surface, low temperature flexibility to compensate for thermal contraction of the seal, extrusion resistance to compensate for wider gaps which are encountered in dynamic glands, and abrasion resistance to hold to a minimum the wearing away or eroding of the seal due to rubbing.

2.14 Selecting a Compound

Having discussed the major aspects of seal design that affect compound selection, here is a summary of the necessary steps to follow, always keeping in mind that standard compounds should be used wherever possible for availability and minimum cost.

1. If military fluid or rubber specifications apply, select the compound from Table 8-2 or 8-3 in Section VIII, Specifications.

2. For all other applications, locate all fluids that will come in contact with the seal in the Fluid Compatibility Tables in Section VII.

3. Select a compound suitable for service in all fluids, considering the mechanical (pressure, dynamic, static) and temperature-time requirements of the application.

4. If a compound of different durometer from that listed in the Fluid Compatibility Tables in Section VII must be used, contact the O-Ring Division for a harder or softer compound in the same base polymer.

2.15 Compound Similarity

General purpose O-ring compounds are listed by polymer and Shore A durometer hardness for ease of selection. Note that the last two digits of Parker O-Ring compound numbers indicate this type A hardness. For example, compound E0540-80 is an 80-durometer material. The one exception is compound 47-071, which is a 70-durometer compound.

Butadiene, chlorosulfonated polyethylene, isoprene, natural rubber, and a few other elastomers do not generally perform as well as the listed polymers in seal applications, and Parker does not normally offer O-rings in these materials.

See Table 2-2 for comparison of similar properties by polymer family.

2.16 Testing

An elastomer is seldom under the same confinement conditions when laboratory physical property tests are made as when installed as a seal. The usual compression, lack of tension, and limited room for expansion when installed, all result in a different physical response from what is measured on an identical but unconfined part.

Example: A silicone compound tested in hydrocarbon fuel in the free state may exhibit 150% swell. Yet seals of such a compound confined in a gland having volume only 10% larger than the seal, may well perform satisfactorily. Complete immersion may be much more severe than an actual application where fluid contact with the seal is limited through design. The service could involve only occasional splash or fume contact with the fluid being sealed. Different parts made from the same batch of compound under identical conditions will give varying results when tested in exactly the same way because of their difference in shape, thickness, and surface to volume relationship (see Figure 2-25). Humidity alone has been found to affect the tensile strength of some compounds.

Correlation between test data and service conditions is not a simple problem; it is an industry-wide problem. Until improvement can be made, manufacturers and users must use the available data to the best of their ability. In essence, it is the misapplication of data, not the measurements, which causes difficulty. However, with data in some other form, such misapplication might be greatly reduced. ASTM Designation D471 (Standard Method of Test for Change in Properties of Elastomeric Vulcanizates Resulting from Immersion in Liquids) states: "In view of the wide variations often present in service conditions, this accelerated test may not give any direct correlation with service perfor-

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Design Development
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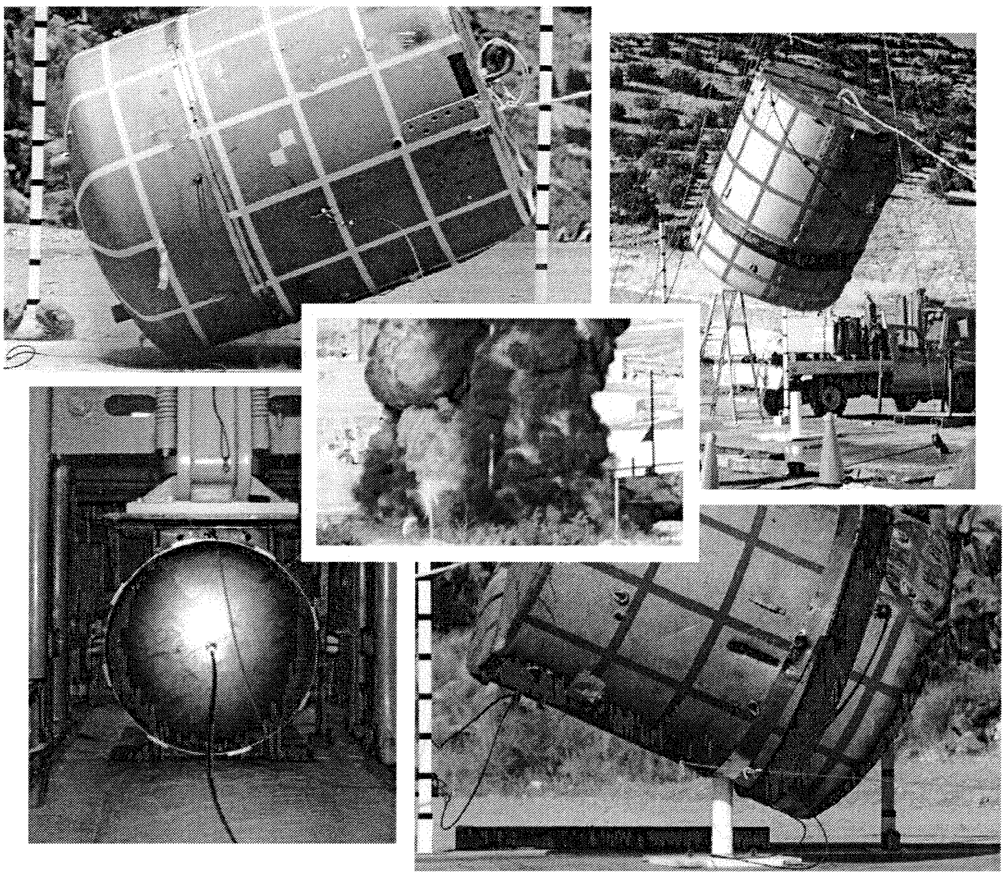
of the
TRUPACT-II Package



TRU Solutions
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016-03-09, Rev. 1
October 2002

- The dished head design was shown not to compromise the ability of the packaging to adequately withstand the effects of the 30-foot free drop events. The top-down end drop did not "bottom out" the polyurethane foam at the center of the lid and did not result in "snap-through" or any other significant distortion of the inner shell of the OCA. For the center of gravity over the corner free drop, the same conclusions were reached for the knuckle region of the inner and outer shells of the OCA.
- Testing demonstrated that use of a dished head better protects the seal regions from the consequences of the puncture event than use of a flat head. Although some of the puncture tests did allow perforation of the exterior steel shell, the depth of penetration into the polyurethane foam was significantly reduced from the damage observed in one-half-scale testing of a flat head.
- One testing anomaly did occur during one of the puncture events when the welded joint between the dished head and the cylindrical shell failed over a length of approximately 12 inches (see Figure 3-11). As a result, the weld joint detail was modified using ASME Code guidance for transitions in thickness and a requirement imposed to radiograph test (or optionally liquid penetrant test) all welds on the exterior shell of the OCA.
- Selected photos of the three-quarter-scale test unit are included as Figure 3-9 through Figure 3-12.

3.7 Elastomer O-ring Seal Performance Tests

3.7.1 Introduction

A variety of elastomer O-ring seal performance tests were performed as part of the TRUPACT-II package design development process. The purpose of the various tests was to establish the low and high temperature leaktight performance characteristics of the elastomer O-ring seals to be used in the TRUPACT-II package design. In addition to temperature sensitivity, the tests also investigated the effects of relative movement of the sealing surfaces enclosing the elastomeric O-ring seals. After testing a variety of elastomers and a variety of O-ring seal sizes (i.e., cross-sectional diameters), a 0.400-inch diameter butyl (Rainier Rubber RR0405-70 (Reference 3) compound) O-ring seal was selected for use in the TRUPACT-II package. This particular combination of size and material ensures that the TRUPACT-II O-ring seals will remain leaktight over the temperature range of interest even if the upper and lower seal flange sealing surfaces are separated a maximum amount (radially and axially) relative to one another. It is important to note that the generic term "butyl" can include a large number of elastomeric compounds. The specific use of Rainier Rubber RR0405-70 butyl rubber compound ensures that leaktight O-ring seals will always be maintained with the TRUPACT-II package.

3.7.2 Test Hardware

Two different test fixtures were developed for use in this elastomer O-ring seal performance test program. The basic approach used to develop the two fixtures was identical. Both test fixtures consisted of a center circular disc that fit within a mating bore. Each test fixture included hydraulic cylinders or jack screws so that the disc could be offset radially relative to the bore. Two O-ring seal grooves representative of the grooves used in the TRUPACT-II package design were machined into the outer edge of the disc so that full-size O-ring seal cross-sectional diameters could be tested. In order to verify leaktightness, a test port was drilled between the two O-ring seal grooves in the disc section and attached to a helium leak detector.

The disc and mating bore diameters were sized so that the test program could specifically study worst-case, minimum compressions occurring on the O-ring seals. Sizing was such that when the center disc was shifted within the bore to the point where metal-to-metal contact occurred between the disc and the bore, the resultant minimum compression on the O-ring seal (at a location 180° away from the contact point) was approximately equal to the minimum compression that would exist in a TRUPACT-II production unit. In a production unit, minimum O-ring seal compression corresponds to a situation where the upper and lower seal flanges are radially and axially separated a maximum amount. Although the TRUPACT-II package design includes a slightly tapered bore (approximately 4°), it was not necessary to explicitly include this feature in the test fixtures. The tapered bore slightly reduces O-ring compression when the lid and body seal flanges are separated a maximum amount axially. By specifically considering this effect when determining the minimum O-ring seal compression possible in a TRUPACT-II production unit, the taper is implicitly considered in the test program. Further discussion of this minimum compression state is provided in Section 4.3.3.2, *Specific As-Built Conditions*.

Although full size cross-sectional diameters were used for the O-ring seals and the surrounding groove and gland geometries, the overall diameter of each test fixture was reduced relative to the TRUPACT-II packaging design to achieve a practical size for testing. A reduced diameter was considered to be fully acceptable since cross-sectional geometries and resultant O-ring seal compression are the parameters of importance relative to maintaining a seal. The primary difference between the two test fixtures was in their overall size. One test fixture used a bore diameter of 39.07 inches and the other a bore diameter of 12.74 inches. For discussion purposes herein, the two test fixtures will therefore be referred to as the "large" and the "small" test fixture. Figure 3-13 presents the design of the large test fixture, and Figure 3-14 presents the design of the small test fixture. Photos of the large test fixture are provided as Figure 3-15 and Figure 3-16, and photos of the small test fixture are included as Figure 3-17 through Figure 3-19.

Other hardware used for testing included elastomeric O-ring seals, appropriate refrigeration and heating units (Figure 3-20 shows the environmental chamber used in conjunction with the small test fixture), and helium leak test equipment. The test fixtures were instrumented with thermocouples to monitor temperatures in the vicinity of the O-ring seals and to ensure uniform heating or cooling of the fixtures.

With respect to the O-ring seals, the cross-sectional diameters of the O-ring seals that were actually tested were always on the low side of the tolerance specified for production (production O-ring seals are specified as 0.400 ± 0.010 inches, whereas all O-ring seals tested were in the 0.387 to 0.400-inch range). All tests reported herein used O-ring seals that were lubricated with small amounts of Dow Corning high vacuum grease prior to installation within the test fixtures. Use of this lubricant enhances the lid assembly operation. In TRUPACT-II packages, O-ring seals will always be lubricated prior to lid installation.

3.7.3 Test Conditions

The test conditions used for investigating the performance characteristics of the elastomeric O-ring seals were selected to simulate worst-case temperature and worst-case minimum compression conditions for the O-ring seals. Tests at -40 °F with the disc centered in the bore (simulating normal cold conditions), tests at -20 °F that shifted the disc into metal-to-metal contact with the bore (simulating a free drop or 40-inch puncture event at -20 °F that resulted in a worst-case permanent deformation of the sealing surfaces), and tests at elevated temperatures for

8-hour periods of time with the disc offset within the bore (simulating a hypothetical accident fire event following a worst-case free drop) were specifically included. All helium leakage tests were performed either by flooding the environmental chamber with helium or by enclosing the test fixture in a plastic bag and flooding the bag with helium.

A step-by-step description of a typical O-ring seal test is shown below. Specific steps included for each test are evident from tabulated results (see Table 3-1):

1. Assemble the test fixture at ambient temperature conditions (approximately 70 °F).
2. Perform the leakage rate test with the disc centered in the bore.
3. Chill the test fixture to -40 °F and perform the leakage rate test.
4. Allow the test fixture to warm to -20 °F.
5. Shift the disc within the bore to achieve a condition of minimum compression on the O-ring seals.
6. Perform the leakage rate test while holding the temperature at -20 °F.
7. Heat the test fixture to an elevated temperature while maintaining the worst-case minimum O-ring seal compression.
8. Maintain the test fixture at the elevated temperature for 8 hours.
9. Pull a vacuum between the O-ring seals with the test fixture at the elevated temperature; helium leakage rate tests are not possible at elevated temperatures due to the tendency for the O-ring seals to quickly saturate with helium.
10. Chill the test fixture to -20 °F while still maintaining the worst-case displaced configuration.
11. Perform the leakage rate test while holding the temperature at -20 °F.

The final item to be included in this section is a quantification of the amount of compression on the O-ring seals for each of the two test fixtures. The procedure for calculating the minimum O-ring seal compression for each test performed in the large and small test fixtures will now be illustrated. For an example calculation, Test No. 3 for the small test fixture with the disc offset will be used. The same calculational procedure is used for all test cases both for the disc offset and centered in the bore. Dimensional data needed for the calculations and the results for all load cases are presented in Table 3-1.

Four (4) quantities are needed for the O-ring seal compression calculation: O-ring seal cross-section diameter, O-ring seal inside diameter (stretch), O-ring seal groove depth, and the maximum gap between the disc outside diameter and the bore inside diameter. The step-by- step calculational procedure is presented below for the small fixture Test No. 3 with the disc offset:

- **Step 1:** The following items can be obtained from Table 3-1:

  W_{min} = 0.387 inch (minimum O-ring cross-sectional diameter)

  W_{max} = 0.399 inch (maximum O-ring cross-sectional diameter)

  G = 0.052 inch (maximum gap)

  D = 0.265 ±0.001 inch (upper O-ring groove depth; see Note 7 in Table 3-1)

- **Step 2:** Determine the reduction in O-ring seal cross-section diameter:

  The reduction in O-ring cross-section diameter due to stretch can be determined from Figure 4-29. For the percent stretch values listed in Table 3-1, reading from the "observed" curve gives:

  - 2.0% Stretch → 1.7% Reduction
  - 4.1% Stretch → 3.1% Reduction

- **Step 3:** Calculate the reduced O-ring seal cross-section diameter:

  The reduced O-ring seal cross-section diameter is calculated by applying the percent reduction values determined in Step 2 to the minimum and maximum O-ring seal cross-section diameters from Step 1 as follows:

$$W_{R\,min} = W_{min}\left(1 - \frac{\text{Maximum Reduction}}{100}\right) = (0.387)\left(1 - \frac{3.1}{100}\right) = 0.375 \text{ inch}$$

$$W_{R\,max} = W_{max}\left(1 - \frac{\text{Minimum Reduction}}{100}\right) = (0.399)\left(1 - \frac{1.7}{100}\right) = 0.392 \text{ inch}$$

- **Step 4:** Calculate the nominal O-ring seal compression:

$$\text{Minimum Compression} = W_{Rmin} - D_{max} - G = 0.375 - 0.266 - 0.052 = 0.057 \text{ inch}$$

$$\text{Maximum Compression} = W_{Rmax} - D_{min} - G = 0.392 - 0.264 - 0.052 = 0.076 \text{ inch}$$

Expressing the nominal O-ring seal compression as a percent gives:

$$\text{Minimum Compression} = \left(\frac{0.057}{0.375}\right) \times 100 = 15.2\%$$

$$\text{Maximum Compression} = \left(\frac{0.076}{0.392}\right) \times 100 = 19.4\%$$

Note that the minimum and maximum O-ring seal compression values above represent a range of minimum compression. This is true because the maximum gap that results in minimum compression was used in the calculations. The range of values is due to dimensional tolerances.

Following the calculational procedure above, minimum O-ring seal compressions were calculated for all tests. The results are summarized in Table 3-1. Corresponding minimum compressions for production units are 23.6% to 37.7% for the initially centered configuration and 17.0% to 31.5% for the worst-case offset configuration (production unit minimum compression range for the offset configuration is available from Section 4.3.3.2, *Specific As-Built Conditions*).

3.7.4 Test Results

Results presented are obtained from testing of a number of Rainier Rubber RR0405-70 butyl rubber O-ring seals. Two tests using the large test fixture and five using the small test fixture have been performed that demonstrate that the RR0405-70 butyl rubber material is an appropriate choice for use in the TRUPACT-II package. The higher temperature tests were performed using the small test fixture due to the difficulty of uniformly heating the large test fixture. The results from these tests are summarized in Table 3-1. As indicated by this table, with O-ring seal compressions at the lowest end possible for a worst-case production unit, leaktight sealing conditions can be maintained over the temperature range applicable to the TRUPACT-II package.

The test results confirm that the O-ring seals selected for use in the TRUPACT-II package will remain leaktight if subjected to a normal cold temperature of -40 °F, if subjected to worst-case reductions in percent compression at -20 °F (such as could occur in a hypothetical accident condition 30-foot free drop event), and if subjected to temperatures of up to 400 °F for periods of up to 8 hours (such as could occur in a hypothetical accident condition thermal or fire event). Additionally, following a fire, the O-ring seals will remain leaktight when cooled to -20 °F. Importantly, based on the results of the hypothetical accident condition free drop, puncture drop, and fire tests performed on three certification test units, minimum O-ring seal compressions and maximum O-ring seal temperatures are never actually expected to reach the values considered in this seal performance test program. Results of the certification testing program indicated that deformations in the seal regions were not excessive and the maximum temperature obtained in the vicinity of the O-ring seals as the result of fire testing was 260 °F (see Section 4.0, *Full-Scale Certification Testing*). The test results imply that a level of conservatism exists in the TRUPACT-II package seal design.

Figure 3-21 and Figure 3-22 present photos of O-ring seals following removal from the test fixtures. As shown, for temperatures up to 400 °F and hold times of up to 8 hours, the O-ring seals remained somewhat flexible and, as reported in Table 3-1, maintained a leaktight seal. However, exposure for 8 hours at 450 °F led to a stiffening and cracking of the O-ring seal, and an inability of the seal to remain leaktight. The upper temperature limit for the RR0405-70 butyl rubber O-ring seal material therefore falls somewhere between 400 °F and 450 °F; thus, a 400 °F upper temperature limit is conservatively selected.

3.8 Additional Elastomer O-ring Seal Performance Tests

3.8.1 Introduction

This section describes additional elastomer O-ring seal performance tests conducted in June of 1999 in order to determine the minimum compression required for RR0405-70 elastomer O-ring seals to be used in the TRUPACT-II packaging design. The original tests were conducted in 1989 (see Section 3.7, *Elastomer O-ring Seal Performance Tests*). The purpose of the original tests was to establish the low and high temperature leaktight performance characteristics of the RR0405-70 elastomer O-ring seals. In addition to temperature sensitivity, the original tests also investigated the effects of relative movement of the seal surfaces enclosing the elastomeric O-ring seals. The original tests showed that the O-ring seals were leaktight for compressions as low as 15%. The new set of tests show that the O-ring seals are, in fact, leaktight at low and high temperature conditions when under a minimum compression as low as 12%.

3.8.2 Test Hardware

The test fixture used in the original seal performance test was modified for lower O-ring compression. The test fixture (see Figure 3-23) consists of a center circular disc (see Figure 3-24) that fits within a mating bore of the test fixture base (Figure 3-25). The fixture includes a set of jackscrews so that the disc can be offset radially relative to the bore. The two O-ring seal grooves, representative of the grooves used in the TRUPACT-II package design, were machined

Table 3-1 – Summary of O-ring Seal Region Dimensional Data and O-ring Seal Compression Calculations

Test Fixture⑦	Test Number	O-ring Seal Cross-Sectional Diameter (inches)①				Stretch (%)		Maximum Gap (inches)		Minimum Compression (%)⑧				Temperature for "Leaktight" Leak Test (Leakage ≤ 2.0 × 10⁻⁸ scc/s, helium)				
		O-ring Seal No. 1		O-ring Seal No. 2				Center Disk	Offset Disk	Center Disk		Offset Disk		Center Disk④		Offset Disk④		
		Min	Max	Min	Max	Min	Max			Min	Max	Min	Max	Ambient	-40 °F	-20 °F	8 hrs⑤	-20 °F
Large	1	0.395	0.400	0.395	0.400	0.9	3.0	0.035	0.066	23.1	25.8	15.1	17.9	Yes	Yes	Yes	200 °F	Yes
	2	0.390	0.395	0.390	0.395	0.9	3.0	0.038	0.066	21.3	24.0	13.9	16.9	Yes	N/A	N/A	250 °F	Yes
Small	1	0.387	0.397	0.387	0.396	2.0	4.1	0.026	③	22.1	25.6	14.9	20.0	Yes	Yes	Yes	350 °F	Yes
	2	0.388	0.398	0.387	0.398	2.0	4.1	0.029	0.050	21.3	25.1	15.7	19.7	Yes	Yes	⑥	450 °F	No
	3	0.387	0.397	0.387	0.399	2.0	4.1	0.027	0.052	21.9	25.8	15.2	19.4	Yes	Yes	Yes	400 °F	Yes
	4	②	②	②	②	2.0	4.1	0.027	0.053	21.9	25.8	14.9	19.1	Yes	Yes	Yes	400 °F	Yes
	5	②	②	②	②	2.0	4.1	0.026	0.050	22.1	26.0	15.7	19.9	Yes	Yes	Yes	400 °F	Yes

Notes:

① Material for all O-ring seal test specimens is butyl rubber compound RR-0405-70, Rainier Rubber Co., Seattle, WA.

② Not measured; calculations assume the worst-case range as taken from Small Test Fixture Tests Numbers 1 - 3 (i.e., Ø0.387-inch minimum to Ø0.399-inch maximum).

③ Range of values is 0.048-inch minimum to 0.053-inch maximum due to an indirect method of gap measurement (used for this test only).

④ A "Yes" response indicates that helium leakage testing demonstrated that the leak rate was ≤ 1.0×10^{-7} scc/s, air (i.e., "leaktight" per ANSI N14.5). In all cases, measured leak rates were ≤ 2.0×10^{-8} scc/s, helium, for tests with a "Yes" response.

⑤ No helium leak tests were performed at elevated temperatures due to O-ring seal permeation and saturation by helium gas. The ability of the test fixture to establish a rapid, hard vacuum between the O-ring seals was used as the basis for leak test acceptance at elevated temperatures. All tests rapidly developed a hard vacuum, with the exception of Test Number 2 at an elevated temperature of 450 °F, which slowly developed a vacuum.

⑥ Initial leakage of 1.0×10^{-5} scc/s, helium; became leaktight (≤ 2.0×10^{-8} scc/s, helium) approximately one minute later.

⑦ O-ring seal groove depths are 0.259/0.261-inch for the large test fixture, and 0.264/0.266-inch for the small test fixture.

⑧ Corresponding production unit minimum compressions are 23.6% to 37.7% for a lid centered on a body (as initially installed) and displaced a maximum amount axially, and 17.0% to 31.5% for a lid displaced a maximum amount both radially and axially.