CC Technologies
a DNV company

"A Literature Survey on the Selection Criterion and Compatibility of Elastomeric Materials to the Ethanol-Gasoline Mixtures "

PRCI
Final Report – #81173762 &81173763 / Static and Dynamic Seal Testing
August 29, 2008

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For

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Executive Summary

This report provides a comprehensive literature review and a survey on the selection criterion and compatibility of elastomeric materials to gasoline mixtures containing various concentrations of oxygenated hydrocarbons, with a special emphasis on Ethanol (EtOH). A brief overview of practical and technical considerations in the usage of EtOH blends is also provided. A special emphasis is given on the compatibility of elastomeric gaskets, O-rings, and seals to the EtOH blends. A wide spectrum of material properties, such as, mechanical properties, chemical resistance, swelling and permeability to oxygenated gasoline mixtures of various elastomeric materials are compiled from literature and various standards in the public and private domains.

The literature survey mainly highlighted that:

- Many qualitative recommendations exist for elastomeric materials for use in E-10 and E-85 fuel blends. For example, acrylonitrile, nitrile rubbers, fluorocarbons, and chloroprene polymers are all recommended as elastomeric materials.

- The results of the surveys conducted by Underwriters Laboratories, Inc. (UL) on the E85 dispenser material compatibility indicated that some elastomeric material incompatibility was observed in Brazil, such that dynamic synthetic rubber components, such as, nitrile rubber, are reported to exhibit excessive swelling or deterioration. The UL survey also indicated that no modifications were needed for static seal applications in many cases. Replacement of nitrile rubber components with the fluoroelastomeric materials were recommended for the dynamic loading conditions. No information was found on the degradation of E85 dispensing equipment being significantly faster than that of gasoline handling equipment.

- Swelling levels over 20 percent are reported to cause several problems including, overfill of the seal housing groove, seal extrusion damage, extremely high stresses in the seal and in the housing, occasional fracture of metal components and progressive degradation of elastomers.

- Several factors such as, glass transition temperature, filler loading, degree of crosslinking and liquid viscosity affect the maximum fluid absorption and swelling level of elastomers.

- The maximum absorption of a liquid by an elastomer is reported to mainly rely upon the difference in solubility parameters (δ) of fluids and elastomers, such that fluid absorption is more likely as the δ values get closer.

- The researchers at DuPont Performance Elastomers reported volumetric swell and permeation rate test results for six Viton® fluoroelastomers of varying fluorine contents in six different blends of fuel and ethanol ranging from 100% ASTM Fuel C hydrocarbon test fuel to 100% ethanol. Their results indicated that:

- The lower fluorine types of Viton swelled more than the higher fluorine types. The highest swelling was observed with all six types of Viton® whenever CE-25, i.e., 25% ethanol with ASTM Fuel C was used as the test fuel.

- The permeation results are reported to exhibit very similar trends to those of volumetric swell results such that the CE-25 fuel consistently exhibited the highest permeation rate regardless of the FKM polymer tested. Permeation rates of Viton elastomers with lower fluorine content are observed to reach a peak of ~100 g-mm/m^2/day in CE-25 fuel while they are determined to be ~25 g-mm/m^2/day in Fuel C and ~20 g-mm/m^2/day in neat ethanol.

- No literature data was found for evaluating the effect of batching in pipelines or subsequent fluid transitions in fuel dispensing equipment on the performance of elastomeric seals. Thus, testing of elastomers both upon their exposure to the gasoline-Ethanol blends and followed by their exposure to neat gasoline is planned to determine whether swelling of elastomers is reversible. Flow loop testing may be another approach for evaluating these materials under more realistic conditions.

- There is a scarcity of experimental data or a well-defined test standard available in the literature for the evaluation of properties of elastomeric seals under dynamic loading conditions. It's decided that a set of tests will be performed on elastomeric seals either by designing a new test apparatus which will simulate dynamic loading conditions or by following ASTM test standards.

- Based on this literature review, a set of test activities is proposed for evaluation of the performance of various elastomers exposure to several EtOH/gasoline blends.

- A brief survey of pipeline companies was conducted and based on that the elastomeric materials being used in hydrocarbon liquids service were identified.

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1.0 Introduction to Ethanol and Ethanol / Gasoline Blends

Ethanol is not only an effective oxygenate but also a fuel octane improver. Recent documentation by DOE[4] indicates that the market for E85 blends has been rapidly growing as a result of continuously increasing gasoline prices. As the consumer demand for alternative fuel vehicles (AFVs) is growing, car manufacturers are working to produce more flexible fuel vehicles (FFVs), which are capable of operating on E85 or gasoline or a combination of the two. Several key factors affecting E85 growth were examined during 2006 and 2007[4]. In October 2007, Underwriters Laboratories, Inc. (UL) announced standardized testing procedures for E85 fuel dispensers to examine the unique properties of alcohol fuels when blended with gasoline. UL has also started accepting dispensing products for evaluation and certification testing using new test procedures. Prior to the testing completion and a dispenser listing, most jurisdictions will allow alternate equivalent dispenser designs to be submitted for approval. Each jurisdiction has its own process and policies in granting variances or waivers to approve uncertified designs. To date, numerous states and organizations have chosen to grant variances or waivers or produced written positions on measures related to uncertified products. More information on the UL certification of E85 dispensing equipment could be found on the Alternative Fuels and Advanced Vehicles Data Center (AFDC) web site at *www.eere.energy.gov/afdc/resources/technology_bulletin_0307.html*.

March 2008 statistics[8] indicate that 1,365 retail stations (out of 170,000 stations) in US are providing E85 across the US. According to the Renewable Fuels Association (RFA) statistical survey, as of July 2007, there are 123 ethanol plants with 6.444 billion gallons of capacity in USA.

According to a report prepared by the Oak Ridge National Laboratory (ORNL) on ethanol[2], "Among existing ethanol plants, five ethanol plants are located on navigable waters enabling them to ship via barge. Two additional plants have initiated programs to transport their product overland to navigable waters. Majority of the remaining plants ship by a combination of rail and transport truck although some of the smaller plants ship exclusively by transport truck. These shipping capabilities are claimed to provide the ethanol industry to reach any market in the neighboring forty-eight states in a reasonably efficient way. In the case of waterborne shipments to coastal markets it is essential to first barge the product to the Gulf Coast, usually New Orleans, LA, where it is staged for shipment to the west coast by ship via the Panama Canal or the east coast by ocean going barge. Transportation costs can be as low as a few cents per gallon in markets close to the plants or as much as 14-15 cents per gallon in the case of shipping from the Midwest to the west coast. A recent development that will further influence the product transportation mode of ethanol is product commingling. While product commingling is routine in the petroleum industry, it has been rarely observed among ethanol plants. This is due to the fact that in the initial developmental years ethanol was largely produced by a number of Midwestern based plants for consumption primarily in the Midwest. As a result, there was little advantage in pursuing product commingling. Nowadays, more distant markets are involved and this drives a need for more efficient transportation. Companies with plants that have water access have been discussing product commingling with landlocked plants. The goal here is that landlocked production could be commingled for water accessible production. This would enable landlocked producers to access markets that are serviced more effectively by waterborne cargo. It would also give water accessible plants the ability to ship more product by barge while continuing to service Midwestern customers with the commingled product they receive from landlocked plants. The commingling is expected to contribute to much greater transportation

efficiencies and lower overall distribution costs." Pipelines can provide a lower cost, higher throughput transportation mode to distant markets.

Although the cheapest mode of transportation to many markets is usually via pipelines, ethanol and gasoline-ethanol blends are not currently shipped by pipelines owing to several technical and management challenges. Among the technical challenges are:

- Stress corrosion cracking of steel in fuel grade ethanol due primarily to the presence of dissolved oxygen
- Ethanol's ability to dissolve and carry impurities that are present inside multi-product pipeline systems, thus affecting the resulting fuel grade ethanol quality
- The possibility of corrosion in the presence of high concentrations of water. For example, the State of California[6] stated in 2003 that "as ethanol has a corrosive effect on the seals and valves of the pipelines, it has to be blended at the loading racks of distribution centers".
- The potential for degradation of elastomeric materials, such as seals and gaskets, in ethanol.

The present review report focuses on the effect of ethanol on elastomeric materials, mainly static seals and gaskets.

Both the gasoline distribution infrastructure[2] and ethanol distribution infrastructure[2] are depicted in Figures 1 and 2, respectively while a schematic of a typical gasoline ethanol blending set up at a bulk terminal[2] is provided in Figure 3. In addition, a summary of all available fuel distribution specifications is listed in Table 1[3].

Figure 1 Schematic of Gasoline Distribution System Infrastructure[2]

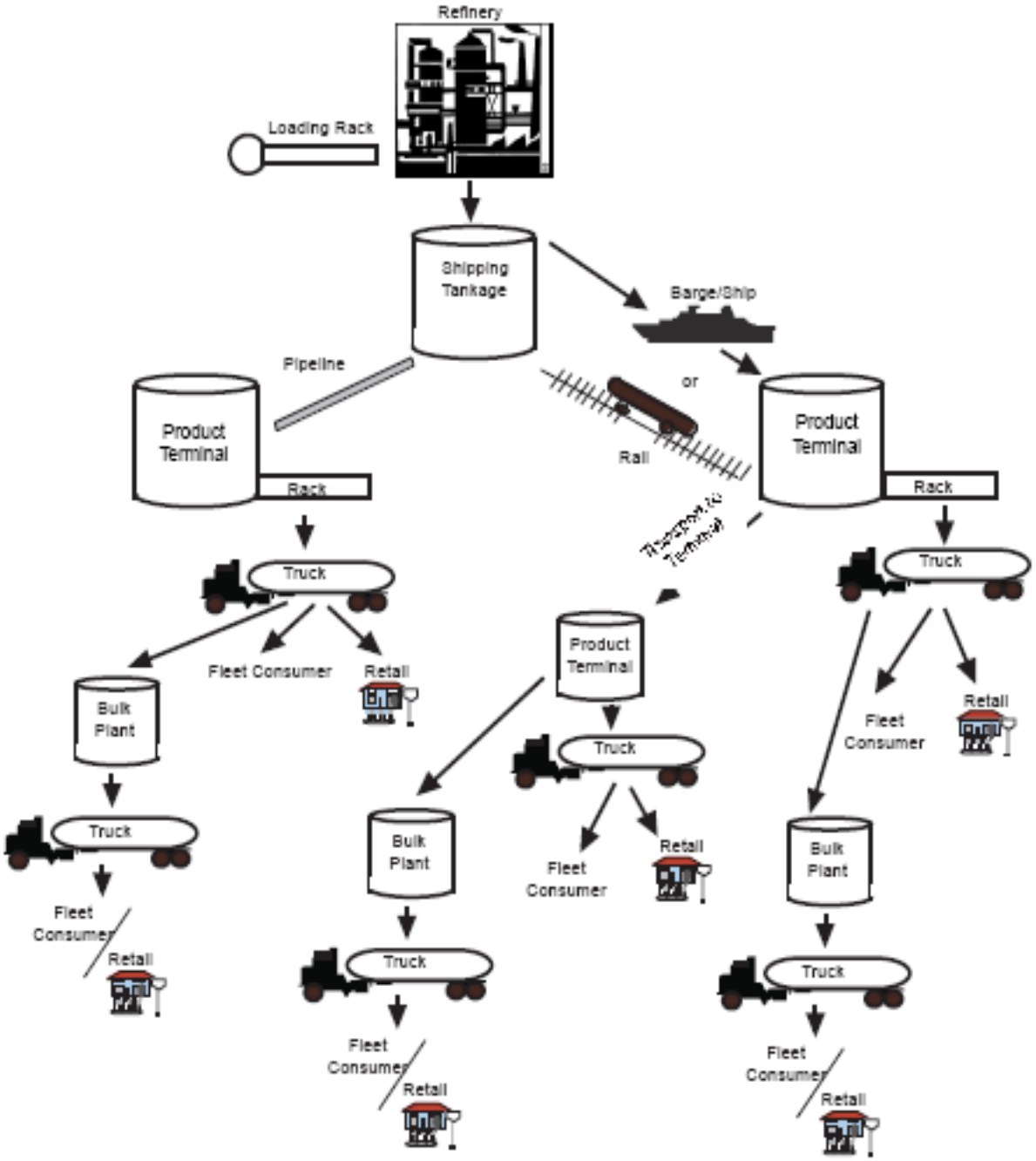


Figure 2 Schematic of Ethanol Distribution Infrastructure[2]

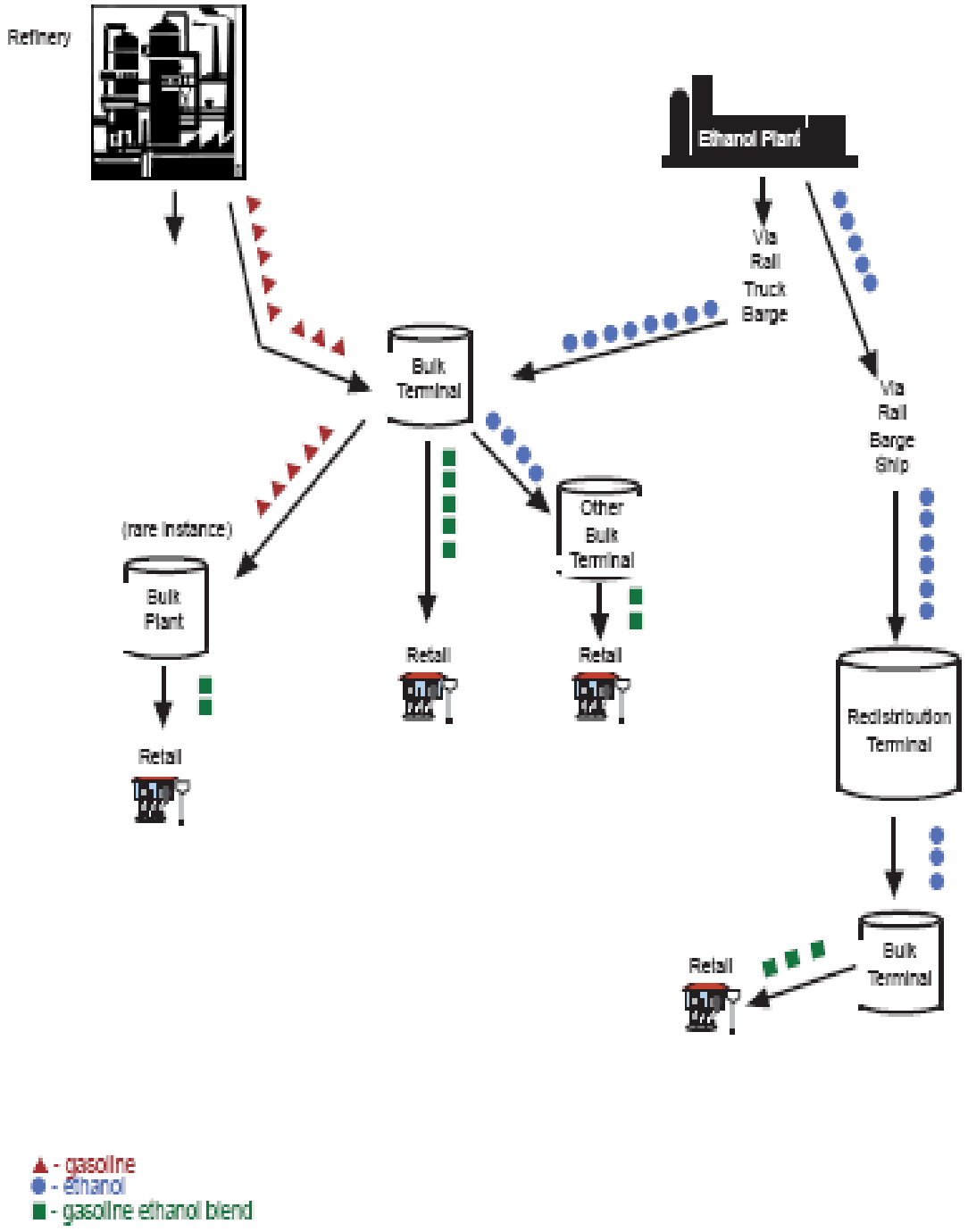


Figure 3 Schematic of Gasoline-Ethanol Blending at Bulk Terminal[2]

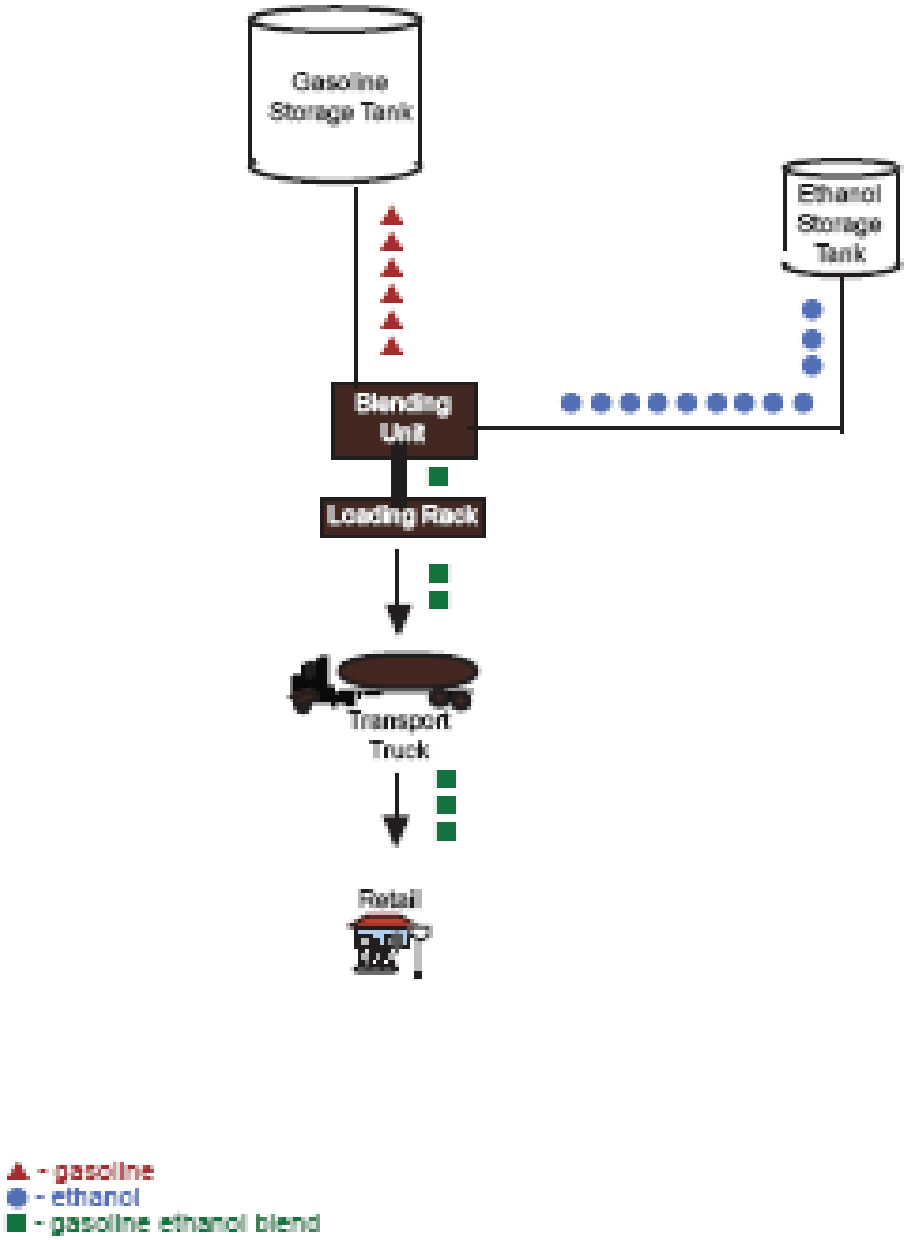


Table 1 Fuel Distribution and Specifications for FGE, E85 blends [3]

Ethanol Fuel Stage	Fuel Specifications	Fuel Storage	Fuel Transport
Mass Production Stage 98-95% Ethanol with 2-5% ASTM 4806 or BATF CFR Title 27 Parts 19-21 Denaturant Certif. of Analysis Meet BATF tax regulat.	ASTM D4806/ ASTM D5798 Note 1, 2 Internal quality control & external customer batch sampling No regulatory checks	API 650, 12 D & 12 F Bare steel tanks, floating roof or gas shielding Reduces H_2O Note 3 & O_2 Note 4	API 1625, USCG, DOT Rail car 80 %, Ship/barge 15 %, Truck 5 %
Bulk Distribution Stage Splash/injection blend E10-E85 plus additives in tank or truck per customer order Note 2	ASTM D4806/ ASTM D5798 Note 1, 2 Internal quality control & external customer batch sampling No regulatory checks	API 650, 12 D & 12 F Bare steel tanks, floating roof or closed vessel Reduces H_2O Note 3 & O_2 Note 4	US DOT regulations Truck Tanker 100 % Closed Vessel
Local Dispensing Stage Fuel isn't changed from truck except by mixing with existing tank fuel & UST contaminants Note 3	ASTM D4806/ ASTM D5798 Note 1, 2 Internal quality control & external customer batch sampling No regulatory & customer checks	UL 58, UL 1316 & UL 1746 Bare steel, FRP or composite tanks No method to reduce UST contaminants Note 3	UL 87 etal- Dispensers Cars, ATVs, etc.

Note 1 The ASTM specification for Gasoline/Ethanol fuel blends with E85-75 is ASTM D5798, for FGE is ASTM D 4806 and for E10 is ASTM D4814.

Note 2 Corrosion inhibitors and biocides are not required by any ASTM fuel specification. Some producers add corrosion inhibitors but not biocides.

Note 3 Contaminants include water, salts, acids & other substances. Low contaminant potential exists at production & distribution facilities due to storage type, transfer methods and basic QC checks. High contaminant potential exists at local stations from many sources and the lack of effective fuel quality measures.

Note 4 Oxygen (from several potential sources) absorbed in fuel may promote corrosion.

1.1 Storing and dispensing of EtOH and EtOH/gasoline blends

According to the most recent report[4] published by DOE, the equipment used for storing and dispensing gasoline and diesel fuels is similar to the equipment used for alcohol-based fuels. In many cases, existing gasoline and diesel fuel systems may also be used to store and dispense E85 provided that compatible materials are used in the storage and dispensing systems. EPA states that most metal underground storage tanks (USTs) meeting the EPA's December 1998 regulations can also be used to store E85. However, it's also indicated that fiberglass storage tanks manufactured before 1992 should NOT be used with E85. The components of a typical E85 underground storage system and dispensing equipment are provided in Figures 4 and 5, respectively[4].

Figure 4 Typical Fuel Dispenser and Underground Storage Piping Equipment [4]

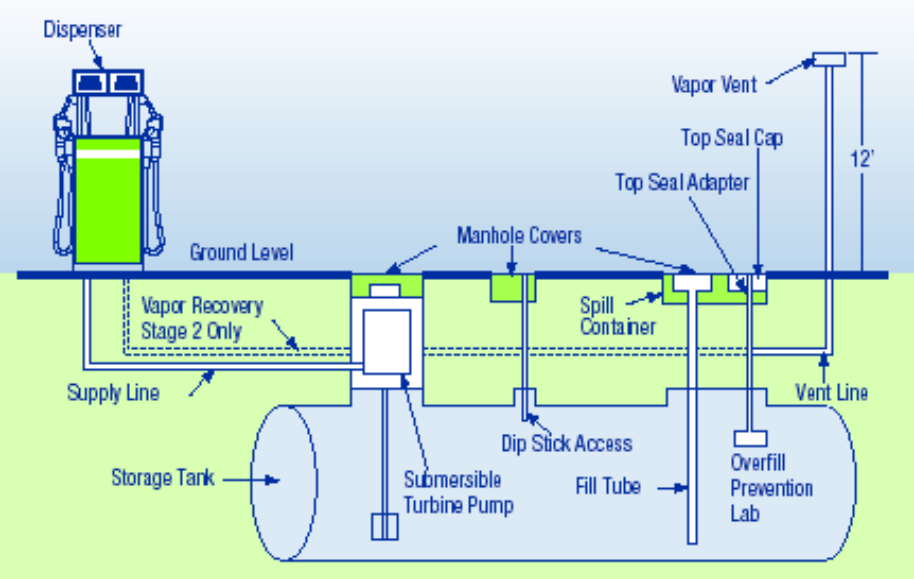
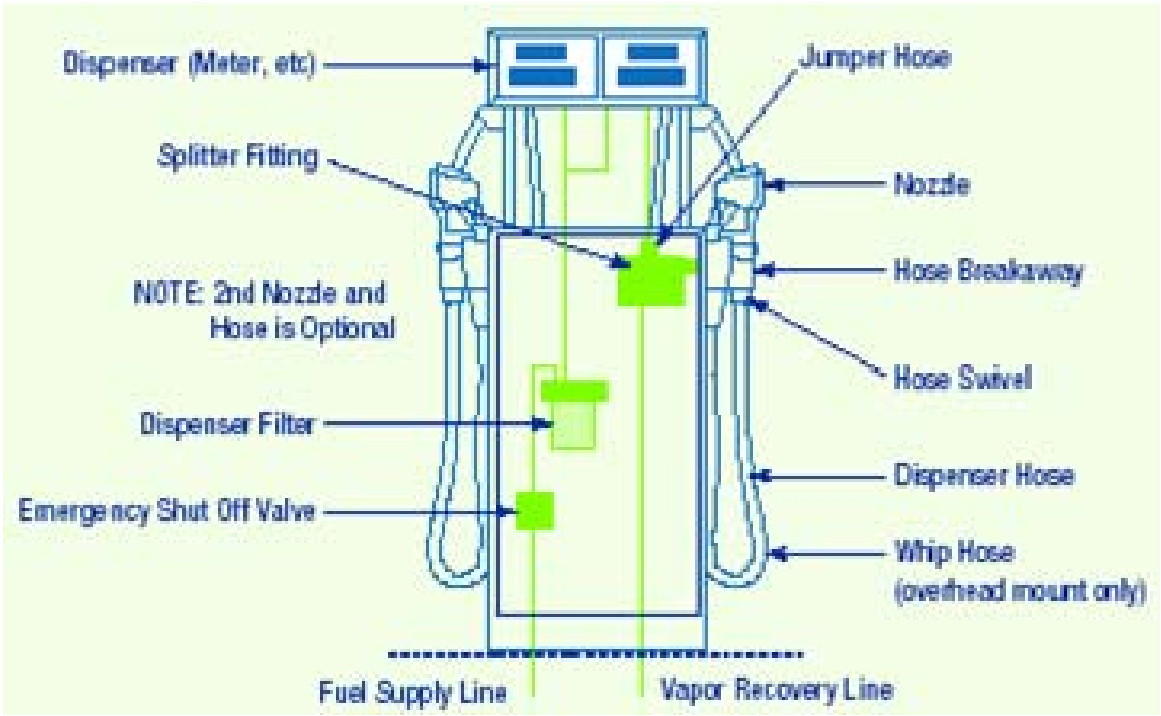


Figure 5 Schematic of a typical E85 Dispensing Equipment[4]



1.2 Permeation of EtOH/gasoline blends into Nonmetals

The electrostatic interactions between molecules can significantly control the chemical potential or activity of a solution, which plays an important role in the equilibrium absorption and permeation of chemicals by a nonmetallic material[11]. Although the mechanism is not very-well understood, the presence of ethanol in fuel facilitates the permeation of hydrocarbons through certain elastomers and thermoplastics, and to a lesser degree in thermoset products[11]. Permeation refers to the mass transport of a substance (or solvent) through a membrane that is driven by a chemical potential or activity gradient. Permeation is dependent on numerous factors, such as solvent-material interaction, the surface-area-to-thickness ratio of the nonmetal, and the degree of crosslinking (e.g., elastic contraction) in a material[11]. Permeability is the dissolved concentration multiplied by the diffusivity.

It is known that ethanol and hydrocarbons do not permeate through metals and, to a lesser degree, the same could be said for thermoset products, such as fiberglass-reinforced polymeric materials. Nonetheless, the same phenomenon isn't necessarily true for elastomers and thermoplastics, particularly the materials that have very little to no cross-linking. The lack of cross-linking can affect the rate of permeation.

The permeation of gasoline or ethanol through a nonmetal can give rise to changes in the physical, chemical, and mechanical properties of an elastomer or polymer. For instance, permeation can result in excessive swelling. This can ultimately cause malfunctioning of an elastomer or polymer that performs an important dynamic function, such as a pump seal or pump impeller as well as the ones performing under static loads.

Excessive permeation and swelling can also lead to plasticization in elastomers and polymers. In the case of elastomers, certain chemicals such as antioxidants and heat stabilizers are added to nonmetals to control certain performance properties. Since these additives are not chemically bound, excessive swelling in a material can ultimately lead to the extraction of these plasticizers as the solvent passes through the material. This could result in a measurable loss in strength and flexibility of the elastomer or polymer. A sampling of recommended elastomers and polymers exposure to dilute and concentrated ethanol-gasoline blends is provided in Tables 2 and 3, respectively. [4,13]

Table 2 Elastomers compatible with low and high concentration Ethanol Fuels [4,13]

Elastomer Compatibility with **E10** Fuels		Elastomer Compatibility with **E85** Fuels	
Recommended	Not Recommended	Recommended	Not Recommended
• Acrylonitrile (hoses & gaskets) • Fluorocarbon • Fluorosilicone • Natural Rubber • Polychloroprene (hoses & gaskets) • Polysulfide Rubber	• Acrylonitrile (seals) • Urethane Rubber • Polychloroprene (seals)	• Nitrile rubbers • Polychloroprene • Polytetrafluoroethylene • Fluorocarbon • Acrylonitrile	• Natural rubber • Cork gasket material • Leather

Table 3 Polymers compatible with low and high concentration Ethanol Fuels [4,13]

Polymer Compatibility with **E10** Fuels		Polymer Compatibility with **E85** Fuels	
Recommended	Not Recommended	Recommended	Not Recommended
• Acetyl • Polyamide • Polypropylene • Polytetrafluoroethylene • Fiberglass-reinforced plastic	• Alcohol-based pipe dope • Polyurathene	• Polyamide • Polypropylene • Polyethylene	• Methyl-methacrylate • Polyvinyl chloride • Alcohol-based pipe dope • Polyurathene • Polyester bonded fiberglass laminates

1.3 Outline of the survey of E85 fuel dispensing operations in the U.S.

Underwriters Laboratories Inc. (UL) issued a report[14] on the E85 fuel dispensing equipment usage in the U.S. in February 2007 based on the visual observations collected from ethanol refueling stations in the Midwest US. The results of this survey have shown that E85 fuel exposures have indicated no major safety or maintenance problems. Nonetheless, some leakage problems were identified with swivels, possibly a few hoses and other containment components, which required replacement parts. No information was found on the degradation of E85 dispensing equipment being significantly faster than that of gasoline handling equipment. It was also indicated that this conclusion might not reflect the reality and it might have been a result of the limitations of the survey.

1.4 Outline of the survey of EtOH fuel dispensing operations in Brazil

Underwriters Laboratories Inc. (UL) also issued a report[15] on the ethanol fuel dispensing equipment usage in Brazil by May 2007 based on the information gathered from five service stations in Rio de Janeiro and Sao Paulo, Brazil. Ethanol dispensing is available at a large majority of Brazil's 30,000 refueling stations. Some ethanol (92.6% ethanol / 7.4% water) dispenser hydraulic components (e.g., strainer, pump, meter, etc.) were confirmed to be identical to those used for dispensing Brazilian gasoline fuel (25% ethanol/75% gasoline) in Brazil. The results of this survey highlighted that Brazilian dispenser manufacturers identified some material compatibility issues during the thirty years of ethanol usage in Brazil such that dynamic synthetic rubber components, like nitrile rubber, would experience excessive swelling or deteriorate. Manufacturers indicated that such materials were replaced with those more resistant to degradation from alcohols, such as fluoroelastomers. On the other hand, it was also reported that in many cases no modifications were needed for static seals. Manufacturers stated that early experience with alcohol fuel exposures showed some minor corrosion and a build-up of bio residue in hydraulic components. It is indicated that aluminum (plated and unplated), iron, steel, brass and copper dispenser parts are in use in the ethanol fuel dispensers in Brazil. The survey concluded that no significant safety or maintenance problems associated with ethanol fuel dispensers currently in use were observed in Brazil.

2.0 Introduction to Elastomers

Elastomers (rubbers) are an amorphous class of polymers, characterized by their ability to display large extensions, which are reversible. Elastomers, both natural and synthetic, have common characteristics including elastic recovery after stress, flexibility, extrusion resistance and relative impermeability to gases and liquids. These polymers are above their glass transition temperature, T_g, at ambient temperature but they have to be crosslinked by vulcanization to prevent flow. Vulcanization requires heat and is performed in conjunction with the molding process. The introduction of a relatively few crosslinks in effect irreversibly anchors the chains in a three-dimensional network. As a result, permanent chain slippage is largely avoided during elongation and almost all chains return to their original location upon release of the strain, thus, the materials exhibit elastic behavior. This elastic nature associated with high deformation renders elastomers very useful for many sealing applications.

It is also important to emphasize that both mechanical properties and the chemical resistance of elastomers mainly rely on their formulation developed to provide the cured rubber with the right property mix. The major parameters affecting the performance of a seal elastomer compound, and which can be controlled at the compounding stage of processing are chemistry of base polymer, vulcanization agents, cure chemicals, type of fillers, antidegradants and softeners. For comparison purposes, the operation range of the most commonly used classes of elastomers, exposure to air is provided in Table 4.

Table 4 Operating Temperature Range of Common Elastomers exposure to Air [16]

Elastomer	Temperature range °F Min	°F Max	°C Min	°C Max
NR, natural rubber	−59	175	−50	80
IR, isoprene rubber	−59	175	−50	80
CR, neoprene rubber	−13	203	−25	95
SBR, Buna-S	−66	175	−56	80
NBR, nitrile rubber, Buna-N	−40	250	−40	105
IIR, butyl rubber	−30	300	−34	149
CIIR, chlorobutyl rubber	−30	300	−34	149
CSM, Hypalon	−20	250	−30	105
BR, polybutadiene rubber	−150	200	−101	93
EA, ethylene-acrylic rubber	−40	340	−40	170
ABR, acrylate-butadeine rubber	−40	340	−40	170
EPDM, ethylene-propylene	−65	300	−54	149
SBS, styrene-butadiene-styrene		150		65
SEBS, styrene-ethylene-butylene-styrene	−102	220	−75	105
ST, polysulfide	−50	212	−45	100
FA, polysulfide	−30	250	−35	121
AU, polyurethane	−65	250	−54	121
Polyamides	−40	300	−40	149
PE, polyesters	−40	302	−40	150
TPE, thermoplastic elastomers	−40	277	−40	136
SI, silicone	−60	450	−51	232
FSI, fluorosilicone	−100	375	−73	190
HEP, vinylidene fluoride	−40	450	−40	232
FKM, fluoroelastomers	−10	400	−18	204
ETFE, ethylene-tetrafluoroethylene elastomer	−370	300	−223	150
ECTFE, ethylene-chlorotrifluoroethylene elastomer	−105	340	−76	171
FFKM perfluoroelastomers	−58	600	−50	316

In a nutshell, elastomers exhibit the following characteristics at normal working temperatures and pressures:

- Largely resilient and reversibly elastic;
- Soft, that is, Young's modulus is low for a solid material, and is a function of strain; the value is in the range 1-100 MPa with most practical primary sealing materials having moduli nearer the bottom of this range;
- Ability to maintain constant volume on deformation; with a very high bulk modulus. They are considered virtually incompressible in the dry state, although some compaction can be noted at high pressures reached in upstream gaseous applications.
- Capable of transmitting pressure in a similar way to the liquids, i.e. not only in the direction of applied pressure. This is a very important feature particularly in many elastomeric seal designs.
- Deformable.

There are over 20 classes of elastomers each of which has its own unique properties and performance that can be modified by the inclusion of other ingredients. The major constituents affecting the performance of a seal elastomer compound and which could be controlled during compounding stage can be summarized as:

- Base rubbery polymer
- Cure system
- Post-cure
- Plasticizers
- Fillers
- Softeners
- Antidegradants

While a qualitative comparison of properties of several elastomers is provided in Table 5, a quantitative comparison of many physical and mechanical properties of several chemically resistant elastomers is summarized in Table 6.

Table 5 Comparison Chart of Properties of Common Elastomers [16]

Property	Elastomer										
	Natural rubber (NR)	Isoprene (IR)	Neoprene (CR)	Butadiene-styrene (Buna S)	Nitrile-NBR (Buna N)	Butyl (IIR)	Chlorobutyl (CIIR)	Hypalon (CSM)	Polybutadiene (BR)	Ethylene-acrylic (EA)	Acrylate-butadiene (ABR)
Abrasion resistance	E	E	G	G	G	G	G	G	G	E	G
Acid resistance	P	P	GE	P	F	G	P	E	G	PG	G
Chemical resistance:											
Aliphatic hydrocarbons	P	P	G	P	E	P	E	G	P	G	E
Aromatic hydrocarbons	P	P	F	P	G	P	P	F	P	F	P
Oxygenated (ketones, etc.)	G	G	P	G	P	G	P	P	G	P	P
Oil and gasoline	P	P	FG	P	E	P	E	G	P	G	E
Animal and vegetable oils	PG	PG	G	PG	E	E	G	G	PG	G	G
Resistance to:											
Water absorption	E	E	G	GE	FG	G	G	G	G	G	G
Ozone	P	P	GE	P	P	E	E	E	P	E	E
Sunlight aging	P	P	E	P	P	G	E	E	P	E	E
Heat aging	P	G	G	F	G	G	P	E	G	E	E
Flame	P	P	G	P	P	P	P	G	P	P	P
Electrical properties	G	G	F	E	F	E	PF	E	G	FG	P
Impermeability	G	G	G	GE	G	E	G	G	G	G	F
Compression set resistance	E	E	F	G	GE	P	F	G	G	G	G
Tear resistance	GE	GE	FG	P	FG	GE	G	G	G	G	G
Tensile strength	E	E	G	G	GE	G	G	GE	G	G	G
Water/steam resistance	E	E	F	G	GE	G	G	GE	G	G	G
Weather resistance	P	P	E	P	F	E	E	E	G	G	G
Adhesion to metals	E	E	E	E	E	G	G	G	E	G	G
Adhesion to fabrics	E	E	E	E	G	G	G	G	E	G	G
Rebound:											
Cold	E	E	E	G	G	P	F	G	E	P	F
Hot	E	E	E	G	G	G	F	G	E	P	F

[a]E, excellent; G, good; F, fair; P, poor; PF, poor to fair; PG, poor to good; GE, good to excellent.

Property	Elastomer										
	Ethylene-acrylic (EA)	Acrylate-butadiene (ABR)	Acrylic ester–acrylic halide (ACM)	Ethylene-propylene (EPDM)	Styrene-butadiene-styrene (SBS)	Styrene-ethylene-butylene-styrene (SEBS)	Polysulfide (ST)	Polysulfide (FA)	Urethane (AU)	Polyamides	Polyester (PE)
Abrasion resistance	E	G	FG	GE	G	GE	PF	PF	E	E	E
Acid resistance	PG	G	P	G	E	E	F	G	P	FG	F
Chemical resistance:											
Aliphatic hydrocarbons	G	E	E	P	P	P	E	E	E	G	P
Aromatic hydrocarbons	F	P	P	P	P	P	E	E	P	G	G
Oxygenated (ketones, etc.)	P	P	P	GE	P	P	G	G	P	G	F
Oil and gasoline	G	E	E	P	F	FG	E	E	E	G	G
Animal and vegetable oils	G	G	G	G	P	G	G	E	E	FG	G
Resistance to:											
Water absorption	G	G	G	GE	E	E	G	G	G	E	E
Ozone	E	E	E	E	E	E	E	E	E	E	E
Sunlight aging	E	E	E	E	E	E	E	E	E	E	E
Heat aging	E	E	E	E	E	E	E	E	E	E	E
Flame	P	P	P	P	P	P	P	P	P	P	P
Electrical properties	FG	G	PF	G	P	FG	E	E	G	G	G
Impermeability	P	P	P	P	P	P	P	P	P	P	P
Compression set resistance	G	G	F	GE	G	G	P	P	F	G	G
Tear resistance	G	G	G	GE	G	G	P	P	GE	G	G
Tensile strength	G	G	PF	GE	G	G	F	F	P	G	G
Water/steam resistance	G	G	F	E	FG	FG	E	E	G	G	G
Weather resistance	G	E	E	E	F	G	E	E	E	G	G
Adhesion to metals	G	G	G	GE	G	G	P	P	G	G	G
Adhesion to fabrics	G	G	G	G	G	G	P	P	E	G	G
Rebound:											
Cold	F	G	F	G	G	G	P	P	E	F	G
Hot	F	G	F	G	G	G	P	P	E	F	G

Property	Elastomer										
	Silicone (SI)	Thermoplastic (TPE)	Polyester (PE)	Polyamides	Urethane (AU)	Polysulfide (FA)	Polysulfide (ST)	Styrene-ethylene-butylene-styrene (SEBS)	Styrene-butadiene-styrene (SBS)	Ethylene-propylene (EPDM)	Acrylic ester–acrylic halide (ACM)
Abrasion resistance	P	G	E	E	E	PF	PF	GE	G	GE	FG
Acid resistance	FG	G	F	FG	P	G	G	E	E	G	P
Chemical resistance:											
Aliphatic hydrocarbons	G	P	P	G	E	E	E	P	P	P	E
Aromatic hydrocarbons	P	P	G	G	P	E	E	P	P	P	P
Oxygenated (ketones, etc.)	P	P	F	G	P	G	G	P	P	GE	P
Oil and gasoline	P	FG	G	G	E	E	E	G	F	P	P
Animal and vegetable oils	G	G	G	FG	E	E	G	G	P	G	G
Resistance to:											
Water absorption	G	E	E	G	G	G	E	E	E	GE	G
Ozone	E	E	E	E	E	E	E	E	E	E	E
Sunlight aging	E	E	E	E	E	E	E	E	E	E	E
Heat aging	E	E	E	E	E	E	E	E	E	E	E
Flame	P	P	P	P	P	P	P	P	P	P	P
Electrical properties	G	G	G	G	G	G	G	G	G	G	G
Impermeability	G	P	P	G	G	G	G	G	G	G	G
Compression set resistance	G	P	P	G	G	G	P	P	F	G	F
Tear resistance	G	G	G	G	G	G	P	P	F	G	G
Tensile strength	G	G	G	G	G	G	F	F	F	G	G
Water/steam resistance	G	G	G	G	G	G	F	F	F	G	G
Weather resistance	G	G	G	G	E	E	E	E	E	E	E
Adhesion to metals	G	G	G	G	G	G	E	E	E	E	E
Adhesion to fabrics	G	G	G	G	G	G	E	E	E	E	E
Rebound:											
Cold	G	G	G	G	E	E	E	E	E	E	E
Hot	G	G	G	G	E	E	E	E	E	E	E

Property	Elastomer										
	Fluorosilicone (FSI)	Vinylidene fluoride (HFP)	Fluoroelastomers (FKM)	Ethylene-tetrafluoro-ethylene (ETFE)	Ethylene-chlorotrifluoro-ethylene (ECTFE)	Perfluoroelastomers (FPM)
Abrasion resistance	P	G	G	G	E	G
Acid resistance	FG	E	E	E	E	G
Chemical resistance:						
Aliphatic hydrocarbons	E	G	G	G	E	G
Aromatic hydrocarbons	G	G	E	E	E	G
Oxygenated (ketones, etc.)	P	G	P	G	E	FG
Oil and gasoline	E	G	E	E	E	E
Animal and vegetable oils	G	G	E	E	E	E
Resistance to:						
Water absorption	G	G	GE	G	E	G
Ozone	E	E	E	E	E	E
Sunlight aging	E	E	E	E	E	E
Heat aging	E	E	E	E	E	E
Flame	P	G	G	G	E	P
Electrical properties	G	G	GE	G	E	G
Impermeability	G	G	GE	G	E	G
Compression set resistance	GE	GE	GE	G	G	G
Tear resistance	G	G	G	G	G	G
Tensile strength	G	G	G	G	G	G
Water/steam resistance	G	G	G	G	G	G
Weather resistance	G	G	G	G	G	E
Adhesion to metals	E	G	E	E	E	E
Adhesion to fabrics	E	G	E	E	E	E
Rebound:						
Cold	G	G	G	E	E	E
Hot	G	G	E	F	E	E

Table 6 Physical and Mechanical Properties of Elastomers frequently employed in Chemical Processing Applications [17]

Property	Trade Name: Viton	Aflas	Fluoro silicone	Kalrez	Adiprene	Neoprene	Hypalon	Nordel
	Chemical Name: Fluorinated Hydro-carbon	Tetrafluoro Ethylene Propylene Copolymer	Fluoro silicone	Perfluoro Elastomer	Poly-urethane	Poly-Chloroprene	Chloro Sulfona-ted Poly-Ethylene	Ethylene Propylene Copolymer
Continuous-Use Temp, °C Min	-29 to -57	-29	-80 to -68	-38	-54	-62	-54	-59
Continuous-Use Temp, °C Max	227	204 to 230	232	290 to 315	121	149	135	163
Tensile Strength, MPa	3.4-20.7	13.8-22.1	3.4-9.6	3.4-10.3	2.1-24.1	3.4-27.6	-	2.1-24.1
Tens. Mod. at 100 % elong.,MPa	1.4-14	6.2-17.2	6.2	6.2-13.1	0.7-20.7	0.7-20.7	3.1-3.4	0.7-20.7
Hardness (Durometer)	50A-95A	60A-100A	35A-80A	65A-95A	30A-90A	15A-95A	40A-100A	30A-90A
Comp. Set @ Temp., °C	9-16, 70 hr @ 24	25, 70 hr @ 93	17-25, 22 h @ 149	20-40, 70 h @ 21	20-60, 70 h @ 21	20-60, 70 h @ 100	38-80, 22 h @ 100	20-60, 70 h @ 100
Elongation, %	100-500	50-400	100-480	60-170	100-700	100-800	100-700	100-700

Even though elastomers are mostly elastic; they also exhibit some viscous characteristics which are associated with frequency or time-dependent changes. This feature becomes much more evident particularly under the following deformation modes:

- damping i.e. energy dissipation upon loading and unloading
- increasing stiffness with rate of loading or frequency of loading
- stress relaxation i.e. reduction of force over time under constant deformation
- creep i.e. increasing deformation with time under constant load

Thus static seal performance relies on stress relaxation and creep (extrusion through the extrusion gap) as these deformation modes influence sealing stress retention or long-term seal integrity. On the other hand, damping and increasing stiffness with frequency are important for dynamic applications, such as; flexible hoses, flexible joints and pulsation bladders.

Failure of an elastromeric material is usually associated with either a physical or chemical change or possibly both. Various modes of eventual elastomeric material failure are observed under different loading and environmental conditions. While the most frequently observed modes of failures in elastomers are described in Table 7, a list of what types of elastomeric failures are observed in specific elastomeric components frequently employed in oil-off shore industries is provided in Table 8.

Table 7 Definitions of commonly observed deterioration modes of elastomers[18].

Failure mode	*Description*
Fracture/rapid tearing	The ultimate strength properties of the elastomer are exceeded. Should be considered for extremes of operational requirement (pressure, elevated temperature, load etc), remembering that the strength properties magnitudes may reduce with time due to thermal ageing and fluid absorption.
Rapid gas decompression or explosive decompression (ED)	Gas dissolved in the elastomer under high pressure conditions comes out of solution and forms bubbles in the material when the external pressure is lost. The bubbles may grow sufficiently to cause fracture of the material (e.g. seals) or of an interface (e.g. between the liner and adjacent layer in a hose).
Stress relaxation	Reduction of force over time under constant deformation conditions resulting in loss of ability to seal for unenergised seals. Contributions from both physical effects and chemical ageing effects. It is usually the latter that govern long-term performance. For seals, the effects are countered by swelling due to thermal expansion and absorption of fluids.
Creep	Increase in deformation with time under constant force/pressure conditions. Contributions from both physical effects and chemical ageing effects. It is usually the later that governs long-term performance. Associated with extrusion failures in seals.
Swelling	Absorption of fluids over time resulting in excessive stress if constrained (e.g. seal) or excessive deformation and weakening of the elastomer if unconstrained. Enhanced by thermal expansion effects. Governed by the compatibility of the fluid with the material. A small amount can be beneficial, e.g. in low pressure gas line seals, abandonment permanent plugs.
Thermal contraction	Caused by reductions in temperature which may also result in hardening and increased stress relaxation; the combined effect may result in loss of sealing force in seals at low temperatures. Associated with the T_g of the elastomer.
Chemical degradation (ageing)	Chemical changes due to attack either by a constituent of the contacting fluid, including environmental oxygen (aerobic ageing) or ongoing vulcanisation (anaerobic ageing) . Resultant changes in mechanical properties might include stiffness changes that may affect functional performance, e.g. an increase in stiffness resulting from ageing may result in excessive fatigue forces being generated in flexible joints.
UV and ozone cracking	Component surfaces exposed to UV and ozone prior to installation or during service must be sufficiently resistant, e.g. hose covers.
Fatigue crack growth	Crack growth under repeated strain cycling in dynamically loaded components (flexible joints, hoses). Fatigue resistance may be reduced by elevated temperatures, ageing and swelling by fluids.
Abrasion/erosion	Loss of material over time by rubbing against another surface or fluid flow with and abrasive medium.
Bond failure	Hose end fittings and the metal plates in flexible joints are bonded to elastomer layers. Appropriate bonding agents for the type of elastomer and metal should be used. The bond is formed during the curing (vulcanization) process. Inadequate bond strength may be a result of inadequate manufacturing conditions or degradation caused by fluid ingress and corrosion.

Table 8 Possible Deterioration Mechanisms for various elastomeric components[18]

Failure mode	*Static seal*	*Packers& plugs*	*Repair clamps*	*Dynamic seal*	*Hoses*	*Flexible joints*	*Valve sleeves*	*Pulsation bladder & bellows*
Fracture/rapid tearing	x	x	x	x	x	x	x	x
Explosive decompression (ED)	x		x		x	x		
Stress relaxation	x		x	x	x			
Creep/ extrusion	x	x	x					
Swelling	x	x	x	x	x			
Thermal contraction	x	x						
Chemical degradation (ageing)	x	x	x	x	x	x	x	x
UV and ozone cracking					x		x	
Fatigue crack growth				x	x	x	x	x
Abrasion/ erosion				x	x			
Bond failure					x	x		

2.1 Permeation of Fluids into Elastomers

Permeation is the migration of fluids through the thickness of a polymeric material. It is a major concern particularly when elastomers are used in chemical handling and processing industries. It can be evidenced by swelling, blistering and discoloration.

Permeation is essentially a three-step process which involves an instant liquid-uptake on the polymer surface governed by solubility parameters of both permeant and polymer, migration of liquid through the polymeric material determined by diffusivity and desorption of the liquid on the other side of the polymeric materials. Generally, the presence of oxygenates accelerates permeation of hydrocarbon fuels in elastomers and thermoplastics. Alcohols, particularly methanol, produce more permeation than does methyl tertiary butyl ether (MTBE).

The steady-state permeation rate, breakthrough time and the identity of the permeating species are of great importance to system integrity. It's also noticed that most researchers of gasoline permeation report total permeability and permeance (i.e., the permeability coefficient normalized by the thickness of the membrane) values for the fuel blends. Critical factors influencing the permeation rate of polymers are summarized in Table 9.

Table 9 Rules-of-Thumb affecting the Permeation rate of polymers[19]

Factors affecting permeation	Change in Factor	Change in Permeation
Voids in polymer	⇓	⇓
Polymer crystallinity	⇑	⇓
Polymer chain stiffness	⇑	⇓
Polymer interchain forces	⇑	⇓
Polymer temperature	⇓	⇓
Permeant size/shape	⇑	⇓
Permeant concentration	⇓	⇓
Polymer thickness	⇑	⇓
Permeant temperature	⇓	⇓
Permeant/polymer chemistry and ratio	⇓	⇓

Linear Permeation theory is often expressed by Fick's Law. Mass flow by permeation is proportional to the product of diffusivity, solubility and the activity of a solvent molecule. Diffusivity is known to range over several orders of magnitude among polymers: elastomers generally have the highest values while thermoset materials usually have the lowest values. The diffusivity depends upon the inverse square root of the molecular mass of the diffusing solvent whereas the solubility depends upon a binary interaction parameter that is governed by the enthalpy of mixing of polymer and solvent. Therefore a high permeability may be observed with either small, volatile solvents or with solvents that strongly associate with the matrix material or both.

Any solvent which can absorb into a material will also permeate through it. The phenomenon of solvent permeation is therefore limited to polymeric materials. The permeation rate of oxygenated gasoline is greater than non-oxygenated gasoline in common hose materials. In general, alcohol blended fuels are more permeable than ether blends with MeOH being most aggressive. Greater permeability is observed in elastomers (hoses, seals, gaskets, packing) relative to thermoplastics (flexible piping, sumps, vapor recovery, tubing) and composites (rigid piping). In general, fluorinated elastomers and thermoplastics offer better permeation resistance than nonfluorinated materials. Permeation of solvents through polymers is a thermally activated process. The permeation rates of oxygenated fuels in elastomers are reported to double every 10 to 15 ^{0}C. The time required to reach steady state permeation of a polymer also relies strongly on the type of material in use and the thickness of the part. For instance, fluorocarbon based elastomers[23] and thermoplastics are reported to require much more time to reach equilibrium absorption than hydrocarbon based polymers.

Permeation of water containing ethanol into elastomers has to be carefully evaluated due to not only degradation of elastomers will be accelerated but also the presence of water in ethanol can lead to phase separation. This is one of the important reasons why ethanol is not so easily transported via pipelines. It is water soluble, thus, has a tremendous affinity to absorb or pick up water. Water accumulation in pipelines is quite commonly observed such that water usually enters into the pipelines through the terminals and refinery tank roofs or it can also be dissolved in fuels during refinery processes. Introduction of water containing ethanol into pipelines creates lots of risks in using ethanol as a transportation fuel. Furthermore, if gasohol is shipped in a pipeline, the water may strip some of the ethanol out, resulting in sub-octane fuel. According to

a report prepared by the Oak Ridge National Laboratory[2], it was stated that once an ethanol blend phase-separates it is extremely difficult and almost impossible to reblend.

2.2 Swelling of Elastomers

Any contacting fluids will be absorbed into elastomers; in time, the elastomer can swell. The presence of absorbed fluid in sufficient quantities, with associated swelling, can weaken the polymer in several ways. The fluid molecules can push the polymer molecules apart (plasticization) or the soluble constituents of an elastomer might be leached out by the contacting fluid which causes a reduction in component dimensions. Furthermore, the fluid might be chemically hostile, thus attacking the elastomer surface initially and continuing inside its bulk after absorption. Not only the physical dimensions of a part can be influenced from swelling but also the mechanical properties can deteriorate. Therefore, the degree of solvent absorption by the material at equilibrium is a critical performance parameter for all nonmetallic materials exposed to a chemical environment.

Elastomers are more susceptible to fluid uptake and swelling than thermoplastics; yet, this argument can only be relevant to the amorphous regions of semi-crystalline thermoplastics where the effects are typically smaller owing to constraints from surrounding crystalline regions.

For swelling of an elastomer in a pure solvent, Flory[25] proposed an equation which relates activity coefficient of a solvent absorbed in an elastomer, $\Omega_{i,E}$ to the solvent-elastomer interaction parameter, $\chi_{i,E}$, elastic retraction constant, ε, and dilution entropy of the solvent, $\nu_{i,E}$, as follows:

$$Ln\left(\Omega_{i,E}\right) \cong \nu_{i,E} + \chi_{i,E}{\nu_{i,E}}^{2} + \varepsilon\left({\nu_{i,E}}^{1/3} - \nu_{i,E}/2\right)$$

The first term on the right hand side of the above equation refers to the dilution entropy of the solvent in the elastomer. The enthalpy of dilution is expressed by the second term. The last term accounts for a contribution to chemical potential due to the elastic retraction energy in the material. This theory provides a useful framework to qualitatively discuss the compatibility of many polymeric materials exposed to solvents although Flory developed the theory only for elastomers exposure to pure solvents. For instance, the elastic retraction parameter is proportional to the number density of cross-links in the neat material. Since thermosets are cross-linked more than elastomers they typically swell less than elastomers in any given solvent.

The role of the polymer-solvent interaction parameter, $\chi_{i,E}$ is very important such that no interaction enthalpy exists when this value is zero and intermediate swelling is observed. This type of swelling is driven by entropy and competes with elastic retraction energies. Such cases are very typical of non-polar polymers exposed to conventional non-oxygenated gasoline. On the other hand, if the polymer-solvent interaction parameter is positive, the resulting interaction is endothermic. This implies that the polymer prefers interacting with itself rather than with the solvent molecules. The resulting solvent absorption will be very low because swelling is impeded by the heat of mixing as well as elastic retraction. This phenomenon is used as a useful strategy for obtaining fuel resistance such that incorporation of acid-base sites to the polymer backbone ensures repelling of the non-polar solvent molecules in non-oxygenated gasoline. Most fluorocarbon elastomers, nitrile rubber and polychloroprene elastomers, gain

their resistance to gasoline through this approach. If the value of $\chi_{i,E}$ is negative, then the enthalpy of mixing polymer and solvent becomes exothermic. An exothermic interaction implies that complementary attractive forces exist between Lewis acid and/or Lewis base sites on the polymer backbone and on the solvent molecule. In such cases, swelling will be relatively high as it is driven by the enthalpy and the entropy of mixing. Such type of interactions may occur when polar polymers come into contact with polar oxygenated hydrocarbons. Thus, Flory's theory supports that the degree of solvent uptake in a material is governed by both the activity of the solvent molecule in solution and the interaction parameter of the polymer-solvent pair.

Another approach commonly used in explaining the interactions of elastomers with fluids relies upon the "solubility parameter" concept. Any liquid or elastomer has a "solubility parameter", δ. This is a thermodynamic property which depends upon the energy of attraction between molecules. If two chemical species have the same, or similar, solubility parameter values, upon mixing, they are likely to have a strong affinity for one another. Hence an elastomer will have a tendency to absorb a liquid of similar δ, and be swollen by it. As the difference between the solubility parameters of polymer and solvent increases, their affinity for each other decreases. There are some other factors which can inhibit the extent of swelling of an elastomer in a compatible liquid. However, for those elastomers which are inclined to swell significantly in some liquids, a good indication of which liquids cause larger swelling in a particular elastomer can be estimated from knowledge of their respective solubility parameters. The most frequently used unit for δ in the literature is $(cal/cm^3)^{1/2}$.

Intermixing results from a thermodynamic balance of the enthalpy of mixing (heat content) with the entropy of mixing (involving structural aspects). The solubility parameter, δ, is directly related to the enthalpy term.

One of the tools of determining the δ value of an elastomer is using the solubility parameter spectroscopy (SPS)[18]. When elastomeric samples are immersed in a series of carefully selected liquids or miscible liquid mixtures of known δ, and a plot (spectrum) of swelling vs. liquid solubility parameter can be developed. The δ value for the elastomer is determined by the δ value coinciding with the maximum of the plot. The width of the solubility parameter peak in SPS shows the δ range across which substantial swelling of an elastomer can occur in low viscosity solvents. As solvent viscosity increases, the width and height of the peak generally decrease.

Intermediate liquid δ values are obtained by mixing liquids of known solubility parameter. The δ value of the mixture is equal to the volume-weighted sum of the individual component liquid δ values. This phenomenon can have important consequences in some applications. Thus the mass uptake of a miscible liquid mixture by an elastomer may be very much greater than the swelling which would occur in the presence of either one of the component liquids alone. If the mixture consists of more than two liquid components, an analogous situation would apply.

A list of solubility parameters[18], δ, of common solvents and elastomers associated with gasoline research are provided in Table 10. The solubility parameter values for the elastomers tabulated in Table 10 were determined by using solubility parameter spectroscopy.

Table 10 Solubility parameters for a range of solvents and elastomers[18]

Solvent	δ
iso-octane	6.90
hexane	7.33
octane	7.60
diethylether	7.74
decane	7.77
p-xylene	8.83
m-xylene	8.87

Solvent	δ
Toluene	8.97
o-xylene	9.03
ethyl acetate	9.10
Benzene	9.22
MEK	9.56
Acetone	9.74
1,2-dichloroethane	9.96

Solvent	δ
propanol	12.0
ethanol	12.9
methanol	14.5
ethylene glycol	14.5
water	23.2

Elastomer	δ [1]	δ range [2]	Elastomer	δ [1]	δ range [2]
EPDM	8.25	7.5 - 9.0	ECO	10.7	9.0 - 12.5
FEPM	9.0	8.5 - 10.0	FKM I	10.9	9.0 - 12.5
LOW NBR	9.3	8.5 - 11.0	HIGH NBR	11.0	9.0 - 12.0
HNBR	9.6	8.5 - 11.5	FKM III	*	(10.5 - 11.5) [1]
FKM II	10.7	9.0 - 12.0	FFKM	*	*

where [1] indicates the units $(cal/cm^3)^{1/2}$, * indicates swelling not measurable and [2] indicates where low viscosity uptake is above about 70% of peak value. See Table 18 for descriptions of the elastomers listed above.

The level of liquid absorbed by sealing elastomers can be controlled by a number of variables. These are mainly structural aspects, thermodynamically resulting from the entropic contribution to the free energy equation. If the δ difference between liquid and polymer are significantly different there is no chance of swelling but if they are similar, swelling may occur. The following structural considerations then become important:

- **Glass transition temperature**: swelling will be decreased in an elastomer with a high T_g, that is, in a polymer with little free volume available for absorption of liquid.
- **Crosslinking**: since crosslinks set an obstacle against swelling, swelling is reduced by high levels of crosslinking. For instance, after ageing samples of the HNBR for various times in an aggressive environment, resulting in rubber to form additional chemical crosslinks; the rate of solvent uptake and the equilibrium level of absorption are reduced.
- **Filler**: Swelling is reduced by the use of high filler loadings: implying less elastomer available to absorb fluid.

The benefits of reduced volume swell due to the presence of fillers and crosslinking may need to be counterbalanced against the probable reductions in the desirable physical properties, such as tear strength, and operational issues, such as ease of installation. Other factors which can influence swelling can be summarized as:

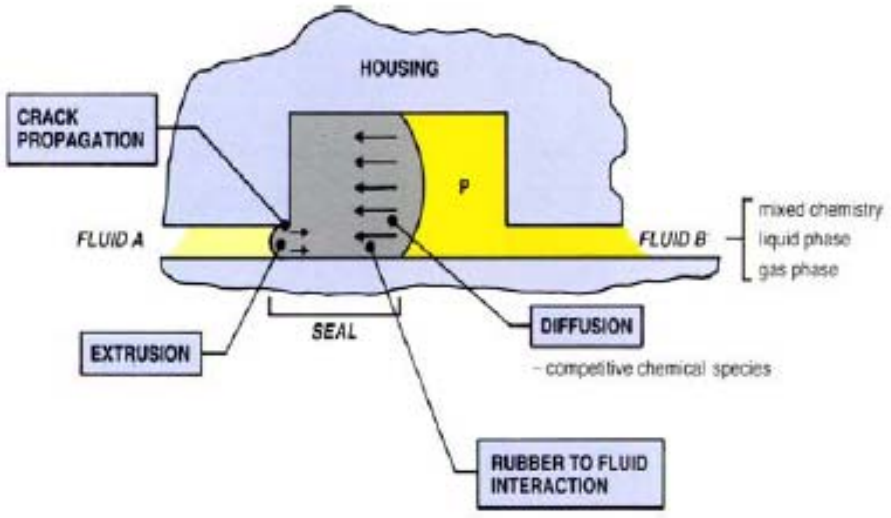
- Increasing liquid **viscosity** lowers the rate of absorption and the level of equilibrium mass uptake.
- Increasing **temperature** may increase swelling by a modest amount.
- During liquid immersion, soluble non-bound ingredients in the elastomer can be removed by **leaching**; this is usually (but not always) a small effect.
- An elastomer exposed to an **immiscible liquid mixture** will eventually swell as if it' s exposed to the more compatible liquid (i.e., the one with the nearest δ), even if the sample does not directly contact that liquid in a pure form.
- Volume swell is an important measurement to apply when considering tolerances for housing design.

2.3 Selection Criteria Used for Choosing Right Elastomers for an Application

Elastomers are usually devised as per specific needs of each engineering application. Vulcanization converts the thermoplastic compound into the desired thermoset shape. Crosslinks between the polymer chains impart strength and elasticity to the sealing product. With the wide spectrum of materials available in the market, it is important for customers to confer with the manufacturers when deciding on the suitability of particular material for an application.

As schematically depicted in Figure 6, it is crucial to consider all the details of the local fluid environment of an elastomeric part, such as seals or gaskets, on the low pressure side as well as on the fluid side - including possible variations around the periphery due to fluid stratification. In particular, atmospheric oxygen can diffuse into a seal and contribute to elastomer's ageing. It is also important to distinguish physico-chemical effects, such as swelling or leaching, from purely chemical effects, such as, oxidation.

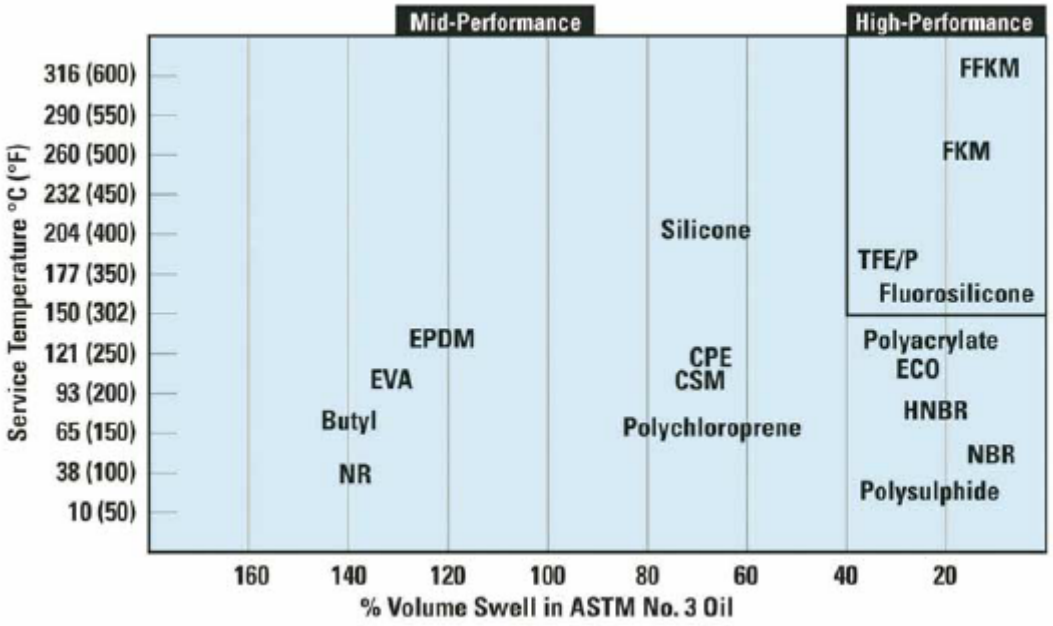
Figure 6 A schematic depicting potential deterioration modes which can develop during operation of an O-ring seal exposure to fluid.



As a general guideline for evaluating the relative performance of rubber products used in automotive and other related industries, ASTM D2000 defines a classification system. Figure 7 shows the resistance of elastomers to heat aging and swelling in oil. Although this chart is a valuable tool for characterizing and ranking elastomers, it does not focus on chemical and thermal resistance of elastomers in aggressive chemical processes. To anticipate the degree of chemical attack on the backbone and/or crosslinks of a rubber part, several factors such as, field experience, laboratory testing and guidance from material experts must be taken into account.

Generally, elastomers are rated as per their suitability with various media including fluids, weather, ozone, etc. Most of the times, elastomers are expected to perform in more than one medium. That's why, it is imperative to understand all circumstances to which an elastomer may be exposed.

Figure 7 Comparison Chart of Resistance of Elastomers to Aging and Swelling in ASTM oil #: 3.



Upon exposure to a liquid environment, elastomers usually exhibit one of the followings:

- Absorb the liquid and swell,
- Chemically react with the fluid and have a change in their polymer structure.
- Solubles may be extracted from the elastomer, which in turn causes a decrease in volume.

Sometimes, rather than the polymer itself adsorbing or desorbing, the other ingredients of an elastomer that a compounder used to make a part may adsorb or desorb the fluids. Most

chemical resistance guides associate the volumetric swell with the part performance in certain chemicals. Generally, below 5-10% swell is considered excellent. Although swelling is a commonly accepted, key criterion for evaluating elastomeric parts, other properties should also be measured.

The mechanical properties of an elastomer will generally vary after prolonged exposure to high temperatures. For example, while natural rubber will be gummy, polychloro-prene slowly hardens with the temperature. Usually, the service requirements will dictate the extent to which hardening or softening is undesirable with an elastomer. The rate at which properties of an elastomer alter amplifies logarithmically with temperature. Relatively small changes in temperature may, therefore, cause large variations in the elastomeric materials performance. Heat ageing tests are usually conducted 70-hour exposure in thermally controlled hot air. While this may correlate well with long exposure periods, it may not correspond to higher temperature in other chemical media. In critical applications, engineers should consult with the part manufacturers to see if long term exposure in a particular medium has been evaluated and documented. Furthermore, tests should be performed under conditions that closely mimic the actual processing environment.

There are many mechanical properties that influence elastomer performance including but not limited to compression set, tensile strength, elongation, hardness and abrasion resistance. These properties help determining the durability of elastomeric parts in particular applications. Compounders can alter the ingredients and/or the cure system to impart the required characteristics of an elastomeric part.

According to a technical report[1] published by Materials Technology Institute, Inc., a set of important issues to be considered by both the gasket manufacturers and the end-users in evaluating new polymers for elastomeric gasket applications (in the forms of flat sheets or envelope styles) are listed as follows:

- *Questions to be asked by the gasket manufacturers:*
  - How does the cost of this polymer compare with other competitive gasket materials?
  - How does this polymer compare with other competitive polymers regarding leaching of contaminants? [Empirical data – important only for certain applications]
  - How does the deformation under compressive load (creep) compare with other gasket materials? [ASTM D695]
  - What are the chemical and temperature limitations of this polymer? [Empirical data]
  - How do the compressive set (rebound) properties of this gasket material compare with other competitive alternatives, and are gaskets made from this polymer suitable for cyclic loading (i.e. temperature cycling)? [ASTM D-395]
  - How well does this material conform to and seal flat surfaces? [DIN 3535]
  - What bolt loadings should I specify for use with gaskets made from this polymer? [Empirical data]

- What are the health and safety issues in working with this polymer, including such issues as polymer fume fever and flammability of fumes given off? [Empirical data]

♦ *Questions to be asked by the end-users:*

- How have the above questions been answered, and do those answers affect the end-user's decision to use this polymer?
- What are the advantages of this polymer over other gasket materials for this application?
- What are the disadvantages of this polymer vs. other gasket materials?
- How does the price of this polymer compare with the alternatives, and is any added cost justified by the pros vs. the cons?

Therefore, several important selection criteria to be considered during selection of elastomeric seals for specific applications can be briefly summarized[25] as follows:

The anticipated service conditions for a proper seal selection:

- Fluid to be sealed, including any contaminants or additives.
- Temperature range, including minimum and maximum operating conditions, as well as thermal cycling and potential excursions.
- Pressure range, including minimum and maximum operating range with an error range and compression/decompression rate if the pressure is high.
- Vacuum application, including where the vacuum is applied and whether it is cyclic.
- Motion, either static or dynamic. If it is dynamic, describe the motion.

The design requirements for a particular sealing application:

- Critical dimensions and tolerances, including groove dimensions and machining tolerances.
- Desired service life. If it is a replacement for a failed seal, which material was used before and why did it fail?
- The grade of polymer. Many types of polymers available in various grades can vary substantially in chemical resistance.
- Component geometry/ description, e.g. O-ring, gasket, diaphragm, etc.
- The effect of chemical media on the seal.
- Assembly considerations, including lubricants, installed stretch, etc.

The inspection requirements for a particular sealing application:

- Defining inspection criteria
- Determining the need for lot sampling
- Setting acceptable quality levels
- Indicating the critical sealing surface.

Material specifications and traceability considerations for a proper seal selection:

- Defining important material specifications by the American Society for Testing and Materials (ASTM), Society of Automotive Engineers (SAE), Underwriters Laboratories (UL), military specifications or other well-recognized local country standards.
- Discussions with seal suppliers about the procedures for specifying and certifying sealing materials.
- Consulting with the supplier if compound changes may occur without a customer's knowledge and how to protect the end-user from it. Are hardness buttons, tensile bars or other test specimens required for incoming material verification?

To summarize, when evaluating an elastomeric seal's performance, not only the seal life but also the maintenance costs should be considered. Choosing the right elastomer for a particular seal application can also avoid costly unscheduled downtime and dangerous leakage, as the sum of the costs related to the quality and durability of the installed seals usually outweighs the seal's initial purchase price. Hence, when selecting materials for a specific sealing application, the guiding principle should be 'value-in-use'.

2.4 Standard Test Methods Employed In the Evaluation of Elastomers

When specifying seals, gaskets for hydraulic, pneumatic and fluid handling systems, ensuring that seal materials suit an application is always a prime concern. Fluid incompatibility, temperature extremes, and many other factors can accelerate the failure of elastomeric materials used in seals or gaskets, thus, leading to leaks and downtime. Material tests provide a powerful tool for evaluating and predicting the relative performance of various elastomeric materials.

In addition to the ASTM standards, Underwriters Laboratories (UL) issued several standards for the evaluation of dispenser products used in the transportation of Gasoline/ethanol blends. While there has been only one UL standard, UL 157 published for evaluation of "gaskets and seals" used with Gasoline/ethanol blends containing ***lower than 15% ethanol***, UL has also issued a bulletin for the evaluation of gaskets and seals used in Gasoline/ethanol blends ***higher than 15% ethanol***. The Standard for Gaskets and Seals, UL 157 covers test procedures and performance criteria for the evaluation of nonmetallic gasket and seal materials not only for general and profile information but also for specific end-product applications. Due to the copyright restrictions, the details of UL 157 standard will not be disclosed in this report [29].

A list of most commonly used ASTM Test Standards for elastomeric materials is compiled in Table 11. A brief description of these tests is also provided. While an outline of the performance requirements of nonmetallic gasket and seal materials exposure to Gasoline/ethanol blends ***higher than 15% ethanol*** is briefly presented in Table 12, those exposure to Gasoline/ethanol blends ***less than 15% ethanol*** materials are covered in UL 157 in much greater detail.

Table 11 Summary of commonly used Elastomeric Test Standards

Adhesion to a Flexible Substrate Adhesion to a Rigid Substrate	ASTM D 413 ASTM D 429
% Ash, % Carbon Black	ASTM D 297 (Part 34) ASTM D 297 (Part 38)
Stress Relaxation	ASTM D 1390
Permeation Resistance	ASTM E96
Deterioration in an Air Oven	ASTM D 573
Chemical Resistance (Change in Hardness and Volume/70hrs.)	ASTM D 471
Compression Set, Method B	ASTM D 395
Compression Deflection	ASTM D 575
Hardness (ISO) Hardness (Durometer)	ASTM D 1415 ASTM D 2240
Heat Aging 70 hrs./250^{0}F Change in Hardness	ASTM D 573 ASTM D 865
Identification by Infrared	ASTM D 3677
Tear Resistance	ASTM D 624
Tensile, Elongation, and Modulus Properties	ASTM D 412
Total Extractables, Density	ASTM D 297 (Part 20)

A brief description of these ASTM test standards are paraphrased from the ASTM website (www.astm.org) , as follows:

Adhesion to a Flexible Substrate

ASTM D413-98e1 - Standard Test Methods for Rubber Property—Adhesion to Flexible Substrates - These test procedures cope with the determination of the adhesion strength between plies of fabric bonded with rubber or the adhesion of the rubber layer in items made from rubber, then attached to other material. These test methods could be useful when the adhered surfaces are uniformly circular or approximately plane as in hose, belting, rubber-covered sheet metal, or tire carcasses.

Adhesion to a Rigid Substrate

ASTM D429-03 Standard Test Methods for Rubber Property-Adhesion to Rigid Substrates - These test procedures are routinely employed for testing the static adhesion strength of rubber to rigid materials (in most cases, metals). Procedure A is the method for a rubber part assembled in between two parallel metal plates. Procedure B is the routine for perpendicular stripping of a test-rubber part assembled to a single metal plate. Procedure C is useful when measuring the adhesion of rubber to metal with a conical sample. Procedure D involves the adhesion test post-vulcanization (PV) bonding of rubber to metal. Procedure E is used for perpendicular stripping of a test rubber tank lining assembled to a single metal plate. Procedure F involves a rubber part assembled in between two parallel convex-shaped metal plates. Procedure G is used to measure bond durability for rubber-to-metal bonded components with a double shear cylindrical sample. Procedure H is employed when measuring of bond durability for rubber-to-metal bonded parts with a quadruple shear cylinder sample.

Percent Ash, Percent Carbon Black

ASTM D297-93e2 - Standard Test Methods for Rubber Products-Chemical Analysis - These test procedures deal with the quantitative and qualitative analysis (including ash analysis and fillers analysis, including % Carbon Black) of the composition of rubber products. Many of these test routines can be used for the analysis of synthetic and natural crude rubbers.

Deterioration in an Air Oven

ASTM D573-04 - Standard Test Method for Rubber—Deterioration in an Air Oven – This test procedure provides a method to measure the influence of elevated temperature on the physical properties of vulcanized rubber. This test routine can be used to assess rubber compounds on a laboratory comparison basis.

Chemical Resistance (Change in Hardness, Volume & Oil Resistance over 70 hrs)

ASTM D471- Standard Test Method for Rubber Property-Effect of Liquids - This test procedure deals with the required methods to evaluate the comparative ability of rubber-like and rubber compositions to withstand the effect of liquids. It is designed for testing samples cut from fabric coated with vulcanized rubber, samples of vulcanized rubber cut from standard sheets, or finished articles of commerce.

Compression Set Method B

ASTM D395-03 Standard Test Methods for Rubber Property—Compression Set - These test procedures outline the testing of rubber to be used in applications where the rubber will be subjected to compressive stresses in liquid media or air. The test method applies to the rubbers used in seals, vibration dampers, and machinery mountings. Method B involves the testing involving compression set under constant force in air.

Compression Deflection

ASTM D575-91 - Standard Test Methods for Rubber Properties in Compression - These test procedures outline the test methods for determining the compression-deflection characteristics of rubber compounds other than those usually classified as sponge rubber and hard rubber.

Hardness (ISO)

ACTIVE STANDARD: D1415-05 Standard Test Method for Rubber Property—International Hardness - This test procedure deals with the method for measuring the hardness of rubber. The hardness is obtained by the difference in penetration depth of a specified dimension ball under two conditions of contact with the rubber – first, with a small initial force, and second, with a much larger final force. The differential penetration is measured at a specific time and then converted to a hardness scale value.

Hardness (Durometer)

ASTM D2240-05 - Standard Test Method for Rubber Property—Durometer Hardness - This test procedure outlines twelve types of rubber hardness measurement devices known as durometers: Types A and D. The procedure for determining indentation hardness of substances classified as vulcanized (thermoset) rubber, thermoplastic elastomers, cellular materials, elastomeric materials, gel-like materials, and some plastics are also described.

Identification by Infrared

ASTM D3677-00 - Standard Test Methods for Rubber--Identification by Infrared Spectrophotometry - These test procedures are based on the infrared examination of films and pyrolysis products (pyrolyzates) can be used for rubber identification. Additionally, these test routines apply to rubbers in the raw state and, when compounded, both in the uncured and cured state.

Tear Resistance

ASTM D624-00e1 - Standard Test Method for Tear Strength of Conventional Vulcanized Rubber and Thermoplastic Elastomers - This test procedure outlines the methods for measuring a property of thermoplastic elastomers and conventional vulcanized thermoset rubber referred to as tear strength.

Tensile, Elongation and Modulus Properties

ASTM D412-98a-e1 - Standard Test Methods for Vulcanized Rubber and Thermoplastic Elastomers—Tension - These test procedures deal with methods used to evaluate the tensile (tension) properties of thermoplastic elastomers and vulcanized thermoset rubbers. There are two procedures – Test Procedure A covers dumbbell and straight section samples, while Test Procedure B covers cut ring samples.

ASTM D297 (Part 20)- Standard Test Methods for Rubber Products-Chemical Analysis

These test procedures outline the quantitative and qualitative analysis of rubber products. Many of these test methods apply to the analysis of synthetic and natural rubbers.

Table 12 Performance Requirements set by UL for the Nonmetallic Gasket and Seal Materials exposure to Gasoline/ethanol Blends Higher Than 15% Ethanol[26].

Test media	Time and temperature	Properties required	Requirements
Gasoline/ethanol blends higher than 15% ethanol (static applications [a])			
CE25a and CE85a (tests conducted separately with each test media)	1000 h at 23 ± 2°C	Volume change	Minus 1 to plus 40 percent
	1000 h at 23 ± 2°C	Extraction	Maximum of 10 percent weight loss
	1000 h at 23 ± 2°C	Compression set (+)	Maximum of 35 percent
Gasoline/ethanol blends higher than 15% ethanol (dynamic applications [b])			
CE25a and CE85a (tests conducted separately with each test media)	1000 h at 23 ± 2°C	Tensile strength	Minimum of 60 percent of as-received
	1000 h at 23 ± 2°C	Elongation	Minimum of 60 percent of as-received
	1000 h at 23 ± 2°C	Volume change	Minus 1 to plus 40 percent
	1000 h at 23 ± 2°C	Extraction	Maximum of 10 percent weight loss

a - Static applications are those where the seal is not subject to movement.

b - Dynamic applications are those where the seal is subject to movement.

(+) – Compression set evaluation shall be conducted in accordance with Par 7 of UL 157 with the exception that the 1000 h immersion at 23 ± 2°C replaces the 70°C oven exposure.

CE25a – a mixture, by volume, of 75 percent ASTM Fuel C and 25 percent aggressive ethanol as defined in SAE J1681.

CE85a - a mixture, by volume, of 15 percent ASTM Fuel C and 85 percent aggressive ethanol as defined in SAE J1681.

3.0 Properties of Elastomeric Materials with and without Exposure to EtOH/Gasoline Blends

There have been several studies conducted by various research groups for the evaluation of elastomeric materials with and without exposure to EtOH/gasoline blends. A representative set of material properties compiled from most recent studies will be summarized in this section.

A general reference book summarizing the compatibility data for elastomers is published by Schweitzer [16]. This book contains some information on alcohols and diethyl ether but not the ethers that are commonly used in reformulated gasoline. Table 13 is constructed from this reference book to compare compatibility of the most frequently used 10 elastomers exposed to oxygenated and non-oxygenated hydrocarbons. It is important to note that these corrosion resistance charts are only applicable for *pure elastomers* without presence of any additives.

Table 13 Corrosion Resistance Chart of Most Common Elastomers .[16]

Trade Name	Chemical Description of Elastomers	Benzene	Toluene	Octane	Acetone	Water, salt	Methanol	Ethanol	Gasoline, Leaded	Gasoline, refined	Gasoline, sour	Gasoline, Unleaded
ABR	Acrylate-butadiene rubber	U	U		U	S	U	U	S	S	S	S
Butyl IIR	Butyl Rubber	U	U		S	S	S	S				
XNBR	Carboxylic acrylonitrile-butadiene rubber	U				S						
FPM	Perfluoroelastomers, Chemraz, Kalrez	S	S	S	S	S	S	S	S	S	S	S
FKM	Fluoroelastomers, Viton, Fluorel, Technoflon	S	S	S	U	S	U	S	S	S	S	S
EPDM	Ethylene propylene diene, Nordel	U	U	U	S	S	S	S	U		U	U
EPT	Ethylene propylene terpolymer	U	U	U	U	S	S	S	U	U	U	U
ECTFE	Ethylene-Chlorotrifluoroethylene elastomer, Halar	S	S		S	S	S	S	S			S
NBR	Buna-N, Nitrile	U	S	S	U	S	S	S	S	S	S	S
AU	Polyurethane	U	U		U	U	U	U	S	S	S	S

S: Suitable for service, U: Unsuitable for service and Blank: No data is available

The studies conducted at Shell Oil Company[22] for the evaluation of permeability and solubility of elastomers exposure to ASTM Fuel C with 15-20 vol. % MeOH and 10-15 vol. % EtOH indicated that fluoroelastomers and fluoroplastics revealed the lowest levels of permeation in alcohol blends while fluorosilicones and nitrile elastomers showed the highest level. The results of these measurements for gasoline blends containing no oxygenates and gasoline blends with EtOH and MeOH are presented from Tables 14 to 16. Similarly, Stahl and Stevens reported the permeation rates of elastomers[21] to decrease with an increase in acrylonitrile content in NBRs and to decline with an increase in fluorine content in FKMs.

Table 14 Permeability, solubility and mass flow properties of elastomers exposed to gasoline blends containing no oxygenates[22].

ASTM FUEL C								
Material	*Primary Application*	*Permeability ($g*mm/m^2/d$)*	*Solubility ($g/mm*m^2$)*	*Diffusivity (mm^2/day)*	*activity*	*A/L (m^2/mm)*	*Q (g/d)*	*t = 1/D (d/mm^2)*
Elastomers								
FKM	Hose liner Seals	1 to 7	8 to 110	0.06 to 0.13	1	1 to 2	1 to 14	8 to 30
NBR/blends	Hose	192* to 1200	230 to 760	0.9 to 1.6	1	0.5 to 1	100* to 1200	0.5 to 1

Table 15 Permeability, solubility and mass flow properties of elastomers exposed to modified ASTM Fuel C, containing 10 to 15 percent by volume EtOH[22].

ASTM FUEL C + 10 to 15 % volume EtOH								
Material	*Primary Application*	*Permeability ($g*mm/m^2/d$)*	*Solubility ($g/mm*m^2$)*	*Diffusivity (mm^2/day)*	*activity*	*A/L (m^2/mm)*	*Q (g/d)*	*t = 1/D (d/mm^2)*
Elastomers								
FKM	Hose liner Seals	2 to 100	52 to 270	0.03 to 0.37	1	1 to 2	6 to 100	
NBR/blends	Hose	1000 to 2000	170 to 560	3.5 to 5.8	1	0.5 to 1	600 to 2700	

Table 16 Permeability, solubility and mass flow properties of elastomers exposed to modified ASTM Fuel C, containing 15 to 20 percent by volume MeOH[22].

ASTM FUEL C + 15 to 20 % volume MeOH								
Material	*Primary Application*	*Permeability ($g*mm/m^2/d$)*	*Solubility ($g/mm*m^2$)*	*Diffusivity (mm^2/day)*	*activity*	*A/L (m^2/mm)*	*Q (g/d)*	*t = 1/D (d/mm^2)*
Elastomers								
FKM	Hose liner Seals	6 to 50	52 to 340	0.11 to 0.15	1	1 to 2	6 to 100	
NBR/blends	Hose	1300 to 2700	370 to 780	2.7 to 3.2	1	0.5 to 1	600 to 2700	

Researchers at DuPont Performance Elastomers[20] investigated the performance of six fluoroelastomers (FKM) of varying fluorine contents in six different blends of Fuel C-ethanol. The elastomers used in DuPont's tests included the following:

1 - Viton® GLT-600S: ***64% fluorine*** low temperature, specialty FKM polymer of VF2-PMVE-TFE-csm made with Advanced Polymer Architecture (APA) technology.

2 - Viton® GBLT-600S: ***66% fluorine*** low temperature, specialty FKM polymer of VF2-PMVE-TFE-csm made with Advanced Polymer Architecture (APA) technology.

3 - Viton® GFLT-600S: ***67% fluorine*** low temperature, specialty FKM polymer of VF2-PMVE-TFE-csm made with Advanced Polymer Architecture (APA) technology.

4 - Viton® GF-600S: ***70.2% fluorine*** standard FKM polymer of VF2-HFP-TFE-csm made with Advanced Polymer Architecture (APA) technology.

5 - Viton® F-605C: ***70% fluorine*** standard molded goods FKM polymer of VF2-TFE-HFP with bisphenol curatives included.

6 - VTR-9209: ***69% fluorine*** standard FKM polymer of VF2-TFE-HFP with bisphenol curatives included. Used in fuel hose applications.

The fuels utilized in the DuPont[20] Performance Elastomers' study comprised the following systems:

1- Fuel C (50% iso-octane / 50% toluene)
2- CE-10, 10% ethanol blended into 90% Fuel C
3- CE-25, 25% ethanol blended into 75% Fuel C
4- CE-50, 50% ethanol blended into 50% Fuel C
5- CE-85, 85% ethanol blended into 15% Fuel C
6- CE-100, 100% ethanol

The changes in the permeation rate of these elastomers are measured as per ASTM E96, using the Thawing Albert cup method. All of the tests were run for 672 hours at 40°C with the results

being expressed in permeation rate units of grams-mm/m^2/day. While the changes in the permeation rates of all of these fluoroelastomers[20] are plotted in Fig. 8, the volumetric swell test results as per ASTM D471, for the same polymers in the six fuel blends are shown in Figure 9. The high fluorine polymers did show less of a difference in volume swell among the various fuels and fuels–ethanol blends that were tested. In all cases the lowest swells were seen with the neat fuels – either Fuel C or ethanol.

Figure 8 Permeation rate of various fluoroelastomers after being exposure to different concentration levels of ethanol-Fuel C blends[20].

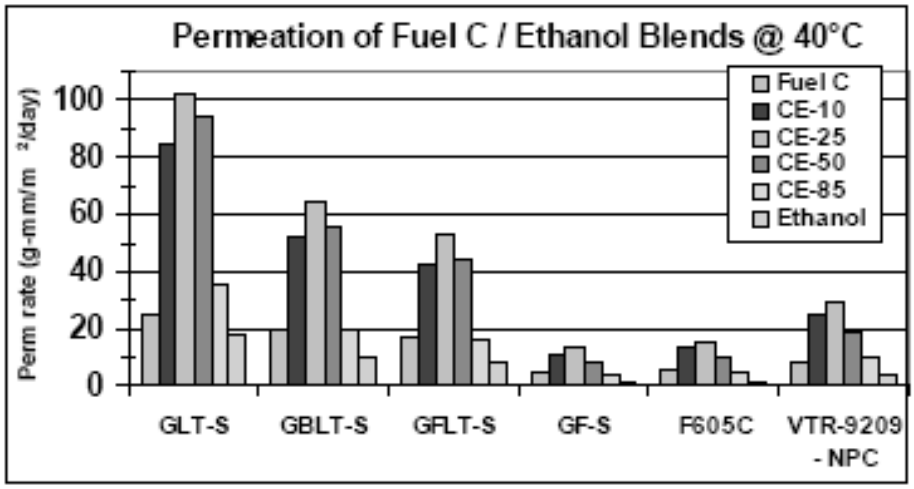
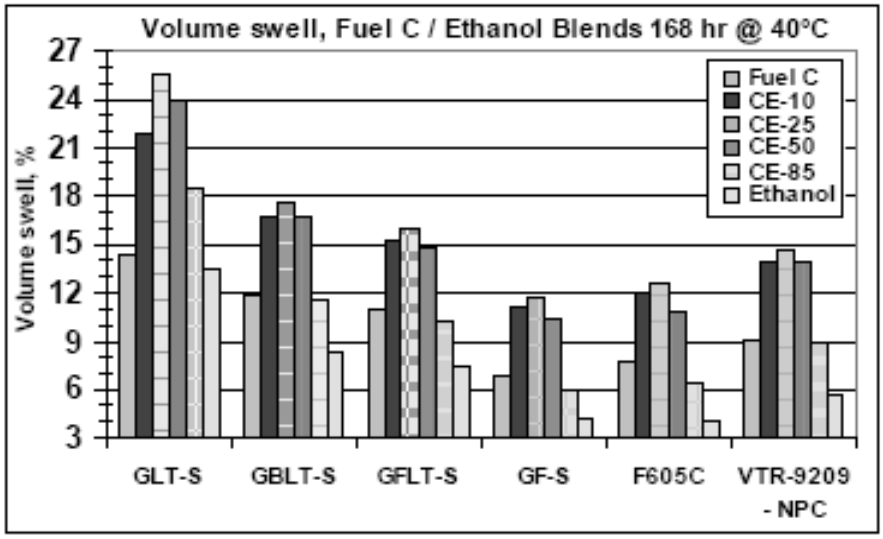


Figure 9 Volumetric Swell of various fluoroelastomers after being exposure to different concentration levels of ethanol-Fuel C blends[20].



DuPont Performance Elastomers' research findings have shown the following trends:

- Lower fluorine containing FKMs revealed higher permeation rates than higher fluorine containing FKMs in all of the fuels tested,
- Trends in fuel permeation resistance are found to very closely follow the trends in volume swell of FKM polymers,
- Neat 100% Fuel C or 100% ethanol tests exhibited lower permeation rates than the blends of Fuel C and ethanol in all the FKM polymers,
- The fuel which showed the highest levels of permeation for all FKM polymers was CE-25, i.e., Fuel C with 25% ethanol.
- The FKM polymers with the highest fluorine content, 70.2%, GF-600S showed the lowest permeation rates in all fuels tested.
- Of the specialty, low temperature types of FKM tested, GBLT-600S showed a considerably lower permeation rate than did GLT-600S in all fuels and has a low temperature glass transition close to that of GLT-600S
- Lower fluorine FKM showed a higher volume swell than higher fluorine FKM in all the fuels tested
- Blends of Fuel C and ethanol swelled all the FKM polymers more than they did in neat, 100% Fuel C or 100% ethanol
- The worst case fuel for volume swell of all the FKM polymers was CE-25, Fuel C with 25% ethanol
- 70.2% fluorine GF-600S showed the lowest volume swell in all fuels tested
- In low temperature FKM polymer testing, GBLT-S showed considerably lower volume swell than GLT-600S in all fuels
- Trends in volume swell seem to follow the trends seen in hardness change with the exception of F-605C, and the hose FKM VTR-9209 which was not postcured.

In another survey[18] conducted by *MERL Ltd*., a detailed review on the usage of elastomeric seals in contact with fluids in the offshore Oil & Gas production systems was provided along with a set of guidelines for the selection of elastomers to function well in such chemically aggressive environments. They also tested a great number of elastomers and observed a wide range of glass transition temperatures (which also influences low temperature performance of elastomers) associated with the different FKMs from the one supplier, as summarized in Table 17.

Table 17 Comparisons of Glass Transition Temperature and Volumetric Swell Data of various "Viton" Elastomers after exposure to MeOH[18].

Viton type	*Weight % fluorine*	*Tg (°C)*	*Methanol swell (%)*
A	66	-17	75 – 105
B	68	-14	35 – 45
F	70	-8	5 – 10
High performance			
GLT	64	-30	75 – 105
GBL		-15	65
GF	70	-8	5 – 10
GFLT	66.5	-24	5 – 10
ETP	67	-11	low

Researchers in MERL Ltd. also reported a list of selected elastomeric materials frequently used in offshore sealing applications. These elastomers are given in Table 18.

Table 18 Selected Elastomers employed in Sealing Applications[18].

Elastomer	*Type, comments*
EPDM	ethylene-propylene-diene monomer, low viscosity, 50-53% ethylene
LOW NBR	nitrile, 22% acrylonitrile content, cold polymerised
HIGH NBR	nitrile, 38% acrylonitrile content, cold polymerised
HNBR	hydrogenated nitrile, 38% acrylonitrile content, cold polymerised, essentially fully saturated
ECO	copolymer of epichlorhydrin and ethylene oxide
FKM I	copolymer of hexafluoropropylene and vinylidene fluoride; *ca* 66% fluorine content
FKM II	tetrapolymer of vinylidene fluoride, tetrafluoroethylene, perfluoromethylvinylether and a cure site monomer; *ca* 67% fluorine content
FKM III	speciality fluoroelastomer, high fluorine content
FFKM	terpolymer of tetrafluoroethylene, perfluoromethylvinylether and a cure site monomer; fully fluorinated elastomer
FEPM	copolymer of tetrafluoroethylene and propylene - sometimes coded TFE/P

Summary of Effects of EtOH and EtOH/Gasoline Blends on the Properties of Elastomeric Materials

The effects of Ethanol/gasoline blends on the elastomeric seals and gaskets can be outlined as:

- Fluids can dissolve into the surface of an elastomer, with diffusion carrying them into the bulk polymer.
- Different elastomers and liquids have different solubility parameter, δ , values.
- Maximum absorption of a liquid by an elastomer depends on the difference in δ values; the closer they are, the more likely is fluid absorption.
- Other factors such as glass transition temperature, filler loading, degree of crosslinking, and liquid viscosity also affect maximum fluid absorption and swelling level.
- Volume swell becomes important for housing tolerance considerations.
- Dissolved liquids diffuse into the elastomer bulk over a period of time depending on:
    - ♦ value of the diffusion coefficient (which depends on the fluid and the elastomer)
    - ♦ seal section and geometry.
- Diffusion is driven by concentration gradient, not by pressure.
- Leaching effects are usually more than compensated for by swelling - but note that the leaching of protective agents, for example, antioxidants, has a knock-on effect on durability.
- Liquid uptake by elastomers results in swell:
    - ♦ swelling < 20% by volume is not usually a problem in static applications
    - ♦ swelling > 20% can result in:
        - * overfill of the seal housing groove
        - * seal extrusion damage
        - * extremely high stresses in the seal and in the housing
        - * occasionally, metal components being fractured
        - * progressive degradation, such as a loss in physical and mechanical properties.
- Methanol can be particularly detrimental to some elastomers, but for physico-chemical reasons only.
- Corrosion inhibitors, especially those of high pH, can chemically degrade some elastomers.
- A small degree of positive swell is reported to be beneficial for the retention of sealing force.

4.0 Proposed Test Activities For Evaluating The Compatibility of Elastomeric Materials To Ethanol/Gasoline Blends

Based on the review of literature described in the previous chapters, it's concluded that the properties of most interest for the evaluation of elastomeric seals are:

- swelling
- loss of mechanical properties
- permeation of ethanol or gases

For the evaluation of performance of elastomers under static loading conditions, at least four types of tests on five or six different types of elastomers will be conducted after they are exposed to four different concentration levels of gasoline/EtOH blends as shown in Table 19. The tests will be run at least at two temperatures, one at 25^0C and the other at 40^0C. For this purpose, an aluminum aging block oven with 30 test tube holes is purchased from Benz Materials Testing Instruments.

To evaluate the effect of subsequent fluid transitions in the fuel dispensing equipment on the elastomeric seal performance while the elastomers are first subjected to gasoline/ethanol blends and then to the neat gasoline blends, it is decided to conduct at least three swelling test measurements. While the first one of these measurements will be done without any EtOH exposure, the second one will be made after EtOH-gasoline exposure for a reasonably long period and the third one will be carried out after exposing all samples to the neat Gasoline. This will help us to evaluate whether swelling of elastomers is reversible or not. Upon completion of the preliminary test matrix presented in Table 19, further tests, such as permeation of elastomers, will also be pursued if the results of the test matrix in Table 19 are considered unsatisfactory for assessing compatibility of elastomers subjected to EtOH-gasoline blends under static loading conditions.

Table 19 Test Matrix for the Evaluation of Compatibility of Elastomeric Seals to the FGE/Gasoline Blends under Static Loading Conditions

Type of Tests	Type of Blends	Type of Elastomers	Specimen Dimensions (Sheets of Material)
Swelling Tests, ASTM D471	95 % FGE 10 % FGE 30 % FGE 0 % FGE	PTFE Buna-N Low-Swell Buna-N Viton Viton GF Viton GFLT	Rectangular Bars (Recommended in D471) 25 x 50 x 2 ± 0.1 mm
Compression - Set Tests, ASTM D395 Test B	95 % FGE 10 % FGE 30 % FGE 0 % FGE	PTFE Buna-N Low-Swell Buna-N Viton Viton GF Viton GFLT	Circular Disks D: 13.0 ± 0.2 mm t : 6.0 ± 0.2 mm
Durometer Hardness Tests ASTM D2240	95 % FGE 10 % FGE 30 % FGE 0 % FGE	PTFE Buna-N Low-Swell Buna-N Viton Viton GF Viton GFLT	Rectangular Bars L, W : 12 x 12 mm t ≥ 6.0 mm
Stress Relaxation Tests, ISO 3384 (to be considered if / when resources become available)	95 % FGE 10 % FGE 30 % FGE 0 % FGE	PTFE Buna-N Low-Swell Buna-N Viton Viton GF Viton GFLT	
Estimation of life-time, ISO 11346 (to be considered if / when resources become available)	95 % FGE 10 % FGE 30 % FGE 0 % FGE	PTFE Buna-N Low-Swell Buna-N Viton Viton GF Viton GFLT	
Tensile Tests, ASTM D412 (to be considered if / when resources become available)	95 % FGE 10 % FGE 30 % FGE 0 % FGE	PTFE Buna-N Low-Swell Buna-N Viton Viton GF Viton GFLT	Rectangular Bars (Recommended in D412) 40 x 128 x 2 ± 0.2 mm

Evaluation of elastomeric seals performance under dynamic loading conditions is under consideration at the moment. As there are no standard test protocols to assess the effect of FGE on dynamic seals employed in pipeline transportation, either an application based test apparatus will be constructed to mimic the dynamic loading conditions of the seals or some of the following ASTM standard tests will be conducted:

- ASTM F37: Standard Test Methods for Sealability of Gasket Materials
- ASTM D4065-06: Standard Practice for Plastics: Dynamic Mechanical Properties: Determination and Report of Procedures
- ASTM D2990-01: Standard Test Methods for Tensile, Compressive, and Flexural Creep and Creep-Rupture of Plastics

A brief description of each of these tests will be provided below.

ASTM F37: Standard Test Methods for Sealability of Gasket Materials

This test method provides a means of assessing the sealing properties of sheet and solid form-in-place gasket materials at room temperature. It is devised for both liquid leakage measurements, as described in Method A and for both liquid and gas leakage measurements as described in Method B. Both of these test methods can be used for evaluating the sealing characteristics of a gasket material under various compressive flange loads.

ASTM D4065-06: Standard Practice for Plastics: Dynamic Mechanical Properties: Determination and Report of Procedures

This test method is designed to provide means of measuring the transition temperatures, elastic, and loss moduli of plastics over a range of temperatures, frequencies, or time, by free vibration and resonant or nonresonant forced vibration techniques. Viscoelastic properties of plastics can be evaluated while the test sample is subjected to different modes of dynamic loading, such as, tensile, bending or shear.

ASTM D2990-01: Standard Test Methods for Tensile, Compressive, and Flexural Creep and Creep-Rupture of Plastics

This test method comprises measurement of the extension or compression with respect to time and time-to-rupture, or failure of a specimen subject to constant tensile or compressive load under specific environmental conditions.

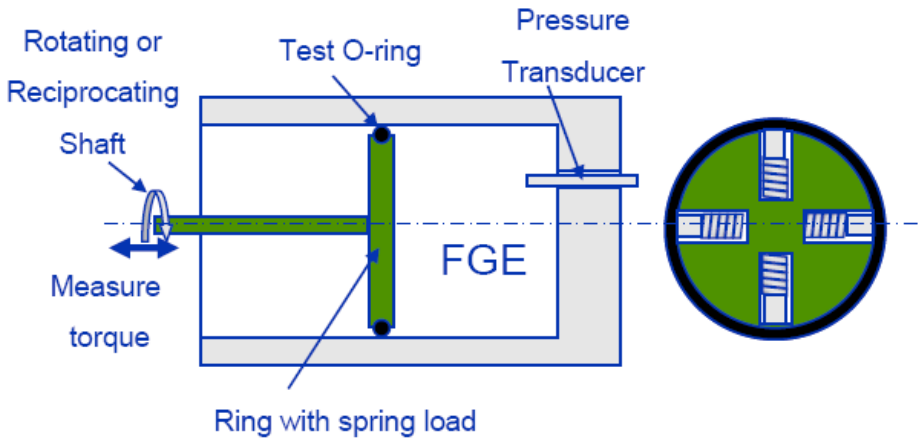
It is concluded that there is a scarcity of literature data available for the evaluation of dynamic seals (particularly, those used with EtOH-gasoline blends) as dynamic seals usually entail far more extensive testing than static seals due to a number of reasons including but not limited to the following:

- the effect of varying compressive/shear loading on elastomeric materials,
- the difficulty of maintenance of seal shape during relative movement,
- the effect of wear of the mating surface on the seal material.

As mentioned above, as an alternative to the ASTM tests, application based dynamic seal test equipment can be custom-made. An example of this is the “seal configuration test” developed by Yentzen[27], et al. to test elastomeric seals under oxygen exposure. In this test apparatus, the

wear of the material in an environment was evaluated as a function of the time to failure by leakage. A shaft with an O-ring groove was fitted with the elastomer of interest. The shaft is then slid into a test cell, which can be filled with the desired test environment (in our case, FGE/gasoline blend) and sealed. The tests could be run while a shaft is reciprocated over a known stroke and frequency during a pre-determined number of cycles. A schematic of this test set up is provided in Figure 10.

Figure 10 Conceptual schematic of the dynamic seal testing device



Further investigation of dynamic seals and if needed, the design of a new test apparatus for the evaluation of elastomeric seals under dynamic loading conditions will be pursued in the future phases of this project.

5.0 Summary and Recommendations

A comprehensive literature review and a survey on the current practices used in gasoline/EtOH industry and their reported effects on the performance of elastomeric seal materials were compiled from various resources and test standards in the public and private domains. In light of the knowledge gained from this literature survey outlined in the first three chapters, a set of test activities was proposed in the Chapter IV for the evaluation of the performance of elastomeric seals exposed to EtOH/gasoline blends under dynamic and static loading conditions.

The major findings of this survey along with some recommendations could be outlined as:

- For a satisfactory performance, an elastomeric seal material should possess the following features:
    - Good mechanical property levels suitable for service temperature, pressure and seal design. Some of the important properties comprise:
        - Compression set
        - Stress relaxation rate
        - Young's modulus

  - Elongation/strain at break
  - Tear strength
- Good resistance to swelling/shrinking in gasoline blends containing oxygenates in contact with the seals during service.
- Good resistance to chemical attack by any of the fluids which contact the seal during service; a seal is often exposed to two different media; one is often air.
- Good stability at the extremes of the service temperature range; temperature effects interact with all of the above factors.

- According to the API Report 1132 [28] , the results of a survey conducted in forty-four petroleum and other companies based on their use of nonmetallic materials exposure to oxygenated fuels showed that most companies increased their usage of FKM type materials and PTFE for elastomer parts subjected to static sealing and dynamic sealing while in contact with gasoline containing oxygenates (EtOH and MeOH).
- Maximum absorption of a liquid by an elastomer depends on the difference in δ values; the closer they are, the more likely is fluid absorption.
- Dissolved liquids diffuse into the elastomer bulk over a period of time depending on both the value of the diffusion coefficient (which depends on the fluid and the elastomer) and the seal section and geometry.
- Volume swelling is an important measurement when considering tolerances for housing design. Some of the factors influencing the swelling of elastomers are:
  - Increasing liquid **viscosity** lowers the rate of absorption and the level of equilibrium mass uptake.
  - Increasing **temperature** may increase swelling by a modest amount.
  - An elastomer exposed to an **immiscible liquid mixture** will eventually swell as if it' s exposed to the more compatible liquid (i.e., the one with the nearest δ), even if the sample does not directly contact that liquid in a pure form.
- Swelling of elastomers over 20 % are reported to cause several problems including, overfill of the seal housing groove, seal extrusion damage, extremely high stresses in the seal and in the housing, occasional fracture of metal components and progressive degradation of elastomers.
- The researchers at DuPont Performance Elastomers reported volumetric swell and permeation rate test results for six Viton® fluoroelastomers of varying fluorine contents in six different blends of fuel and ethanol ranging from 100% ASTM Fuel C hydrocarbon test fuel to 100% ethanol. Their results indicated that:

  - The lower fluorine types of Viton swelled more than the higher fluorine types. The highest swelling was observed with all six types of Viton® whenever CE-25, i.e., 25% ethanol with ASTM Fuel C was used as the test fuel.
  - The permeation results are reported to exhibit very similar trends to those of volumetric swell results such that the CE-25 fuel consistently exhibited the highest permeation rate regardless of the FKM polymer tested. Permeation rates of Viton elastomers with lower fluorine content are observed to reach a peak of ~100 g-mm/m^2/day in CE-25 fuel while they are determined to be ~25 g-mm/m^2/day in Fuel C and ~20 g-mm/m^2/day in neat ethanol.

- The results of the surveys conducted by Underwriters Laboratories Inc. (UL) on the E85 dispenser material compatibility indicated that some elastomeric material incompatibility issues are observed in the usage of ethanol in Brazil such that dynamic synthetic rubber components, such as, nitrile rubber, are reported to exhibit excessive swelling or deterioration while it was indicated that no modifications were needed for static seal applications in many cases. Replacement of nitrile rubber components with the fluoroelastomeric materials were recommended for the dynamic loading conditions. No information was found on the degradation of E85 dispensing equipment being significantly faster than that of gasoline handling equipment.
- There is not enough data or a well-defined test standard in the literature for evaluating the properties of elastomeric seals under dynamic loading conditions. A set of tests will be performed on elastomeric seals either by designing a new test apparatus which will simulate dynamic loading conditions or by following ASTM test standards.
- So as to understand whether swelling of elastomers is reversible or not, the effect of subsequent fluid transitions in fuel dispensing equipment on the elastomeric seal performance will be evaluated after subjecting elastomers first to the gasoline/ethanol blends and then to the neat gasoline blends.

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7.0 ABBREVIATIONS

AFDC	Alternative Fuels and Advanced Vehicles Data Center
AFV	Alternative fuel vehicle
AHJ	Authorities having jurisdiction
AST	Aboveground storage tank
BTU	British thermal unit
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
EPA	U.S. Environmental Protection Agency
EPAct	Energy Policy Act
FFV	Flexible fuel vehicle
LEV	Low Emission Vehicle
NEVC	National Ethanol Vehicle Coalition
RFA	Renewable Fuels Association
UL	Underwriters Laboratories, Inc.
LDV	Light-duty vehicle
NREL	National Renewable Energy Laboratory
UST	Underground storage tank
FGE	Fuel Grade Ethanol
E10	10% ethanol, 90% gasoline
E85	85% ethanol,15% hydrocarbons
ETBE	Ethyl tertiary butyl ether
MTBE	Methyl tertiary butyl ether
HC	Hydrocarbon
NMHC	Non-methane hydrocarbon
FPM	International designation for Fluoroelastomers according to ISO standards
FKM	ASTM Designation for Fluoroelastomers
FFKM	ASTM Designation for Perfluoroelastomers

8.0 Glossary

ABRASION - progressive wearing away of a surface in service by mechanical action such as scraping, rubbing, or erosion.

ABRASION RESISTANCE - resistance of a rubber compound to wearing away when in dynamic contact with an abrasive surface.

ABSORPTION - physical mechanism by which one substance attracts and takes up another substance (liquid, gas, or vapor) into its interior.

ACCELERATED LIFE TEST - any set of test conditions designed to reproduce in a short time the deterioration obtained under normal service conditions.

ACCELERATED SERVICE TEST - bench or service test in which a particular service condition, such as speed, temperature, or continuity of operation, is exaggerated so as to obtain a more rapid result.

ACCELERATOR - chemical which speeds the vulcanization of an elastomer, so that it takes place in a shorter time or at a lower temperature. Picking up where an activator leaves off, an accelerator is often used in conjunction with a catalyst, hardener, or curing agent.

ACID RESISTANT - able to withstand the degrading effects of acids.

ACTIVATOR - chemical which initiates the vulcanization of an elastomer.

ACTUAL SIZE - exact size of an O-ring or seal in decimal dimensions (inches or millimeters), including tolerances.

ADDITIVE - material added to an elastomeric compound to alter its properties, e.g. a reinforcing agent to improve strength or a plasticizer to aid flexibility and processibility.

ADHERE - (a) to cling or stick together; or (b) to cause two surfaces to stick together.

ADHESION - tendency of rubber or other material to stick to a contact surface; may result from chemical or physical interlocking.

ADDHESIVE - substance used to hold materials together.

ADSORPTION - physical mechanism by which one substance attracts another substance (either solid, liquid, gas, or vapor) to its surface.

AERATION - air (or gas) bubbles built up within a liquid.

AFTER CURE - uncontrolled continuation of vulcanization after the desired cure has been effected and the heat source removed; not the same as post cure.

AGING - change in rubber characteristics over time brought about by environmental factors such as heat and light.

AIR CHECKS / TRAPS - surface marks or depressions on a molded rubber product resulting from air getting trapped between the material being cured and the mold surface.

AIR CURING - vulcanization of rubber in air as opposed to steam or press vulcanization.

ALCOHOLS - organic compounds containing the hydroxyl (-OH) group; used as starting points in the production of synthetic resins, synthetic rubbers, and plasticizers.

ALIPHATIC HYDROCARBONS - organic compounds recognizable by their straight chains of carbon atoms. Three subgroups comprise aliphatic hydrocarbons: paraffins (alkanes), olefins (alkenes), and acetylenes (alkynes).

AMBIENT TEMPERATURE - temperature of the environment surrounding a component; not necessarily the same as atmospheric temperature.

AMINE - chemical used as a curing agent for fluoroelastomers; also a film-forming inhibitor used to prevent corrosion in oil-field tubular goods.

AMORPHOUS - non-crystalline in structure; may be used in reference to polymers whose molecular chains are irregular and that therefore do not fit closely together.

ANILINE POINT - lowest temperature at which equal volumes of aniline and a petroleum fluid will completely dissolve in one another. The aniline point of oil is a measure of the aromatic content or the amount of unsaturated hydrocarbons present. The lower the aniline point, the higher the level of unsaturants, and the higher the potential for swelling certain rubber compounds.

ANTI-DEGRADANT - chemical added to an elastomeric compound to shield against the degrading effects of environmental elements like oxygen or ozone.

ANTI-EXTRUSION RING (DEVICE) - relatively hard, high modulus ring (or similar device) placed in the gland between the O-ring and the groove side walls, to prevent extrusion of the seal into the clearance gap; also known as a back-up ring.

ANTIOXIDANT - chemical added to a rubber compound to resist oxidation.

ANTIOZONANT - chemical added to a rubber compound to resist ozone (O_3) degradation.

AROMATIC HYDROCARBONS - organic compounds recognizable by their rings of carbon atoms. Benzene, for example, is a six carbon ring with three double bonds. Other aromatic hydrocarbons include toluene and xylene.

AS 568A - Aerospace Standard Uniform Dash Numbering System; specifies O-ring sizes based on their inside diameter (I.D.) and cross-section (W); supersedes and cancels AS 568 and ARP 568.

ASSEMBLED STRETCH - amount of stretch as measured once a seal is seated in the groove.

ATMOSPHERIC CRACKING - cracking and degradation of the physical properties of a rubber product exposed to atmospheric conditions; also known as weathering.

AXIAL SEAL - an O-ring that seals on a plane perpendicular to its axis instead of on its outside diameter (O.D.) or inside diameter (I.D.); also known as a face seal.

AXIAL SQUEEZE - compression on an O-ring's top and bottom surfaces, as with face (flange) type designs.

BACK-UP RING - relatively hard, high modulus ring placed in the gland between the O-ring and the groove side walls, to prevent extrusion of the seal into the clearance gap; also known as an anti-extrusion ring or device.

BACKRIND - ragged indentation at the parting line of a finished rubber product resulting from molding stresses.

BANBURY MIXER - specific type of internal mixer in which rubber compounds are blended.

BI-DIRECTIONAL SEAL - seal which provides fluid sealing on both sides.

BLEEDING - migration of plasticizers, waxes, or other compound ingredients to the surface of a molded rubber product; also known as blooming.

BLEMISH - mark or deformity on the surface of a molded product.

BLISTER - raised area on the surface of a molded product caused by the pressure of internal gases.

BLOOM - creamy or dusty deposit appearing on the surface of a molded rubber product; caused by the migration of certain compound ingredients to the rubber's surface after molding and storage.

BLOOMING - migration of plasticizers, waxes, or other compound ingredients to the surface of a molded rubber product; also known as bleeding.

BOND - (a) to unite two materials; or (b) the mechanical, chemical, or adhesive force which binds an elastomer to another object. Mechanical bonds use interlocking design characteristics to ensure continued physical contact. Chemical bonds are based on internal cross-linking. Adhesive bonds rely on cements or other external adhesives.

BREAK-OUT FRICTION - static frictional force which must be overcome to initiate movement; also known as static friction or stiction.

BRITTLENESS - tendency to crack upon deformation.

BRITTLENESS POINT - lowest temperature at which a rubber sample will not fracture or crack when struck once.

BUNA N - copolymer of butadiene and acrylonitrile; also known as NBR or nitrile rubber.

BUNA S - copolymer of butadiene and styrene; also known as SBR or styrene butadiene rubber.

BUTT JOINT - joining two seal ends such that the junction is perpendicular to the mold parting line.

BUTYL - copolymer of isobutylene and isoprene.

CATALYST - chemical that causes or accelerates the cure of a rubber compound, but that does not usually become a chemical component of the end product.

CAVITY - hollow space within the mold in which uncured rubber is shaped and vulcanized; also known as mold cavity.

CHAIN EXTENDER - chemical combined with a polyurethane pre-polymer; acts much like a cross-linking or vulcanizing agent used to cure rubber.

CHAIN SCISSION - breaking of molecular bonds within the backbone of a polymer due to chemical or thermal attack that divides the polymer chains into smaller segments, with a resulting loss in physical properties; also known simply as scission.

CHAMFER - beveled edge in a component to facilitate assembly of a seal onto a rod or shaft, or into a cylinder or housing; also known as a lead-in chamfer.

CHECKING - cracking or crazing of an elastomer's surface due to the action of sunlight; also known as sun checking.

CHLORINATED HYDROCARBONS - organic compounds having chlorine and hydrogen atoms in their chemical structure. Examples include trichloroethylene, methylene chloride, and methyl chloroform.

CHLORINATION - surface treatment using chlorine gas that reduces break-out and running friction in molded rubber seals.

CLEARANCE GAP - the gap between two mating surfaces.

CLEAVAGE - breaking of any chemical bond; most commonly refers to the breaking of cross-link bonds between polymer chains or sidegroups that are pendent to the polymer backbone.

COEFFICIENT OF THERMAL EXPANSION - may be linear or volumetric: (a) the coefficient of linear thermal expansion is the change in length per unit of length for a one degree rise in temperature; and (b) the coefficient of volumetric thermal expansion is the change in volume divided by the product of the original volume and the change in temperature. The coefficient of volumetric thermal expansion is three times the coefficient of linear thermal expansion for a solid material.

COLD FLEXIBILITY - ability of an elastomeric product to resist cracking or breaking when flexed or bent at low temperatures; also known as low temperature flexibility.

COLD FLOW - increasing deformation of a rubber material under a constant compressive load; also known as creep.

COLD RESISTANT - able to function in low temperature applications.

COMMERCIALLY SMOOTH - surface smoothness that is acceptable for use.

COMPATIBILITY - a seal material's resistance to having its chemical (and by extension, its physical) properties degraded (either temporarily or permanently) as a result of contact with a liquid or gas.

COMPOSITE SEAL - seal composed of two (or more) separate materials, such as rubber and metal, generally bonded together.

COMPOUND - (a) molecules made up of differing atoms; and (b) a mixture of polymers and other ingredients to produce an elastomeric material.

COMPRESSION MODULUS - ratio of compression stress (force in psi) to resulting compression strain (noted as a percentage of the original specimen thickness).

COMPRESSION MOLDING - thermoset molding technique in which the uncured rubber compound is put in a heated, open mold cavity and the mold is closed under pressure (often in a hydraulic press). The material flows to completely fill the cavity. Pressure is maintained until curing is complete.

COMPRESSION SEAL - seal effected by compressing a rubbery material between mating surfaces.

COMPRESSION SET - (a) the amount, expressed as a percentage of deflection, by which a rubber specimen does not return to its original thickness following release of a compressive load; and (b) the end result of a progressive stress relaxation. In terms of the life of a seal, stress relaxation is like dying, whereas compression set is like death.

CONDUCTIVE RUBBER - rubber material that is capable of conducting electricity, usually static electricity. To be classified as conductive, an elastomer must have a direct current resistivity of less than 105 ohm/cm.

COPOLYMER - polymer composed of two different monomers, chemically combined. For example, Buna N is a copolymer of butadiene and acrylonitrile.

CORROSION - progressive wearing away of a surface in service by chemical action.

CORROSIVE - material property that promotes corrosion of a mating sealing surface.

COVALENT BOND - bond between atoms consisting of a pair of shared electrons.

CRACKING - sharp breaks or fissures in a rubber surface caused by excessive strain and/or exposure to detrimental environmental conditions, such as ozone, weather, or ultraviolet (UV) light; also known as crazing.

CREEP - increasing deformation of a rubber material under a constant compressive load; also known as cold flow.

CRITICAL TEMPERATURE (T_c) - (a) regarding gases, the temperature above which a gas cannot be liquefied, regardless of the amount of pressure applied to it; and (b) regarding rubber compounds, the temperature above which a rubber can no longer strain crystallize.

CROSS-SECTION - (a) view of a seal, cut at right angles to the mold parting line, exposing the seal's internal structure; and (b) one-half the difference between the outside diameter (O.D.) and inside diameter (I.D.) of a seal; also known as width (W).

CRYOGENIC - pertaining to very low temperatures. Some molded articles are deflashed in cryogenic chambers.

CRYSTALLINE - containing crystals; may be used in reference to polymers whose molecular chains are very regular and that therefore fit closely together into a rigid pattern.

CURE - heat-induced process whereby the long chains of the rubber molecules become cross-linked by a vulcanizing agent to form three-dimensional elastic structures. This reaction transforms soft, weak, non-cross-linked materials into strong elastic products; also known as vulcanization.

CURE CURVE - graphic representation plotted by a batch testing device (such as an oscillating disk rheometer) showing a rubber sample's state of cure for a given time and temperature.

CURE DATE - the quarter and year indicating the molding date of a rubber part. For example, "1Q00" denotes a cure date in the first quarter (January, February, or March) of 2000.

CURING TEMPERATURE - temperature at which a rubber product is vulcanized.

CYCLE TIME - the time that elapses between a given point in one molding cycle and the same point in the next cycle (for example, loading of raw stock, through molding and unloading of finished parts, then back to reloading again). Generally speaking, the longer the cycle time, the more the process costs and the more expensive the finished part will be.

CYLINDER - chamber in which a piston, ram, rod, or shaft operates.

DAMPER - device capable of minimizing motion or dissipating energy, such as a shock absorber. Because an elastomer has a viscous phase, it can be thought of as a damper, i.e. the elastomer resists motion (deformation), making it an effective seal material.

DASH NUMBER - three-digit number preceded by a dash as specified by SAE Aerospace Standard 568A to indicate the O-ring size based on its inside diameter (I.D.) and cross-section (W); also known as size number.

DEFLASH - process of removing excess material (flash) from the parting line of a molded rubber product.

DEFLECTION - change in the shape of a seal as a result of compression; also known as deformation.

DEGASSING - the intentional, controlled evaporation of volatile substances out of a rubber material.

DEGRADATION - breakdown in chemical structure and/or loss of physical properties after exposure to harmful agents (such as heat, sunlight, oxygen, ozone, or weather).

DETERIORATION A condition of permanent chemical change in the seal compound effecting its performance.

DIAMETRAL CLEARANCE GAP - the difference in diameters between two mating surfaces to be sealed.

DIENE RUBBER - rubber containing a double bond in the main chain; such double bonds are vulnerable to attack (such as by oxygen, ozone, and UV light).

DIFFERENTIAL PRESSURE - difference in the amount of force being exerted on the high-pressure side of a seal (the side facing system pressure) relative to the low-pressure side (the side facing away from

system pressure). Differential pressure is responsible for forcing a seal toward the low pressure side of a gland.

DIISOCYANATE - hard segment in the polyurethane backbone; imparts toughness and heat resistance.

DOUBLE-ACTING SEAL - dynamic reciprocating seal capable of sealing in both directions of movement.

DOUBLE BOND - covalent bond consisting of two pairs of shared electrons. A double bond occurring between two carbon atoms (such as is found in the butadiene segment of nitrile rubber) is inherently more chemically reactive and is a site for both cross-linking and chemical attack.

DRY RUNNING - absence of liquid or lubrication in a dynamic sealing application.

DUROMETER - (a) an instrument that measures the hardness of rubber by its resistance to surface penetration of an indenterpoint; and (b) the numerical scale indicating the hardness of rubber. See also "Shore A Durometer" and "Shore D Durometer."

DYNAMIC - describes an application in which the mating surfaces to be sealed are in relative motion to each other.

DYNAMIC FRICTION - friction resulting from relative motion between two contacting surfaces.

DYNAMIC SEAL - seal functioning in an environment in which there is relative motion (e.g. reciprocating, rotary, or oscillating) between the mating surfaces being sealed.

ELASTICITY - an elastomer's inherent ability to readily regain its original size and shape after being released from a deforming load.

ELASTOMER - any natural or synthetic material meeting the following requirements: (a) it must not break when stretched 100%; and (b) after being held at 100% stretch for five minutes then released, it must return to within 10% of its original length within five minutes.

ELASTOMERIC COMPOUND - combination of a base polymer and additives.

ELECTRON - small, negatively-charged particle orbiting the nucleus of an atom; for electrically-neutral atoms, the number of electrons equals the number of positively-charged protons within the nucleus.

ELEMENT - term referring to a single type of atom making up a substance.

ELONGATION - percentage increase in original length (strain) of a specimen produced by a tensile force (stress) applied to the specimen. "Ultimate elongation" is the elongation at the moment the specimen breaks.

ENCAPSULATION - enclosure or jacket surrounding another material; for example, a Teflon® encapsulation over an O-ring core molded from a different material.

ENDOTHERMIC - absorbing heat.

EVAPORATION - direct conversion of a fluid from liquid to vapor.

EXOTHERMIC - giving off heat, as during a chemical reaction.

EXPLOSIVE DECOMPRESSION - phenomenon occurring in rubber seals after exposure to high-pressure gas. This gas permeates into the elastomer through flaw sites present in all molded rubber products. During an equilibrium shift (lowered pressure), the gas then expands within the seal, causing internal ruptures in high shear modulus (hard) materials and surface blisters in low shear modulus (soft) materials. Explosive decompression can be likened to "getting the bends."

EXTEND - add fillers or other low-cost materials to an elastomeric mixture in an effort to reduce costs and to increase the amount of compound that is available for use, i.e. "extend" its usage.

EXTENDER - relatively inexpensive and inert material added to an elastomeric compound to reinforce or modify properties (e.g. physical, mechanical, electrical, thermal), impart certain processing properties, or reduce costs; also known as a filler.

EXTRACTION - removal from a material, as when fuel or other system fluids chemically remove a compound's plasticizer, leading to seal shrinkage.

EXTRUSION - pressure-induced distortion or extension of part of a seal into the clearance gap between mating seal surfaces.

FACE - front surface of a seal; in an O-ring, the two surfaces that are perpendicular to its axis.

FACE SEAL - an O-ring that seals on a plane perpendicular to its axis instead of on its outside diameter (O.D.) or inside diameter (I.D.); also known as an axial seal.

FATIGUE RESISTANCE - capable of withstanding fatigue caused by repeated bending, extension, or compression; also known as flex resistance.

FILLER - relatively inexpensive and inert material added to an elastomer to reinforce or modify properties (e.g. physical, mechanical, electrical, thermal), impart certain processing properties, or reduce cost; also known as an extender.

FLASH - excess rubber remaining on the parting line of a molded rubber product.

FLAWS - surface imperfections that occur infrequently (i.e. not in a pattern), as with an isolated scratch or crack in the metal of a gland.

FLEX CRACKING - surface cracks caused by repeated flexural cycling.

FLEX RESISTANCE - capable of withstanding fatigue caused by repeated bending, extension, or compression; also known as fatigue resistance.

FLOW LINES - imperfections in a molded rubber product caused by imperfect flow of the material during molding; also known as flow cracks or flow marks.

FLUID - a liquid or a gas.

FLUOROCARBON - carbon backbone, organic compound having fluorine atoms in its chemical structure. Presence of the fluorine provides increased chemical and high temperature resistance.

FRICTION - motion resistance resulting from contact between mating surfaces, usually accompanied by liberation of heat energy.

FRICTION (BREAK-OUT) - static frictional force which must be overcome to initiate movement; also known as static friction or stiction.

FRICTION (RUNNING) - dynamic frictional force which must be overcome to maintain movement.

FUEL (AROMATIC) - fuel containing aromatic (ringed) hydrocarbons (such as benzene, toluene, and xylene). Aromatic fuels cause high swell of rubber.

FUEL (NON-AROMATIC) - fuel containing aliphatic (straight chain) hydrocarbons (such as octane). Non-aromatic fuels cause less rubber swell than aromatic fuels.

GASKET - static seal effected when a deformable material is sandwiched and compressed between two mating surfaces.

GATE MARK - raised spot or small depression seen on an injection or transfer molded product; caused when the finished molded part is removed from the injection nozzle (gate or sprue) through which the material is injected into the mold cavity; also known as a sprue mark.

GLAND - machined cavity into which an O-ring or other seal is fitted; includes the groove and the mating surface to be sealed.

GLASS TRANSISTION (T_g) - temperature at which a viscous polymer loses all ability to flow or store energy, becoming hard and brittle (like glass).

GOUGH-JOULE EFFECT - tendency of a stretched rubber specimen to retract when heated.

GROOVE - machined recess within a gland into which an O-ring or other seal is fitted.

HARDNESS - measure of rubber's relative resistance to an indenter point on a testing device. Shore A durometers gauge soft to medium-hard rubber. Shore D durometers are more accurate on samples harder than 90 Shore A.

HEAT AGING - loss of physical properties as a result of exposure to heat.

HEAT BUILD-UP - temperature rise in a molded rubber product due to hysteresis during repeated deformations.

HEAT RESISTANCE - rubber compound's capacity to undergo exposure to some specified level of elevated temperature and retain a high level of its original properties.

HERMETIC SEAL - an airtight seal.

HETEROPOLYMER - polymer composed of differing monomers.

HOMOGENOUS - used to describe a rubber material of uniform composition, with no fabric or metal reinforcement.

HOMOPOLYMER - polymer composed of identical monomers.

HYDROCARBONS - organic compounds with both hydrogen and carbon in their chemistry. Many organic compounds are hydrocarbons. Aliphatic hydrocarbons, such as butane, have a straight-chain structure. Aromatic hydrocarbons, such as benzene, are ringed structures.

HYDROGENATION - addition of hydrogen atoms to an organic compound to reduce the number of carbon-to-carbon double bonds that would otherwise be weak links in the polymer chain. For example, the hydrogenation of nitrile produces a great compound (HNBR) with both high strength and superior oxidation resistance.

HYDROGEN BOND - an electrostatic attraction between a hydrogen atom in one molecule and a small electronegative atom (like fluorine, oxygen, or nitrogen) in an adjoining molecule. Though not nearly as strong as covalent bonds, hydrogen bonds are present in such numbers in hydrocarbon polymers that they are an important source of polymer strength.

HYDROLYSIS - chemical decomposition as a result of contact with water.

HYGROSCOPIC - capable of absorbing moisture, especially from the air.

HYSTERESIS - percent of energy lost per cycle of deformation, or 100% minus the resilience percentage. Hysteresis is the result of internal friction and is evident by the conversion of mechanical energy into heat.

I.D. - inside diameter of a seal or component.

IDENTIFICATION - colored stripes or dots on seals to differentiate among rubber compounds.

IMMERSION - putting an article into a fluid so that it is totally covered.

IMMISCIBLE - not capable of being mixed. With elastomers, "immiscible" is generally analogous to "insoluble" and refers to a substance (such as a seal) that cannot be dissolved in a fluid (such as the fluid being sealed). In order to have long seal life, it is important to maximize immiscibility.

IMPACT - forceful contact between two bodies, at least one of which is in motion.

INERT - inactive or non-reactive; often used to describe a material (like Teflon®) that is impervious to many chemicals.

INHIBITOR - chemical added to an elastomeric compound to ensure vulcanization does not proceed too quickly.

INJECTION MOLDING - process in which preheated rubber is injected under pressure from the heating chamber through a series of runners and sprues and into a closed, heated mold cavity, then vulcanized. Injection molding is ideal for high-volume production of molded rubber parts.

INORGANIC - containing chemical structures not based on the carbon atom.

INSOLUBLE - not susceptible to being dissolved in a fluid.

INSTALLATION STRETCH - amount of stretch that a seal undergoes as it is being placed in the groove.

ION - atom with an electrical charge (either positive or negative) due to unequal numbers of protons and electrons. An ion with more protons than electrons will have a positive charge, whereas an ion with more electrons than protons will have a negative charge.

IONIC BOND - strong electrical attraction between oppositely charged atoms (ions).

ISO - International Organization for Standardization, a non-governmental organization whose primary aim is to develop guidelines on what constitutes an effective quality management system.

ISOTOPE - one of two or more distinct forms of a given element. Isotopes have the same atomic number (due to identical numbers of protons) but different atomic masses (due to unlike numbers of neutrons).

LAY - direction of the primary roughness pattern on a gland surface.

LEACHING - removal of soluble components, as when system fluids remove a compound's plasticizer, leading to seal shrinkage.

LEAD-IN (CHAMFER) - beveled edge in a component to facilitate assembly of a seal onto a rod or shaft, or into a cylinder or housing.

LEAK RATE - rate at which a fluid (liquid or gas) passes a seal or barrier.

LIFE TEST - laboratory test used to determine the length of a product's life in a defined set of service conditions.

LOAD - actual pressure at a sealing face; normally the sum of the interference load and the fluid pressure at work on the seal.

LOGY - term used to describe a material with poor visco-elastic properties.

LOW TEMPERATURE FLEXIBILITY - ability of an elastomeric product to resist cracking or breaking when flexed or bent at low temperatures.

MACROMOLECULE - large chainlike molecule, formed during a process called "polymerization," in which small molecules (monomers) form chemical bonds between one another; also known as a polymer.

MATING SURFACES - points where different parts of an assembly meet.

MAXIMUM CURE - point at which a rubber sample is cured as much as possible without being over-cured.

MAXIMUM TEMPERATURE - highest temperature a rubber compound can withstand prior to undergoing a physical or chemical change.

MEMORY - an elastomer's ability to regain its original size and shape following deformation.

MICROPORES - very tiny pores on the surfaces of a gland. The presence of micropores, even on finely-machined metal surfaces, contributes to break-out friction. However, these pores also help hold lubricants, so their total elimination is not advantageous.

MINIMUM TEMPERATURE - lowest temperature a rubber compound can withstand prior to losing rubbery properties.

MISCIBLE - capable of being mixed. In the case of elastomers, "miscible" is generally analogous to "soluble" and refers to a substance (such as an elastomeric seal) that can be dissolved in a fluid (such as the fluid being sealed). In order to have long seal life, it is important to minimize miscibility.

MISMATCH - asymmetrical seal cross section caused by dimensional or mating differences in mold sections.

MODULUS - the force in psi (stress) required to produce a certain elongation (strain), usually 100%; a good indication of toughness and resistance to extrusion; also known as tensile modulus or tensile stress.

MODULUS OF ELASTICITY - ratio of the stress (force in psi) to the strain (percent increase in original length) as measured on a rubber specimen; also known as Young's modulus (E); not the same as tensile modulus.

MOISTURE RESISTANCE - able to resist absorbing moisture from the air or during water immersion.

MOLD - (a) to shape or process a material into a usable form; and (b) metal tools, usually steel or aluminum, machined and assembled so as to create openable cavities for the purpose of shaping and vulcanizing rubber.

MOLD CAVITY - hollow space within the mold in which uncured rubber is shaped and vulcanized; also known simply as a cavity.

MOLD FINISH - surface finish of the mold; determines the surface finish of any product taken from that mold.

MOLD LUBRICANT - coating used in the mold cavity to prevent a molded rubber product from sticking to the cavity during removal; also known as mold release.

MOLD MARKS - imperfections in a molded rubber product replicating surface defects on the mold itself.

MOLD REGISTER - accuracy of alignment of mold plates and cavities. An improperly aligned mold is said to be off-register and will produce mismatched parts.

MOLD RELEASE - coating used in the mold cavity to prevent a molded rubber product from sticking to the cavity during removal; also known as mold lubricant.

MOLD SHRINKAGE - dimensional loss in a molded rubber product that occurs during cooling after it has been removed from the mold.

MOLD STORAGE - holding area in which removable mold plates are stored when not in use.

MOLECULAR WEIGHT - sum of the atomic masses of the elements forming a molecule.

MOLECULE - an electrically neutral aggregate of chemically bonded atoms.

MONOMER - small molecule capable of reacting with other molecules to form large chainlike molecules (macromolecules) called polymers.

MOONEY VISCOMETER - shearing disk device used to gauge the viscosity of a rubber sample under heat and pressure. Named for developer Melvin Mooney, this was once the standard tool for determining processing characteristics but has now largely been replaced by the rheometer.

MULTIPLE CAVITY MOLD - mold in which more than one article can be made at a time.

NEUTRON - non-charged particle within the nucleus of an atom; hydrogen is the only atom which contains no neutrons.

NIBBLING - progressive mode of seal failure that occurs when excessive pressure forces a portion of an O-ring or other rubber seal into a clearance gap. Expansion and contraction of the gap (breathing) caused by pressure cycling traps extruded portions of the seal in the gap, resulting in bite-like portions (nibbles) being removed from the seal.

NITRILE (BUNA-N) - copolymer of butadiene and acrylonitrile widely used in O-rings and other seals.

NOMINAL SIZE - approximate size of an O-ring or seal in fractional dimensions (inches); typically given solely for reference purposes; also known as nominal dimension.

NON-FILL - defect in a finished molded part caused by the rubber failing to completely fill the mold cavity.

OCCLUSION - (a) mechanical process by which vapors, gases, liquids, or solids are entrapped within the folds of a given substance during working or solidification; and (b) the materials entrapped by this process.

O.D. - outside diameter of a seal or component.

OFF-REGISTER - mismatched O-ring cross-section caused by misalignment of mold cavities.

OIL RESISTANT - ability of vulcanized rubber to resist swelling and deterioration due to oil exposure.

OIL SWELL - increase in volume of a rubber product as a result of oil absorption.

OPTIMUM CURE - vulcanization state yielding the most desirable properties.

ORGANIC - containing chemical structures based on the carbon atom.

O-RING - solid elastomer ring seal of circular cross-section; technically, a torus.

OSCILLATING SEAL - rotary seal with limited, reversing travel; as in an on/off valve.

OUTGASSING - phenomenon occurring in vacuums where the volatile materials in a rubber compound are vaporized and released into the environment.

OVER CURE - longer than optimum vulcanization causing some properties to be degraded. Over-cure can be of two types. In the first type, the material continues to harden, the modulus rises, and both tensile strength and elongation fall. In the second type, the rubber begins to break down. The material softens, and the modulus, tensile strength, and elongation all decrease.

OXIDATION - reaction of oxygen with a rubber compound, usually resulting in surface cracking and/or changes in the physical properties of the material.

OZONE (O_3) - unstable form of oxygen (usually generated by electricity) that can cause surface cracking in some elastomers.

OZONE RESISTANCE - ability of a rubber material to withstand exposure to ozone without cracking or otherwise deteriorating.

PACKING - generic name for a compression-type dynamic seal housed within a gland.

PARTING LINE - mark on a molded rubber article showing where separate parts of the mold cavity met.

PERIPHERAL SQUEEZE - compression applied to the O.D. of a seal when installed in a bore that is smaller than the O.D. of the seal.

PERMANENT SET - amount of deformation in a rubber part after a distorting load has been removed.

PERMEABILITY - measure of the ease with which a liquid or gas can pass through a rubber material.

PIGMENT - substance included in a material mixture to colorize it in a specific way.

PIT OR POCK MARK - small surface void in a molded rubber product caused by mechanical erosion (wear) or chemical action.

PLASTICIZER - chemical substance added to a rubber compound to soften the elastomer, provide flexibility at low temperatures, and improve processing; also known as a softener.

POISSON'S RATIO - ratio of the change in width per unit of width to the change in length per unit of length. For most rubber materials, Poisson's ratio is essentially equal to 0.5.

POLARITY - imbalance in electrical charge (dipole moment) caused by covalent bonds occurring between two dissimilar atoms. The difference in electrical charges of each atom creates a slight negative charge on one atom and a slight positive charge on the other atom. Since hydrocarbon oils are usually non-polar, they are repelled by polymers that have polarity, resulting in increased oil resistance and other properties not found in elastomers containing only carbon and hydrogen atoms.

POLYMER - large chainlike molecules (macromolecules) made up of small repeating units (monomers). When two different monomers are chemically combined, the resulting product is called a copolymer. When three different monomers are involved, the result is a terpolymer.

POLYMERIZE - to chemically unite two or more monomers or polymers to form a molecule with a higher molecular weight.

POLYOL - soft segment in the polyurethane backbone; imparts rubber-like softness and flexibility.

POROSITY - quality or state of having pores or holes in a material.

POST CURE - controlled continuation of vulcanization, usually in an oven, to complete the curing process, drive off residual byproducts, and provide stabilization of parts; not the same as after cure.

POTABLE - (a) drinkable; and (b) a liquid that is safe or suitable for drinking.

PRE-POLYMER - polyurethane polyol and diisocyanate mixture prior to combination with a chain extender.

PROFILOMETER - an instrument used to gauge surface roughness, i.e. to determine the "profile" of a given surface.

PROTON - positively-charged particle within the nucleus of an atom; for electrically-neutral atoms, the number of protons exactly equals the number of negatively-charged electrons orbiting the nucleus. The number of protons in an atom is also said to be that element's atomic number, e.g. carbon has six protons, so its atomic number is 6.

QUAD RING - solid elastomeric ring seal with a four-lobed cross-section.

QPL - Military Qualified Products List; listing of commercial products shown in pretesting to meet the demands of a specification, particularly a federal specification.

QS 9000 - Quality System developed by the automotive industry to supplement the ISO 9000 standard.

RADIAL SEAL - O-ring or seal having compression applied to its outside diameter (O.D.) and inside diameter (I.D.).

RADIAL SQUEEZE - compression on an O-ring's outside diameter (O.D.) and inside diameter (I.D.), as with cap and plug type configurations.

RADIUS - (a) the distance from the center of a circle to the edge, or one-half the diameter; and (b) to round off a sharp corner, as in the "radiusing" of a gland's top edges to prevent them from nicking or cutting an O-ring during installation.

RECIPROCATING SEAL - dynamic seal used to seal pistons or rods that are in linear motion.

REINFORCING AGENT - material added to an elastomer to improve physical properties such as tensile strength, tensile modulus, and compression modulus.

RELATIVE HUMIDITY - ratio of the amount of water vapor present in the air to the greatest amount that could be present at a given temperature; expressed as a percentage.

RELAXATION - decrease in the force exerted against a mating part by a rubber component that has been under a constant load for a period of time.

REPEATABILITY - consistency of test results taken within a single lab. For example, the similarity (or lack thereof) of multiple durometer readings taken on a single sample with the same tester.

REPRODUCIBILITY - consistency of test results taken among several different labs. For example, the similarity (or lack thereof) of multiple durometer readings taken on a single sample with a series of different testers.

RESILIENCE - a compound's ability to rapidly regain original size and shape following deformation. Also known as rebound.

REVERSION - condition in an elastomer caused by thermal or chemical attack whereby chemical bonds are broken with a resulting loss in physical properties.

RHEOMETER - cure meter which determines and plots a cure curve illustrating the state of cure for a given time and temperature; typically either an Oscillating Disk Rheometer (ODR) or a Moving Die Rheometer (MDR).

ROOT MEAN SQUARE (RMS) - The square root of the sum of the squares of deviation from true flat; a measure of surface roughness (as with glands or shafts) generally noted in microinches.

ROTARY SEAL - seal capable of sealing between a rotating shaft and an outer surface, such as a groove or housing bore.

ROUGHNESS - closely-spaced irregularities on a gland's surface that are the result of manufacturing and/or cutting (as by tools or abrasive materials.

ROUGHNESS AVERAGE (Ra) - measure of the roughness of a metal surface; determined by averaging the absolute value of the deviations from a mean line over a set evaluation length.

RUBBER - natural or synthetic elastomeric substance.

RUNNING FRICTION - dynamic frictional force which must be overcome in order to maintain movement. Running friction generally necessitates the use of some form of lubrication.

RUNOUT (SHAFT) - phenomenon which occurs when the shaft's axis and the axis of rotation are different, causing the shaft to wobble or gyrate; expressed in inches followed by the abbreviation "TIR" (Total Indicator Reading).

SATURATED BONDS - single bonds between carbon atoms and other atoms (such as hydrogen) that are less reactive and less prone to chemical attack than carbon-to-carbon double or triple bonds. The carbon atoms in the backbone of an organic polymer are each capable of forming four individual and separate single covalent bonds.

SATURATION - (a) addition of atoms to a compound to occupy the otherwise "open" or unbonded sites on a polymer chain; results in a more stable, less reactive compound. For example, a highly-saturated organic compound has almost every carbon atom already bonded to a hydrogen atom and therefore has

a dramatically reduced ability to interact with other compounds and an increased resistance to chemical attack. Saturation using hydrogen atoms is also known as hydrogenation; and (b) state in which most of the carbon atoms in an organic polymer's backbone have formed four individual and separate covalent bonds, resulting in increased chemical resistance as there are fewer double bonds that are susceptible to chemical attack.

SCISSION - breaking of molecular bonds within the backbone of a polymer due to chemical or thermal attack that divides the polymer chains into smaller segments, with a resulting loss in physical properties; also known as chain scission.

SCORCHING - premature curing of rubber during storage or processing, usually caused by excessive heat.

SEAL - device that prevents fluid flow.

SEAL WIDTH (W) - axial dimension of a seal. In an O-ring, this is the same as the cross-section.

SERVICE - operating conditions, such as temperature, pressure, chemical environment, and surface speeds, under which a seal must perform.

SERVICE TEMPERATURE - range of temperatures to which a rubber compound will be subjected in a given application.

SHAFT - rotating or reciprocating component that operates within a cylinder or housing.

SHEAR - deformation of a material or surface as a result of sliding or rubbing contact with another surface.

SHEAR MODULUS (G) - measure of stiffness or resistance to deformation taken in shear rather than in tension; technically, the ratio of a shearing stress (force in psi) to shearing strain (amount of linear deflection divided by the specimen thickness). In rubber materials, shear modulus is one-third of Young's modulus (E); not the same as tensile modulus.

SHELF-AGING - degradation of a rubber material's properties that occurs in storage over time.

SHELF LIFE - length of time a molded rubber compound can be stored without suffering significant loss of physical properties.

SHORE A DUROMETER - instrument used to gauge soft to medium hard rubber based on resistance to a frustum (truncated) cone indenter point; most accurate for materials below 90 Shore A.

SHORE D DUROMETER - instrument used to gauge hard rubber based on resistance to a sharp, 30° angle indenter point; most accurate for materials at or above 90 Shore A.

SHRINKAGE - (a) after vulcanization, dimensional loss in a molded rubber product that occurs after it has been removed from the mold and allowed to cool; and (b) in seal service, a decrease in seal volume due to extraction of soluble components from the rubber compound by environmental fluids.

SILICONE RUBBER - silicon-oxygen backbone elastomer with excellent high temperature and low temperature properties.

SINGLE-ACTION SEAL - dynamic reciprocating seal capable of sealing in only one direction of movement.

SIZE - actual size refers to the actual dimensions of an O-ring or seal, including tolerances. Nominal size refers to the approximate size in fractional dimensions.

SIZE NUMBER - three-digit number preceded by a dash as specified by SAE Aerospace Standard 568A to indicate the O-ring size based on its inside diameter (I.D.) and cross-section (W); also known as dash number.

SKIVING - slicing of a seal's surface, as by gland edges during installation.

SOLUBLE - susceptible to being dissolved in a fluid.

SOLVENT - any substance, typically a liquid, capable of dissolving other substances.

SOUR CRUDE - petroleum oil contaminated with hydrogen sulfide (H_2S).

SOUR GAS - natural gas contaminated with hydrogen sulfide (H_2S).

SPECIFIC GRAVITY - ratio of the weight of a given substance to the weight of an equal volume of water at a specified temperature. Specific gravity is often used to identify rubber compounds.

SPIRAL FAILURE - type of O-ring failure occurring when one portion of the ring tends to roll while another portion slides in the gland, causing twisting and seal failure.

SPRUE MARK - raised spot or small depression seen on an injection or transfer molded product; caused when the finished molded part is removed from the injection nozzle (sprue or gate) through which the material is injected into the mold cavity; also known as a gate mark.

SQUEEZE - compression of an O-ring's cross-section between mating surfaces; noted as both a decimal measurement (in inches and/or millimeters) and as a percentage of the original cross-section (width). Radial compression occurs on the outside diameter (O.D.) and inside diameter (I.D.). Axial compression occurs on the top and bottom surfaces.

STATIC - describes an application in which there is no relative motion between the mating surfaces to be sealed.

STATIC FRICTION - initial frictional force which must be overcome to initiate movement; also known as break-out friction or stiction.

STATIC SEAL - seal functioning in an environment in which there is no relative motion between the mating surfaces being sealed.

STICK-SLIP - irregular or jerky seal motion caused by varying amounts of static and dynamic friction.

STICTION - initial frictional force which must be overcome to initiate movement; also known as static friction or break-out friction.

STOICHIOMETRY, PERCENT - level of curative (chain extender) used on a given pre-polymer. Percentages used have varying effects on the physical properties of the finished elastomer.

STRAIN CRYSTALLIZATION - partial crystallization of an elastomer that temporarily results when a stretching force causes the tangled macromolecular chains to untangle and align to form crystals; the chains revert to their normal state of entanglement when the force is removed. Most elastomers do not strain crystallize, but natural rubber, chloroprene (Neoprene®), and hydrogenated nitrile will.

STRESS RELAXATION - steady decline in sealing force when an elastomer is compressed over a period of time. In terms of the life of a seal, stress relaxation is like dying, whereas compression set is like death.

STRETCH - measured as a percentage increase in the inside diameter (I.D.) of an O-ring, stretch results in a reduction and flattening of the seal's cross-section. There are two types of stretch: installation stretch (as the seal is being placed in the groove) and assembled stretch (once the seal is seated).

SUBLIMATION - direct conversion of a substance from a solid state to a vapor state, and from a vapor back to a solid. The substance does not become liquid during either transition.

SUN CHECKING - cracking or crazing of an elastomer's surface due to the action of sunlight; also known simply as checking.

SURFACE FINISH - average value of exterior roughness, often expressed in microinches RMS (Root Mean Square) or Ra (roughness average).

SWELL - volumetric increase of an elastomeric material when in contact with a fluid.

TEAR RESISTANCE - resistance to the growth of a nick or cut in a rubber specimen when tension is applied.

TEAR STRENGTH - Tear strength is a measure of a material's resistance to tear, noted in pounds per inch. Typically, the tear strength of most compounds is relatively low. If less than 100 lbs. / in., the seal may nick or cut easily during assembly and fail prematurely under further flexing or stress. Poor tear strength also may indicate poor resistance to abrasion, an important consideration in dynamic seal applications.

TEMPERATURE (MAXIMUM) - highest temperature a rubber compound can withstand prior to undergoing a physical or chemical change.

TEMPERATURE (MINIMUM) - lowest temperature a rubber compound can withstand prior to losing rubbery properties.

TEMPERATURE RANGE - minimum and maximum temperature limits within which a rubber material will effectively perform.

TEMPERATURE (SERVICE) - range of temperatures to which a rubber compound will be subjected in a given application.

TENSILE MODULUS - the force in psi (stress) required to produce a certain elongation (strain), usually 100%; a good indication of toughness and resistance to extrusion; also known as modulus or tensile stress.

TENSILE STRENGTH - force in pounds per square inch (psi) required to break a rubber specimen.

TENSILE STRESS - the force in psi (stress) required to produce a certain elongation (strain), usually 100%; a good indication of toughness and resistance to extrusion; also known as modulus or tensile modulus.

TENSION SET - increase in the length of an elastomeric specimen following initial stretching and release.

TERPOLYMER - polymer composed of three different monomers chemically combined.

TETRAPOLYMER - polymer composed of four different monomers chemically combined.

THERMAL EXPANSION - linear or volumetric expansion of a material due to a temperature increase.

THERMOPLASTIC - an ionically-bonded polymeric material capable of being softened and formed when heated and injected into a cool mold. Upon cooling in the mold, a thermoplastic material will harden (freeze) and regain its original properties. A thermoplastic material can be reprocessed many times.

THERMOSET - polymeric material that forms permanent covalent bonds in an irreversible chemical reaction known as cross-linking, curing, or vulcanizing. Although the cured part can later be softened by heat, it cannot be remelted or reprocessed without extensive chemical treatment.

TIR - Total Indicator Reading; a measurement of shaft eccentricity that results when the shaft centerline is different from its axis of rotation.

TOLERANCE - allowable deviation (plus and minus) from a specified dimension.

TOLERANCE BUILD-UP - sum of the tolerances of all of the elements in a sealing system (e.g. I.D., cross-section, gland dimension); also known as tolerance stack-up.

TOOL - alternative name for a mold.

TORQUE - turning or twisting force that produces, or tends to produce, rotation of a shaft.

TORSIONAL STRENGTH - ability of a material to resist twisting and its damaging effects.

TORUS - donut-shaped ring; another name for an O-ring.

TPE - thermoplastic elastomer with rubber-like properties that is processed by injection molding, blow molding, extrusion, etc.

TPU - thermoplastic polyurethane elastomer that is processed by injection molding, blow molding, or extrusion.

TRANSFER CHAMBER - area within a transfer mold in which the elastomeric compound is heated prior to being squeezed down through a sprue, a runner, and a gate leading into a closed mold cavity to be shaped and vulcanized; also known as a pot.

TRANSFER MOLDING - method of molding thermosetting. The elastomeric compound is placed in a transfer chamber (pot) which is part of the mold, heated, then squeezed down through a sprue, a runner, and a gate leading into a closed mold cavity to be shaped and vulcanized. The advantages of transfer molding are that vulcanization is faster, so the process is more efficient, and the part is formed with little or no flash.

TRIM - removal of excess material from a molded rubber product.

TRIM CUT - damage done to a molded rubber product by excessive trimming.

UNDER-CURE - degree of incomplete vulcanization resulting in undeveloped physical properties and tackiness.

UNI-DIRECTIONAL SEAL - seal which provides fluid sealing on only one side.

UNSATURATED BONDS - double or triple bonds between carbon atoms creating sites that can undergo numerous chemical reactions, including addition of hydrogen atoms (hydrogenation), cross-linking, or chemical deterioration such as oxidation.

VAN DER WAALS FORCES - weak electrostatic attractions between polymer chains that are adjacent but that have not yet been cross-linked. These intermolecular forces are at their peak when a material is cool. Heating the material weakens the forces and “loosens” the chains, thus increasing pliability and making molding possible.

VISCO-ELASTIC - describes rubber-like materials having both a viscous phase (like a damper) and an elastic phase (like a spring).

VISCOMETER - shearing disk device used to gauge the viscosity of a rubber sample under heat and pressure. Often referred to as the Mooney Viscometer, this device was once the most common tool for determining processing characteristics but has now largely been replaced by the rheometer.

VISCOSITY - resistance to flow; the thicker the substance (such as a liquid), the more viscous it is, i.e. the less it flows.

VOID - unintended empty space, such as a pit or air pocket.

VOLATILE - readily vaporizable at a relatively low temperature.

VOLUME CHANGE - increase (swell) or decrease (shrinkage) in the volume of a specimen which has been immersed in a fluid, noted as a percentage of original volume.

VOLUME SHRINKAGE - volumetric decrease of an elastomeric material when in contact with a fluid; also known simply as shrinkage.

VOLUME SWELL - volumetric increase of an elastomeric material when in contact with a fluid; also known simply as swell.

VULCANIZATE - cured rubber compound.

VULCANIZATION - heat-induced process whereby the long chains of the rubber molecules become cross-linked by a vulcanizing agent to form three-dimensional elastic structures. This reaction transforms soft, weak, non-cross-linked materials into strong elastic products; also known as cure.

VULCANIZING AGENT - material added to an uncured batch of rubber that causes the polymer chains to crosslink to one another (vulcanize), forming a three-dimensional elastic structure; also known as curing agent.

WEATHERING - cracking and degradation of the physical properties of a rubber product exposed to atmospheric conditions; also known as atmospheric cracking.

WEEPAGE - seal leakage of less than one drop per minute; not necessarily an indication of seal failure.

WIDTH (W) - another term for the cross-section of an O-ring.

WIPER - flexible ring used to remove dirt, dust, mud, and other contaminants from a rod or a shaft in order to prevent them from entering a hydraulic, pneumatic, or mechanical system; also known as a wiper ring.

9.0 Appendix – Survey of Pipeline Companies

A brief survey of pipeline companies that are members of the ethanol SCC projects was conducted. The result of the survey is shown in Table A-1. The elastomers used do not necessarily indicate the materials tht will be chosen for ethanol service.

Table A- 1. Result of Survey of Pipeline Companies

Materials	Responses Received						Compatibility Literature	Comments
	A	B	C	D	E	F		
PTFE (teflon)	X	X	X	X	X	X		Some companies use rope packings
Buna-N	X	X	X	X		X	Excellent	
Polyurethane		X					Good	
Low-Swell Buna-N		X				X		
Reinforced Nitrile with Nylon		X						
Low Temperature nitrile		X						
Nitrile 90 Durometer		X						
Neoprene		X						
Viton		X		X		X	Excellent	
Kalrez		X	X		X	X		
Ekonol filled PTFE		X						
Graphite		X		X				Some companies use rope packings
Iglide T-500 (by Igus)		X						
Carboline Plasite 7122 HAR		X						Not an elastomer
Nitrile				X				
Viton A			X					
Viton GFLT			X		X			
Viton F			X					
Nylon			X					
Chemrez			X		X	X		
Garlock Gylon						X		
Viton Brown FKM						X		
Viton HK						X		

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