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LOW TEMPERATURE COMPRESSION SET RESISTANT O-RING MATERIALS

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14. ABSTRACT
This report was developed under SBIR Topic AF99-145. Materials used in the construction of aircraft hydraulic and fuel system o-rings and seals must provide long-term performance in aggressive chemical environments over a wide range of temperatures and loads. Current materials, while chemically compatible with existing aircraft fuels and hydraulic fluids, are subject to both low temperature and high temperature performance deficiencies and failure. New o-ring materials are needed that exhibit good low temperature performance characteristics at -40 °F (with a preference for -65 °F performance) while maintaining durability and service life requirements at operating temperatures up to 225 °F in fuels systems and 275 °F in hydraulic fluid systems. Multiple materials representing eight different classes of rubber chemistries were evaluated under this program for high temperature resistance to aircraft hydraulic fluids and jet fuels, and low temperature sealing performance before and after 3- and 28-day high temperature fluid exposure. Performance criteria and program test methods were derived from MIL-P-83461 and MIL-P-53153. *In situ* compression stress relaxation testing was also performed to evaluate static sealing performance as a function of fluid exposure time at high and low temperatures. The results of the testing performed under this program demonstrate the deficiencies of conventional o-ring materials, and the availability of new classes of o-ring materials that provide exceptional high temperature chemical stability and low temperature performance.

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EXECUTIVE SUMMARY

Materials used in the construction of aircraft hydraulic and fuel system o-rings and seals must provide long-term performance in aggressive chemical environments over a wide range of temperatures and loads. Current materials, while chemically compatible with existing aircraft fuels and hydraulic fluids, are subject to both low temperature and high temperature performance deficiencies and failure. New o-ring materials are needed that exhibit good low temperature performance characteristics at -40° F (with a preference for -65° F performance) while maintaining durability and service life requirements at operating temperatures up to 225° F in fuel systems and 275° F in hydraulic fluid systems.

Under Phase I of this SBIR program, METSS demonstrated the technical feasibility of using newly available material technologies to meet the performance criteria required of low temperature compression set resistant o-rings for use in advanced aircraft hydraulic and fuel systems. Under the Phase II program, multiple materials representing eight different classes of rubber chemistries were evaluated for high temperature resistance to aircraft hydraulic fluids and jet fuels, and low temperature sealing performance before and after 3- and 28- days of high temperature fluid exposure. Performance criteria and program test methods were derived from MIL-P-83461 and MIL-P-53153. *In situ* compression stress relaxation testing was also performed to evaluate static sealing performance as a function of fluid exposure time at high and low temperatures.

The work presented in this report builds on other efforts under which METSS has screened a large number of emerging rubber technologies to identify candidates to support the development of seals for low temperature (-40° F to -65° F requirements) compression set resistant applications in aircraft hydraulic and fuel systems, while still exhibiting long-term stability in aircraft fluids at temperatures up to 275° F. The results of the testing and evaluation efforts performed under this program demonstrate the deficiencies of conventional o-ring materials and highlight recent developments in rubber chemistry that have extended the performance range of these specialty rubbers at both low and high temperature extremes, even in chemically aggressive environments.

1.0 INTRODUCTION

1.1 BACKGROUND

Materials used in the construction of aircraft hydraulic and fuel system o-rings must provide long-term performance in aggressive chemical environments over a wide range of temperatures and loads. Existing seals are manufactured from nitrile rubber compounds that tend to lose elasticity with prolonged exposure to temperatures above 200° F. Furthermore, low temperature use of nitrile seals is limited to about -20° F. At temperatures approaching -20° F, nitrile seals not only lose sealing capacity and exhibit compression set but can also become brittle and may crack after prolonged high temperature exposure, potentially resulting in damage to aircraft systems and components. Due to the current limitation of nitrile seals, leakage eventually occurs during service and is not always detected in time to prevent primary system failure or collateral damage. This is a significant problem that affects both military and commercial aircraft.

While high temperature performance is typically adequate in most aircraft applications, nitrile seals can be severely degraded at the higher operating temperatures of today's advanced fighter aircraft. Low temperature performance, however, is perhaps the main concern with existing seal materials, as the nitrile rubbers and fluorosilicones used to support low temperature sealing requirements are either weak or prone to compression set, typically losing their elasticity (and therefore their ability to seal) after a relatively short period of service, and conventional fluoroelastomers have limited low temperature performance capabilities. These performance issues have created a need for the development of new materials that can meet the stringent demands of aircraft hydraulic fluid and fuel system o-ring seals.

1.2 PROGRAM EMPHASIS

This report will demonstrate the technical feasibility of using existing material technologies, as commercially available or in a modified form, to meet the performance demands of seals used in aircraft hydraulic system applications. Materials representing eight different classes of rubber chemistries were evaluated for high temperature resistance to aircraft hydraulic fluids and jet fuels, and low temperature sealing performance before and after 3 and 28 days of high temperature fluid exposure. While conventional o-ring materials were evaluated for comparative purposes, program emphasis was placed on recent developments in rubber chemistry that have extended the performance range of specialty elastomers at both low and high temperatures.

The performance requirements and test methods for o-ring materials used in aircraft hydraulic systems were defined by MIL-P-83461 - *Packing, Preformed, Petroleum Hydraulic Fluid Resistant, Improved Performance at 275 °F.* The advanced performance requirements targeted under this program included:

- O-ring materials must demonstrate high temperature (275° F) resistance to MIL-PRF-83282, MIL-PRF-87257 and MIL-PRF-5606 aircraft hydraulic fluids, as well as MIL-PRF-23699 engine oil.
- O-ring materials must demonstrate low compression set and the ability to seal at low temperatures (-65° F/-40° F) before and after high temperature fluid exposure.

The performance requirements and test methods for o-ring materials used in aircraft fuel systems were defined by MIL-P-5315 - *Packing, Preformed, Hydrocarbon Fuel Resistant.* The advanced performance requirements targeted under this program included:

- O-ring materials must demonstrate high temperature (225° F) resistance to JP-8, JP-8+100 and Jet Reference Fluid (JRF).
- O-ring materials must demonstrate low compression set and the ability to seal at low temperatures (-65° F/-40° F) before and after high temperature fluid exposure.

In addition to compression set testing, *in situ* compression stress relaxation (CSR) testing was also performed to evaluate static sealing performance as a function of fluid exposure time at high and low temperatures. CSR testing proved to be a reliable method of evaluating the performance of the candidate o-ring materials as it provided a direct means of monitoring high temperature performance degradation and low temperature sealing capacity.

2.0 CANDIDATE MATERIALS

2.1 PHASE II TARGET MATERIALS

An extensive effort was conducted to identify candidate material technologies and suppliers to support the program efforts. Methods of identification included literature and patent searches, discussions with rubber and raw material suppliers, rubber compounders, and a search for available information on the Internet. Based on the results of the Phase I program efforts, the work conducted under the Phase II program emphasized the identification and evaluation seals based on the following materials:

- ***Nitrile Rubbers and Highly Saturated Nitrile Rubbers*** – Nitrile rubbers (NBR) demonstrate excellent resistance to hydrocarbons. However, conventional nitrile rubbers offer limited high temperature performance and must be heavily plasticized to achieve good low temperature performance. Saturated (hydrogenated) nitrile rubbers (HNBR) offer exceptional performance characteristics and superior thermal-oxidative stability over a much broader temperature range. Originally intended to be an extension of standard nitrile rubbers with higher oxidation resistance, these materials are competing with fluorinated materials for high temperature and severe service environments. Several commercially available formulations provide excellent high temperature resistance and low temperature performance through specific modification of the precursor materials and specialty compounding. These materials offer other favorable characteristics, including good tensile properties, wear resistance, and durability. Commercially available materials claim service performance over a temperature range of -65° to 350° F.
- ***Epichlorohydrin Rubbers*** – Epichlorohydrin rubber materials have been commercially available since the mid 1960's and, due to the presence of oxygen in their backbone, exhibit excellent chemical resistance to hydrocarbons. Recent refinements of these materials have produced materials with increased low temperature flexibility.
- ***Fluoroelastomers*** – Fluoroelastomers are known for their chemical resistance and would be an ideal o-ring candidate for the present application if their low temperature properties could be improved. Under the Phase II program, particular emphasis was placed on evaluating new advancements in fluoroelastomer materials, including a new class of PFEs that offer exceptional low temperature and high temperature performance, excellent chemical resistance, and good mechanical properties.
- ***Fluorosilicones*** – Advanced fluorosilicones and fluorosilicone blends were also evaluated. Fluorosilicones are a very flexible class of fluoroelastomers, formed by copolymerization with silicone, which, while offering excellent resistance to low temperatures, are typically prone to compression set due to the inherent weakness imparted by the length of the silicone chain incorporated into the backbone of the copolymer.

2.2 MATERIALS SELECTED FOR TESTING

At the beginning of the Phase II program, over 80 materials from various suppliers were identified for possible consideration under the program. Samples were obtained for 55 of these materials. After an initial evaluation of product form and intended applications, this list was narrowed down to the list of 43 candidate materials that were tested under the program, as shown in Table 1. A quick evaluation of this list generates the following summary of test materials based on general material classification:[1]

Material Classification	Number of Materials
• Nitrile Rubbers (NBR)	7
• Hydrogenated Nitrile Rubbers (HNBR)	8
• Epichlorohydrin Rubbers (ECO)	2
• Fluorosilicones (FS)	2
• Fluoroelastomers (FKM)	9
• PFEs (PFE)	8
• PFE-Vinylidene Fluoride Rubbers (PFE-VF)	3
• Experimental Fluoroelastomers (X-FKM)	4

In providing this summary, care has been taken to try to differentiate emerging material technologies based on advanced fluoroelastomer chemistries from the more conventional fluoroelastomers (e.g., Viton®) that are currently used to support aircraft applications. The newer materials, generally characterized as pefluoroethers (PFE), PFE-vinylidene fluoride (PFE-VF) rubbers, and experimental fluoroelastomers (X-FKM), represent recent advances or new classes of materials based on fluoropolymer chemistry being developed to support high performance sealing applications. A brief description of the PFE rubbers and PFE-VF is provided. Details of X-FKM material chemistry have not been disclosed. The other material classes represented by the test set are conventional elastomers commonly used in o-ring applications and, therefore, do not require additional description.

2.2.1 PFE Rubbers

The basic chemical formula for the PFE rubbers evaluated under the program is presented in Figure 1. This structure has excellent chemical resistance due to the presence of the fluorine side groups instead of hydrogen groups that are prone to attack by aggressive chemicals. Rubbers based on this chemistry also exhibit excellent flexibility due to the presence and frequency of the oxygen bond in the backbone structure.

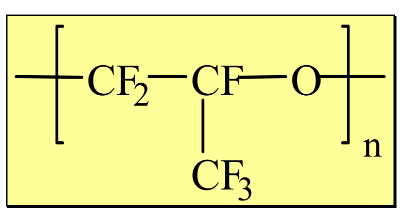

Figure 1. Basic chemical structure of PFE rubber.

[1] Specific materials information has been provided to the Air Force, including suppliers and product codes. Generic material descriptions are used in this report for reasons of supplier confidentiality.

A unique feature of this rubber is the method used to provide the cross-links. To support cross-linking, trifunctional silane moieties are added as end-caps to chain ends, which yield a cross-linked structure having the form similar to that illustrated in Figure 2.

2.2.2 PFE-VF Rubber

The basic structure of the PFE-VF rubber is presented in Figure 3.[2] While this material may be considered a subclass of PFE elastomers, this material differs from the PFE described in Figures 1 and 2 in both repeat unit structure and the nature of the cross-links. In the PFE-VF materials evaluated under this program, the cross-links are introduced by replacing one of the hydrogen atoms on the VF segments using polyhydroxy diols or diamines.

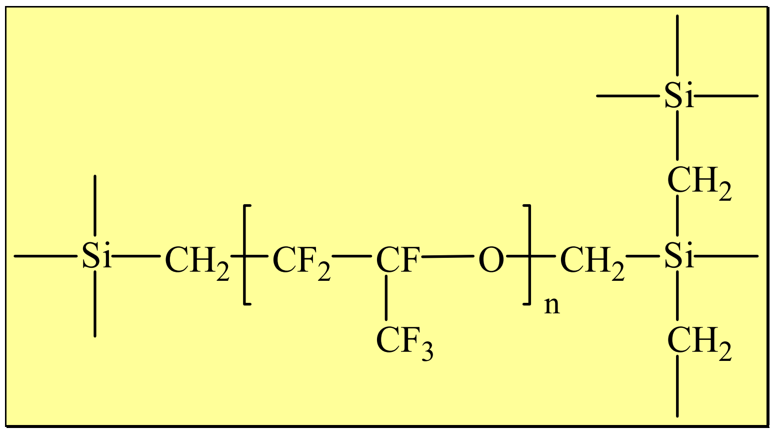

Figure 2. Basic chemical structure of cross-linked PFE rubber.

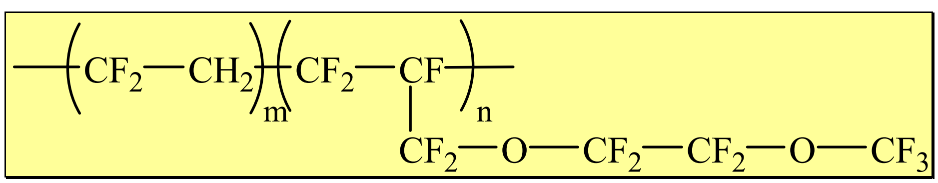

Figure 3. Basic structure PFE-VF rubber.

An attempt was made to investigate polyphosphazine fluoroelastomer (PNF) polymers and copolymers under the program. However, METSS was unable to obtain adequate samples for evaluation. These polymers, based on phenoxy ethers containing nitrogen-phosphorous atoms in their backbone, exhibit a high level of flexibility and low temperature performance. Although PNF materials are not currently commercially available, their demonstrated resistance to hydrocarbons and excellent performance properties (including chemical resistance and low temperature flexibility) across a range of temperatures made them worthy of consideration under the program.

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[2] Actual commercial materials may have proprietary molecular structures that are not accurately represented by the structure presented in Figure 3.

During the course of the program, each of the materials suppliers was provided information on the performance of their materials after testing and evaluation against the stated performance criteria. Willing suppliers were allowed to reformulate and resubmit samples for further consideration. Several of the program suppliers were very active participants in the Phase II program, submitting multiple formulation iterations or material advancements to support the program efforts. A standard L-stock nitrile sample (NBR-L), compounded for compliance with MIL-P-83461, was prepared and qualified by Akron Rubber Development Laboratory (ARDL) and included in all of the program efforts as a test control.

Table 1. Candidate Materials

Material ID	Material Type	Material ID	Material Type
3	Fluoroelastomer (FKM)	33	Nitrile (NBR)
4	Epichlorohydrin (ECO)	34	Nitrile (NBR)
5	Fluoroelastomer (FKM)	35	Hydrogenated Nitrile (HNBR)
6	Fluoroelastomer (FKM)	36	Hydrogenated Nitrile (HNBR)
8	Nitrile (NBR)	37	Fluoroelastomer (FKM)
9	Fluoroelastomer (FKM)	38	PFE (PFE)
10	Fluorosilicone (FVMQ)	39	PFE (PFE)
11	Fluoroelastomer (FKM)	40	PFE (PFE)
12	Epichlorohydrin (ECO)	41	PFE-Vinylidene Fluoride Rubber (PFE-VF)
13	Hydrogenated Nitrile (HNBR)	42	PFE (PFE)
17	Hydrogenated Nitrile (HNBR)	43	Nitrile (NBR)
18	Hydrogenated Nitrile (HNBR)	51	Experimental Fluoroelastomer (X-FKM)
19	Hydrogenated Nitrile (HNBR)	52	PFE-Vinylidene Fluoride Rubber (PFE-VF)
20	Hydrogenated Nitrile (HNBR)	53	PFE-Vinylidene Fluoride Rubber (PFE-VF)
21	Fluoroelastomer (FKM)	54	Experimental Fluoroelastomer (X-FKM)
22	Hydrogenated Nitrile (HNBR)	55	Experimental Fluoroelastomer (X-FKM)
23	Fluoroelastomer (FKM)	68	PFE (PFE)
25	Fluoroelastomer (FKM)	94	PFE (PFE)
29	Fluorosilicone (FVMQ)	94	PFE (PFE)
30	Nitrile (NBR)	100	PFE (PFE)
31	Nitrile (NBR)	200	Experimental Fluoroelastomer (X-FKM)
32	Nitrile (NBR)		

3.0 EXPERIMENTAL

The experimental portion of the program was quite extensive, covering four different test fluids, multiple exposure conditions and a breadth of performance criteria. Experimental methods are described in this section. Experimental results and discussion are presented in Section 4.0. The experimental efforts were conducted using a tiered approach so poor performers could be identified early during the course of the experimental work using simpler test methods. Complete testing and performance evaluation were reserved for the best performing materials. Multiple sets of tests were conducted on the best performing samples to verify observed performance and validate program results.

3.1 TESTING AND EVALUATION - COMPRESSION MOLDED TEST SAMPLES

Initial sample characterization data were obtained using test samples that were die-cut from compression molded slabs. The use of die-cut samples allowed more materials to be evaluated under the program as a number of the materials under program consideration were experimental in nature and not used in o-ring applications at the onset of the program efforts; as such, obtaining o-ring samples was difficult and it was easier to support testing, evaluation and reformulation efforts using compression molded plaques. For consistency and ease of comparison, all candidate materials were initially tested from samples die-cut from plaques before moving on to o-ring fabrication, testing and qualification efforts. All of the plaques used to support the program efforts were prepared and cured by the material providers for optimum performance. The data generated on samples cut from the molded plaques provided a solid basis for selecting candidate materials for further program consideration and progression to o-ring test sample preparation and testing efforts. Testing and evaluation methods for the compression molded test plaques are presented in this section.

3.1.1 High Temperature Fluid Aging

High temperature resistance to aircraft hydraulic fluids and fuels was determined by aging test samples in accordance with ASTM D 471: *Test Method for Rubber Property - Effects of Liquids*. Initial aviation fuel testing was conducted at 225º F using JP-8 and JP-8+100. Initial hydraulic fluid aging was conducted at 275º F using MIL-PRF-83282 and MIL-PRF-87257. Fluid aging experiments were conducted in friction air ovens for 3-day and 28-day periods. Test temperatures were maintained within ±3° F for the duration of the high temperature fluid aging experiments. Individual test specimens or replicate samples of the same material were aged in separate vessels with Teflon® lined lids to eliminate the possibility of cross-contamination. All test measurements performed on fluid aged samples were performed after excess fluid was removed from the samples and the samples were allowed to cool to room temperature.

3.1.2 Volume Swell, Weight Gain and Hardness Measurements

Volume swell, weight gain and hardness change measurements were performed on the candidate test materials after high temperature fluid aging. Initial experiments were conducted using ¾-inch diameter samples that were die-cut from cured sheets of the candidate test materials. After initial characterization (weight, hardness and dimensional volume), replicate samples (three for each test) were immersed in separate two-ounce vials of the target test fluids and placed in preheated friction air ovens for 3 and 28 days. A glass marble was placed in the bottom of the vial so the test sample would rest in an upright position to maximize fluid exposure. After aging, the samples were removed from the test fluids and allowed to cool to room temperature prior to postaging characterization.

Hardness measurements were performed in accordance with ASTM D 2240: *Test Method for Rubber Property - Durometer Hardness*. Due to the thickness of the test specimens, replicate samples had to be stacked (as allowable under the test method) to support accurate hardness determination. All hardness measurements were performed using a Gardner Shore A hardness tester and test stand. Hardness readings were taken immediately after full contact between the tester and sample.

3.1.3 Tensile Property Characterization

Tensile property measurements were performed in accordance with ASTM D 412: *Standard Test Methods for Rubber Properties in Tension*, using Type C dumbbell specimens (three replicates per test condition) that were die-cut from compression molded plaques. Tensile property testing was performed on as-received materials as well as tensile specimens that were fluid aged for 3- and 28- days in the target fluids. During fluid aging, tensile test specimens were fixed vertically on a rack and placed in one quart jars containing the appropriate test fluid; care was taken to make sure test specimens were separated during aging. Reported results include tensile strength (psi) and elongation at break (%) for unaged samples, and change (%) in tensile strength and elongation at break for aged samples. All tensile property measurements were performed at a constant cross-head displacement of 2 inches per minute using a Tinius Olsen 5000 universal testing machine. Elongation measurements reported in this document reflect cross-head displacement and not actual specimen strain data.

3.1.4 Dynamic Mechanical Analysis

Dynamic Mechanical Analysis (DMA) experiments were performed on all of the candidate materials, before and after fluid aging, to characterize low temperature mobility and define low temperature transitions.[3] Test samples measured ½-inch wide by 3-inches long; sample thickness was dependent on the thickness of the test plaques provided by the material suppliers, which were nominally 0.08 inches.[4] Fluid aged samples were aged in 4 oz jars. Two test samples (one each for 3- and 28- day aging) were aged in each jar, using a stainless steel wire spacer to separate samples and hold them in a vertical position during aging. All experiments were performed using a TA Instruments DMA 983 equipped with a liquid nitrogen cooling accessory (LNCA). DMA experiments were conducted in dual cantilever mode, with a grip spacing of 45 mm and 7 in-lb clamping force holding the sample. All DMA experiments were conducted at 1 Hz, scanning at 5° C/min from -100º C to 50º C.

3.1.5 Percent Extractables

The percent extractables was determined using the DMA test specimens. The weight of each specimen was determined prior to fluid aging. After the DMA experiments, the samples were dried under temperature and vacuum to remove all residual fluids and a final weight measurement was taken to determine the percent of materials extracted during the fluid aging experiments.

3.1.6 Compression Set Measurements

Compression set measurements were performed at room temperature and -40º F, both before and after fluid aging. Room temperature experiments were conducted in accordance with ASTM D 395: *Standard Test Methods for Rubber Property - Compression Set*. Low temperature compression set measurements were performed in accordance with ASTM D 1229: *Standard Test Methods for Rubber Property -*

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[3] ASTM D 2231: *Standard Practice for Rubber Properties in Forced Vibration*

[4] The actual dimensions (average of three per dimension) were determined for each sample tested and the data were input in the DMA analysis software for proper data analysis.

Compression Set at Low Temperatures. All compression set experiments (including the fluid aging experiments) were performed at 25% deflection using three replicate samples for each test condition.[5] All samples were allowed to recover for 30 minutes after removal from the compression set test jigs prior to measuring the final sample height for compression set determination. Room temperature compression set measurements were performed after 70 hours of compression at room temperature in air and in the test fluids. Low temperature compression set measurements of unaged samples were performed after 70 hours of compression in air at -40° F. Additional low temperature compression set measurements were performed after high temperature fluid aging. In this case, the test samples/vessels were allowed to cool to room temperature before removing the compression test jigs from the test fluids and then allowed to equilibrate for 22 hours at each of the test temperatures before compression set determination. All measurements for compression set were obtained at the actual compression set test temperature, i.e., room temperature and -40° F.

Compression set experiments were performed using ½-inch diameter discs that were die-cut from compression molded test plaques. Due to the limited thickness of the test plaques, several die-cut discs had to be stacked for each sample replicate to form the approximate ¼-inch high test sample geometry required by the test method. Three replicates of each sample were tested in each of the compression set experiments. Each set of three replicates was compressed between two triangular test plates with three height adjustable setscrews placed at each corner to fix the compression of the test samples at 25% and one tensioning screw fixed in the middle of the test jig to compress the o-rings to the setscrew height. The size and thickness of the triangular compression plates ensured constant deflection (compression) across each of the three replicate samples.

3.2 TESTING AND EVALUATION – O-RINGS

The best performing materials were selected based on the initial sample characterization data obtained using the die-cut test samples. Some o-rings of relatively poor performance were retained through the o-ring testing for comparative purposes. Standard size 214 o-ring samples were obtained for each of these materials and additional testing was performed on both aged and unaged o-ring test samples. There is a significant amount of overlap in the experimental methods presented for the die-cut samples, as separate o-ring testing was required to evaluate the effects of o-ring geometry and processing methods on final product performance. Initial testing and evaluation methods for o-ring samples are presented in this section. Some refinements in test procedures were used to support final testing and evaluation efforts for the best performing materials (see Section 3.3).

3.2.1 High Temperature Fluid Aging

High temperature resistance to aircraft hydraulic fluids and fuels was determined by aging test samples in accordance with ASTM D 471: *Test Method for Rubber Property - Effects of Liquids*. Aviation fuel testing was conducted at 225º F using JP-8 and JP-8+100. Hydraulic fluid aging was conducted at 275º F using MIL-PRF-83282 and MIL-PRF-87257. Fluid aging experiments were conducted in friction air ovens for 3-day and 28-day periods. All o-rings were fluid aged in 4-oz glass jars with Teflon® lid liners. A wire hook was fixed to each lid to suspend the o-ring samples in the test fluid. Each jar contained 3 o-rings separated by a thin metal spacer to prevent the individual o-rings from sticking together during high temperature fluid exposure. Test temperatures were maintained within ±3° F for the duration of the high temperature fluid aging experiments. All test measurements performed on fluid aged samples were performed after excess fluid was removed from the samples and the samples were allowed to cool to room temperature.

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[5] Samples were under 25% compression during fluid aging.

3.2.2 Physical Property Characterization

Dimensional volume and weight measurements were performed on o-ring samples before and after high temperature fluid aging to determine weight gain and volume swell. After initial testing, fluid aged samples were dried under temperature and vacuum to remove all residual fluids and a final weight measurement was performed to determine the percent of materials extracted from the o-rings during fluid aging. The tensile properties of the o-rings, both before and after fluid aging, were determined in accordance with ASTM D 1414: *Standard Test Method for Rubber O-Rings*. Reported results include tensile strength (psi) and elongation at break (%). All o-ring tensile property measurements were performed at a constant cross-head displacement of 20 inches per minute using a Tinius Olsen 5000 universal testing machine. Ultimate tensile stress and ultimate elongation values for the o-rings were determined by methods outlined in the ASTM. Three replicates of each of o-ring material were used in each experiment.

3.2.3 Compression Set Measurements

O-ring compression set measurements were performed at room temperature, -40º F and -65º F, both before and after fluid aging, in accordance with methods outlined in ASTM D 1414: *Standard Test Method for Rubber O-Rings*, with the exception that compression set values were determined based on the average thickness of the o-rings measured before and after the compression set experiments. All compression set experiments (including the fluid aging experiments) were performed at 25% deflection using three replicate samples for each test condition.[6] All samples were allowed to recover for 30 minutes after removal from the compression set test jigs prior to measuring the final sample height for compression set determination. Room temperature compression set measurements were performed after 70 hours of compression at room temperature in air and in the test fluids. Low temperature compression set was determined after 22 hours of compression in air at -40° F and -65° F. After high temperature fluid aging, the test samples/vessels were allowed to cool to room temperature before removing the compression test jigs from the test fluids and then allowed to equilibrate 22 hours at each of the test temperatures before compression set determination. All measurements for compression set were obtained at the actual compression set test temperature, i.e., room temperature, -40 ° F and -65° F.

Compression set measurements were performed on size 214 o-rings, using three replicates for each experimental condition. Replicate o-rings were compressed by placing a 1¼ diameter compression washer against the head of a 1¼ x $^{7}/_{16}$-inch bolt, followed by a series of ¾-inch diameter spacer washers. An o-ring was then placed against the compression washer with the spacer washers fitting inside of the o-ring. This was followed by another compression washer, and another series of spacer washers and another o-ring. After the last of the three o-ring test replicates, a nut was placed on the bolt and the fixture was tightened until the compression washers and spacer washers were firmly in contact with one another. The height of the spacer washers was determined to ensure the o-rings were tested at approximately 25% deflection.

3.2.4 CSR Testing

Low temperature CSR measurements were conducted on the best performing o-ring materials. CSR measurements involved placing an o-ring between two plates under constant strain and then measuring the sealing force exerted by the o-ring sample as a function of time (stress decay). The CSR equipment used to support these experiments was fabricated by ARDL and consisted of a (a) computer interface, (b)

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[6] Samples were under 25% compression during fluid aging.

system controller and (c) environmental chamber with six load cells (Figure 4). The computer supports data acquisition and interfacing with the system controller for easy programmability. The six load cells connect to platens that compress the rubber test specimens (Figure 5). A mechanical loading arm and micrometer attachment are used to fix the initial displacement (% deflection or compression) of two identical test samples (replicates) based on the initial thickness of the two samples.[7] A fluid reservoir allows the samples to be tested in compression while immersed in the target test fluid (Figure 6). A thermoelectric plate and external liquid circulation cooling system is used to control the temperature of the samples during testing to within ±0.5°F at any test temperature between approximately -65° F and 350º F. A modified cooling head was used to support high temperature fuel aging experiments to safely accommodate the volatility of the test fuels.

Duplicate o-ring samples were tested in each experiment. In each case, the initial compression was set at 25% deflection at room temperature prior to executing the test sequence. The sealing force exerted by the o-rings was monitored for the duration of the test sequence. Two series of CSR tests were conducted during the course of the program:

1. <u>CSR Profile 1</u> - CSR measurements were performed at -40° F on candidate o-ring materials (both before and after fluid aging) to evaluate the ability of these materials to maintain a sealing force at low temperatures. After 48 hours of low temperature relaxation, the samples were heated back up to room temperature (25° C/77° F) at a controlled rate over the course of one hour. CSR measurements continued at room temperature for an additional 48 hours to evaluate the recovery process. Fluid aged samples (3 days in JP-8+100 at 225° F/107° C or 3 days in MIL-PRF-83282 at 275° F/135° C) were aged external to the compression set device and then tested in the same manner as the unaged samples. O-ring samples were not compressed during external fluid aging.

2. <u>CSR Profile 2</u> - In the second series of experiments, candidate o-ring materials were compressed to 25% deflection at room temperature, both in air and in the target test fluids, and then subjected to the following temperature profile while the sealing force exerted by the o-rings was constantly measured:

    - Temperature equilibrated at 25º C (77º F)
    - Temperature ramped up to the fluid aging temperature over a period of 1 hour
    - Temperature held at the fluid aging temperature for 70 hours
    - Temperature cooled to 25º C (77º F) over a period of 1 hour
    - Temperature held at 25º C (77º F) for 10 hours
    - Temperature cooled to -40º C (-40º F) over a period of 1 hour
    - Temperature held at -40°C (-40º F) for 48 hours
    - Temperature ramped up to 25º C (77º F) over a period of 1 hour
    - Temperature held at 25º C (77º F) for 1 hour.

[7] Care was taken to select replicate o-rings samples with the same approximate thickness.

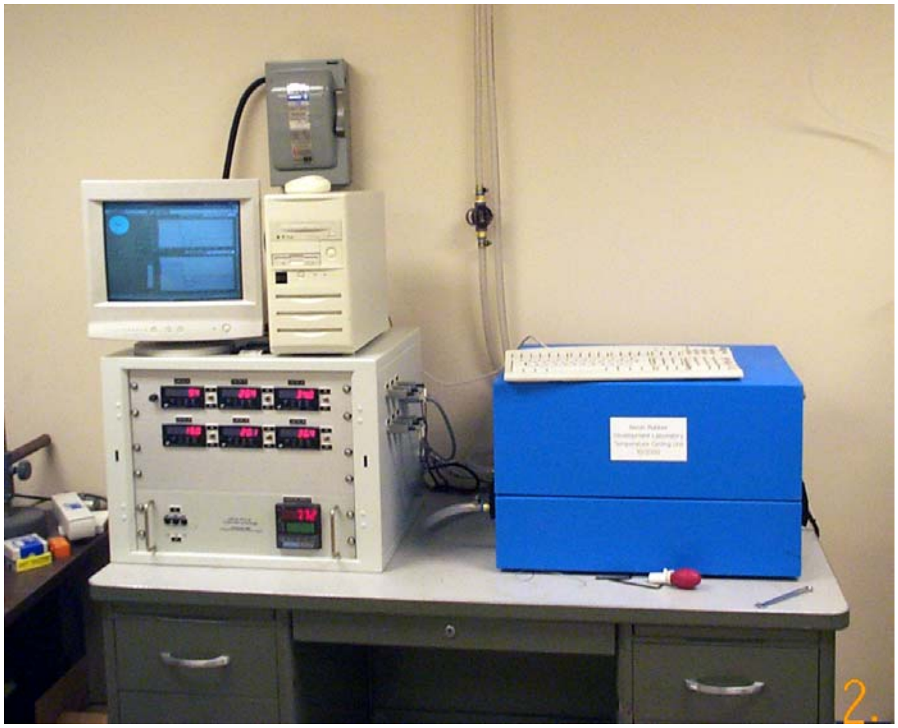

Figure 4. CSR measurement system.

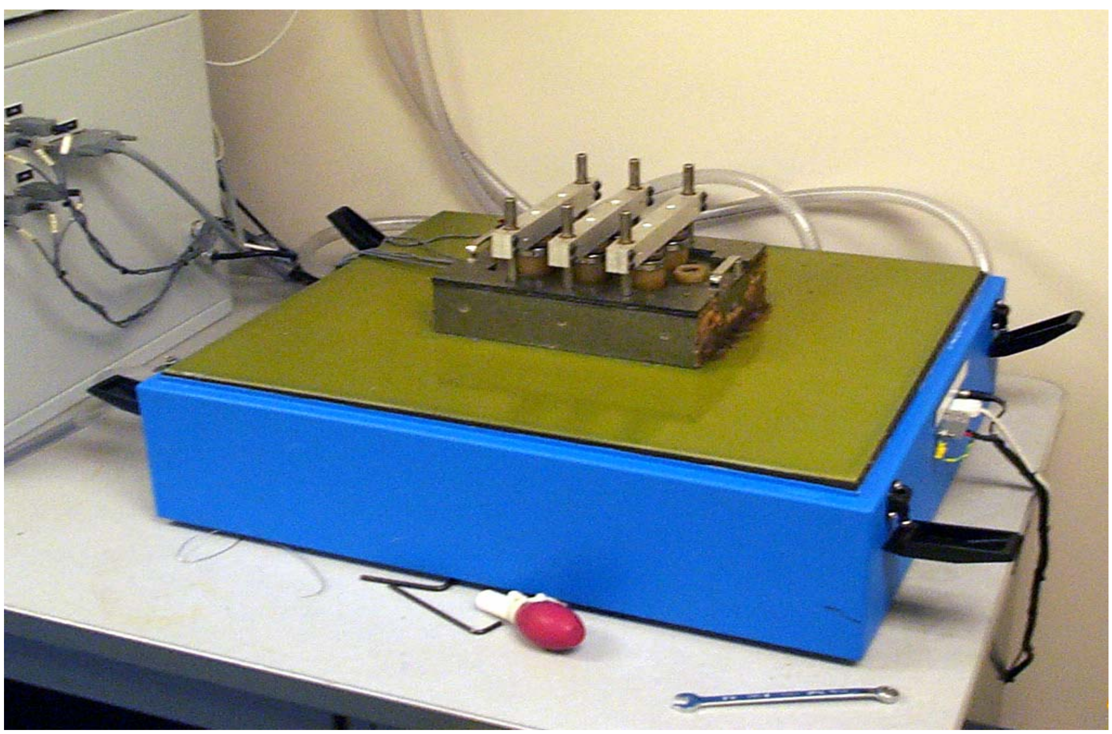

Figure 5. CSR load cell configuration.

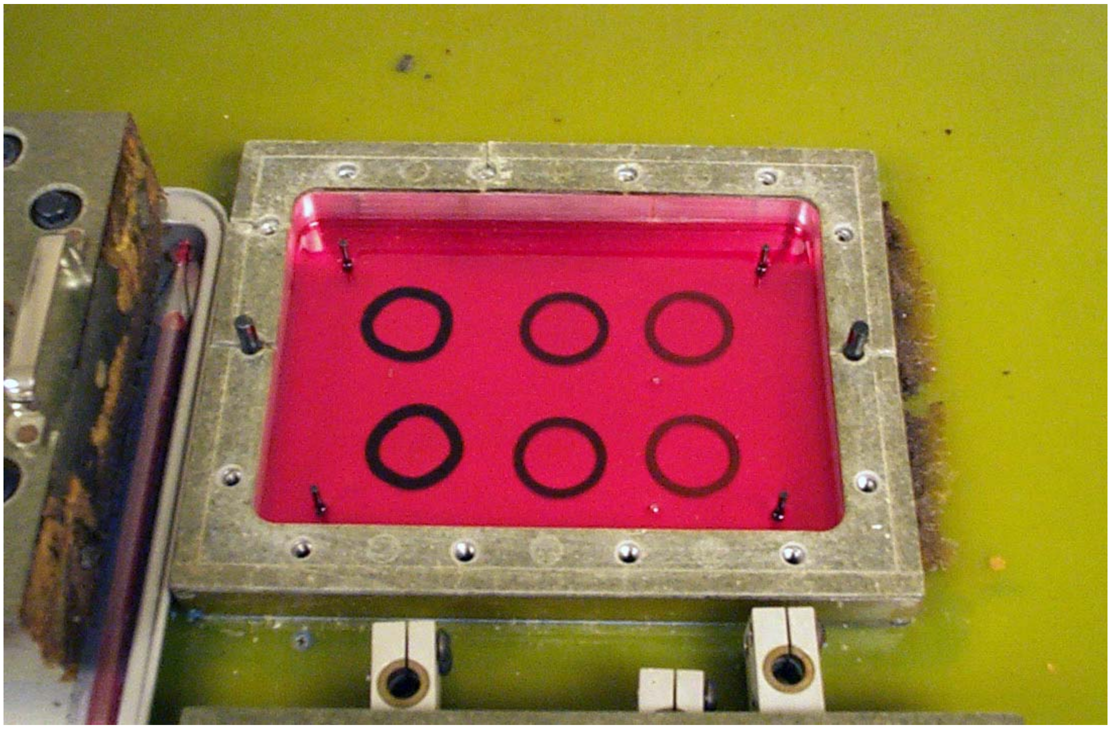

Figure 6. Fluid reservoir with o-rings immersed in MIL-PRF-83282.

3.2.5 Corrosion and Adhesion Testing

Corrosion and adhesion testing was performed in accordance with methods outlined in the military performance specifications (e.g., MIL-P-83461, Section 4.6.3 for hydraulic fluids and MIL-P-5315, Section 4.7.4.7 for fuel systems) to determine the compatibility of candidate o-ring materials with aircraft hydraulic and fuel system fluids and metal components. Test fluids included MIL-PRF-83282, MIL-PRF-87257, JP-8 and JP-8+100. Test metal substrate materials included four aluminum alloys (2024, 6061 and 7075), two stainless steels (440C and 304), aircraft-quality 4130 steel, and brass, bronze, and magnesium (all per the performance specifications). Candidate o-rings were evaluated for compatibility with all metals in all fluids. Metal surfaces were prepared and cleaned in accordance with the military specifications prior to test initiation.

The test o-rings and the target metals were preconditioned in a humidity chamber at 75º F and 92% relative humidity for 72 hours and then dipped in the test fluids.[8] The o-rings (two size 214 o-rings per metal assembly) were then sandwiched between target metals, held together under a 20 lb load and maintained in this configuration at 75º F and 92% relative humidity for a period of 14 days. At the end of the exposure period, the assemblies were taken apart. Any evidence of adhesion between the o-ring and the metal was noted, both during disassembly and through observation of the metal surface. In addition, the metal surfaces were observed for discoloration, deposits, pitting, or other indications of corrosion induced during the contact period.

[8] 92% RH was maintained by sealing materials in a container with a saturated solution of potassium hydrogen phosphate.

3.3 FINAL TESTING AND EVALUATION

Experimental procedures were repeated on the best performing low temperature compression set resistant o-ring materials to verify program results and generate a final set of data on final commercial products formulations. In addition to 3-day fluid aging in JP-8+100, MIL-PRF-83282 and MIL-PRF-87257, final testing and evaluation efforts included additional fluid aging experiments in JRF, MIL-PRF-5606, and MIL-PRF-23699. Fluid aging in JP-8 was eliminated in the final test sequence due to problems sourcing additional fluid.

3.3.1 Test Modifications and Additions

While the general test procedures for the final testing and evaluation efforts remained the same, there were some procedural changes that were implemented during final testing to ensure more accurate data collection and reporting. These changes, which were based on refined methods practiced in industry to ensure data consistency, included:

- *Volume Change* - Volume change was determined volumetrically (using Archimedes principles) instead of using dimensional volume change measurements.
- *Compression Set* - Compression set was determined based on thickness values measured at marked locations. Previous measurements used average thickness data leaving open the possibility that local variations in thickness could affect compression set values.

The final testing and evaluation efforts included an additional series of room temperature and low temperature (-40° F) compression set experiments on samples that were aged in air, JP-8+100 and MIL-PRF-83282 for 60 days at room temperature (75° F).

3.3.2 Final Compression Stress Relaxation Testing

In a final series of CSR experiments, o-rings of the best performing materials were compressed to 25% deflection (at room temperature) in the CSR device and aged *in situ* in air, as well as in MIL-PRF-83282, MIL-PRF-87257, MIL-PRF-5606 and MIL-PRF-23699 hydraulic fluids for 3 days at 275° F and then cooled to -40° F to determine the low temperature sealing capacity of the o-rings after high temperature fluid aging under compression. The test sequence was repeated for samples aged *in situ* in JP-8+100 for 3 days at 225° F.[9] The profile for the final CSR experiments was the same as CSR Profile 2, presented in Section 3.2.4. The response of the o-rings was constantly monitored during the course of the thermal program. Duplicate samples (size 214 o-rings) were tested for each material.

3.3.3 Third Party Data Verification

In addition to final in-house test validation efforts, samples of the best performing materials were submitted to an outside testing laboratory (ARDL) to verify program test results. Third party testing included:

- Original property verification including tensile properties, hardness, compression set (room temperature, -40° F and -65° F)

[9] Acquisition issues prohibited addition testing in JP-8.

- Change in properties after 70 hours of fluid aging in MIL-PRF-83282 at 275° F
- Change in properties after 70 hours of fluid aging in JP-8+100 at 225° F
- Change in properties after 70 hours of aging in air at 275° F.

In addition to the testing performed by ARDL, University of Dayton Research Institute (UDRI) conducted dynamic sealing performance testing on the best performing materials in accordance with methods outlined in MIL-P-83461.[10] All tests were conducted at 275° F in MIL-PRF-5606 hydraulic fluid at 1500 psig, using a 4-inch stroke length at 30 cycles per minute. Two duplicate o-rings were tested per test.

[10] UDRI referenced AMS-R-83461.

4.0 RESULTS AND DISCUSSION

The testing and evaluation efforts progressed through a series of steps starting with the screening tests conducted on compression molded rubber test plaques to eliminate obviously poor performers and rank the other materials being evaluated under the program according to performance. Fluid aging resistance and low temperature flexibility were emphasized during the initial screening experiments. Initial compression set testing (room and low temperature) and physical property evaluations were also performed using plaques of test materials. Testing and evaluation efforts proceeded to o-ring samples for the materials that were not eliminated by the screening experiments. Complete sets of test data were obtained for the best performing o-ring materials. For comparative purposes, a standard NBR-L control and at least one sample from each of the materials classifications evaluated under the program were included in most testing.

All of the program results were confirmed through a second series of testing and evaluation efforts conducted on the best performing program materials. The retest efforts not only confirmed program test data and conclusions, but also provided for some measure of batch to batch variability and, in some instances, to generate a complete set of data on final commercial product formulations.[11] Third party test results provided further verification of material performance.

The results presented in this section are provided in the same general sequence as the testing and evaluation efforts conducted under the program. Emphasis is placed on creating and presenting a basis for selecting the best performing program materials. As such, once a basis for eliminating a given material form further program consideration is presented, additional available data generated on these materials may not be discussed so emphasis can be placed on supporting the decisions to move forward with testing, evaluation and qualification of the best performing materials identified under the program. For ease of presentation, data tables are presented at the end of each subsection.

4.1 EVALUATION OF COMPRESSION MOLDED TEST SLAB SAMPLES

The results of the testing performed on samples die-cut from compression molded test plaques are presented in this section. The actual performance of individual test samples or material classes is discussed in the context of the present application. Reasons for eliminating samples from further program consideration are presented along with a discussion of the relative ranking of materials used to identify which materials would be emphasized in subsequent testing and evaluation efforts. At this stage of the testing and evaluation, the data were evaluated loosely against the performance requirements of MIL-P-83461 for o-rings used in hydraulic fluid systems and MIL-P-5315 for o-rings used in jet fuel applications.

The results of the Phase I program established a basis for selecting materials to test under the Phase II program. As such, only a small number of materials were eliminated from further program consideration based on the results of the testing performed on the die-cut samples. Some materials were eliminated prior to testing based on available form or obvious performance deficiencies.

4.1.1 Volume Swell, Weight Gain and Hardness

An extensive amount of ASTM D 471 volume swell and weight gain testing was conducted under the program on die-cut samples from compression molded plaques to screen the physical stability and

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[11] Improvements in formulations were made during the course of the program so final materials may not have been available during the course of the entire program efforts and, therefore, would not have been subjected to the complete battery of tests.

resistance of the candidate o-ring materials to high temperature fluid exposure. All tests were performed in triplicate using methods previously described. The results reported are the average and standard deviation of measurements taken on the three replicate samples for fluid weight gain and dimensional volume swell. The hardness measurements reported (initial hardness and hardness change) for each sample are the average and standard deviation of nine measurements for each sample condition – three hardness measurements for each of the three replicate samples. For comparative purposes, data are presented in each table for the standard NBR-L material.

For ease of presentation, the tabulated fluid aging data are presented as follows:

- Table 2. D 471, Die-cut Samples – 3 Days in MIL-PRF-83282 @ 275° F
- Table 3. D 471, Die-cut Samples – 3 Days in MIL-PRF-87257 @ 275° F
- Table 4. D 471, Die-cut Samples – 3 Days in JP-8 @ 225° F
- Table 5. D 471, Die-cut Samples – 3 Days in JP-8+100 @ 225° F
- Table 6. D 471, Die-cut Samples – 28 Days in MIL-PRF-83282 @ 275° F
- Table 7. D 471, Die-cut Samples – 28 Days in MIL-PRF-87257 @ 275° F
- Table 8. D 471, Die-cut Samples – 28 Days in JP-8 @ 225° F
- Table 9. D 471, Die-cut Samples – 28 Days in JP-8+100 @ 225° F.

MIL-P-83461 requirements for hydraulic system o-rings include an initial Shore A hardness of 70 to 80, an allowable change in hardness of -10 to +5 after 70 hours of fluid aging, and a change in volume of 5 to 15% after 70 hours of fluid aging. A review of the 3-day and 28-day aging data for test materials aged in MIL-PRF-83282 and MIL-PRF-87527 demonstrates that most of the materials selected for evaluation performed exceptionally well against the stated criteria.

Only one of the materials, a nitrile rubber (43), demonstrated extremely high volume swell under all test conditions. Other NBR materials (e.g., 30 and 34) demonstrated relatively high volume swell in both hydraulic fluids. After 28 days of fluid aging in MIL-PRF-87257, some of the HNBR and FKM materials also demonstrated relatively high volume swell. While the performance of these materials is not unreasonable for o-ring sealing materials in some applications, their performance is further outside of the performance specification than other materials, making then some of the poorer performers. Also, as noted in the data, some of the materials demonstrated negative volume swell and weight loss (4-ECO and 11-FKM), demonstrating the susceptibility of these materials to extraction by the hydraulic fluids.

Initial hardness and hardness change were not evaluated as critically as the weight and volume change, data as the primary purpose of the initial screening testing was to evaluate chemical compatibility with the hydraulic fluids under high temperature conditions and material hardness is a relatively easy property to modify. At this stage of the program, some of the PFE sample formulations (38 and 39) and one of the FVMQ samples (29) demonstrated a Shore A hardness of about 60, which is lower than the performance specification and most of the other materials tested. It is worth noting that PFE sample 43 is a formulation modification of samples 38 and 39, yet it demonstrates an acceptable hardness of 74. Two of the X-FKM samples (54 and 55) were too hard for the present application (Shore A > 90), but demonstrated good performance otherwise, while X-FKM sample 51 demonstrated acceptable hardness. Newer generations of this material are also available in the appropriate hardness range. A small number of the samples tested generated a significant change in hardness after fluid aging. After 28 days of fluid aging the final hardness of some of these samples exceeded a Shore A value of 90 (83282 = 9-FKM, 31 and 32-NBRs; 87257 = 8-NBR), possibly due to the extraction of low molecular weight plasticizing agents. ECO (12) demonstrated a significant decrease in hardness after 28 days of hydraulic fluid aging.

Based on the results of the initial hydraulic fluid screening studies, it is clear that sample 43-NBR should be eliminated from further consideration in hydraulic fluid applications. In general, the NBR materials did not perform as well as the other classes of materials in the D 471 screening tests. The weight loss and change in hardness of some of the ECO and FVMQ materials is also a cause for concern given their performance relative to the other samples. The initial hardness of some of the PFE and the X-FKM materials is noteworthy but, given the exceptional high temperature fluid resistance of these materials, was not viewed as a reason for product elimination at this stage of the program as other compounds of these same general chemistries are available in the required hardness range. MIL-PRF-87257 appears to be slightly more aggressive in the hydraulic fluid aging studies. This may be expected due to the lower viscosity Polyalphaolephin (PAO) materials used in the formulation of MIL-PRF-87257 relative to MIL-PRF-83282.

MIL-P-5315 requirements for o-rings used in aircraft fuel applications include an initial Shore A hardness of 60 to 70 and a change in volume of 0 to 10% after 70 hours of fluid aging. No additional requirement is provided for change in hardness after fluid aging. A review of the 3- and 28-day aging data for materials aged in JP-8 and JP-8+100 demonstrates that most of the materials selected for evaluation performed exceptionally well against the stated criteria. In general, the NBR materials demonstrated greater susceptibility to jet fuel relative to the other materials classes tested, with sample 43-NBR continuing to demonstrate poor performance and NBR samples 30, 33 and 34 consistently demonstrating relatively high volume swell in JP-8 and JP-8+100. Even the control samples (0- NBR-L) tested outside of the specifications at the high temperature fluid aging conditions targeted under this program. Samples 4-ECO continued to demonstrate some negative volume swell after 3 days of fluid aging. After 28 days of fuel aging, some of the FKM materials (e.g., 5 and 6) were showing signs of relatively high volume swell, especially in JP-8+100.

Initial hardness and hardness change were also reviewed. As the hardness requirement for fuel applications is Shore A 60 to 70, even the softer PFE materials evaluated under the program (38 and 39) fall within the specification. A number of the HNBR samples evaluated, and some of the FKM materials, tested harder than the hardness specification, as did the two X-FKM materials mentioned previously.

The results of the fuel aging experiments are similar to the hydraulic fluid aging experiments. Sample 43-NBR should clearly be eliminated from further consideration in either application. In general, the jet fuels were more aggressive toward the NBR and HNBR materials than the hydraulic fluids. This was true for some of the FKM samples as well. The PFE, PFE-VF and X-FKM materials demonstrated exceptional stability to JP-8 and JP-8+100.

Table 2. D 471, Die-cut Samples, 3 Days in MIL-PRF-83282 @ 275° F

Material ID	Material Type		ΔV (%)	ΔM (%)	Hardness	
					Initial	ΔH
0	**Control NBR-L**	**Mean**	**7.41**	**6.36**	**73.89**	**-2.33**
		σ	**1.95**	**0.06**	**0.78**	**0.43**
3	FKM	Mean	4.18	1.35	65.22	-3.44
		σ	0.33	0.09	0.83	0.51
4	ECO	Mean	-7.14	-5.85	63.67	10.22
		σ	1.28	0.09	1.12	0.84
5	FKM	Mean	2.95	1.15	77.44	-3.89
		σ	2.48	0.06	3.54	1.39
6	FKM	Mean	3.48	1.15	65.56	-4.78
		σ	0.52	0.08	0.53	0.19
8	NBR	Mean	-2.10	-1.27	71.89	2.89
		σ	0.88	0.45	0.60	0.19
9	FKM	Mean	2.51	1.11	84.22	1.00
		σ	1.71	0.03	0.44	0.58
10	FVMQ	Mean	3.27	1.80	82.89	-3.11
		σ	0.28	0.03	0.78	0.84
11	FKM	Mean	-0.25	0.99	78.11	5.56
		σ	3.43	0.24	7.11	3.79
12	ECO	Mean	0.90	0.45	77.11	2.44
		σ	1.35	0.01	0.60	0.38
13	HNBR	Mean	-1.32	-0.98	75.78	-0.67
		σ	0.96	0.04	0.44	0.67
17	HNBR	Mean	3.45	2.79	72.00	-1.33
		σ	0.51	0.11	0.71	0.67
18	HNBR	Mean	3.98	2.61	83.44	-2.33
		σ	0.15	0.11	0.53	0.33
19	HNBR	Mean	5.20	2.56	83.44	-2.44
		σ	0.69	0.15	0.73	0.51
20	HNBR	Mean	4.40	2.58	84.00	-3.11
		σ	1.17	0.15	0.87	0.77
21	FKM	Mean	3.39	6.00	78.44	-3.11
		σ	1.48	7.31	0.53	0.38
22	HNBR	Mean	4.08	2.50	84.89	-3.22
		σ	0.87	0.04	0.33	0.69
23	FKM	Mean	7.70	1.87	77.22	-0.67
		σ	1.46	0.08	1.48	1.86
25	FKM	Mean	4.73	1.30	74.22	-3.00
		σ	0.70	0.03	0.67	0.33
29	FVMQ	Mean	7.88	3.96	58.67	-4.33
		σ	2.63	0.40	0.87	0.33
30	NBR	Mean	12.70	9.35	68.56	-4.22
		σ	0.40	0.05	1.59	1.17

Table 2. Cont'd. D 471, Die-cut Samples, 3 Days in MIL-PRF-83282 @ 275° F

Material ID	Material Type		ΔV (%)	ΔM (%)	Hardness	
					Initial	ΔH
0	**Control NBR-L**	**Mean**	**7.41**	**6.36**	**73.89**	**-2.33**
		σ	**1.95**	**0.06**	**0.78**	**0.43**
31	NBR	Mean	3.66	1.18	83.89	1.00
		σ	0.23	0.13	0.78	0.67
32	NBR	Mean	4.83	3.00	81.67	0.11
		σ	0.39	0.26	0.50	0.19
33	NBR	Mean	7.47	4.82	73.44	-2.44
		σ	1.81	0.91	2.13	0.51
34	NBR	Mean	10.53	5.88	76.00	-5.67
		σ	4.09	0.08	0.71	0.33
35	HNBR	Mean	7.46	4.59	78.89	-2.33
		σ	1.66	0.04	0.60	0.33
36	HNBR	Mean	5.47	2.83	77.11	0.67
		σ	2.34	0.09	1.69	1.20
37	FKM	Mean	6.19	1.86	73.67	-3.44
		σ	1.01	0.03	0.60	0.51
38	PFE	Mean	2.65	0.36	58.33	-1.00
		σ	1.91	0.07	0.87	0.33
39	PFE	Mean	0.57	0.51	59.56	-0.22
		σ	2.80	0.01	1.13	0.96
40	PFE	Mean	2.49	0.39	66.78	0.00
		σ	0.60	0.12	3.90	0.58
41	PFE-VF	Mean	3.03	0.40	76.78	-2.67
		σ	0.67	0.98	0.44	0.33
42	PFE	Mean	3.78	0.30	73.67	-0.33
		σ	0.88	0.09	0.50	0.58
43	NBR	Mean	60.82	32.72	79.67	1.44
		σ	1.90	0.09	0.50	1.64
51	X-FKM	Mean	0.90	0.65	71.89	-1.56
		σ	0.38	0.01	0.60	0.51
52	PFE-VF	Mean	1.18	1.13	71.22	-2.89
		σ	0.65	0.04	0.67	0.51
53	PFE-VF	Mean	2.07	1.17	66.67	-4.78
		σ	1.22	0.03	1.12	0.38
54	X-FKM	Mean	4.52	1.22	> 90	nd[12]
		σ	1.25	0.11		
55	X-FKM	Mean	3.98	1.01	> 90	nd
		σ	0.22	0.07		

[12] nd = not determined (for all Tables)

Table 3. D 471, Die-cut Samples, 3 Days in MIL-PRF-87257 @ 275° F

Material ID	Material Type		ΔV (%)	ΔM (%)	Hardness	
					Initial	ΔH
0	**Control NBR-L**	**Mean**	**nd**	**nd**	**73.89**	**nd**
		σ			**0.78**	
3	FKM	Mean	9.50	2.72	66.44	-6.11
		σ	0.45	0.10	1.01	1.50
4	ECO	Mean	-2.86	-3.84	65.00	5.89
		σ	4.76	0.26	0.71	1.84
5	FKM	Mean	5.63	1.90	77.00	-6.67
		σ	1.92	4.93	1.41	1.20
6	FKM	Mean	8.69	2.82	65.89	-8.44
		σ	1.07	0.08	1.27	0.19
8	NBR	Mean	2.58	0.58	74.11	1.56
		σ	2.18	0.22	0.33	3.27
9	FKM	Mean	9.29	5.38	85.89	-2.22
		σ	0.89	0.17	0.33	0.19
10	FVMQ	Mean	5.94	3.13	85.33	-6.67
		σ	3.51	0.07	0.87	0.58
11	FKM	Mean	-1.33	2.81	76.33	-7.00
		σ	3.19	0.13	2.24	2.08
12	ECO	Mean	3.58	2.32	79.44	-5.78
		σ	3.71	1.00	0.53	4.11
13	HNBR	Mean	3.24	0.72	76.89	-2.22
		σ	1.81	0.06	0.78	0.51
17	HNBR	Mean	4.48	5.83	72.78	-4.89
		σ	1.23	0.10	0.44	1.02
18	HNBR	Mean	4.90	4.71	84.00	-2.89
		σ	2.57	0.12	0.50	0.51
19	HNBR	Mean	7.68	4.50	84.11	-3.00
		σ	1.08	0.13	0.33	0.33
20	HNBR	Mean	9.47	4.90	84.78	-4.89
		σ	1.71	0.12	0.44	0.19
21	FKM	Mean	4.01	2.42	79.56	-4.33
		σ	0.31	0.10	1.01	0.33
22	HNBR	Mean	7.04	4.34	84.33	-4.56
		σ	0.99	0.02	0.50	0.69
23	FKM	Mean	5.89	2.25	78.33	-3.00
		σ	2.10	0.03	0.87	0.88
25	FKM	Mean	4.08	1.77	74.56	-2.78
		σ	0.28	0.03	0.53	0.19
29	FVMQ	Mean	7.93	5.42	61.00	-7.67
		σ	1.02	0.05	0.71	0.88
30	NBR	Mean	16.53	14.81	70.78	-8.67
		σ	5.78	0.03	0.67	1.00

Table 3. Cont'd. D 471, Die-cut Samples, 3 Days in MIL-PRF-87257 @ 275° F

Material ID	Material Type		ΔV (%)	ΔM (%)	Hardness	
					Initial	ΔH
0	**Control NBR-L**	**Mean**	**nd**	**nd**	**73.89**	**nd**
		σ			**0.78**	
31	NBR	Mean	8.75	5.52	83.78	-2.11
		σ	2.22	1.61	0.67	0.38
32	NBR	Mean	11.44	7.46	80.00	-2.22
		σ	1.73	0.46	0.50	1.02
33	NBR	Mean	15.96	11.67	71.56	-8.22
		σ	1.54	1.85	2.83	2.17
34	NBR	Mean	16.05	10.83	76.00	-9.78
		σ	1.37	0.23	0.00	0.51
35	HNBR	Mean	8.63	7.69	78.78	-4.56
		σ	1.26	0.13	0.44	0.19
36	HNBR	Mean	12.09	8.36	77.78	-4.78
		σ	1.77	0.10	0.67	0.51
37	FKM	Mean	7.36	2.79	73.00	-4.11
		σ	0.59	0.05	0.71	0.84
38	PFE	Mean	1.00	0.71	60.22	-4.78
		σ	2.83	0.02	1.20	0.69
39	PFE	Mean	1.55	1.05	61.33	-5.00
		σ	1.32	0.01	0.71	0.33
40	PFE	Mean	1.76	0.53	71.44	-2.67
		σ	0.51	0.02	0.53	0.33
41	PFE-VF	Mean	3.47	1.48	77.11	-4.78
		σ	1.53	0.01	0.93	0.69
42	PFE	Mean	2.09	0.53	73.78	-1.78
		σ	1.35	0.02	0.44	0.51
43	NBR	Mean	88.96	48.67	79.78	-11.56
		σ	5.31	1.37	0.83	2.34
51	X-FKM	Mean	-1.90	1.21	73.22	-2.56
		σ	1.30	0.01	0.97	0.84
52	PFE-VF	Mean	3.70	1.76	71.56	-1.67
		σ	0.77	0.05	1.01	0.33
53	PFE-VF	Mean	6.13	1.82	68.67	-3.11
		σ	1.56	0.03	1.50	0.19
54	X-FKM	Mean	6.75	2.17	> 90	nd
		σ	1.49	0.15		
55	X-FKM	Mean	5.77	1.85	> 90	nd
		σ	1.69	1.45		

Table 4. D 471, Die-cut Samples, 3 Days in JP-8 @ 225° F

Material ID	Material Type		ΔV (%)	ΔM (%)	Hardness	
					Initial	ΔH
0	**Control NBR-L**	**Mean**	**19.72**	**14.573**	**73.78**	**-10.89**
		σ	**3.73**	**2.03**	**0.83**	**1.45**
3	FKM	Mean	12.83	4.96	65.00	-9.22
		σ	0.69	0.07	0.71	0.19
4	ECO	Mean	-1.56	-2.96	63.00	0.78
		σ	0.67	0.07	0.87	1.54
5	FKM	Mean	5.78	1.97	74.11	-7.78
		σ	0.88	2.59	0.78	0.84
6	FKM	Mean	13.39	4.93	63.33	-6.89
		σ	7.26	0.07	0.50	0.51
8	NBR	Mean	10.02	4.34	71.11	-1.78
		σ	3.20	0.04	0.60	0.19
9	FKM	Mean	13.93	8.69	84.78	-4.44
		σ	1.43	0.10	0.44	0.38
10	FVMQ	Mean	8.65	4.44	82.89	-7.00
		σ	0.43	0.02	0.60	0.33
11	FKM	Mean	4.21	2.31	71.22	-9.78
		σ	9.14	0.13	12.05	4.24
12	ECO	Mean	5.72	3.35	75.89	-5.67
		σ	0.95	0.04	0.78	1.15
13	HNBR	Mean	8.66	4.77	74.89	-6.22
		σ	1.20	0.06	1.54	0.96
17	HNBR	Mean	10.01	10.42	72.22	-6.44
		σ	2.75	0.07	0.67	1.26
18	HNBR	Mean	11.36	9.00	82.78	-6.89
		σ	1.38	0.15	0.44	0.84
19	HNBR	Mean	11.42	9.10	83.00	-6.67
		σ	0.21	0.15	0.00	0.00
20	HNBR	Mean	13.31	9.20	83.78	-7.00
		σ	1.53	0.16	0.67	0.33
21	FKM	Mean	2.84	2.41	77.33	-2.22
		σ	2.15	0.05	0.71	0.38
22	HNBR	Mean	11.67	8.87	84.33	-7.78
		σ	1.52	0.02	0.50	0.69
23	FKM	Mean	2.91	2.85	76.56	-2.56
		σ	1.40	0.07	0.53	0.38
25	FKM	Mean	-0.49	2.33	71.44	-2.44
		σ	3.89	0.27	1.24	0.84
29	FVMQ	Mean	12.82	7.12	56.78	-7.00
		σ	2.33	0.01	0.44	0.00
30	NBR	Mean	30.31	20.26	67.44	-8.44
		σ	3.73	0.29	1.81	1.50

Table 4. Cont'd. D 471, Die-cut Samples, 3 Days in JP-8 @ 225° F

Material ID	Material Type		ΔV (%)	ΔM (%)	Hardness	
					Initial	ΔH
0	**Control NBR-L**	**Mean**	**19.72**	**14.573**	**73.78**	**-10.89**
		σ	**3.73**	**2.03**	**0.83**	**1.45**
31	NBR	Mean	15.96	9.38	82.78	-4.56
		σ	0.42	0.21	0.44	0.51
32	NBR	Mean	18.13	10.45	79.44	-7.67
		σ	0.64	0.15	0.88	0.33
33	NBR	Mean	21.23	14.03	71.44	-7.00
		σ	2.01	0.56	0.73	0.33
34	NBR	Mean	25.26	15.33	74.22	-12.11
		σ	0.41	0.10	0.67	0.77
35	HNBR	Mean	17.26	12.32	77.67	-6.44
		σ	0.70	0.04	0.50	0.51
36	HNBR	Mean	17.28	11.39	75.44	-6.67
		σ	2.56	0.07	1.01	0.67
37	FKM	Mean	-0.75	3.03	73.11	-2.89
		σ	0.88	0.15	0.93	0.69
38	PFE	Mean	3.23	2.03	56.89	-1.11
		σ	1.17	0.03	0.93	1.58
39	PFE	Mean	5.08	2.89	58.00	-1.78
		σ	0.34	0.02	1.00	1.26
40	PFE	Mean	1.97	1.59	69.11	-0.78
		σ	2.28	0.01	0.60	1.07
41	PFE-VF	Mean	4.71	1.77	74.78	-2.33
		σ	0.46	0.05	0.97	1.53
42	PFE	Mean	4.48	-1.04	72.56	-0.67
		σ	1.17	4.54	0.73	0.33
43	NBR	Mean	72.14	40.60	77.33	-28.67
		σ	0.61	0.70	0.87	13.18
51	X-FKM	Mean	5.02	2.84	72.33	-1.89
		σ	0.19	0.01	0.71	0.84
52	PFE-VF	Mean	2.79	2.03	69.89	-0.11
		σ	2.82	0.03	1.05	0.69
53	PFE-VF	Mean	-2.35	2.00	65.00	-0.22
		σ	0.61	0.01	0.50	0.84
54	X-FKM	Mean	7.15	2.20	> 90	nd
		σ	1.14	0.03		
55	X-FKM	Mean	6.94	2.02	> 90	nd
		σ	0.80	0.05		

Table 5. D 471, Die-cut Samples, 3 Days in JP-8+100 @ 225° F

Material ID	Material Type		ΔV (%)	ΔM (%)	Hardness	
					Initial	ΔH
0	**Control NBR-L**	**Mean**	**nd**	**nd**	**73.78**	**nd**
		σ			**0.83**	
3	FKM	Mean	11.89	5.14	64.33	-5.56
		σ	1.76	0.04	1.00	0.84
4	ECO	Mean	-1.27	-2.64	63.89	0.44
		σ	0.77	0.11	1.27	0.38
5	FKM	Mean	4.51	2.43	76.22	-3.78
		σ	2.10	0.11	1.92	1.50
6	FKM	Mean	14.70	5.86	61.89	-3.67
		σ	3.24	0.15	0.60	0.88
8	NBR	Mean	10.64	4.85	75.56	-3.67
		σ	1.19	0.13	1.13	0.88
9	FKM	Mean	16.18	8.48	86.22	-7.22
		σ	0.53	0.58	0.44	0.51
10	FVMQ	Mean	8.69	4.80	85.00	-10.78
		σ	1.85	0.11	0.00	0.51
11	FKM	Mean	11.90	3.00	83.67	-7.00
		σ	3.01	9.76	0.71	1.20
12	ECO	Mean	10.60	3.62	79.22	-7.44
		σ	1.14	0.10	0.44	0.38
13	HNBR	Mean	10.27	4.93	78.78	-9.78
		σ	1.10	0.12	0.97	0.69
17	HNBR	Mean	16.82	10.85	70.44	-7.89
		σ	2.83	0.02	0.88	0.38
18	HNBR	Mean	12.55	8.88	82.56	-7.78
		σ	1.07	0.04	0.73	0.38
19	HNBR	Mean	11.97	8.89	83.11	-8.44
		σ	0.68	0.13	0.60	0.19
20	HNBR	Mean	13.87	8.91	83.56	-8.22
		σ	1.05	0.04	0.53	0.38
21	FKM	Mean	4.55	2.48	77.44	-3.22
		σ	1.58	0.13	0.73	0.51
22	HNBR	Mean	12.64	8.66	83.33	-7.78
		σ	1.13	0.14	0.50	0.19
23	FKM	Mean	6.07	2.49	77.11	-4.33
		σ	2.06	0.03	0.93	1.15
25	FKM	Mean	6.43	2.29	73.11	-4.44
		σ	0.96	0.08	1.69	1.35
29	FVMQ	Mean	10.70	7.38	57.00	-5.33
		σ	1.24	0.05	0.50	1.73
30	NBR	Mean	30.95	19.82	68.00	-7.78
		σ	1.55	0.08	1.00	1.07

Table 5. Cont'd. D 471, Die-cut Samples, 3 Days in JP-8+100 @ 225° F

Material ID	Material Type		ΔV (%)	ΔM (%)	Hardness	
					Initial	ΔH
0	**Control NBR-L**	**Mean**	**nd**	**nd**	**73.78**	**nd**
		σ			**0.83**	
31	NBR	Mean	16.03	8.99	82.56	-5.33
		σ	1.36	0.05	0.53	0.88
32	NBR	Mean	16.34	10.37	79.78	-6.33
		σ	0.68	0.54	0.67	1.45
33	NBR	Mean	19.62	13.36	72.56	-6.33
		σ	1.54	0.70	0.88	1.73
34	NBR	Mean	23.96	14.79	74.56	-10.44
		σ	1.02	0.50	0.52	1.39
35	HNBR	Mean	17.62	11.95	76.67	-5.11
		σ	0.94	0.08	0.50	0.96
36	HNBR	Mean	17.63	10.76	75.89	-6.00
		σ	2.17	0.27	0.60	1.20
37	FKM	Mean	9.43	2.41	70.56	-0.44
		σ	0.73	0.09	0.73	1.58
38	PFE	Mean	5.00	2.07	57.00	0.67
		σ	0.94	0.02	0.50	0.58
39	PFE	Mean	7.37	3.00	58.78	1.00
		σ	2.10	0.04	0.67	0.88
40	PFE	Mean	3.45	1.66	69.67	-1.22
		σ	1.46	0.02	0.71	0.51
41	PFE-VF	Mean	4.44	1.72	74.67	-3.22
		σ	1.10	0.15	0.71	0.19
42	PFE	Mean	3.66	1.66	72.33	-0.89
		σ	0.44	0.90	0.71	0.38
43	NBR	Mean	111.28	63.13	76.56	-36.00
		σ	4.84	3.77	0.88	1.76
51	X-FKM	Mean	3.66	2.85	71.89	0.44
		σ	2.20	0.03	1.17	0.77
52	PFE-VF	Mean	4.47	2.03	71.11	-1.00
		σ	2.37	0.01	1.69	1.20
53	PFE-VF	Mean	3.25	2.01	67.67	-1.56
		σ	1.78	0.01	1.41	1.20
54	X-FKM	Mean	7.27	2.23	> 90	nd
		σ	2.80	0.12		
55	X-FKM	Mean	7.34	2.03	> 90	nd
		σ	0.79	0.02		

Table 6. D 471, Die-cut Samples, 28 Days in MIL-PRF-83282 @ 275° F

Material ID	Material Type		ΔV (%)	ΔM (%)	Hardness	
					Initial	ΔH
0	**Control NBR-L**	**Mean**	**7.41**	**6.36**	**73.89**	**7.00**
		σ	**1.95**	**0.06**	**0.78**	**0.33**
3	FKM	Mean	5.86	1.84	65.22	-3.44
		σ	1.71	0.09	0.83	1.84
4	ECO	Mean	-5.60	-4.55	63.67	3.00
		σ	1.89	0.14	1.12	0.58
5	FKM	Mean	3.05	1.13	77.44	-4.33
		σ	1.31	0.26	3.54	1.53
6	FKM	Mean	4.23	1.77	65.56	-5.33
		σ	0.88	0.05	0.53	0.58
8	NBR	Mean	-0.42	1.08	71.89	13.89
		σ	1.24	0.42	0.60	0.19
9	FKM	Mean	2.52	2.79	84.22	> 90
		σ	0.93	0.15	0.44	
10	FVMQ	Mean	2.08	1.08	82.89	-3.00
		σ	0.31	0.03	0.78	0.58
11	FKM	Mean	2.27	2.30	78.11	6.01
		σ	0.81	0.49	7.11	3.53
12	ECO	Mean	4.36	3.99	77.11	-16.33
		σ	0.89	0.02	0.60	0.88
13	HNBR	Mean	2.86	2.48	75.78	3.22
		σ	2.14	0.80	0.44	0.51
17	HNBR	Mean	5.67	5.20	72.00	3.00
		σ	0.95	0.26	0.71	0.88
18	HNBR	Mean	4.10	3.14	83.44	-2.11
		σ	0.72	0.10	0.53	0.51
19	HNBR	Mean	3.62	3.12	83.44	-1.67
		σ	0.21	0.16	0.73	0.67
20	HNBR	Mean	4.63	3.10	84.00	-1.11
		σ	0.40	0.15	0.87	0.69
21	FKM	Mean	3.81	1.99	78.44	-2.44
		σ	1.69	0.04	0.53	0.19
22	HNBR	Mean	5.16	3.14	84.89	-1.78
		σ	0.62	0.02	0.33	0.19
23	FKM	Mean	9.71	4.79	77.22	1.56
		σ	2.35	0.06	1.48	1.95
25	FKM	Mean	6.76	3.70	74.22	1.00
		σ	1.52	0.36	0.67	0.33
29	FVMQ	Mean	5.77	2.60	58.67	-5.33
		σ	1.75	0.30	0.87	1.45
30	NBR	Mean	18.27	15.54	68.56	-3.89
		σ	0.97	0.08	1.59	1.71

Table 6. Cont'd. D 471, Die-cut Samples, 28 Days in MIL-PRF-83282 @ 275° F

Material ID	Material Type		ΔV (%)	ΔM (%)	Hardness	
					Initial	ΔH
0	**Control NBR-L**	**Mean**	**7.41**	**6.36**	**73.89**	**7.00**
		σ	**1.95**	**0.06**	**0.78**	**0.33**
31	NBR	Mean	6.13	4.64	83.89	> 90
		σ	1.21	1.03	0.78	
32	NBR	Mean	4.46	5.62	81.67	> 90
		σ	0.85	0.66	0.50	
33	NBR	Mean	10.83	10.50	73.44	3.56
		σ	2.41	3.47	2.13	0.51
34	NBR	Mean	8.26	7.86	76.00	-4.00
		σ	4.10	0.05	0.71	0.88
35	HNBR	Mean	7.45	4.59	78.89	-2.33
		σ	1.67	0.04	0.60	0.33
36	HNBR	Mean	5.68	5.81	77.11	8.67
		σ	3.97	1.11	1.69	0.88
37	FKM	Mean	5.05	2.14	74.11	-3.00
		σ	1.70	0.20	0.60	1.67
38	PFE	Mean	2.46	0.33	58.33	1.00
		σ	0.62	0.07	0.87	0.33
39	PFE	Mean	1.27	0.40	59.56	2.22
		σ	1.83	0.03	1.13	1.07
40	PFE	Mean	2.53	0.34	66.78	1.00
		σ	0.83	0.06	3.90	1.20
41	PFE-VF	Mean	7.01	2.49	76.78	0.67
		σ	0.81	0.93	0.44	0.33
42	PFE	Mean	3.24	0.39	73.67	-1.67
		σ	2.77	0.05	0.50	0.33
43	NBR	Mean	64.65	34.93	79.67	3.00
		σ	2.77	0.70	0.50	0.88
51	X-FKM	Mean	1.70	0.82	71.89	2.67
		σ	1.17	0.45	0.60	0.58
52	PFE-VF	Mean	6.01	2.61	71.22	1.44
		σ	2.45	0.80	0.67	0.51
53	PFE-VF	Mean	9.63	3.45	66.67	1.00
		σ	0.51	0.83	1.12	0.00
54	X-FKM	Mean	5.03	1.73	> 90	nd
		σ	1.14	0.07		
55	X-FKM	Mean	4.34	1.64	> 90	nd
		σ	0.84	0.18		

Table 7. D 471, Die-cut Samples, 28 Days in MIL-PRF-87257 @ 275° F

Material ID	Material Type		ΔV (%)	ΔM (%)	Hardness	
					Initial	ΔH
0	**Control NBR-L**	**Mean**	**nd**	**nd**	**73.78**	**nd**
		σ			**0.83**	
3	FKM	Mean	17.99	4.67	66.44	-10.67
		σ	0.37	0.21	1.01	0.51
4	ECO	Mean	-2.31	-4.46	65.00	-1.44
		σ	3.67	1.95	0.71	4.06
5	FKM	Mean	9.30	2.12	77.00	-6.00
		σ	5.64	4.70	1.41	1.86
6	FKM	Mean	13.28	3.99	65.89	-6.67
		σ	3.09	0.15	1.27	1.20
8	NBR	Mean	5.31	3.23	74.11	> 90
		σ	1.56	1.08	0.33	
9	FKM	Mean	11.10	8.43	85.89	3.22
		σ	0.95	0.23	0.33	0.88
10	FVMQ	Mean	4.96	2.32	85.33	-7.89
		σ	1.21	0.11	0.87	1.20
11	FKM	Mean	-2.54	4.47	76.33	0.56
		σ	5.88	0.08	2.24	2.17
12	ECO	Mean	5.89	2.47	79.44	-21.22
		σ	1.44	2.14	0.50	2.12
13	HNBR	Mean	8.62	5.00	76.89	1.67
		σ	3.25	1.59	0.78	0.69
17	HNBR	Mean	9.59	9.87	72.78	-0.56
		σ	1.74	0.83	0.44	0.19
18	HNBR	Mean	8.58	6.19	84.00	-0.11
		σ	0.33	0.26	0.50	0.51
19	HNBR	Mean	10.79	6.68	84.11	0.44
		σ	1.99	1.69	0.33	0.19
20	HNBR	Mean	11.87	7.97	84.78	0.44
		σ	1.64	1.31	0.44	0.58
21	FKM	Mean	3.92	2.90	79.56	-5.22
		σ	0.94	0.17	1.01	0.58
22	HNBR	Mean	6.87	5.53	84.33	-1.89
		σ	0.66	0.21	0.50	0.33
23	FKM	Mean	9.82	5.36	78.33	-0.44
		σ	0.63	0.30	0.87	0.77
25	FKM	Mean	8.36	4.89	74.56	-0.22
		σ	1.35	0.52	0.53	0.19
29	FVMQ	Mean	3.17	4.27	61.00	-12.22
		σ	0.87	0.08	0.71	0.33
30	NBR	Mean	22.47	21.16	70.78	-7.11
		σ	5.98	0.23	0.67	0.58

Table 7. Cont'd. D 471, Die-cut Samples, 28 Days in MIL-PRF-87257 @ 275° F

Material ID	Material Type		ΔV (%)	ΔM (%)	Hardness	
					Initial	ΔH
0	**Control NBR-L**	**Mean**	**nd**	**nd**	**73.78**	**nd**
		σ			**0.83**	
31	NBR	Mean	10.70	8.33	83.78	3.22
		σ	3.07	2.01	0.67	0.38
32	NBR	Mean	12.42	9.41	80.00	6.33
		σ	2.35	1.13	0.50	1.39
33	NBR	Mean	21.39	16.37	71.56	4.78
		σ	3.12	0.91	2.83	3.34
34	NBR	Mean	17.82	13.74	76.00	-6.22
		σ	1.44	0.43	0.00	0.00
35	HNBR	Mean	13.77	13.45	78.78	4.56
		σ	0.86	0.62	0.44	1.64
36	HNBR	Mean	14.53	10.95	77.78	-0.22
		σ	1.34	0.60	0.67	0.19
37	FKM	Mean	6.99	2.81	73.00	-3.00
		σ	0.92	0.04	0.71	0.19
38	PFE	Mean	0.57	0.65	60.22	0.22
		σ	1.49	0.00	1.20	0.33
39	PFE	Mean	2.62	0.98	61.33	-0.22
		σ	1.90	0.02	0.71	0.38
40	PFE	Mean	0.00	0.55	71.44	0.11
		σ	0.76	0.01	0.53	0.69
41	PFE-VF	Mean	8.08	4.12	77.11	-1.56
		σ	0.94	0.02	0.93	0.33
42	PFE	Mean	1.11	0.59	73.78	-1.78
		σ	0.71	0.03	0.44	0.69
43	NBR	Mean	93.82	52.04	79.78	-10.22
		σ	2.92	1.67	0.83	1.71
51	X-FKM	Mean	-1.18	1.08	73.22	0.00
		σ	0.60	0.06	0.97	0.33
52	PFE-VF	Mean	9.08	4.57	71.56	-1.44
		σ	0.96	0.47	1.01	0.58
53	PFE-VF	Mean	13.37	4.65	68.67	-4.00
		σ	0.99	0.08	1.50	0.38
54	X-FKM	Mean	8.80	2.65	> 90	nd
		σ	1.65	0.15		
55	X-FKM	Mean	5.92	2.28	> 90	nd
		σ	0.09	0.04		

Table 8. D 471, Die-cut Samples, 28 Days in JP-8 @ 225° F

Material ID	Material Type		ΔV (%)	ΔM (%)	Hardness	
					Initial	ΔH
0	**Control NBR-L**	**Mean**	**19.72**	**14.573**	**73.78**	**-1.89**
		σ	**3.73**	**2.03**	**0.83**	**0.78**
3	FKM	Mean	17.38	7.21	65.00	-4.22
		σ	1.50	0.24	0.71	0.38
4	ECO	Mean	-5.40	-3.68	63.00	3.33
		σ	1.60	0.08	0.87	2.89
5	FKM	Mean	5.07	2.29	74.11	-5.11
		σ	2.48	2.69	0.78	1.02
6	FKM	Mean	17.58	6.79	63.33	-5.78
		σ	8.09	0.17	0.50	0.69
8	NBR	Mean	6.16	3.97	71.11	7.11
		σ	0.32	0.05	0.60	0.19
9	FKM	Mean	12.40	8.54	84.78	-2.22
		σ	0.94	0.20	0.44	0.84
10	FVMQ	Mean	7.94	4.73	82.89	-7.00
		σ	0.59	0.05	0.60	1.33
11	FKM	Mean	14.75	3.26	71.22	-3.33
		σ	7.81	0.38	12.05	6.77
12	ECO	Mean	0.34	-16.99	75.89	-2.11
		σ	1.56	1.07	0.78	0.51
13	HNBR	Mean	12.07	30.54	74.89	-9.78
		σ	1.82	1.76	1.54	1.17
17	HNBR	Mean	13.78	10.66	72.22	-3.78
		σ	0.66	0.05	0.67	0.96
18	HNBR	Mean	11.97	9.08	82.78	-6.11
		σ	0.48	0.08	0.44	0.19
19	HNBR	Mean	11.41	9.37	83.00	-5.22
		σ	0.94	0.23	0.00	0.51
20	HNBR	Mean	12.88	9.67	83.78	-6.56
		σ	0.40	0.60	0.67	0.51
21	FKM	Mean	5.25	2.76	77.33	-2.33
		σ	2.37	1.99	0.71	0.67
22	HNBR	Mean	13.34	9.31	84.33	-6.56
		σ	0.81	0.25	0.50	0.38
23	FKM	Mean	4.95	3.04	76.56	-2.00
		σ	0.47	0.03	0.53	0.33
25	FKM	Mean	6.24	2.50	71.44	-0.44
		σ	0.60	0.11	1.24	0.69
29	FVMQ	Mean	10.15	6.76	56.78	-3.56
		σ	2.35	0.10	0.44	1.35
30	NBR	Mean	25.95	19.48	67.44	-3.44
		σ	3.58	0.31	1.81	0.69

Table 8. Cont'd. D 471, Die-cut Samples, 28 Days in JP-8 @ 225° F

Material ID	Material Type		ΔV (%)	ΔM (%)	Hardness	
					Initial	ΔH
0	**Control NBR-L**	**Mean**	**19.72**	**14.573**	**73.78**	**-1.89**
		σ	**3.73**	**2.03**	**0.83**	**0.78**
31	NBR	Mean	12.13	3.81	82.78	-0.78
		σ	0.62	6.87	0.44	1.02
32	NBR	Mean	12.96	9.34	79.44	-3.78
		σ	1.25	0.18	0.88	0.96
33	NBR	Mean	17.32	13.09	71.44	-2.67
		σ	1.38	0.60	0.73	1.00
34	NBR	Mean	23.34	14.94	74.22	-8.00
		σ	2.33	0.17	0.67	1.45
35	HNBR	Mean	17.25	12.38	77.67	-3.11
		σ	0.47	0.04	0.50	0.38
36	HNBR	Mean	15.71	10.46	75.44	-4.00
		σ	2.27	0.24	1.01	0.88
37	FKM	Mean	10.21	4.56	73.11	-5.44
		σ	1.69	0.81	0.93	1.68
38	PFE	Mean	2.50	1.95	56.89	2.44
		σ	0.27	0.01	0.93	0.38
39	PFE	Mean	4.83	2.76	58.00	3.00
		σ	1.20	0.08	1.00	0.58
40	PFE	Mean	2.22	1.56	69.11	2.22
		σ	0.85	0.04	0.60	0.19
41	PFE-VF	Mean	3.83	1.67	74.78	-0.89
		σ	0.41	0.05	0.97	1.07
42	PFE	Mean	4.15	-1.03	72.56	1.67
		σ	1.21	4.56	0.73	0.33
43	NBR	Mean	77.69	49.24	77.33	-31.44
		σ	5.75	1.50	0.87	3.10
51	X-FKM	Mean	3.90	2.87	72.33	-1.44
		σ	2.76	0.02	0.71	0.69
52	PFE-VF	Mean	5.90	1.94	69.89	-0.33
		σ	2.49	0.01	1.05	0.88
53	PFE-VF	Mean	3.67	1.90	65.00	-1.33
		σ	1.58	0.04	0.50	0.33
54	X-FKM	Mean	6.81	1.94	> 90	nd
		σ	2.16	0.12		
55	X-FKM	Mean	5.41	1.60	> 90	nd
		σ	0.38	0.01		

Table 9. D 471, Die-cut Samples, 28 Days in JP-8+100 @ 225° F

Material ID	Material Type		ΔV (%)	ΔM (%)	Hardness	
					Initial	ΔH
0	**Control NBR-L**	**Mean**	**nd**	**nd**	**73.78**	**nd**
		σ			**0.83**	
3	FKM	Mean	1.75	-2.75	64.33	2.11
		σ	1.54	1.10	1.00	1.50
4	ECO	Mean	-3.57	-4.12	63.89	-3.11
		σ	1.55	0.32	1.27	0.69
5	FKM	Mean	27.02	13.18	76.22	-21.89
		σ	0.27	0.92	1.92	1.35
6	FKM	Mean	40.60	-34.29	61.89	-7.33
		σ	8.19	2.32	0.60	0.33
8	NBR	Mean	10.90	4.50	75.56	2.33
		σ	1.55	0.51	1.13	0.67
9	FKM	Mean	15.73	7.92	86.22	-4.11
		σ	1.13	0.80	0.44	0.51
10	FVMQ	Mean	10.92	4.70	85.00	-12.89
		σ	2.62	0.33	0.00	1.58
11	FKM	Mean	11.35	2.84	83.67	-10.00
		σ	8.27	9.69	0.71	0.00
12	ECO	Mean	11.53	2.08	79.22	-17.11
		σ	1.67	1.00	0.44	1.07
13	HNBR	Mean	10.46	4.21	78.78	-6.44
		σ	0.46	0.08	0.97	1.39
17	HNBR	Mean	19.43	10.40	70.44	-5.67
		σ	0.41	0.84	0.88	0.67
18	HNBR	Mean	13.42	8.74	82.56	-7.56
		σ	0.03	3.16	0.73	0.51
19	HNBR	Mean	14.12	8.77	83.11	-9.00
		σ	3.64	0.07	0.60	0.33
20	HNBR	Mean	15.95	8.86	83.56	-8.67
		σ	0.51	0.01	0.53	0.33
21	FKM	Mean	9.22	3.03	77.44	-3.67
		σ	1.25	0.04	0.73	0.33
22	HNBR	Mean	14.41	8.64	83.33	-8.33
		σ	1.52	0.19	0.50	0.33
23	FKM	Mean	8.57	3.40	77.11	-4.78
		σ	0.36	0.13	0.93	0.69
25	FKM	Mean	5.01	2.55	73.11	-1.89
		σ	0.88	0.22	1.69	1.02
29	FVMQ	Mean	9.49	6.26	57.00	-10.89
		σ	1.76	0.25	0.50	1.54
30	NBR	Mean	27.60	18.41	68.00	-8.56
		σ	1.81	0.04	1.00	0.77

Table 9. Cont'd. D 471, Die-cut Samples, 28 Days in JP-8+100 @ 225° F

Material ID	Material Type		ΔV (%)	ΔM (%)	Hardness	
					Initial	ΔH
0	**Control NBR-L**	**Mean**	**nd**	**nd**	**73.78**	**nd**
		σ			**0.83**	
31	NBR	Mean	13.03	7.26	82.56	-3.00
		σ	2.22	0.17	0.53	0.33
32	NBR	Mean	11.54	12.15	79.78	-3.11
		σ	1.23	6.94	0.67	0.96
33	NBR	Mean	13.89	11.15	72.56	-6.22
		σ	4.33	0.56	0.75	0.51
34	NBR	Mean	23.35	13.81	74.56	-10.00
		σ	3.58	0.14	0.53	0.67
35	HNBR	Mean	15.52	11.80	76.67	-3.56
		σ	1.37	0.14	0.50	0.96
36	HNBR	Mean	14.29	8.86	75.89	-2.44
		σ	1.21	0.50	0.60	2.78
37	FKM	Mean	5.29	2.88	70.56	-1.56
		σ	1.40	0.13	0.73	0.51
38	PFE	Mean	0.13	2.05	57.00	-0.11
		σ	0.87	0.04	0.50	0.51
39	PFE	Mean	1.79	2.73	58.78	4.11
		σ	0.36	0.02	0.67	0.51
40	PFE	Mean	3.51	1.59	69.67	0.78
		σ	2.40	0.06	0.71	1.64
41	PFE-VF	Mean	4.44	1.87	74.67	-2.78
		σ	2.59	0.03	0.71	1.39
42	PFE	Mean	3.00	1.59	72.33	-0.11
		σ	1.71	0.91	0.71	0.51
43	NBR	Mean	143.56	84.21	76.56	< 20
		σ	6.48	2.88	0.88	
51	X-FKM	Mean	7.86	2.82	71.89	-0.33
		σ	3.00	0.11	1.17	1.00
52	PFE-VF	Mean	6.17	-5.17	71.11	-2.33
		σ	1.54	12.46	1.69	1.15
53	PFE-VF	Mean	5.93	10.97	67.67	-5.00
		σ	2.05	15.72	1.41	0.33
54	X-FKM	Mean	7.82	1.66	> 90	nd
		σ	1.59	0.06		
55	X-FKM	Mean	5.79	1.43	> 90	nd
		σ	1.11	0.07		

4.1.2 Physical Property Characterization

Tensile properties were determined for as-received and fluid aged samples using Type-C dumbbell samples die-cut from the compression molded test plaques. Initial tensile property data were used to screen the candidate test materials against the basic physical property requirements of the existing military performance specifications for aircraft o-rings. Retention of tensile properties after fluid aging was also used as an important criterion for program consideration as property retention after aging provides an excellent indication of long term sealing performance. The results reported in this section are the average and standard deviation of measurements taken on three replicate samples for unaged samples, and the relative change (%) in physical properties of the materials after fluid aging -based on the average properties of the aged samples (three replicates) relative to the average properties of the unaged samples. Data are presented in each table for the standard NBR-L material for comparative purposes. Tensile property data are not reported for all samples under all fluid aging conditions. In some cases, this was due to limited sample availability. In other cases, sample testing was discontinued based on poor performance.

For ease of presentation, the tabulated fluid aging data are presented as follows:

- Table 10. Tensile, Die-cut Samples – 3 Days in MIL-PRF-83282 @ 275° F
- Table 11. Tensile, Die-cut Samples – 3 Days in MIL-PRF-87257 @ 275° F
- Table 12. Tensile, Die-cut Samples – 3 Days in JP-8 @ 225° F
- Table 13. Tensile, Die-cut Samples – 3 Days in JP-8+100 @ 225° F
- Table 14. Tensile, Die-cut Samples – 28 Days in MIL-PRF-83282 @ 275° F
- Table 15. Tensile, Die-cut Samples – 28 Days in MIL-PRF-87257 @ 275° F
- Table 16. Tensile, Die-cut Samples – 28 Days in JP-8 @ 225° F
- Table 17. Tensile, Die-cut Samples – 28 Days in JP-8+100 @ 225° F.

Tensile property requirements for hydraulic system o-rings (per MIL-P-83461) include an initial tensile strength and elongation at break of at least 1350 psi and 125%, respectively, with no more than a 40% reduction in properties after 70 hours of hydraulic fluid aging. It should be noted that these tensile property specifications are for o-rings and not for die-cut tensile bars, so a generous allowance for the potential impact of sample geometry was allowed in this portion of the performance evaluation.

With a few exceptions, the initial tensile properties of most of the candidate materials were reasonably close to the performance specification. One of the FKM materials (11) demonstrated very poor tensile properties and was not deemed suitable for o-ring application. Sample 4-ECO demonstrated marginal performance. Both of these materials also demonstrated a propensity for volume contraction during aging, so these materials were eliminated from further consideration under the program. Some of the most chemically resistant candidate materials also demonstrated marginal tensile properties, including two of the PFE (40 and 42) and one of the PFE-VF materials (54).

Most of the candidate o-ring materials demonstrated exceptionally good retention of properties after high temperature fluid aging in both hydraulic fluids, even after 28 days of exposure. As a class, the NBR materials demonstrated relatively moderate performance, demonstrating the greater susceptibility of these materials to high temperature fluid degradation. As expected, the HNBR materials proved to be more resistant to aging than the NBR materials, although HNBR samples 22 and 36 demonstrated a significant decrease in performance after 28 days of hydraulic fluid aging. Samples 11-FKM and 12-ECO demonstrated relatively poor performance, but these samples were already considered candidates for elimination based on poor D 471 performance.

Some of the materials tested (e.g., 25-FKM, 42-PFE, 35-HNBR, 51-X-FKM and 54-X-FKM) demonstrated an increase in tensile properties instead of a decrease. Where a significant decrease in tensile properties is indicative of molecular weight degradation (real or apparent), an increase in tensile properties is usually associated with postcuring, secondary cross-linking or loss of low molecular weight components, including plasticizers. All of these can be a consequence of the high temperature aging fluid aging process.

Tensile property requirements for o-rings used in aircraft fuel system applications (per MIL-P-5315) include an initial tensile strength and elongation at break of at least 1000 psi and 200%, respectively. No additional requirements are provided for fluid aged samples, so an approximate 40% reduction in properties after 70 hours of fuel aging was used as a metric to be consistent with the hydraulic fluid testing and evaluation efforts. Once again, it should be noted that the tensile property specifications are for o-rings and not for die-cut tensile bars, so a generous allowance for the potential impact of sample geometry was allowed in the performance evaluation.

The initial tensile properties for fuel system o-rings are somewhat relaxed from that for hydraulic fluid systems. The initial properties of 11-FKM materials were still deemed too low for fuel system o-ring applications, and while 4-ECO demonstrated acceptable performance, this material still demonstrated a propensity for volume contraction during fuel aging, so it was eliminated from further consideration under the program. Some of the most chemically resistant candidate materials also demonstrated marginal tensile properties, including two of the PFE (40 and 42) and one of the PFE-VF materials (54). However, other compounds based on these same formulations (from the same suppliers), e.g., 40-PFE, 42-PFE and 51-X-FKM, met the tensile property requirements, so the property retention data (after aging) of these samples are still very much of interest.

In general, after 3 and 28 days of aging in JP-8, the NBR and HNBR samples demonstrated greater deterioration in properties than most of the other candidate materials. The best performing samples continued to fall within the PFE, PFE-VF and X-FKM classes of materials, with tensile property changes consistently falling within the range of ±5 to ±25%, even after 28 days in JP-8 at 225° F.

The trends and results demonstrated after aging in JP-8+100 at 225° F are very much the same, but more pronounced as JP-8+100 appears to be the more aggressive chemical formulation. The NBR and HNBR materials demonstrated a significant decrease in tensile properties after 28 days of aging in JP-8+100. The PFE, PFE-VF and X-FKM materials continued to be very good performers relative to the other materials tested with good retention in properties after fuel aging.

Table 10. Tensile, Die-cut Samples, 3 Days in MIL-PRF-83282 @ 275° F

Material ID	Material Type		Unaged		Fluid Aged	
			Tensile Strength (psi)	Elongation @ Break (%)	ΔTensile Strength (%)	ΔElongation @ Break (%)
0	**Control NBR-L**	**Mean**	**2947.53**	**884.48**	**-40.1**	**-46.6**
		σ	**843.01**	**203.64**		
3	FKM	Mean	2871.42	984.73	-33.37	-22.43
		σ	284.23	191.84		
4	ECO	Mean	892.53	434.35	nd	nd
		σ	47.47	18.53		
5	FKM	Mean	1706.00	444.27	1.34	2.18
		σ	80.60	11.90		
6	FKM	Mean	2735.74	977.61	-17.01	-9.14
		σ	171.07	12.41		
8	NBR	Mean	2442.33	616.28	-41.71	-66.35
		σ	85.28	17.65		
10	FVMQ	Mean	945.90	189.06	-11.82	-19.25
		σ	28.11	10.72		
11	FKM	Mean	483.87	239.19	-40.90	-85.85
		σ	31.22	253.19		
12	ECO	Mean	1533.09	452.67	-40.48	-67.06
		σ	183.53	42.28		
13	HNBR	Mean	3958.10	557.25	-13.69	-27.67
		σ	178.68	13.99		
17	HNBR	Mean	3355.65	561.58	-8.33	-25.33
		σ	505.82	73.11		
18	HNBR	Mean	3297.06	359.03	-19.03	-19.56
		σ	230.47	14.41		
19	HNBR	Mean	3412.55	375.06	-22.39	-26.39
		σ	90.79	16.90		
20	HNBR	Mean	3458.76	354.96	-11.96	-20.14
		σ	134.59	5.01		
21	FKM	Mean	1296.03	396.69	nd	nd
		σ	49.81	14.98		
22	HNBR	Mean	3221.70	358.52	-11.96	-30.45
		σ	117.33	13.68		
23	FKM	Mean	1481.23	253.94	nd	nd
		σ	275.39	49.49		
25	FKM	Mean	1433.42	331.04	5.35	-19.29
		σ	322.49	66.69		
29	FVMQ	Mean	846.67	491.35	-31.61	-23.93
		σ	68.04	17.07		
30	NBR	Mean	1802.50	335.37	nd	nd
		σ	140.62	7.65		

Table 10. Cont'd. Tensile, Die-cut Samples, 3 Days in MIL-PRF-83282 @ 275° F

Material ID	Material Type		Unaged		Fluid Aged	
			Tensile Strength (psi)	Elongation @ Break (%)	ΔTensile Strength (%)	ΔElongation @ Break (%)
0	**Control NBR-L**	**Mean**	**2947.53**	**884.48**	**-40.1**	**-46.6**
		σ	**843.01**	**203.64**		
31	NBR	Mean	1364.61	119.59	-13.39	-39.57
		σ	726.50	44.24		
32	NBR	Mean	1780.09	189.06	-47.06	-60.83
		σ	255.04	13.45		
33	NBR	Mean	1957.04	339.95	-59.92	-51.27
		σ	168.80	30.32		
34	NBR	Mean	1486.64	431.55	-4.88	-6.13
		σ	136.68	55.06		
35	HNBR	Mean	2181.74	260.31	46.60	18.57
		σ	827.61	76.72		
36	HNBR	Mean	1818.29	227.23	-38.61	-20.38
		σ	83.64	16.83		
37	FKM	Mean	1475.93	369.21	-28.38	-22.61
		σ	115.87	14.08		
38	PFE	Mean	1056.36	452.93	-22.90	-15.11
		σ	137.55	16.45		
39	PFE	Mean	1108.98	506.36	-8.23	-19.10
		σ	213.28	67.57		
40	PFE	Mean	807.70	258.27	nd	nd
		σ	46.79	4.66		
41	PFE-VF	Mean	1811.33	228.50	-16.44	-19.38
		σ	71.16	4.47		
42	PFE	Mean	682.54	152.67	nd	nd
		σ	125.13	47.82		
43	NBR	Mean	1370.62	619.85	-58.20	-86.66
		σ	178.73	33.37		
51	X-FKM	Mean	1015.74	221.12	11.31	-9.78
		σ	80.64	6.88		
52	PFE-VF	Mean	1791.88	244.53	-6.14	-21.95
		σ	123.70	17.68		
53	PFE-VF	Mean	1162.82	318.32	-15.01	-18.68
		σ	591.62	116.02		
54	X-FKM	Mean	516.51	192.88	93.15	180.87
		σ	234.90	184.56		
55	X-FKM	Mean	994.93	509.67	-10.12	14.83
		σ	155.00	7.09		

Table 11. Tensile, Die-cut Samples, 3 Days in MIL-PRF-87257 @ 275° F

Material ID	Material Type		Unaged		Fluid Aged	
			Tensile Strength (psi)	Elongation @ Break (%)	ΔTensile Strength (%)	ΔElongation @ Break (%)
0	**Control NBR-L**	**Mean**	**2947.53**	**884.48**	**nd**	**nd**
		σ	**843.01**	**203.64**		
3	FKM	Mean	2871.42	984.73	-42.03	-26.43
		σ	284.23	191.84		
4	ECO	Mean	892.53	434.35	nd	nd
		σ	47.47	18.53		
5	FKM	Mean	1706.00	444.27	-38.81	-25.49
		σ	80.60	11.90		
6	FKM	Mean	2735.74	977.61	-45.22	-21.76
		σ	171.07	12.41		
8	NBR	Mean	2442.33	616.28	-29.86	-55.90
		σ	85.28	17.65		
10	FVMQ	Mean	945.90	189.06	-19.67	-26.65
		σ	28.11	10.72		
11	FKM	Mean	483.87	239.19	-29.92	-83.62
		σ	31.22	253.19		
12	ECO	Mean	1533.09	452.67	-31.90	-53.29
		σ	183.53	42.28		
13	HNBR	Mean	3958.10	557.25	-17.64	-27.85
		σ	178.68	13.99		
17	HNBR	Mean	3355.65	561.58	-25.19	-31.81
		σ	505.82	73.11		
18	HNBR	Mean	3297.06	359.03	-19.79	-20.48
		σ	230.47	14.41		
19	HNBR	Mean	3412.55	375.06	-17.89	-18.59
		σ	90.79	16.90		
20	HNBR	Mean	3458.76	354.96	-16.67	-19.57
		σ	134.59	5.01		
21	FKM	Mean	1296.03	396.69	-32.30	-30.53
		σ	49.81	14.98		
22	HNBR	Mean	3221.70	358.52	-9.99	-22.14
		σ	117.33	13.68		
23	FKM	Mean	1481.23	253.94	nd	nd
		σ	275.39	49.49		
25	FKM	Mean	1433.42	331.04	21.73	1.08
		σ	322.49	66.69		
29	FVMQ	Mean	846.67	491.35	-24.37	-18.28
		σ	68.04	17.07		
30	NBR	Mean	1802.50	335.37	nd	nd
		σ	140.62	7.65		

Table 11. Cont'd. Tensile, Die-cut Samples, 3 Days in MIL-PRF-87257 @ 275° F

Material ID	Material Type		Unaged		Fluid Aged	
			Tensile Strength (psi)	Elongation @ Break (%)	ΔTensile Strength (%)	ΔElongation @ Break (%)
0	**Control NBR-L**	**Mean**	**2947.53**	**884.48**	**nd**	**nd**
		σ	**843.01**	**203.64**		
31	NBR	Mean	1364.61	119.59	-3.12	-29.36
		σ	726.50	44.24		
32	NBR	Mean	1780.09	189.06	-32.85	-38.22
		σ	255.04	13.45		
33	NBR	Mean	1957.04	339.95	-28.89	-22.08
		σ	168.80	30.32		
34	NBR	Mean	1486.64	431.55	-16.72	-4.83
		σ	136.68	55.06		
35	HNBR	Mean	2181.74	260.31	54.31	97.36
		σ	827.61	76.72		
36	HNBR	Mean	1818.29	227.23	-28.10	14.22
		σ	83.64	16.83		
37	FKM	Mean	1475.93	369.21	-30.64	-10.27
		σ	115.87	14.08		
38	PFE	Mean	1056.36	452.93	-17.49	-9.61
		σ	137.55	16.45		
39	PFE	Mean	1108.98	506.36	-29.52	-21.41
		σ	213.28	67.57		
40	PFE	Mean	807.70	258.27	2.43	-11.92
		σ	46.79	4.66		
41	PFE-VF	Mean	1811.33	228.50	-10.96	-6.01
		σ	71.16	4.47		
42	PFE	Mean	682.54	152.67	10.50	52.00
		σ	125.13	47.82		
43	NBR	Mean	1370.62	619.85	nd	nd
		σ	178.73	33.37		
51	X-FKM	Mean	1015.74	221.12	nd	nd
		σ	80.64	6.88		
52	PFE-VF	Mean	1791.88	244.53	-39.97	-29.45
		σ	123.70	17.68		
53	PFE-VF	Mean	1162.82	318.32	-9.28	-0.08
		σ	591.62	116.02		
54	X-FKM	Mean	516.51	192.88	nd	nd
		σ	234.90	184.56		
55	X-FKM	Mean	994.93	509.67	nd	nd
		σ	155.00	7.09		

Table 12. Tensile, Die-cut Samples, 3 Days in JP-8 @ 225° F

Material ID	Material Type		Unaged		Fluid Aged	
			Tensile Strength (psi)	Elongation @ Break (%)	ΔTensile Strength (%)	ΔElongation @ Break (%)
0	**Control NBR-L**	**Mean**	**2947.53**	**884.48**	**-35.4**	**-38.5**
		σ	**843.01**	**203.64**		
3	FKM	Mean	2871.42	984.73	-48.11	-32.17
		σ	284.23	191.84		
4	ECO	Mean	892.53	434.35	nd	nd
		σ	47.47	18.53		
5	FKM	Mean	1706.00	444.27	-20.82	-22.28
		σ	80.60	11.90		
6	FKM	Mean	2735.74	977.61	-48.25	-25.77
		σ	171.07	12.41		
8	NBR	Mean	2442.33	616.28	-42.89	-13.38
		σ	85.28	17.65		
10	FVMQ	Mean	945.90	189.06	77.40	11.04
		σ	28.11	10.72		
11	FKM	Mean	483.87	239.19	-53.50	-87.34
		σ	31.22	253.19		
12	ECO	Mean	1533.09	452.67	-27.16	-36.99
		σ	183.53	42.28		
13	HNBR	Mean	3958.10	557.25	-33.68	-20.87
		σ	178.68	13.99		
17	HNBR	Mean	3355.65	561.58	-34.63	-27.00
		σ	505.82	73.11		
18	HNBR	Mean	3297.06	359.03	-23.62	-11.98
		σ	230.47	14.41		
19	HNBR	Mean	3412.55	375.06	-12.15	-7.26
		σ	90.79	16.90		
20	HNBR	Mean	3458.76	354.96	-27.79	-22.58
		σ	134.59	5.01		
21	FKM	Mean	1296.03	396.69	12.91	-39.90
		σ	49.81	14.98		
22	HNBR	Mean	3221.70	358.52	-36.60	-31.51
		σ	117.33	13.68		
23	FKM	Mean	1481.23	253.94	-15.87	-11.92
		σ	275.39	49.49		
25	FKM	Mean	1433.42	331.04	-11.89	-0.54
		σ	322.49	66.69		
29	FVMQ	Mean	846.67	491.35	-29.19	-23.25
		σ	68.04	17.07		
30	NBR	Mean	1802.50	335.37	-67.13	-52.12
		σ	140.62	7.65		

Table 12. Cont'd. Tensile, Die-cut Samples, 3 Days in JP-8 @ 225° F

Material ID	Material Type		Unaged		Fluid Aged	
			Tensile Strength (psi)	Elongation @ Break (%)	ΔTensile Strength (%)	ΔElongation @ Break (%)
0	**Control NBR-L**	**Mean**	**2947.53**	**884.48**	**-35.4**	**-38.5**
		σ	**843.01**	**203.64**		
31	NBR	Mean	1364.61	119.59	nd	nd
		σ	726.50	44.24		
32	NBR	Mean	1780.09	189.06	-43.41	-36.34
		σ	255.04	13.45		
33	NBR	Mean	1957.04	339.95	nd	nd
		σ	168.80	30.32		
34	NBR	Mean	1486.64	431.55	nd	nd
		σ	136.68	55.06		
35	HNBR	Mean	2181.74	260.31	45.45	95.50
		σ	827.61	76.72		
36	HNBR	Mean	1818.29	227.23	nd	nd
		σ	83.64	16.83		
37	FKM	Mean	1475.93	369.21	-21.58	-11.58
		σ	115.87	14.08		
38	PFE	Mean	1056.36	452.93	-3.12	-11.52
		σ	137.55	16.45		
39	PFE	Mean	1108.98	506.36	-6.26	-12.01
		σ	213.28	67.57		
40	PFE	Mean	807.70	258.27	7.90	-11.13
		σ	46.79	4.66		
41	PFE-VF	Mean	1811.33	228.50	-27.28	-17.71
		σ	71.16	4.47		
42	PFE	Mean	682.54	152.67	22.63	25.67
		σ	125.13	47.82		
43	NBR	Mean	1370.62	619.85	nd	nd
		σ	178.73	33.37		
51	X-FKM	Mean	1015.74	221.12	-5.65	-12.11
		σ	80.64	6.88		
52	PFE-VF	Mean	1791.88	244.53	-17.49	-16.23
		σ	123.70	17.68		
53	PFE-VF	Mean	1162.82	318.32	12.57	5.04
		σ	591.62	116.02		
54	X-FKM	Mean	516.51	192.88	nd	nd
		σ	234.90	184.56		
55	X-FKM	Mean	994.93	509.67	1.92	13.83
		σ	155.00	7.09		

Table 13. Tensile, Die-cut Samples, 3 Days in JP-8+100 @ 225° F

Material ID	Material Type		Unaged		Fluid Aged	
			Tensile Strength (psi)	Elongation @ Break (%)	ΔTensile Strength (%)	ΔElongation @ Break (%)
0	**Control NBR-L**	**Mean**	**2947.53**	**884.48**	**nd**	**nd**
		σ	**843.01**	**203.64**		
3	FKM	Mean	2871.42	984.73	-22.54	-6.74
		σ	284.23	191.84		
4	ECO	Mean	892.53	434.35	119.91	144.76
		σ	47.47	18.53		
5	FKM	Mean	1706.00	444.27	-21.07	-20.73
		σ	80.60	11.90		
6	FKM	Mean	2735.74	977.61	-53.12	-32.27
		σ	171.07	12.41		
8	NBR	Mean	2442.33	616.28	-2.64	-31.63
		σ	85.28	17.65		
10	FVMQ	Mean	945.90	189.06	nd	nd
		σ	28.11	10.72		
11	FKM	Mean	483.87	239.19	-21.91	-77.87
		σ	31.22	253.19		
12	ECO	Mean	1533.09	452.67	-6.13	-19.96
		σ	183.53	42.28		
13	HNBR	Mean	3958.10	557.25	-28.36	-12.01
		σ	178.68	13.99		
17	HNBR	Mean	3355.65	561.58	-41.28	-26.91
		σ	505.82	73.11		
18	HNBR	Mean	3297.06	359.03	-16.97	0.64
		σ	230.47	14.41		
19	HNBR	Mean	3412.55	375.06	-17.73	-1.49
		σ	90.79	16.90		
20	HNBR	Mean	3458.76	354.96	-25.47	-2.65
		σ	134.59	5.01		
21	FKM	Mean	1296.03	396.69	nd	nd
		σ	49.81	14.98		
22	HNBR	Mean	3221.70	358.52	-51.70	-39.03
		σ	117.33	13.68		
23	FKM	Mean	1481.23	253.94	-14.45	3.01
		σ	275.39	49.49		
25	FKM	Mean	1433.42	331.04	-33.37	-6.69
		σ	322.49	66.69		
29	FVMQ	Mean	846.67	491.35	-22.23	-3.78
		σ	68.04	17.07		
30	NBR	Mean	1802.50	335.37	nd	nd
		σ	140.62	7.65		

Table 13. Cont'd. Tensile, Die-cut Samples, 3 Days in JP-8+100 @ 225° F

Material ID	Material Type		Unaged		Fluid Aged	
			Tensile Strength (psi)	Elongation @ Break (%)	ΔTensile Strength (%)	ΔElongation @ Break (%)
0	**Control NBR-L**	**Mean**	**2947.53**	**884.48**	**nd**	**nd**
		σ	**843.01**	**203.64**		
31	NBR	Mean	1364.61	119.59	-54.94	-41.28
		σ	726.50	44.24		
32	NBR	Mean	1780.09	189.06	-47.44	-39.70
		σ	255.04	13.45		
33	NBR	Mean	1957.04	339.95	-51.13	-42.51
		σ	168.80	30.32		
34	NBR	Mean	1486.64	431.55	-39.78	-18.51
		σ	136.68	55.06		
35	HNBR	Mean	2181.74	260.31	10.21	9.68
		σ	827.61	76.72		
36	HNBR	Mean	1818.29	227.23	-52.51	-8.62
		σ	83.64	16.83		
37	FKM	Mean	1475.93	369.21	-27.26	-0.28
		σ	115.87	14.08		
38	PFE	Mean	1056.36	452.93	nd	nd
		σ	137.55	16.45		
39	PFE	Mean	1108.98	506.36	nd	nd
		σ	213.28	67.57		
40	PFE	Mean	807.70	258.27	nd	nd
		σ	46.79	4.66		
41	PFE-VF	Mean	1811.33	228.50	-38.48	1.56
		σ	71.16	4.47		
42	PFE	Mean	682.54	152.67	nd	nd
		σ	125.13	47.82		
43	NBR	Mean	1370.62	619.85	-82.10	-68.92
		σ	178.73	33.37		
51	X-FKM	Mean	1015.74	221.12	1.60	-5.18
		σ	80.64	6.88		
52	PFE-VF	Mean	1791.88	244.53	-12.11	-11.42
		σ	123.70	17.68		
53	PFE-VF	Mean	1162.82	318.32	-20.21	-7.34
		σ	591.62	116.02		
54	X-FKM	Mean	516.51	192.88	62.42	173.61
		σ	234.90	184.56		
55	X-FKM	Mean	994.93	509.67	-12.73	18.72
		σ	155.00	7.09		

Table 14. Tensile, Die-cut Samples, 28 Days in MIL-PRF-83282 @ 275° F

Material ID	Material Type		Unaged		Fluid Aged	
			Tensile Strength (psi)	Elongation @ Break (%)	ΔTensile Strength (%)	ΔElongation @ Break (%)
0	**Control NBR-L**	**Mean**	**2947.53**	**884.48**	**nd**	**nd**
		σ	**843.01**	**203.64**		
3	FKM	Mean	2871.42	984.73	-25.08	-28.84
		σ	284.23	191.84		
4	ECO	Mean	892.53	434.35	nd	nd
		σ	47.47	18.53		
5	FKM	Mean	1706.00	444.27	-38.56	-44.27
		σ	80.60	11.90		
6	FKM	Mean	2735.74	977.61	-26.21	-25.56
		σ	171.07	12.41		
8	NBR	Mean	2442.33	616.28	nd	nd
		σ	85.28	17.65		
10	FVMQ	Mean	945.90	189.06	-35.30	-47.51
		σ	28.11	10.72		
11	FKM	Mean	483.87	239.19	nd	nd
		σ	31.22	253.19		
12	ECO	Mean	1533.09	452.67	nd	nd
		σ	183.53	42.28		
13	HNBR	Mean	3958.10	557.25	-40.20	-59.18
		σ	178.68	13.99		
17	HNBR	Mean	3355.65	561.58	-38.35	-56.23
		σ	505.82	73.11		
18	HNBR	Mean	3297.06	359.03	-34.72	-52.37
		σ	230.47	14.41		
19	HNBR	Mean	3412.55	375.06	-27.38	-50.61
		σ	90.79	16.90		
20	HNBR	Mean	3458.76	354.96	-32.44	-52.54
		σ	134.59	5.01		
21	FKM	Mean	1296.03	396.69	-25.29	-22.32
		σ	49.81	14.98		
22	HNBR	Mean	3221.70	358.52	-24.24	-59.26
		σ	117.33	13.68		
23	FKM	Mean	1481.23	253.94	nd	nd
		σ	275.39	49.49		
25	FKM	Mean	1433.42	331.04	8.73	5.23
		σ	322.49	66.69		
29	FVMQ	Mean	846.67	491.35	-32.45	-43.76
		σ	68.04	17.07		
30	NBR	Mean	1802.50	335.37	-48.15	-44.76
		σ	140.62	7.65		

Table 14. Cont'd. Tensile, Die-cut Samples, 28 Days, MIL-PRF-83282 @ 275° F

Material ID	Material Type		Unaged		Fluid Aged	
			Tensile Strength (psi)	Elongation @ Break (%)	ΔTensile Strength (%)	ΔElongation @ Break (%)
0	**Control NBR-L**	**Mean**	**2947.53**	**884.48**	**nd**	**nd**
		σ	**843.01**	**203.64**		
31	NBR	Mean	1364.61	119.59	-27.72	-56.60
		σ	726.50	44.24		
32	NBR	Mean	1780.09	189.06	-29.64	-60.43
		σ	255.04	13.45		
33	NBR	Mean	1957.04	339.95	-72.82	-64.75
		σ	168.80	30.32		
34	NBR	Mean	1486.64	431.55	-33.00	-36.91
		σ	136.68	55.06		
35	HNBR	Mean	2181.74	260.31	nd	nd
		σ	827.61	76.72		
36	HNBR	Mean	1818.29	227.23	-67.45	-63.16
		σ	83.64	16.83		
37	FKM	Mean	1475.93	369.21	-21.42	-17.78
		σ	115.87	14.08		
38	PFE	Mean	1056.36	452.93	-17.12	-18.26
		σ	137.55	16.45		
39	PFE	Mean	1108.98	506.36	-23.15	-46.13
		σ	213.28	67.57		
40	PFE	Mean	807.70	258.27	-4.98	-31.92
		σ	46.79	4.66		
41	PFE-VF	Mean	1811.33	228.50	-7.71	-15.37
		σ	71.16	4.47		
42	PFE	Mean	682.54	152.67	24.15	22.25
		σ	125.13	47.82		
43	NBR	Mean	1370.62	619.85	nd	nd
		σ	178.73	33.37		
51	X-FKM	Mean	1015.74	221.12	nd	nd
		σ	80.64	6.88		
52	PFE-VF	Mean	1791.88	244.53	-14.75	-20.77
		σ	123.70	17.68		
53	PFE-VF	Mean	1162.82	318.32	-19.33	-20.88
		σ	591.62	116.02		
54	X-FKM	Mean	516.51	192.88	nd	nd
		σ	234.90	184.56		
55	X-FKM	Mean	994.93	509.67	2.04	7.94
		σ	155.00	7.09		

Table 15. Tensile, Die-cut Samples, 28 Days in MIL-PRF-87257 @ 275° F

Material ID	Material Type		Unaged		Fluid Aged	
			Tensile Strength (psi)	Elongation @ Break (%)	ΔTensile Strength (%)	ΔElongation @ Break (%)
0	**Control NBR-L**	**Mean**	**2947.53**	**884.48**	**nd**	**nd**
		σ	**843.01**	**203.64**		
3	FKM	Mean	2871.42	984.73	-36.75	-36.28
		σ	284.23	191.84		
4	ECO	Mean	892.53	434.35	nd	nd
		σ	47.47	18.53		
5	FKM	Mean	1706.00	444.27	-16.67	-17.70
		σ	80.60	11.90		
6	FKM	Mean	2735.74	977.61	-35.04	-15.59
		σ	171.07	12.41		
8	NBR	Mean	2442.33	616.28	nd	nd
		σ	85.28	17.65		
10	FVMQ	Mean	945.90	189.06	-37.34	-38.09
		σ	28.11	10.72		
11	FKM	Mean	483.87	239.19	nd	nd
		σ	31.22	253.19		
12	ECO	Mean	1533.09	452.67	nd	nd
		σ	183.53	42.28		
13	HNBR	Mean	3958.10	557.25	-37.59	-52.05
		σ	178.68	13.99		
17	HNBR	Mean	3355.65	561.58	-31.90	-45.63
		σ	505.82	73.11		
18	HNBR	Mean	3297.06	359.03	-14.44	-22.04
		σ	230.47	14.41		
19	HNBR	Mean	3412.55	375.06	-34.17	-40.43
		σ	90.79	16.90		
20	HNBR	Mean	3458.76	354.96	-32.95	-46.74
		σ	134.59	5.01		
21	FKM	Mean	1296.03	396.69	-35.98	-25.53
		σ	49.81	14.98		
22	HNBR	Mean	3221.70	358.52	-64.31	-74.88
		σ	117.33	13.68		
23	FKM	Mean	1481.23	253.94	nd	nd
		σ	275.39	49.49		
25	FKM	Mean	1433.42	331.04	-23.47	-19.29
		σ	322.49	66.69		
29	FVMQ	Mean	846.67	491.35	-41.02	-35.53
		σ	68.04	17.07		
30	NBR	Mean	1802.50	335.37	nd	nd
		σ	140.62	7.65		

Table 15. Cont'd. Tensile, Die-cut Samples, 28 Days, MIL-PRF-87257 @ 275° F

Material ID	Material Type		Unaged		Fluid Aged	
			Tensile Strength (psi)	Elongation @ Break (%)	ΔTensile Strength (%)	ΔElongation @ Break (%)
0	**Control NBR-L**	**Mean**	**2947.53**	**884.48**	**nd**	**nd**
		σ	**843.01**	**203.64**		
31	NBR	Mean	1364.61	119.59	-32.65	-47.87
		σ	726.50	44.24		
32	NBR	Mean	1780.09	189.06	-41.25	-62.85
		σ	255.04	13.45		
33	NBR	Mean	1957.04	339.95	-67.20	-51.05
		σ	168.80	30.32		
34	NBR	Mean	1486.64	431.55	-24.82	-12.97
		σ	136.68	55.06		
35	HNBR	Mean	2181.74	260.31	nd	nd
		σ	827.61	76.72		
36	HNBR	Mean	1818.29	227.23	-69.50	-50.06
		σ	83.64	16.83		
37	FKM	Mean	1475.93	369.21	-24.25	-6.75
		σ	115.87	14.08		
38	PFE	Mean	1056.36	452.93	-25.39	-27.02
		σ	137.55	16.45		
39	PFE	Mean	1108.98	506.36	-29.98	-39.40
		σ	213.28	67.57		
40	PFE	Mean	807.70	258.27	1.66	-26.31
		σ	46.79	4.66		
41	PFE-VF	Mean	1811.33	228.50	-23.66	-12.36
		σ	71.16	4.47		
42	PFE	Mean	682.54	152.67	5.78	33.00
		σ	125.13	47.82		
43	NBR	Mean	1370.62	619.85	nd	nd
		σ	178.73	33.37		
51	X-FKM	Mean	1015.74	221.12	nd	nd
		σ	80.64	6.88		
52	PFE-VF	Mean	1791.88	244.53	-32.12	-19.98
		σ	123.70	17.68		
53	PFE-VF	Mean	1162.82	318.32	-14.52	-14.63
		σ	591.62	116.02		
54	X-FKM	Mean	516.51	192.88	nd	nd
		σ	234.90	184.56		
55	X-FKM	Mean	994.93	509.67	nd	nd
		σ	155.00	7.09		

Table 16. Tensile, Die-cut Samples, 28 Days in JP-8 @ 225° F

Material ID	Material Type		Unaged		Fluid Aged	
			Tensile Strength (psi)	Elongation @ Break (%)	ΔTensile Strength (%)	ΔElongation @ Break (%)
0	**Control NBR-L**	**Mean**	**2947.53**	**884.48**	**nd**	**nd**
		σ	**843.01**	**203.64**		
3	FKM	Mean	2871.42	984.73	-28.22	4.34
		σ	284.23	191.84		
4	ECO	Mean	892.53	434.35	nd	nd
		σ	47.47	18.53		
5	FKM	Mean	1706.00	444.27	5.54	46.22
		σ	80.60	11.90		
6	FKM	Mean	2735.74	977.61	-21.48	-1.33
		σ	171.07	12.41		
8	NBR	Mean	2442.33	616.28	-10.91	-45.33
		σ	85.28	17.65		
10	FVMQ	Mean	945.90	189.06	-17.21	1.88
		σ	28.11	10.72		
11	FKM	Mean	483.87	239.19	-55.11	-92.98
		σ	31.22	253.19		
12	ECO	Mean	1533.09	452.67	-33.70	-32.15
		σ	183.53	42.28		
13	HNBR	Mean	3958.10	557.25	-32.47	-13.79
		σ	178.68	13.99		
17	HNBR	Mean	3355.65	561.58	-41.90	-28.82
		σ	505.82	73.11		
18	HNBR	Mean	3297.06	359.03	-33.86	-5.39
		σ	230.47	14.41		
19	HNBR	Mean	3412.55	375.06	-44.45	-23.61
		σ	90.79	16.90		
20	HNBR	Mean	3458.76	354.96	-43.37	-26.02
		σ	134.59	5.01		
21	FKM	Mean	1296.03	396.69	-25.40	-29.63
		σ	49.81	14.98		
22	HNBR	Mean	3221.70	358.52	-18.98	-20.51
		σ	117.33	13.68		
23	FKM	Mean	1481.23	253.94	-16.22	-19.04
		σ	275.39	49.49		
25	FKM	Mean	1433.42	331.04	-14.22	-9.45
		σ	322.49	66.69		
29	FVMQ	Mean	846.67	491.35	-41.27	-26.93
		σ	68.04	17.07		
30	NBR	Mean	1802.50	335.37	-63.72	-48.86
		σ	140.62	7.65		

Table 16. Cont'd. Tensile, Die-cut Samples, 28 Days in JP-8 @ 225° F

Material ID	Material Type		Unaged		Fluid Aged	
			Tensile Strength (psi)	Elongation @ Break (%)	ΔTensile Strength (%)	ΔElongation @ Break (%)
0	**Control NBR-L**	**Mean**	**2947.53**	**884.48**	**nd**	**nd**
		σ	**843.01**	**203.64**		
31	NBR	Mean	1364.61	119.59	nd	nd
		σ	726.50	44.24		
32	NBR	Mean	1780.09	189.06	-47.31	-48.32
		σ	255.04	13.45		
33	NBR	Mean	1957.04	339.95	nd	nd
		σ	168.80	30.32		
34	NBR	Mean	1486.64	431.55	nd	nd
		σ	136.68	55.06		
35	HNBR	Mean	2181.74	260.31	nd	nd
		σ	827.61	76.72		
36	HNBR	Mean	1818.29	227.23	nd	nd
		σ	83.64	16.83		
37	FKM	Mean	1475.93	369.21	-22.19	-10.06
		σ	115.87	14.08		
38	PFE	Mean	1056.36	452.93	-26.37	-24.33
		σ	137.55	16.45		
39	PFE	Mean	1108.98	506.36	-19.12	-20.95
		σ	213.28	67.57		
40	PFE	Mean	807.70	258.27	12.60	7.88
		σ	46.79	4.66		
41	PFE-VF	Mean	1811.33	228.50	-23.39	-20.27
		σ	71.16	4.47		
42	PFE	Mean	682.54	152.67	19.63	23.67
		σ	125.13	47.82		
43	NBR	Mean	1370.62	619.85	nd	nd
		σ	178.73	33.37		
51	X-FKM	Mean	1015.74	221.12	-15.96	-20.6
		σ	80.64	6.88		
52	PFE-VF	Mean	1791.88	244.53	-17.20	-13.32
		σ	123.70	17.68		
53	PFE-VF	Mean	1162.82	318.32	3.80	-4.88
		σ	591.62	116.02		
54	X-FKM	Mean	516.51	192.88	nd	nd
		σ	234.90	184.56		
55	X-FKM	Mean	994.93	509.67	-8.64	14.33
		σ	155.00	7.09		

Table 17. Tensile, Die-cut Samples, 28 Days in JP-8+100 @ 225° F

Material ID	Material Type		Unaged		Fluid Aged	
			Tensile Strength (psi)	Elongation @ Break (%)	ΔTensile Strength (%)	ΔElongation @ Break (%)
0	**Control NBR-L**	**Mean**	**2947.53**	**884.48**	**nd**	**nd**
		σ	**843.01**	**203.64**		
3	FKM	Mean	2871.42	984.73	-60.69	-36.63
		σ	284.23	191.84		
4	ECO	Mean	892.53	434.35	6.76	-0.06
		σ	47.47	18.53		
5	FKM	Mean	1706.00	444.27	-38.06	-8.48
		σ	80.60	11.90		
6	FKM	Mean	2735.74	977.61	-54.75	-30.64
		σ	171.07	12.41		
8	NBR	Mean	2442.33	616.28	-54.63	-74.57
		σ	85.28	17.65		
10	FVMQ	Mean	945.90	189.06	nd	nd
		σ	28.11	10.72		
11	FKM	Mean	483.87	239.19	-22.52	-82.98
		σ	31.22	253.19		
12	ECO	Mean	1533.09	452.67	-71.31	-40.30
		σ	183.53	42.28		
13	HNBR	Mean	3958.10	557.25	-37.60	-29.73
		σ	178.68	13.99		
17	HNBR	Mean	3355.65	561.58	-67.12	-55.78
		σ	505.82	73.11		
18	HNBR	Mean	3297.06	359.03	-84.80	-83.20
		σ	230.47	14.41		
19	HNBR	Mean	3412.55	375.06	-93.28	-84.26
		σ	90.79	16.90		
20	HNBR	Mean	3458.76	354.96	-87.99	-82.08
		σ	134.59	5.01		
21	FKM	Mean	1296.03	396.69	nd	nd
		σ	49.81	14.98		
22	HNBR	Mean	3221.70	358.52	-99.71	-83.61
		σ	117.33	13.68		
23	FKM	Mean	1481.23	253.94	-38.99	-4.01
		σ	275.39	49.49		
25	FKM	Mean	1433.42	331.04	-54.10	-25.98
		σ	322.49	66.69		
29	FVMQ	Mean	846.67	491.35	-85.75	-71.93
		σ	68.04	17.07		
30	NBR	Mean	1802.50	335.37	nd	nd
		σ	140.62	7.65		

Table 17. Cont'd. Tensile, Die-cut Samples, 28 Days in JP-8+100 @ 225° F

Material ID	Material Type		Unaged		Fluid Aged	
			Tensile Strength (psi)	Elongation @ Break (%)	ΔTensile Strength (%)	ΔElongation @ Break (%)
0	**Control NBR-L**	**Mean**	**2947.53**	**884.48**	**nd**	**nd**
		σ	**843.01**	**203.64**		
31	NBR	Mean	1364.61	119.59	-78.16	-66.38
		σ	726.50	44.24		
32	NBR	Mean	1780.09	189.06	-56.25	-48.86
		σ	255.04	13.45		
33	NBR	Mean	1957.04	339.95	-90.04	-95.73
		σ	168.80	30.32		
34	NBR	Mean	1486.64	431.55	-29.74	-21.17
		σ	136.68	55.06		
35	HNBR	Mean	2181.74	260.31	-9.09	-2.05
		σ	827.61	76.72		
36	HNBR	Mean	1818.29	227.23	-85.90	-88.69
		σ	83.64	16.83		
37	FKM	Mean	1475.93	369.21	nd	nd
		σ	115.87	14.08		
38	PFE	Mean	1056.36	452.93	-61.75	-48.31
		σ	137.55	16.45		
39	PFE	Mean	1108.98	506.36	nd	nd
		σ	213.28	67.57		
40	PFE	Mean	807.70	258.27	-2.31	12.41
		σ	46.79	4.66		
41	PFE-VF	Mean	1811.33	228.50	-33.72	15.81
		σ	71.16	4.47		
42	PFE	Mean	682.54	152.67	16.75	65.17
		σ	125.13	47.82		
43	NBR	Mean	1370.62	619.85	-99.60	-91.63
		σ	178.73	33.37		
51	X-FKM	Mean	1015.74	221.12	-19.57	-33.89
		σ	80.64	6.88		
52	PFE-VF	Mean	1791.88	244.53	1.67	-11.42
		σ	123.70	17.68		
53	PFE-VF	Mean	1162.82	318.32	-24.57	-15.54
		σ	591.62	116.02		
54	X-FKM	Mean	516.51	192.88	91.05	189.18
		σ	234.90	184.56		
55	X-FKM	Mean	994.93	509.67	-5.47	8.49
		σ	155.00	7.09		

4.1.3 DMA Measurements

DMA measurements were performed on all candidate materials to characterize low temperature performance, both before and after fluid aging. Glass transition temperatures (T_g) and onset (T_o) values are presented in the following tables:

- Table 18. DMA Data – Before and After 3 and 28 Days in MIL-PRF-83282 @ 275° F
- Table 19. DMA Data – Before and After 3 and 28 Days in MIL-PRF-87257 @ 275° F
- Table 20. DMA Data – Before and After 3 and 28 Days in JP-8 @ 225° F
- Table 21. DMA Data – Before and After 3 and 28 Days in JP-8+100 @ 225° F.

DMA measures the dynamic modulus of materials over a range of temperatures, providing a quick and easy method to generate information that can be used to evaluate low temperature performance. The existence of low temperature transitions can be related directly to low temperature flexibility, mechanical hysteresis, and resilience. These properties are very important to forming and maintaining a proper seal at low temperature. In a DMA trace, departure from the high modulus behavior (exhibited by materials at temperatures below their glass transition) to the rubbery plateau modulus (characteristic of elastomers), occurs over a range of temperatures, with the glass transition temperature (T_g) being the mid-point in this transition. The onset (T_o) of the glass transition region is associated with the transformation from brittle-to-ductile behavior when examining a material that is heated from a low temperature to a high temperature, and, therefore, provides a measure of the material's ability to respond and function adequately at low operational temperatures. Samples with lower T_g and onset values are expected to demonstrate better low temperature performance due to enhanced large scale molecular level mobility at lower temperatures.

The use of the onset temperature as an indicator of low temperature performance in rubbers has been substantiated by Thomas.[13] Thomas demonstrated that the low temperature sealing ability of a variety of fluoroelastomers was maintained down to approximately 25° F below the glass transition temperature. Data generated by METSS in similar research, demonstrated that the temperature associated with the onset of the glass transition region was an average of 22° F below the glass transition temperature, which is consistent with Thomas' results.

The DMA measurements were performed to screen candidate materials for initial low temperature performance and retention of low temperature properties after fluid aging. Not surprisingly, the FVMQ samples demonstrated the best initial low temperature performance and good retention of low temperature mobility after fluid aging in hydraulic fluid and jet fuel. The NBR materials demonstrated very good initial low temperature mobility, but the transition temperatures for these materials shifted to significantly higher temperatures after fluid aging. This behavior is consistent with a loss of low molecular weight contributors to low temperature performance after fluid aging. Similar trends were noted in the HNBR materials, but the initial low temperature performance of the HNBR materials was not as good as the NBRs. With the exception of samples 54-X-FKM and 55-X-FKM, which were too hard to begin with, the PFE, PFE-VF and X-FKM materials demonstrated good initial low temperature performance and exceptional retention of low temperature properties after fluid aging.

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[13] E. W. Thomas, SAE Technical Paper 2001-01-2974, *"Fluoroelastomer Compatibility with Advanced Jet Engine Oils."*

Table 18. DMA Data – Before and After Aging in MIL-PRF-83282 @ 275° F

Material ID	Material Type	Control		3 Day		28 Day	
		Onset (°F)	T_g (°F)	Onset (°F)	T_g (°F)	Onset (°F)	T_g (°F)
0	**NBR-L**	**-47.94**	**33.54**	**nd**	**nd**	**nd**	**nd**
3	FKM	3.0	21.9	8.3	24.1	1.8	20.9
4	ECO	nd	nd	nd	nd	nd	nd
5	FKM	18.4	36.2	14.2	27.6	24.5	43.6
6	FKM	5.2	25.0	15.3	33.2	20.7	44.8
8	NBR	8.1	26.8	24.3	33.9	15.8	56.8
9	FKM	nd	nd	nd	nd	nd	nd
10	FVMQ	-82.1	-63.7	-71.3	-35.0	-86.1	-66.5
11	FKM	-24.2	-6.9	17.9	38.6	25.4	41.1
12	ECO	nd	nd	-29.5	-11.8	nd	nd
13	HNBR	9.5	29.1	10.7	26.3	37.4	62.7
17	HNBR	-5.1	12.0	6.9	25.6	23.2	47.1
18	HNBR	-5.8	18.2	5.1	18.4	17.6	32.5
19	HNBR	-0.4	16.4	5.0	18.6	14.3	32.9
20	HNBR	-8.0	10.8	0.3	22.3	5.6	26.2
21	FKM	8.9	26.8	9.1	28.2	9.1	28.4
22	HNBR	15.3	34.5	0.3	14.6	8.7	30.2
23	FKM	nd	nd	nd	nd	nd	nd
25	FKM	9.0	29.0	6.5	22.4	-8.7	12.4
29	FVMQ	-103.4	-84.4	-76.7	-59.9	-90.9	-70.6
30	NBR	-34.6	4.5	-19.1	2.2	8.0	26.0
31	NBR	-54.2	-16.7	-26.0	10.3	-16.7	44.2
32	NBR	-52.3	-23.8	-38.2	-5.9	-24.4	24.4
33	NBR	-65.5	-26.2	-65.2	-14.3	-18.7	14.3
34	NBR	-20.4	1.0	-20.8	3.8	7.5	27.0
35	HNBR	8.3	23.7	-7.7	12.1	9.3	26.8
36	HNBR	-51.4	-26.3	-34.5	-11.5	-20.9	12.4
37	FKM	4.9	23.2	1.0	25.0	4.1	22.1
38	PFE	nd	nd	nd	nd	-56.4	-36.9
39	PFE	nd	nd	-44.3	-25.4	-56.7	-36.9
40	PFE	-28.9	-11.5	-43.5	-28.6	-51.8	-29.2
41	PFE-VF	-15.7	6.2	-28.6	-12.5	-23.8	-9.8
42	PFE	-37.9	-19.0	-51.3	-35.1	-48.5	-32.4
43	NBR	-34.1	-12.2	nd	nd	nd	nd
51	X-FKM	-44.7	-25.4	-34.6	-3.0	-57.8	-37.8
52	PFE-VF	-26.8	-8.9	-12.5	8.9	-22.8	-7.5
53	PFE-VF	-33.5	-16.5	-16.8	3.3	-32.7	-14.9
54	X-FKM	7.6	34.0	20.2	39.2	13.2	36.3
55	X-FKM	12.7	32.2	11.0	30.1	4.3	31.8

Table 19. DMA Data – Before and After Aging in MIL-PRF-87257 @ 275° F

Material ID	Material Type	Control		3 Day		28 Day	
		Onset (°F)	T_g (°F)	Onset (°F)	T_g (°F)	Onset (°F)	T_g (°F)
0	**NBR-L**	**-47.94**	**33.54**	**nd**	**nd**	**nd**	**nd**
3	FKM	3.0	21.9	5.0	26.1	7.7	25.6
4	ECO	nd	nd	nd	nd	nd	nd
5	FKM	18.4	36.2	13.6	32.1	16.2	35.2
6	FKM	5.2	25.0	1.0	23.7	4.4	24.9
8	NBR	8.1	26.8	24.6	53.7	nd	nd
9	FKM	nd	nd	nd	nd	nd	nd
10	FVMQ	-82.1	-63.7	-80.7	-61.4	-81.0	-61.8
11	FKM	-24.2	-6.9	18.3	42.6	nd	nd
12	ECO	nd	nd	-21.7	3.1	nd	nd
13	HNBR	9.5	29.1	9.8	33.1	24.8	48.8
17	HNBR	-5.1	12.0	-4.0	15.8	21.6	56.6
18	HNBR	-5.8	18.2	7.8	25.0	29.3	74.1
19	HNBR	-0.4	16.4	4.4	22.1	21.9	42.1
20	HNBR	-8.0	10.8	3.2	23.5	-5.1	19.6
21	FKM	8.9	26.8	nd	nd	1.0	25.7
22	HNBR	15.3	34.5	6.6	23.7	22.3	41.6
23	FKM	nd	nd	nd	nd	nd	nd
25	FKM	9.0	29.0	-11.7	11.5	-1.3	17.3
29	FVMQ	-103.4	-84.4	-94.8	-66.4	-74.3	-51.9
30	NBR	-34.6	4.5	-5.6	23.0	-4.9	19.3
31	NBR	-54.2	-16.7	-16.0	27.8	-29.2	-2.7
32	NBR	-52.3	-23.8	-17.0	16.1	-11.9	58.8
33	NBR	-65.5	-26.2	-38.1	2.6	-72.9	-26.3
34	NBR	-20.4	1.0	-6.6	13.0	61.0	41.0
35	HNBR	8.3	23.7	-6.4	15.1	-1.1	18.8
36	HNBR	-51.4	-26.3	-37.5	-9.2	-26.1	39.4
37	FKM	4.9	23.2	2.7	24.4	1.8	23.4
38	PFE	nd	nd	nd	nd	-43.6	-17.9
39	PFE	nd	nd	nd	nd	-53.3	-29.6
40	PFE	-28.9	-11.5	-62.5	-38.4	-57.4	-38.5
41	PFE-VF	-15.7	6.2	-40.7	-19.3	-36.0	-15.0
42	PFE	-37.9	-19.0	-73.1	-43.9	-58.0	-39.8
43	NBR	-34.1	-12.2	nd	nd	nd	nd
51	X-FKM	-44.7	-25.4	-65.8	-31.4	-58.1	-38.0
52	PFE-VF	-26.8	-8.9	-15.9	5.8	-29.7	-11.0
53	PFE-VF	-33.5	-16.5	-18.6	1.8	-32.6	-14.4
54	X-FKM	7.6	34.0	13.1	35.6	nd	nd
55	X-FKM	12.7	32.2	16.3	37.8	14.4	28.3

Table 20. DMA Data – Before and After Aging in JP-8 @ 225° F

Material ID	Material Type	Control		3 Day		28 Day	
		Onset (°F)	T_g (°F)	Onset (°F)	T_g (°F)	Onset (°F)	T_g (°F)
0	**NBR-L**	**-47.94**	**33.54**	**nd**	**nd**	**nd**	**nd**
3	FKM	3.0	21.9	23.9	43.9	13.1	25.6
4	ECO	nd	nd	nd	nd	nd	nd
5	FKM	18.4	36.2	21.9	39.0	15.7	nd
6	FKM	5.2	25.0	8.8	29.2	7.3	23.5
8	NBR	8.1	26.8	17.8	38.2	15.9	34.6
9	FKM	nd	nd	nd	nd	nd	nd
10	FVMQ	-82.1	-63.7	-71.7	-56.0	-72.0	-54.4
11	FKM	-24.2	-6.9	18.5	44.7	21.0	42.9
12	ECO	nd	nd	-32.9	-14.2	-37.2	-16.7
13	HNBR	9.5	29.1	3.5	27.9	11.6	29.8
17	HNBR	-5.1	12.0	-5.4	13.3	-4.1	13.7
18	HNBR	-5.8	18.2	4.6	24.4	7.6	23.1
19	HNBR	-0.4	16.4	1.1	17.5	4.1	22.0
20	HNBR	-8.0	10.8	14.4	39.9	4.3	20.7
21	FKM	8.9	26.8	-3.5	26.6	23.7	25.2
22	HNBR	15.3	34.5	11.0	31.4	9.4	23.5
23	FKM	nd	nd	nd	nd	nd	nd
25	FKM	9.0	29.0	6.2	27.5	-7.8	12.0
29	FVMQ	-103.4	-84.4	-79.7	-55.1	-84.5	-64.6
30	NBR	-34.6	4.5	-17.4	3.0	-14.8	5.3
31	NBR	-54.2	-16.7	-29.5	4.9	-13.9	10.1
32	NBR	-52.3	-23.8	-32.7	-3.0	-26.2	-5.4
33	NBR	-65.5	-26.2	-48.0	-10.0	nd	nd
34	NBR	-20.4	1.0	-0.8	16.6	-0.7	15.6
35	HNBR	8.3	23.7	-9.2	11.5	-5.1	13.0
36	HNBR	-51.4	-26.3	-38.9	-10.8	-33.5	-13.2
37	FKM	4.9	23.2	-0.2	25.2	2.1	23.9
38	PFE	nd	nd	-69.0	-24.7	-59.8	-38.4
39	PFE	nd	nd	-67.9	-46.7	-57.3	-38.7
40	PFE	-28.9	-11.5	-42.6	-26.3	-53.1	-37.9
41	PFE-VF	-15.7	6.2	-29.6	-8.5	-16.7	0.7
42	PFE	-37.9	-19.0	-49.9	-32.4	-44.5	-23.8
43	NBR	-34.1	-12.2	nd	nd	nd	nd
51	X-FKM	-44.7	-25.4	-59.6	-36.1	-47.4	-27.8
52	PFE-VF	-26.8	-8.9	-37.9	-14.6	-28.5	-11.5
53	PFE-VF	-33.5	-16.5	-25.7	-2.4	-34.1	-15.1
54	X-FKM	7.6	34.0	21.4	46.8	nd	nd
55	X-FKM	12.7	32.2	25.5	44.9	3.9	33.2

Table 21. DMA Data – Before and After Aging in JP-8+100 @ 225° F

Material ID	Material Type	Control		3 Day		28 Day	
		Onset (°F)	T_g (°F)	Onset (°F)	T_g (°F)	Onset (°F)	T_g (°F)
0	**NBR-L**	**-47.94**	**33.54**	**nd**	**nd**	**nd**	**nd**
3	FKM	3.0	21.9	4.4	25.3	13.1	27.4
4	ECO	nd	nd	nd	nd	-23.7	-7.6
5	FKM	18.4	36.2	12.7	32.8	16.2	35.5
6	FKM	5.2	25.0	19.8	39.1	8.8	27.1
8	NBR	8.1	26.8	18.4	49.3	22.5	55.7
9	FKM	nd	nd	nd	nd	-12.2	43.6
10	FVMQ	-82.1	-63.7	-64.8	-39.6	-78.3	-61.3
11	FKM	-24.2	-6.9	20.4	45.4	24.5	45.3
12	ECO	nd	nd	-23.1	-2.9	-40.5	-20.8
13	HNBR	9.5	29.1	30.6	52.1	21.6	39.4
17	HNBR	-5.1	12.0	9.2	27.9	16.3	36.3
18	HNBR	-5.8	18.2	18.6	32.3	22.6	41.6
19	HNBR	-0.4	16.4	13.9	27.6	13.3	33.4
20	HNBR	-8.0	10.8	8.9	23.9	-43.2	-15.3
21	FKM	8.9	26.8	9.2	29.3	12.8	30.0
22	HNBR	15.3	34.5	9.1	25.0	9.1	25.3
23	FKM	nd	nd	nd	nd	-18.0	2.2
25	FKM	9.0	29.0	6.7	28.8	-6.9	14.5
29	FVMQ	-103.4	-84.4	-79.3	-56.1	-77.1	-53.3
30	NBR	-34.6	4.5	-1.0	16.7	-14.7	6.8
31	NBR	-54.2	-16.7	nd	nd	-14.0	34.0
32	NBR	-52.3	-23.8	-7.8	20.1	-15.9	24.4
33	NBR	-65.5	-26.2	nd	nd	-1.6	44.1
34	NBR	-20.4	1.0	nd	nd	6.8	26.4
35	HNBR	8.3	23.7	nd	nd	10.9	28.5
36	HNBR	-51.4	-26.3	nd	nd	-7.2	17.1
37	FKM	4.9	23.2	1.6	27.0	7.0	27.5
38	PFE	nd	nd	-60.3	-41.1	-57.6	-34.6
39	PFE	nd	nd	-40.8	-18.5	-45.6	-28.9
40	PFE	-28.9	-11.5	-41.8	-26.7	-49.1	-36.3
41	PFE-VF	-15.7	6.2	-26.7	-10.9	-23.2	-3.3
42	PFE	-37.9	-19.0	-48.1	-32.2	-42.8	-24.3
43	NBR	-34.1	-12.2	nd	nd	-23.2	20.2
51	X-FKM	-44.7	-25.4	-72.4	-28.0	-49.7	-31.7
52	PFE-VF	-26.8	-8.9	-27.2	-9.0	-33.2	-14.9
53	PFE-VF	-33.5	-16.5	-39.8	-19.8	-38.5	-18.4
54	X-FKM	7.6	34.0	nd	nd	nd	nd
55	X-FKM	12.7	32.2	24.8	48.3	7.8	33.8

4.1.4 Percent Extractables

As previously noted, the DMA samples were also used to determine the percent of extractables in each of the candidate materials. The initial weight of each of the DMA samples was recorded as the samples were cut from the compression molded plaques. After DMA measurements, the DMA samples were dried under temperature and vacuum until reaching a final equilibrium weight. The percent of materials extracted during the fluid aging experiments was determined based on these initial and final weight values. In most cases, slightly negative numbers may be attributed to experimental error; in some cases, the samples may not have been fully extracted even after extended periods of vacuum drying.

Extracted material data are reported in the following tables:

- Table 22. Percent of Sample Material Extracted After 3-Day Fluid Aging
- Table 23. Percent of Sample Material Extracted After 28-Day Fluid Aging.

The percent extractable materials from the NBR and HNBR materials are noticeably higher (at least an order of magnitude) than all of the fluorinated chemistries evaluated under the program. The ECO materials also demonstrated a relatively high level of extractable material with fluid aging. As a general comment, the percentage of material extracted by the jet fuel is typically higher than that for hydraulic fluid. The fluorinated materials, including the PFE, PFE-VF and X-FKM materials, performed very well, demonstrating little to no weight loss after 28 days of high temperature fluid aging. This is typical of elastomers that can be used in a relatively pure form, as opposed to products like the nitrile materials that must be compounded to a higher degree with other materials to achieve optimum performance. The data are consistent with the DMA data presented previously.

Table 22. Percent of Sample Material Extracted After 3-Day Fluid Aging

Material ID	Material Type	T_{aging} = 275° F		T_{aging} = 225° F	
		MIL-PRF-83282	MIL-PRF-87257	JP-8	JP-8+100
0	**NBR-L**	**nd**	**nd**	**nd**	**nd**
3	FKM	0.36%	0.73%	0.29%	0.50%
4	ECO	nd	nd	nd	10.90%
5	FKM	0.22%	0.12%	0.19%	0.14%
6	FKM	0.33%	0.72%	0.47%	0.39%
8	NBR	5.12%	5.92%	6.60%	6.80%
9	FKM	nd	nd	nd	3.42%
10	FVMQ	0.44%	0.48%	0.46%	7.14%
11	FKM	0.33%	0.36%	0.80%	0.99%
12	ECO	3.98%	4.35%	5.03%	5.36%
13	HNBR	4.06%	4.57%	nd	7.95%
17	HNBR	3.02%	4.52%	5.75%	5.97%
18	HNBR	2.30%	3.09%	3.92%	3.78%
19	HNBR	2.76%	3.21%	3.93%	4.02%
20	HNBR	3.43%	3.12%	3.95%	3.62%
21	FKM	0.01%	0.01%	0.10%	0.11%
22	HNBR	2.72%	2.87%	2.40%	3.86%
23	FKM	nd	nd	nd	0.15%
25	FKM	-0.03%	-0.05%	0.13%	0.15%
29	FVMQ	0.74%	1.09%	0.71%	0.93%
30	NBR	3.49%	5.78%	8.72%	9.19%
31	NBR	6.96%	9.00%	11.79%	12.07%
32	NBR	6.79%	8.86%	11.51%	11.71%
33	NBR	5.89%	8.13%	11.46%	11.60%
34	NBR	3.88%	6.42%	9.29%	9.41%
35	HNBR	2.41%	1.30%	4.05%	4.13%
36	HNBR	6.48%	8.88%	12.00%	12.22%
37	FKM	0.00%	0.00%	0.06%	0.07%
38	PFE	0.05%	0.02%	0.04%	0.05%
39	PFE	0.11%	0.17%	0.15%	0.14%
40	PFE	0.22%	0.10%	0.09%	0.05%
41	PFE-VF	-0.33%	-0.19%	0.04%	0.06%
42	PFE	0.03%	0.03%	0.08%	0.07%
43	NBR	nd	-2.50%	2.83%	3.04%
51	X-FKM	0.13%	0.26%	0.11%	0.11%
52	PFE-VF	-0.33%	0.06%	0.05%	0.07%
53	PFE-VF	-0.34%	-0.39%	0.07%	0.05%
54	X-FKM	0.17%	-0.32%	0.31%	-0.35%
55	X-FKM	0.21%	0.18%	0.39%	0.40%

Table 23. Percent of Sample Material Extracted After 28-Day Fluid Aging

Material ID	Material Type	T_{aging} = 275° F		T_{aging} = 225° F	
		MIL-PRF-83282	MIL-PRF-87257	JP-8	JP-8+100
0	**NBR-L**	**nd**	**nd**	**nd**	**nd**
3	FKM	1.38%	1.81%	0.30%	0.63%
4	ECO	nd	nd	nd	11.14%
5	FKM	0.10%	0.20%	1.09%	0.14%
6	FKM	1.10%	1.41%	0.04%	0.83%
8	NBR	1.01%	2.65%	6.64%	5.60%
9	FKM	nd	nd	nd	10.12%
10	FVMQ	0.87%	0.89%	0.54%	1.16%
11	FKM	1.18%	1.43%	0.74%	1.18%
12	ECO	6.05%	12.14%	4.96%	5.49%
13	HNBR	1.74%	2.41%	5.54%	6.26%
17	HNBR	1.82%	1.24%	5.26%	6.19%
18	HNBR	3.18%	-5.19%	3.75%	3.96%
19	HNBR	2.95%	3.21%	3.89%	4.17%
20	HNBR	3.25%	-7.97%	3.94%	3.79%
21	FKM	-0.46%	-0.71%	0.03%	0.03%
22	HNBR	3.11%	3.24%	3.75%	3.99%
23	FKM	nd	nd	nd	-0.14%
25	FKM	-1.38%	-1.47%	0.16%	0.17%
29	FVMQ	4.48%	4.16%	0.81%	1.17%
30	NBR	6.65%	5.79%	8.75%	9.38%
31	NBR	2.53%	4.92%	11.68%	10.92%
32	NBR	4.00%	5.57%	11.24%	10.79%
33	NBR	nd	3.44%	11.31%	9.94%
34	NBR	5.88%	6.29%	9.23%	9.67%
35	HNBR	0.47%	0.13%	3.98%	4.39%
36	HNBR	2.56%	5.04%	11.94%	11.26%
37	FKM	-0.12%	-0.12%	-0.02%	-0.02%
38	PFE	0.04%	0.05%	0.05%	0.05%
39	PFE	0.12%	0.18%	0.18%	0.15%
40	PFE	0.03%	-0.01%	0.33%	0.03%
41	PFE-VF	-1.70%	-2.27%	0.03%	0.05%
42	PFE	0.02%	0.17%	0.03%	-0.03%
43	NBR	2.11%	-0.24%	4.24%	4.40%
51	X-FKM	0.19%	0.13%	0.08%	0.08%
52	PFE-VF	-2.12%	-2.12%	0.08%	0.06%
53	PFE-VF	-1.69%	-1.92%	-0.28%	0.05%
54	X-FKM	0.00%	0.30%	0.37%	-0.06%
55	X-FKM	-0.23%	0.00%	1.05%	0.60%

4.1.5 Compression Set Measurements

Compression set measurements on samples cut from the molded test plaques were performed at room temperature and -40º F, both before and after fluid aging as previously described. All compression set measurements were performed in triplicate. Compression set was determined 30 minutes after removing the test samples from the compression set test jig for each test condition described. The ASTM provides for median or average data to be reported, depending on the number of measurements taken. Average data and standard deviations are presented in this report.

Room temperature compression set values were determined after 22 and 70 hours of compression for all unaged materials and after 70 hours of compression in each of the fluids under high temperature aging conditions. Only the 70 hour data are reported to support direct comparison to the 70 hour fluid aged samples. Low temperature compression set values for unaged samples were determined after (1) setting the compression set samples to 25% deflection at room temperature and then (2) allowing the compression set samples to equilibrate at -40°F for 70 hours before (3) measuring the amount of compression set at -40° F. Low temperature compression set values for fluid aged samples were determined after (1) setting the compression set samples to 25% deflection at room temperature, (2) fluid aging the compressed samples for 70 hours under each of the fluid aging conditions, (3) allowing the samples to cool to room temperature before removing the compression test jigs from the test fluids, and then (4) allowing the compression set samples to equilibrate at -40° F for 22 hours before (5) measuring the amount of compression set at -40° F.

The compression set data tables are summarized as follows:

- Table 24. Room Temperature Compression Set for Aged and Unaged Samples
- Table 25. -40° F Compression Set for Aged and Unaged Samples.

MIL-PRF-83461 has a maximum compression set requirement at room temperature of 35% for unaged samples and a 45% maximum requirement for samples aged for 70 hours in hydraulic fluid. MIL-PRF-5315 has a 25% maximum compression set requirement under all test conditions. Some data values are not reported as a number of materials were not tested in one or more of the fluids based on poor performance against other test criteria.

All of the materials tested demonstrated good compression set resistance at room temperature, both before and after fluid aging in MIL-PRF-83282. The lower molecular weight MIL-PRF-87257 proved to be more aggressive than MIL-PRF-83282, with compression set values after fluid aging being greater than 45% for several FKM samples (3, 5, 11). With the exception of a few marginal performers, the NBR and HNBR materials demonstrated relatively good performance overall. The more advanced PFE and PFE-VF fluorinated materials performed very well before and after aging in both hydraulic fluids.

The HNBR samples demonstrated very good room temperature compression set resistance after fluid aging in JP-8 and JP-8+100, as did 29-FVMQ and FKM samples 23 and 37. The performance of the remaining FKM samples was relatively poor. The PFE materials continued to exhibit exceptional performance, as did the X-FKM sample tested. While one of the PFE-VF samples (53) exhibited relatively marginal room temperature compression set resistance after fluid aging in both fuels, the performance of the other samples in this class was very good.

The low temperature (-40° F) performance of the unaged materials tested was very good with the possible exception of 37-FKM, 55-X-FKM and PFE samples 94 and 95. However, no inferences are made from the high compression set values demonstrated by these samples, as inconsistencies relative to the fluid aged data (which are good for these materials) might indicate some error in the experimental measurements or sampling problems. Most of the materials tested demonstrated a significant increase in -40° F compression set after fluid aging in all of the test fluids. Several of the HNBR samples (18, 20 22) performed very well or marginally well in the low temperature measurements, as did one of the NBR samples (32), a low-temperature nitrile. 10-FVMQ demonstrated exceptional low temperature compression set performance. All of the PFE samples demonstrated exceptional resistance to low temperature compression set after aging in hydraulic fluids and fuels. The PFE-VF materials and the X-FKM samples also demonstrated relatively good low temperature compression set performance after fluid aging.

Table 24. RT Compression Set (%) for Aged and Unaged Samples

Material ID	Material Type		Air	MIL-PRF-83282	MIL-PRF-87257	JP-8	JP-8+100
3	FKM	Mean	22.90	33.95	55.76	88.76	79.93
		σ	0.99	6.33	0.89	13.30	5.24
4	ECO	Mean	6.30	5.20	nd	nd	nd
		σ	0.81	0.12			
5	FKM	Mean	26.96	25.79	62.68	71.52	66.81
		σ	2.81	0.69	2.90	5.39	1.58
6	FKM	Mean	25.03	36.71	77.15	59.42	63.65
		σ	1.26	3.95	1.04	1.85	3.50
8	NBR	Mean	7.78	8.22	50.76	36.54	30.85
		σ	0.24	0.39	4.29	2.39	1.89
9	FKM	Mean	5.98	3.93	nd	nd	nd
		σ	1.07	0.82			
10	FVMQ	Mean	6.52	nd	15.59	nd	4.92
		σ	2.03		1.62		0.68
11	FKM	Mean	32.79	22.12	77.10	56.78	84.23
		σ	7.57	5.48	9.54	12.05	3.01
12	ECO	Mean	10.41	10.86	43.70	nd	39.73
		σ	1.55	0.54	3.93		3.27
13	HNBR	Mean	16.33	13.67	48.26	-5.32	nd
		σ	0.85	2.42	4.86	6.42	
17	HNBR	Mean	13.95	6.29	25.46	nd	nd
		σ	1.55	1.32	1.58		
18	HNBR	Mean	10.57	9.10	26.33	8.03	-0.99
		σ	1.92	1.03	1.10	3.28	2.87
19	HNBR	Mean	10.49	11.07	24.33	11.22	14.81
		σ	4.51	1.49	2.13	5.31	9.33
20	HNBR	Mean	11.75	10.12	30.35	9.88	8.91
		σ	5.21	0.10	0.58	0.84	0.30
21	FKM	Mean	8.90	8.38	17.43	15.35	20.48
		σ	0.79	1.35	4.54	1.96	3.09
22	HNBR	Mean	13.55	8.76	24.48	19.62	10.95
		σ	0.50	3.38	3.55	3.09	3.39
23	FKM	Mean	14.69	11.77	nd	27.23	24.52
		σ	2.30	1.39		0.72	0.82
25	FKM	Mean	23.10	22.15	46.94	48.18	44.45
		σ	4.21	1.21	2.19	5.71	5.55
29	FVMQ	Mean	11.68	6.73	43.56	0.95	14.72
		σ	3.47	5.15	3.38	1.09	1.44
30	NBR	Mean	8.17	11.10	nd	nd	nd
		σ	0.86	3.94			

Table 24. Cont'd. RT Compression Set (%) for Aged and Unaged Samples

Material ID	Material Type		Air	MIL-PRF-83282	MIL-PRF-87257	JP-8	JP-8+100
31	NBR	Mean	6.76	7.33	38.41	nd	nd
		σ	0.78	1.38	3.38		
32	NBR	Mean	5.09	nd	30.87	nd	9.69
		σ	0.34		1.32		2.91
33	NBR	Mean	6.19	9.51	47.50	nd	nd
		σ	2.66	2.15	5.97		
34	NBR	Mean	13.26	13.10	36.54	nd	nd
		σ	3.09	5.25	3.80		
35	HNBR	Mean	8.05	9.26	nd	nd	nd
		σ	2.17	2.03			
36	HNBR	Mean	14.74	9.90	61.75	nd	nd
		σ	9.65	2.93	0.94		
37	FKM	Mean	12.74	11.99	20.28	15.98	16.66
		σ	0.48	0.46	0.78	1.76	0.32
38	PFE	Mean	5.19	7.38	7.32	8.47	12.29
		σ	1.21	1.07	0.45	1.66	4.12
39	PFE	Mean	-5.58	1.29	nd	12.93	12.60
		σ	0.69	0.93		0.84	4.03
40	PFE	Mean	6.35	2.24	15.97	13.75	7.28
		σ	2.65	0.90	1.36	1.46	0.93
41	PFE-VF	Mean	nd	nd	28.55	nd	27.86
		σ			3.12		4.53
42	PFE	Mean	3.24	3.82	11.12	10.31	9.71
		σ	0.10	0.82	2.36	0.57	1.18
43	NBR	Mean	10.45	9.17	nd	nd	nd
		σ	4.19	0.05			
51	X-FKM	Mean	3.19	1.35	nd	5.70	7.42
		σ	2.82	1.30		2.38	0.43
52	PFE-VF	Mean	11.06	11.26	20.44	21.09	16.09
		σ	1.52	1.24	0.20	0.88	0.70
53	PFE-VF	Mean	20.21	19.70	33.10	40.81	36.03
		σ	5.91	3.56	2.37	3.03	6.55
54	X-FKM	Mean	30.61	39.51	nd	nd	nd
		σ	2.53	2.08			
55	X-FKM	Mean	33.87	39.25	nd	nd	nd
		σ	2.78	5.64			
94	PFE	Mean	5.73	nd	nd	nd	nd
		σ	0.49				
95	PFE	Mean	12.63	nd	nd	nd	nd
		σ	5.15				

Table 25. -40° F Compression Set (%) for Aged and Unaged Samples

Material ID	Material Type		Air	MIL-PRF-83282	MIL-PRF-87257	JP-8	JP-8+100
3	FKM	Mean	21.47	59.91	69.32	85.21	82.49
		σ	3.85	8.42	6.71	8.08	1.23
4	ECO	Mean	2.85	nd	nd	nd	nd
		σ	0.38				
5	FKM	Mean	15.04	57.33	61.96	89.06	86.75
		σ	6.80	7.43	10.14	0.98	8.12
6	FKM	Mean	18.09	71.66	75.00	59.62	83.71
		σ	1.72	6.54	3.57	14.62	0.78
8	NBR	Mean	4.33	77.79	101.10	51.80	65.61
		σ	1.61	3.10	7.35	2.81	3.94
9	FKM	Mean	3.34	nd	nd	nd	nd
		σ	0.75				
10	FVMQ	Mean	15.91	30.22	46.78	33.95	29.29
		σ	2.46	1.73	1.91	4.00	4.86
11	FKM	Mean	1.57	nd	65.16	73.84	39.66
		σ	1.74		11.11	2.01	5.89
12	ECO	Mean	12.49	82.37	81.52	47.22	47.86
		σ	1.62	4.34	7.22	0.77	3.46
13	HNBR	Mean	11.32	nd	55.77	93.86	70.49
		σ	6.91		10.10	4.59	15.59
17	HNBR	Mean	8.70	nd	nd	nd	nd
		σ	0.18				
18	HNBR	Mean	12.62	38.17	39.60	42.54	64.42
		σ	1.58	4.13	5.23	4.99	7.27
19	HNBR	Mean	8.32	58.25	78.43	64.96	44.89
		σ	1.34	0.73	6.78	1.98	4.97
20	HNBR	Mean	7.49	63.23	50.96	44.39	37.49
		σ	0.61	0.64	5.92	4.55	3.21
21	FKM	Mean	5.70	45.22	30.89	34.07	63.92
		σ	0.88	10.38	5.09	9.26	11.75
22	HNBR	Mean	9.52	41.47	43.98	18.73	40.99
		σ	0.63	7.12	2.35	4.94	1.14
23	FKM	Mean	6.12	nd	nd	45.86	33.11
		σ	7.04			7.20	7.49
25	FKM	Mean	11.35	46.21	65.22	46.74	73.40
		σ	1.88	9.67	9.47	5.47	6.62
29	FVMQ	Mean	13.33	15.53	28.04	15.03	17.03
		σ	1.71	6.47	6.01	2.20	1.63
30	NBR	Mean	4.61	nd	nd	nd	nd
		σ	2.28				

Table 25. Cont'd. -40° F Compression Set (%) for Aged and Unaged Samples

Material ID	Material Type		Air	MIL-PRF-83282	MIL-PRF-87257	JP-8	JP-8+100
31	NBR	Mean	4.78	54.59	50.93	nd	nd
		σ	0.67	7.32	4.27		
32	NBR	Mean	3.78	55.26	51.37	16.63	16.92
		σ	2.46	1.36	4.52	4.39	1.52
33	NBR	Mean	4.65	53.53	63.04	nd	nd
		σ	1.18	3.64	6.06		
34	NBR	Mean	8.90	48.20	57.24	nd	nd
		σ	2.39	4.15	8.33		
35	HNBR	Mean	5.66	98.17	83.74	91.72	79.79
		σ	0.11	13.04	5.99	2.44	5.27
36	HNBR	Mean	3.06	50.72	56.81	nd	nd
		σ	0.48	3.32	2.95		
37	FKM	Mean	92.70	51.99	42.23	57.62	51.30
		σ	3.61	7.90	4.31	16.32	5.30
38	PFE	Mean	4.64	16.43	15.31	16.07	19.19
		σ	1.10	2.42	1.86	3.90	6.34
39	PFE	Mean	2.21	23.38	22.46	14.57	13.21
		σ	3.42	3.44	3.12	4.62	1.67
40	PFE	Mean	2.90	28.98	31.12	24.50	24.51
		σ	0.45	0.56	0.79	5.59	1.24
41	PFE-VF	Mean	nd	55.59	51.47	60.42	67.32
		σ		8.14	2.55	2.24	0.95
42	PFE	Mean	nd	20.66	25.46	16.97	24.11
		σ		1.01	0.34	1.39	1.02
43	NBR	Mean	10.87	nd	nd	nd	nd
		σ	5.95				
51	X-FKM	Mean	7.10	31.58	nd	10.45	9.11
		σ	2.73	17.93		5.77	4.17
52	PFE-VF	Mean	5.46	41.41	51.59	47.02	42.81
		σ	0.82	2.80	4.73	3.56	2.09
53	PFE-VF	Mean	7.87	62.58	62.96	85.34	73.22
		σ	5.78	0.39	1.85	10.63	2.42
54	X-FKM	Mean	19.38	nd	nd	nd	nd
		σ	1.70				
55	X-FKM	Mean	40.88	nd	79.93	19.52	30.49
		σ	1.86		4.44	8.19	16.71
94	PFE	Mean	62.25	27.55	25.71	27.07	18.28
		σ	0.36	1.23	1.68	4.08	0.68
95	PFE	Mean	50.87	34.09	32.61	24.43	19.34
		σ	0.91	3.56	2.38	1.62	0.79

4.2 O-RING TESTING AND EVALUATION

The results of the o-ring testing and evaluation efforts are presented in this section. O-ring testing included (1) advanced testing of the best candidate materials identified through the course of the initial testing and evaluation of the compression molded test slabs, (2) sample materials that were only submitted for testing and evaluation in o-ring form, and (3) representative sample materials from the various classes of materials evaluated under the program.

4.2.1 Volume Swell, Weight Gain and Extracted Materials

ASTM D 471 volume swell and weight gain testing was once again utilized as a method of screening the candidate materials for resistance to the target high temperature aircraft fuels and hydraulic fluids. All tests were performed in triplicate using methods previously described. The results reported in this section are the average and standard deviation of measurements taken on three replicate samples for fluid weight gain and volume swell. Volume swell data reported in this section were determined by dimensional measurements. These data were only used for comparative purposes under the program and may not represent typical volume swell data reported for o-ring materials. After final characterization, o-ring samples were dried under temperature and vacuum until reaching a final equilibrium weight to determine the percent of materials extracted from the o-rings during the fluid aging experiments.

For ease of presentation, the tabulated D 471 o-ring fluid aging data are presented as follows:

- Table 26. D 471 O-ring Data – 3 Days in MIL-PRF-83282 @ 275° F
- Table 27. D 471 O-ring Data – 3 Days in MIL-PRF-87257 @ 275° F
- Table 28. D 471 O-ring Data – 3 Days in JP-8 @ 225° F
- Table 29. D 471 O-ring Data – 3 Days in JP-8+100 @ 225° F
- Table 30. D 471 O-ring Data – 28 Days in MIL-PRF-83282 @ 275° F
- Table 31. D 471 O-ring Data – 28 Days in MIL-PRF-87257 @ 275° F
- Table 32. D 471 O-ring Data – 28 Days in JP-8 @ 225° F
- Table 33. D 471 O-ring Data – 28 Days in JP-8+100 @ 225° F.

Dimensional volume measurements proved to be problematic for the o-rings as the irregular shape of the o-rings after fluid aging created some difficulty in obtaining accurate final measurements, thus the volume data presented in this section was used for relative comparison purposes only and should not be compared to other volume swell data. Because of this, the weight change data were used to validate trends in the data and provide a secondary means of assessing resistance to fluid aging.

As previously stated, MIL-P-83461 requirements for hydraulic system o-rings provide for a change in volume of 5 to 15% after 70 hours of fluid aging and MIL-P-5315 requirements for o-rings used in aircraft fuel applications provide for a change in volume of 0 to 10%. Interestingly, the average volume swell data reported for the samples aged for 3 days in MIL-PRF-83282 is greater than the volume swell data for the samples aged for 28 days. All of the materials aged for 28 days in MIL-PRF-83282 and MIL-PRF-87257 demonstrated acceptable performance. The PFE materials continue to perform exceptionally well, as do samples of the PFE-VF material. A number of the HNBR and FKM materials also performed very well (especially based on the 28-day fluid aging data), so it is difficult to make any assertions based solely on these data. Similar trends are noted in the JP-8 and JP-8+100 data, with the volume swell in the JP-8 appearing to be slightly higher on average.

Table 26. D 471 O-ring Data – 3 Days in MIL-PRF-83282 @ 275° F

Material ID	Material Type		ΔV (%)	ΔM (%)	% Extracted Material
0	**NBR-L**	**Mean**	20.93	6.81	0.09
		σ	6.31	0.18	0.59
3	FKM	Mean	16.07	4.31	1.10
		σ	4.58	1.26	0.31
5	FKM	Mean	8.14	2.67	0.10
		σ	2.40	0.77	0.01
6	FKM	Mean	14.47	3.80	0.89
		σ	1.85	0.26	0.06
10	FVMQ	Mean	18.63	3.11	-0.67
		σ	0.48	1.58	0.94
13	HNBR	Mean	1.11	-1.00	7.58
		σ	0.88	0.24	0.01
18	HNBR	Mean	20.88	2.83	nd
		σ	3.39	0.09	
20	HNBR	Mean	25.85	3.00	3.50
		σ	3.85	0.18	0.06
21	FKM	Mean	19.64	1.75	0.05
		σ	6.61	0.25	0.01
22	HNBR	Mean	23.21	3.18	3.83
		σ	3.52	0.08	0.13
25	FKM	Mean	3.42	2.19	0.28
		σ	1.52	0.36	0.01
29	FVMQ	Mean	12.17	4.18	0.79
		σ	1.79	0.25	0.04
30	NBR	Mean	9.99	9.51	nd
		σ	1.22	0.42	
37	FKM	Mean	14.49	1.68	-0.12
		σ	4.72	0.16	0.20
38	PFE	Mean	1.09	0.34	0.01
		σ	4.31	0.02	0.01
39	PFE	Mean	-0.24	0.63	0.04
		σ	0.65	0.01	0.01
40	PFE	Mean	-0.40	0.18	0.05
		σ	2.52	0.15	0.16
41	PFE-VF	Mean	26.49	0.83	nd
		σ	9.29	0.02	
42	PFE	Mean	15.89	0.33	nd
		σ	7.97	0.02	
51	X-FKM	Mean	16.74	0.56	0.09
		σ	2.41	0.02	0.01
52	PFE-VF	Mean	15.89	0.19	-0.95
		σ	6.43	1.11	0.31
53	PFE-VF	Mean	2.65	2.27	0.02
		σ	3.35	0.18	0.01

Table 27. D 471 O-ring Data – 3 Days in MIL-PRF-87257 @ 275° F

Material ID	Material Type		ΔV (%)	ΔM (%)	% Extracted Material
0	**NBR-L**	**Mean**	2.21	9.98	0.79
		σ	0.70	0.24	0.02
3	FKM	Mean	11.46	2.54	0.64
		σ	1.88	0.32	0.04
5	FKM	Mean	9.77	2.54	0.12
		σ	3.46	0.57	0.01
6	FKM	Mean	11.98	3.31	1.19
		σ	0.59	2.16	0.70
10	FVMQ	Mean	-6.78	2.97	0.61
		σ	0.11	0.05	0.05
13	HNBR	Mean	2.75	-0.03	7.33
		σ	0.95	0.07	0.03
18	HNBR	Mean	3.32	4.74	4.67
		σ	2.34	0.04	0.02
20	HNBR	Mean	2.33	4.59	4.57
		σ	3.56	0.01	0.04
21	FKM	Mean	0.01	3.09	0.08
		σ	2.59	0.06	0.01
22	HNBR	Mean	3.36	4.73	4.24
		σ	3.30	0.02	0.06
25	FKM	Mean	5.04	2.18	0.24
		σ	0.17	0.05	0.01
29	FVMQ	Mean	-23.03	5.79	1.10
		σ	8.07	0.19	0.02
30	NBR	Mean	29.42	22.22	8.72
		σ	2.35	16.75	0.07
33	NBR	Mean	-5.22	10.31	10.02
		σ	3.96	0.34	0.17
37	FKM	Mean	0.40	3.14	-0.04
		σ	4.84	0.03	0.01
38	PFE	Mean	1.23	0.61	-0.02
		σ	1.86	0.01	0.02
39	PFE	Mean	4.88	1.20	0.06
		σ	1.24	0.01	0.01
40	PFE	Mean	0.85	0.53	-0.04
		σ	0.91	0.03	0.00
42	PFE	Mean	-5.37	0.62	0.04
		σ	2.12	0.29	0.03
51	X-FKM	Mean	-2.30	0.10	0.05
		σ	2.27	8.04	0.01
52	PFE-VF	Mean	-5.08	1.44	-0.22
		σ	2.38	0.04	0.01
53	PFE-VF	Mean	4.59	1.61	0.02
		σ	0.29	0.05	1.58

Table 28. D 471 O-ring Data – 3 Days in JP-8 @ 225° F

Material ID	Material Type		ΔV (%)	ΔM (%)	% Extracted Material
0	**NBR-L**	**Mean**	37.85	nd	nd
		σ	2.39		
3	FKM	Mean	16.24	4.45	0.34
		σ	0.47	0.06	0.07
5	FKM	Mean	13.31	2.07	0.07
		σ	1.53	0.08	0.02
6	FKM	Mean	20.48	5.01	0.38
		σ	2.53	1.44	0.06
8	NBR	Mean	18.92	4.97	5.94
		σ	4.48	0.06	0.18
10	FVMQ	Mean	20.35	4.65	0.05
		σ	3.59	0.32	0.29
12	ECO	Mean	6.43	1.62	7.08
		σ	4.42	0.09	0.03
13	HNBR	Mean	7.97	3.63	7.95
		σ	1.20	0.24	0.03
18	HNBR	Mean	29.92	10.95	3.30
		σ	2.31	2.61	2.24
20	HNBR	Mean	29.38	13.67	0.30
		σ	1.53	3.29	2.66
21	FKM	Mean	23.37	4.12	0.35
		σ	0.38	0.33	0.14
22	HNBR	Mean	26.94	6.10	7.15
		σ	3.18	2.33	2.06
25	FKM	Mean	23.37	4.12	0.21
		σ	1.57	0.34	0.02
29	FVMQ	Mean	31.02	8.21	-0.83
		σ	5.20	10.61	10.59
30	NBR	Mean	43.44	16.31	8.44
		σ	4.44	0.35	0.24
32	NBR	Mean	30.25	10.42	10.04
		σ	2.95	0.38	0.39
37	FKM	Mean	19.20	nd	nd
		σ	3.79		
38	PFE	Mean	7.20	2.06	0.01
		σ	0.95	0.01	0.01
39	PFE	Mean	7.29	3.42	0.11
		σ	1.54	0.01	0.18
40	PFE	Mean	3.93	1.86	0.02
		σ	1.12	0.20	0.01
41	PFE-VF	Mean	21.12	2.20	-0.34
		σ	7.39	1.00	0.98
42	PFE	Mean	23.19	5.56	-3.82
		σ	2.52	0.51	0.49
51	X-FKM	Mean	20.19	7.05	-4.01
		σ	3.29	0.13	0.43
52	PFE-VF	Mean	21.15	6.19	-4.45
		σ	1.80	0.42	0.07
53	PFE-VF	Mean	13.09	2.48	0.08
		σ	3.82	0.17	0.01

Table 29. D 471 O-ring Data – 3 Days in JP-8+100 @ 225° F

Material ID	Material Type		ΔV (%)	ΔM (%)	% Extracted Material
0	**NBR-L**	**Mean**	19.25	16.24	1.47
		σ	4.85	0.21	0.03
3	FKM	Mean	17.94	5.85	0.39
		σ	1.28	0.80	0.70
5	FKM	Mean	11.17	2.74	0.06
		σ	2.55	0.36	0.01
6	FKM	Mean	25.67	5.61	0.45
		σ	3.97	1.11	0.02
8	NBR	Mean	11.47	4.69	6.00
		σ	2.05	0.06	0.01
10	FVMQ	Mean	12.89	4.69	0.41
		σ	2.56	0.02	0.01
12	ECO	Mean	7.50	1.74	6.84
		σ	3.37	0.28	0.15
13	HNBR	Mean	8.89	3.22	7.95
		σ	1.27	0.05	0.67
18	HNBR	Mean	19.05	8.83	5.04
		σ	4.37	0.19	0.15
20	HNBR	Mean	17.28	8.78	4.69
		σ	4.24	0.04	0.10
21	FKM	Mean	2.27	3.89	0.22
		σ	3.52	0.39	0.00
22	HNBR	Mean	16.22	8.64	4.77
		σ	2.02	0.10	0.06
25	FKM	Mean	7.84	3.86	0.25
		σ	2.62	0.46	0.00
29	FVMQ	Mean	18.11	7.91	1.03
		σ	8.11	0.15	0.01
30	NBR	Mean	31.31	16.25	8.44
		σ	7.53	0.22	0.04
32	NBR	Mean	14.54	9.78	10.56
		σ	4.46	0.17	0.06
37	FKM	Mean	13.60	2.67	0.07
		σ	2.41	0.06	0.03
38	PFE	Mean	6.67	2.19	-0.01
		σ	4.79	0.02	0.01
39	PFE	Mean	9.15	3.63	0.07
		σ	4.65	0.01	0.01
40	PFE	Mean	4.00	1.85	-0.02
		σ	3.24	0.03	0.01
41	PFE-VF	Mean	11.55	2.00	0.09
		σ	1.92	0.40	0.42
42	PFE	Mean	10.06	1.72	0.06
		σ	3.12	0.00	0.03
51	X-FKM	Mean	10.61	3.01	0.07
		σ	3.00	0.02	0.03
52	PFE-VF	Mean	7.02	1.89	0.00
		σ	0.58	0.03	0.02
53	PFE-VF	Mean	10.77	2.73	0.06
		σ	0.67	0.24	0.01

Table 30. D 471 O-ring Data – 28 Days in MIL-PRF-83282 @ 275° F

Material ID	Material Type		ΔV (%)	ΔM (%)	% Extracted Material
0	**NBR-L**	**Mean**	2.30	10.59	-2.64
		σ	1.17	0.11	0.09
3	FKM	Mean	7.11	2.95	nd
		σ	1.48	0.08	
5	FKM	Mean	4.99	2.83	0.19
		σ	0.40	0.46	0.04
6	FKM	Mean	9.88	3.96	nd
		σ	4.46	0.83	
10	FVMQ	Mean	0.85	0.56	2.96
		σ	1.09	0.04	0.07
13	HNBR	Mean	1.44	-0.99	6.76
		σ	2.51	0.21	0.04
18	HNBR	Mean	4.66	4.21	3.15
		σ	1.19	0.08	0.06
20	HNBR	Mean	4.90	nd	4.40
		σ	0.96		0.07
21	FKM	Mean	6.17	2.95	0.07
		σ	4.53	0.27	0.08
22	HNBR	Mean	5.91	4.47	3.05
		σ	1.10	0.20	0.25
25	FKM	Mean	3.17	2.49	-0.47
		σ	1.76	0.07	0.01
29	FVMQ	Mean	11.79	4.23	1.17
		σ	5.84	0.25	0.90
30	NBR	Mean	5.72	9.00	nd
		σ	0.62	0.11	
33	NBR	Mean	8.57	8.43	5.72
		σ	5.24	0.37	0.33
34	NBR	Mean	7.19	7.14	nd
		σ	2.54	0.14	
36	HNBR	Mean	4.33	2.10	nd
		σ	1.54	0.28	
37	FKM	Mean	3.73	5.29	-2.42
		σ	2.28	4.30	4.12
38	PFE	Mean	3.28	0.33	-0.02
		σ	4.74	0.00	0.00
39	PFE	Mean	5.06	0.58	0.09
		σ	5.51	0.05	0.01
40	PFE	Mean	-0.17	0.33	-0.09
		σ	1.08	0.01	0.01
42	PFE	Mean	-1.12	0.33	nd
		σ	2.20	0.01	
52	PFE-VF	Mean	1.22	1.57	-0.37
		σ	1.85	0.03	0.00
53	PFE-VF	Mean	1.38	1.78	-0.17
		σ	3.15	0.18	0.00

Table 31. D 471 O-ring Data – 28 Days in MIL-PRF-87257 @ 275° F

Material ID	Material Type		ΔV (%)	ΔM (%)	% Extracted Material
0	**NBR-L**	**Mean**	8.28	13.81	-2.67
		σ	2.47	0.04	0.06
3	FKM	Mean	6.29	3.81	nd
		σ	4.79	0.10	
5	FKM	Mean	4.53	2.47	0.16
		σ	0.93	0.15	0.03
6	FKM	Mean	6.51	5.89	-0.79
		σ	5.32	3.30	3.08
10	FVMQ	Mean	2.73	2.74	1.51
		σ	1.16	0.12	0.01
13	HNBR	Mean	0.68	1.15	6.80
		σ	1.74	0.40	0.02
18	HNBR	Mean	5.01	5.72	4.33
		σ	1.51	0.69	0.82
20	HNBR	Mean	6.75	6.30	3.75
		σ	1.81	0.15	0.10
21	FKM	Mean	9.06	5.08	-0.50
		σ	0.29	0.72	0.04
22	HNBR	Mean	4.82	6.12	3.47
		σ	1.12	3.31	2.65
25	FKM	Mean	7.98	3.51	-0.89
		σ	2.34	0.01	0.02
29	FVMQ		3.70	8.21	1.38
			1.40	1.04	0.01
30	NBR	Mean	15.90	19.73	nd
		σ	4.55	0.04	
33	NBR	Mean	9.75	4.20	7.80
		σ	2.42	0.45	0.51
34	NBR	Mean	10.60	12.60	nd
		σ	4.90	0.12	
37	FKM	Mean	8.33	3.59	-0.02
		σ	4.77	0.31	0.01
38	PFE	Mean	3.73	0.61	0.00
		σ	6.14	0.01	0.00
39	PFE	Mean	3.55	1.19	0.04
		σ	4.61	0.01	0.01
40	PFE	Mean	-0.81	0.57	nd
		σ	1.63	0.05	
42	PFE	Mean	-1.23	0.56	nd
		σ	1.84	0.01	
52	PFE-VF	Mean	2.44	1.65	-0.38
		σ	0.44	0.04	0.00
53	PFE-VF	Mean	5.54	3.03	-0.74
		σ	5.73	0.04	0.02

Table 32. D 471 O-ring Data – 28 Days in JP-8 @ 225° F

Material ID	Material Type		ΔV (%)	ΔM (%)	% Extracted Material
0	**NBR-L**	**Mean**	11.51	13.87	-2.42
		σ	1.80	0.14	0.50
3	FKM	Mean	17.37	5.96	nd
		σ	5.79	0.15	
5	FKM	Mean	7.93	2.67	0.22
		σ	1.26	2.31	2.32
6	FKM	Mean	23.88	6.39	0.81
		σ	2.63	0.16	0.11
8	NBR	Mean	8.67	4.43	6.21
		σ	3.05	0.32	0.07
10	FVMQ	Mean	8.17	6.15	0.64
		σ	3.62	0.17	0.02
12	ECO	Mean	7.65	2.44	nd
		σ	2.07	0.08	
13	HNBR	Mean	7.83	2.78	7.93
		σ	1.02	0.01	0.11
18	HNBR	Mean	8.66	9.73	5.00
		σ	7.92	0.12	0.10
20	HNBR	Mean	11.30	9.70	4.99
		σ	6.22	0.15	0.09
21	FKM	Mean	3.04	5.06	-0.01
		σ	2.62	0.08	0.03
22	HNBR	Mean	6.65	9.76	4.51
		σ	0.30	0.20	0.13
25	FKM	Mean	6.66	3.61	-0.14
		σ	0.45	0.25	0.01
29	FVMQ		27.82	11.41	1.15
			6.39	0.51	0.01
30	NBR	Mean	20.34	16.68	9.00
		σ	3.17	0.17	0.07
32	NBR	Mean	30.25	10.42	10.04
		σ	2.95	0.38	0.39
37	FKM	Mean	7.76	2.93	1.29
		σ	3.01	2.60	2.30
38	PFE	Mean	-11.46	1.62	0.01
		σ	2.46	0.01	0.01
39	PFE	Mean	-4.28	3.20	0.08
		σ	2.54	0.02	0.03
40	PFE	Mean	-5.29	1.29	-0.07
		σ	2.77	0.01	0.01
41	PFE-VF	Mean	21.12	2.20	-0.34
		σ	7.39	1.00	0.98
42	PFE	Mean	8.68	2.09	0.02
		σ	3.88	0.28	0.02
51	X-FKM	Mean	1.63	3.31	0.06
		σ	3.27	0.03	0.03
52	PFE-VF	Mean	4.17	2.72	-0.37
		σ	2.69	0.02	0.00
53	PFE-VF	Mean	nd	nd	nd
		σ			

Table 33. D 471 O-ring Data – 28 Days in JP-8+100 @ 225° F

Material ID	Material Type		ΔV (%)	ΔM (%)	% Extracted Material
0	**NBR-L**	**Mean**	10.06	13.22	0.03
		σ	2.59	0.38	0.03
3	FKM	Mean	32.56	10.90	nd
		σ	1.11	0.17	
5	FKM	Mean	10.07	2.21	0.34
		σ	1.64	0.02	0.01
6	FKM	Mean	28.86	9.66	nd
		σ	4.47	0.15	
8	NBR	Mean	7.78	3.91	5.33
		σ	2.44	0.22	0.20
10	FVMQ	Mean	8.24	3.98	1.37
		σ	3.48	0.04	0.02
12	ECO	Mean	11.40	0.27	nd
		σ	2.35	0.10	
13	HNBR	Mean	9.94	2.20	8.05
		σ	0.40	0.05	0.00
18	HNBR	Mean	9.07	8.37	2.61
		σ	6.59	0.12	2.16
20	HNBR	Mean	13.93	8.09	4.68
		σ	0.95	0.09	1.78
21	FKM	Mean	16.85	7.02	-10.02
		σ	1.36	0.19	0.46
22	HNBR	Mean	13.94	8.21	6.50
		σ	1.25	0.09	1.99
25	FKM	Mean	-3.07	5.41	-1.41
		σ	3.14	0.07	0.06
29	FVMQ	Mean	15.45	8.45	1.05
		σ	9.46	0.54	0.03
30	NBR	Mean	13.28	15.43	9.08
		σ	2.49	0.17	0.04
32	NBR	Mean	nd	nd	nd
		σ			
37	FKM	Mean	9.47	2.38	1.71
		σ	2.00	1.38	0.32
38	PFE	Mean	1.87	2.20	-0.02
		σ	2.83	0.02	0.02
39	PFE	Mean	7.51	3.46	0.09
		σ	1.31	0.01	0.03
40	PFE	Mean	0.75	1.83	nd
		σ	2.67	0.03	
41	PFE-VF	Mean	4.50	1.87	nd
		σ	0.49	0.02	
42	PFE	Mean	nd	nd	nd
		σ			
51	X-FKM	Mean	nd	nd	nd
		σ			
52	PFE-VF	Mean	7.04	2.67	5.61
		σ	2.48	0.04	0.17
53	PFE-VF	Mean	14.36	8.07	-4.24
		σ	1.57	0.05	0.03

4.2.2 Physical Property Characterization

Tensile properties were determined for as-received and fluid aged samples using size 214 o-rings. Initial tensile property data were used to determine if the candidate o-ring materials met the basic physical property requirements of the existing military performance specifications for aircraft o-rings. Retention of tensile properties after fluid aging was used as an indication of chemical stability and potential for long term sealing performance. The results reported in this section are the average and standard deviation of measurements taken on three replicate samples for the unaged o-rings, and the relative change (%) in physical properties of the o-rings after fluid aging based on the average properties of the aged o-rings (three replicates) relative to the average properties of the unaged o-rings. Data for the standard NBR-L material are presented in each table for comparative purposes.

For ease of presentation, the tabulated fluid aging data are presented as follows:

- Table 34. O-ring Tensile Data – 3 Days in MIL-PRF-83282 @ 275° F
- Table 35. O-ring Tensile Data – 3 Days in MIL-PRF-87257 @ 275° F
- Table 36. O-ring Tensile Data – 3 Days in JP-8 @ 225° F
- Table 37. O-ring Tensile Data – 3 Days in JP-8+100 @ 225° F
- Table 38. O-ring Tensile Data – 28 Days in MIL-PRF-83282 @ 275° F
- Table 39. O-ring Tensile Data – 28 Days in MIL-PRF-87257 @ 275° F
- Table 40. O-ring Tensile Data – 28 Days in JP-8 @ 225° F
- Table 41. O-ring Tensile Data – 28 Days in JP-8+100 @ 225° F.

Tensile property requirements for hydraulic system o-rings (per MIL-P-83461) include an initial tensile strength and elongation at break of at least 1350 psi and 125%, respectively, with no more than a 40% reduction in properties after 70 hours of hydraulic fluid aging. All of the NBR and HNBR o-rings tested readily met the initial tensile property requirements. The FKM o-rings also demonstrated good tensile property performance with the exception of 5-FKM. One of the FVMQ o-rings (10) demonstrated exceptional tensile properties for a fluorosilicone, but 29-FVQM falls well short of the required tensile performance. The initial tensile properties of the X-FKM sample are in compliance, but results are mixed for the various PFE and PFE-VF samples tested. However, 38-PFE and 52-PFE-VF both have tensile strengths that exceed 1350 psi, clearly demonstrating the ability to formulate compounds based on these materials with the requisite tensile properties for hydraulic fluid system o-rings.

After 3 days of fluid aging in MIL-PRF 83282 and MIL-PRF-87257, the change in tensile properties of most of the o-rings tested remains within specification. PFE samples 40 and 39 demonstrated marginal performance in MIL-PRF-83282 and MIL-PRF-87257, respectively, falling just outside of the 40% allowable decrease in tensile strength. The NBR-L control sample demonstrated greater than 50% loss in properties after 3 days of aging in MIL-PRF-87257 at 275° F, and 30-NBR demonstrated marginal performance after 3 days in MIL-PRF-83282. After 28 days of fluid aging in MIL-PRF-83282, 10-FVMQ demonstrated a significant loss in tensile strength, as did the NBR-L control sample. The NBR-L control also demonstrated poor performance after 28 days of fluid aging in MIL-PRF-83282, as did samples 22-HNBR and 33-NBR. The PFE and PFE-VF samples did very well after 28 days of fluid aging in MIL-PRF-83282 and MIL-PRF-87257.

Tensile property requirements for o-rings used in aircraft fuel system applications (per MIL-P-5315) include an initial tensile strength of at least 1000 psi and elongation at break 200%. No additional requirements are provided for fluid aged samples, so an approximate 40% reduction in properties after 70 hours of fuel aging was used as a metric to be consistent with the hydraulic fluid testing and evaluation efforts. The only o-rings that clearly fall short of the 1000 psi tensile strength requirement are 29-FVQM o-rings. The tensile strength of the 39-PFE o-rings is marginal, but the scatter in the data set is relatively large.

All of the o-rings tested demonstrated good retention of tensile properties after 3 days of fluid aging in JP-8 at 225° F, with the exception of 40-PFE and possibly 21-FKM, which demonstrated relatively marginal performance. Three day aging performance in JP-8+100 was also good, except for 5-FKM. With the exception of the NBR-L control, most of the NBR samples still did remarkably well after 28 days of aging in JP-8 and JP-8+100. 5-FKM demonstrated marginal performance in JP-8 after 28 days. JP-8+100 appeared to be more aggressive, with FKM samples 5, 6 and 21 demonstrating marginal to poor performance after 28 days of fuel aging, as did samples 20-HNBR, 30-NBR and 12-ECO. The PFE and PFE-VF samples continued to show good performance, demonstrating a little more susceptibility to JP-8+100 than JP-8 after 28 days of fluid aging.

Table 34. O-ring Tensile Data – 3 Days in MIL-PRF-83282 @ 275° F

Material ID	Material Type		Unaged		Fluid Aged	
			Tensile Strength (psi)	Elongation @ Break (%)	ΔTensile Strength (%)	ΔElongation @ Break (%)
0	**NBR-L**	**Mean**	2626.49	383.29	-3.59	-33.75
		σ	236.94	46.91		
3	FKM	Mean	1539.07	313.43	-13.49	10.11
		σ	120.71	19.65		
5	FKM	Mean	1033.67	137.99	-26.79	9.78
		σ	405.72	11.12		
6	FKM	Mean	1556.57	319.66	-28.73	-5.70
		σ	303.39	30.79		
10	FVMQ	Mean	1222.49	149.07	0.85	-10.40
		σ	98.25	10.53		
13	HNBR	Mean	3121.32	362.16	-12.70	-21.87
		σ	388.98	40.17		
18	HNBR	Mean	2777.24	233.85	-1.47	-11.31
		σ	483.79	30.76		
20	HNBR	Mean	2678.80	224.00	3.16	-9.95
		σ	805.98	55.40		
21	FKM	Mean	1294.47	189.62	-14.85	10.90
		σ	63.33	8.01		
22	HNBR	Mean	3178.24	263.89	-0.18	-10.51
		σ	169.38	21.21		
25	FKM	Mean	1401.41	226.28	-17.91	-7.59
		σ	114.77	19.52		
29	FVMQ	Mean	727.33	290.31	-14.14	-6.52
		σ	104.87	36.80		
30	NBR	Mean	1528.10	149.72	-46.43	0.00[14]
		σ	314.89	20.71		
37	FKM	Mean	1672.44	273.26	-18.85	-23.27
		σ	22.62	7.91		
38	PFE	Mean	1518.66	336.71	-41.16	-4.86
		σ	163.31	29.42		
39	PFE	Mean	933.34	382.76	-46.29	-43.27
		σ	239.46	37.55		
40	PFE	Mean	1102.09	149.02	-29.66	-1.16
		σ	100.55	18.79		
41	PFE-VF	Mean	1486.20	144.64	13.09	-3.24
		σ	69.96	3.41		
42	PFE	Mean	1090.36	171.62	7.21	-15.76
		σ	58.13	9.55		
51	X-FKM	Mean	1393.14	195.34	-1.21	-19.16
		σ	148.53	14.15		
52	PFE-VF	Mean	1997.32	138.90	19.65	10.90
		σ	435.98	26.75		
53	PFE-VF	Mean	1005.00	178.60	-12.05	10.68
		σ	304.90	23.99		

[14] No change in elongation at break.

Table 35. O-ring Tensile Data – 3 Days in MIL-PRF-87257 @ 275° F

Material ID	Material Type		Unaged		Fluid Aged	
			Tensile Strength (psi)	Elongation @ Break (%)	ΔTensile Strength (%)	ΔElongation @ Break (%)
0	**NBR-L**	**Mean**	2626.49	383.29	-45.09	-54.57
		σ	236.94	46.91		
3	FKM	Mean	1539.07	313.43	-2.14	6.93
		σ	120.71	19.65		
5	FKM	Mean	1033.67	137.99	-31.56	-7.57
		σ	405.72	11.12		
6	FKM	Mean	1556.57	319.66	-15.21	-0.61
		σ	303.39	30.79		
10	FVMQ	Mean	1222.49	149.07	-9.97	-3.50
		σ	98.25	10.53		
13	HNBR	Mean	3121.32	362.16	-6.60	-24.81
		σ	388.98	40.17		
18	HNBR	Mean	2777.24	233.85	3.55	2.68
		σ	483.79	30.76		
20	HNBR	Mean	2678.80	224.00	4.04	4.18
		σ	805.98	55.40		
21	FKM	Mean	1294.47	189.62	-30.72	-10.75
		σ	63.33	8.01		
22	HNBR	Mean	3178.24	263.89	-28.46	-25.47
		σ	169.38	21.21		
25	FKM	Mean	1401.41	226.28	-18.28	-11.78
		σ	114.77	19.52		
29	FVMQ	Mean	727.33	290.31	-25.28	1.75
		σ	104.87	36.80		
30	NBR	Mean	1528.10	149.72	-33.10	11.69
		σ	314.89	20.71		
33	NBR		2593.73	187.37	-18.70	-31.69
			426.83	34.03		
37	FKM	Mean	1672.44	273.26	-29.27	-23.41
		σ	22.62	7.91		
38	PFE	Mean	1518.66	336.71	-37.25	-14.55
		σ	163.31	29.42		
39	PFE	Mean	933.34	382.76	-29.08	-12.81
		σ	239.46	37.55		
40	PFE	Mean	1102.09	149.02	-46.48	-6.97
		σ	100.55	18.79		
42	PFE	Mean	1090.36	171.62	-2.53	-3.59
		σ	58.13	9.55		
51	X-FKM	Mean	1393.14	195.34	-2.96	-16.17
		σ	148.53	14.15		
52	PFE-VF	Mean	1997.32	138.90	-16.47	-1.49
		σ	435.98	26.75		
53	PFE-VF	Mean	1005.00	178.60	-4.53	9.13
		σ	304.90	23.99		

Table 36. O-ring Tensile Data – 3 Days in JP-8 @ 225° F

Material ID	Material Type		Unaged		Fluid Aged	
			Tensile Strength (psi)	Elongation @ Break (%)	ΔTensile Strength (%)	ΔElongation @ Break (%)
0	**NBR-L**	**Mean**	2626.49	383.29	-16.41	-21.69
		σ	236.94	46.91		
3	FKM	Mean	1539.07	313.43	8.57	13.71
		σ	120.71	19.65		
5	FKM	Mean	1033.67	137.99	-41.77	-18.55
		σ	405.72	11.12		
6	FKM	Mean	1556.57	319.66	-3.25	11.21
		σ	303.39	30.79		
8	NBR	Mean	2397.03	331.44	-18.31	-33.11
		σ	55.85	6.15		
10	FVMQ	Mean	1222.49	149.07	-32.67	-28.25
		σ	98.25	10.53		
12	ECO	Mean	1560.40	294.61	-18.68	-19.82
		σ	100.97	20.14		
13	HNBR	Mean	3121.32	362.16	-18.37	-10.39
		σ	388.98	40.17		
18	HNBR	Mean	2777.24	233.85	-27.30	-8.91
		σ	483.79	30.76		
20	HNBR	Mean	2678.80	224.00	-7.82	9.40
		σ	805.98	55.40		
21	FKM	Mean	1294.47	189.62	-45.79	-30.38
		σ	63.33	8.01		
22	HNBR	Mean	3178.24	263.89	-33.64	-15.77
		σ	169.38	21.21		
25	FKM	Mean	1401.41	226.28	-41.83	-22.13
		σ	114.77	19.52		
29	FVMQ	Mean	727.33	290.31	-25.91	-11.17
		σ	104.87	36.80		
30	NBR	Mean	1528.10	149.72	-46.03	-19.46
		σ	314.89	20.71		
32	NBR	Mean	1808.38	127.27	-31.48	-12.56
		σ	77.69	5.85		
37	FKM	Mean	1672.44	273.26	-27.89	-19.82
		σ	22.62	7.91		
38	PFE	Mean	1518.66	336.71	-39.87	-1.24
		σ	163.31	29.42		
39	PFE	Mean	933.34	382.76	nd	nd
		σ	239.46	37.55		
40	PFE	Mean	1102.09	149.02	-55.76	-15.28
		σ	100.55	18.79		
41	PFE-VF	Mean	1486.20	144.64	-14.83	-9.20
		σ	69.96	3.41		
42	PFE	Mean	1090.36	171.62	-7.26	-9.79
		σ	58.13	9.55		
51	X-FKM	Mean	1393.14	195.34	-10.23	-17.40
		σ	148.53	14.15		
52	PFE-VF	Mean	1997.32	138.90	-14.35	1.00
		σ	435.98	26.75		
53	PFE-VF	Mean	1005.00	178.60	-20.12	-0.87
		σ	304.90	23.99		

Table 37. O-ring Tensile Data – 3 Days in JP-8+100 @ 225° F

Material ID	Material Type		Unaged		Fluid Aged	
			Tensile Strength (psi)	Elongation @ Break (%)	ΔTensile Strength (%)	ΔElongation @ Break (%)
0	**NBR-L**	**Mean**	2626.49	383.29	-21.22	-26.24
		σ	236.94	46.91		
3	FKM	Mean	1539.07	313.43	-10.42	8.98
		σ	120.71	19.65		
5	FKM	Mean	1033.67	137.99	-61.07	-37.28
		σ	405.72	11.12		
6	FKM	Mean	1556.57	319.66	-13.87	3.44
		σ	303.39	30.79		
8	NBR	Mean	2397.03	331.44	-13.56	-29.26
		σ	55.85	6.15		
10	FVMQ	Mean	1222.49	149.07	-16.41	0.34
		σ	98.25	10.53		
12	ECO	Mean	1560.40	294.61	-4.11	-8.74
		σ	100.97	20.14		
13	HNBR	Mean	3121.32	362.16	-26.64	-20.10
		σ	388.98	40.17		
18	HNBR	Mean	2777.24	233.85	-13.96	3.31
		σ	483.79	30.76		
20	HNBR	Mean	2678.80	224.00	-13.91	4.27
		σ	805.98	55.40		
21	FKM	Mean	1294.47	189.62	-49.20	-11.11
		σ	63.33	8.01		
22	HNBR	Mean	3178.24	263.89	-48.47	-29.95
		σ	169.38	21.21		
25	FKM	Mean	1401.41	226.28	-45.60	-25.29
		σ	114.77	19.52		
29	FVMQ	Mean	727.33	290.31	-22.00	-3.46
		σ	104.87	36.80		
30	NBR	Mean	1528.10	149.72	-45.14	-14.89
		σ	314.89	20.71		
32	NBR	Mean	1808.38	127.27	-41.66	-7.76
		σ	77.69	5.85		
37	FKM	Mean	1672.44	273.26	-31.05	-19.60
		σ	22.62	7.91		
38	PFE	Mean	1518.66	336.71	-22.77	1.72
		σ	163.31	29.42		
39	PFE	Mean	933.34	382.76	-41.20	-37.99
		σ	239.46	37.55		
40	PFE	Mean	1102.09	149.02	-34.96	-14.10
		σ	100.55	18.79		
41	PFE-VF	Mean	1486.20	144.64	-32.27	-11.64
		σ	69.96	3.41		
42	PFE	Mean	1090.36	171.62	-12.71	-2.89
		σ	58.13	9.55		
51	X-FKM	Mean	1393.14	195.34	-8.66	-11.62
		σ	148.53	14.15		
52	PFE-VF	Mean	1997.32	138.90	-6.91	18.28
		σ	435.98	26.75		
53	PFE-VF	Mean	1005.00	178.60	21.68	13.57
		σ	304.90	23.99		

Table 38. O-ring Tensile Data – 28 Days in MIL-PRF-83282 @ 275° F

Material ID	Material Type		Unaged		Fluid Aged	
			Tensile Strength (psi)	Elongation @ Break (%)	ΔTensile Strength (%)	ΔElongation @ Break (%)
0	**NBR-L**	**Mean**	2626.49	383.29	-60.79	-69.36
		σ	236.94	46.91		
3	FKM	Mean	1529.35	312.72	-30.71	0.53
		σ	104.56	18.70		
5	FKM	Mean	1034.83	159.36	-40.53	0.15
		σ	405.08	38.69		
6	FKM	Mean	1556.15	318.89	-38.06	-2.19
		σ	302.66	29.47		
10	FVMQ	Mean	1222.49	149.07	-75.25	-74.30
		σ	98.25	10.53		
13	HNBR	Mean	3121.32	362.09	-16.48	-43.39
		σ	388.98	40.30		
18	HNBR	Mean	2777.24	233.85	-40.07	-40.34
		σ	483.79	30.76		
20	HNBR	Mean	2678.80	224.00	-25.88	-13.25
		σ	805.98	55.40		
21	FKM	Mean	1294.47	189.62	-41.85	-3.62
		σ	63.33	8.01		
22	HNBR	Mean	3178.24	263.89	-46.79	-45.65
		σ	169.38	21.21		
25	FKM	Mean	1401.41	226.28	-10.53	-5.95
		σ	114.77	19.52		
29	FVMQ	Mean	727.33	290.31	-39.04	-5.51
		σ	104.87	36.80		
30	NBR	Mean	1528.10	149.72	-20.96	3.63
		σ	314.89	20.71		
33	NBR	Mean	2591.48	187.43	-42.19	-33.87
		σ	428.79	33.97		
34	NBR	Mean	1985.05	378.98	-12.77	-11.59
		σ	52.03	10.83		
36	HNBR	Mean	1305.43	118.12	-41.00	-32.40
		σ	273.77	13.50		
37	FKM	Mean	1672.44	273.26	-37.96	-14.64
		σ	22.62	7.91		
38	PFE	Mean	1504.52	336.68	-37.00	-15.53
		σ	187.43	29.46		
39	PFE	Mean	933.34	417.63	5.11	-39.11
		σ	239.46	25.88		
40	PFE	Mean	1097.61	149.02	-29.56	-12.24
		σ	104.40	18.79		
42	PFE	Mean	1090.36	171.62	-21.43	-38.11
		σ	58.13	9.55		
52	PFE-VF	Mean	1997.32	138.90	-14.78	11.14
		σ	435.98	26.75		
53	PFE-VF	Mean	1005.00	178.60	-3.02	8.78
		σ	304.90	23.99		

Table 39. O-ring Tensile Data – 28 Days in MIL-PRF-87257 @ 275° F

Material ID	Material Type		Unaged		Fluid Aged	
			Tensile Strength (psi)	Elongation @ Break (%)	ΔTensile Strength (%)	ΔElongation @ Break (%)
0	**NBR-L**	**Mean**	2626.49	383.29	-73.86	-75.13
		σ	236.94	46.91		
3	FKM	Mean	1529.35	312.72	-4.83	27.98
		σ	104.56	18.70		
5	FKM	Mean	1034.83	159.36	5.49	45.11
		σ	405.08	38.69		
6	FKM	Mean	1556.15	318.89	-27.51	3.25
		σ	302.66	29.47		
10	FVMQ	Mean	1222.49	149.07	-44.87	-33.42
		σ	98.25	10.53		
13	HNBR	Mean	3121.32	362.09	-15.07	-29.92
		σ	388.98	40.30		
18	HNBR	Mean	2777.24	233.85	-16.37	-9.92
		σ	483.79	30.76		
20	HNBR	Mean	2678.80	224.00	-35.83	-27.55
		σ	805.98	55.40		
21	FKM	Mean	1294.47	189.62	-42.33	0.86
		σ	63.33	8.01		
22	HNBR	Mean	3178.24	263.89	-53.92	-48.54
		σ	169.38	21.21		
25	FKM	Mean	1401.41	226.28	-5.30	-13.37
		σ	114.77	19.52		
29	FVMQ	Mean	727.33	290.31	-31.90	-5.05
		σ	104.87	36.80		
30	NBR	Mean	1528.10	149.72	-34.75	1.04
		σ	314.89	20.71		
33	NBR	Mean	2591.48	187.43	-79.75	-91.66
		σ	428.79	33.97		
34	NBR	Mean	1985.05	378.98	-36.52	-25.31
		σ	52.03	10.83		
36	HNBR	Mean	1305.43	118.12	nd	nd
		σ	273.77	13.50		
37	FKM	Mean	1672.44	273.26	-43.25	-25.28
		σ	22.62	7.91		
38	PFE	Mean	1504.52	336.68	-34.10	-14.41
		σ	187.43	29.46		
39	PFE	Mean	933.34	417.63	-12.01	-41.26
		σ	239.46	25.88		
40	PFE	Mean	1097.61	149.02	-28.28	-11.51
		σ	104.40	18.79		
42	PFE	Mean	1090.36	171.62	-17.18	-27.63
		σ	58.13	9.55		
52	PFE-VF	Mean	1997.32	138.90	-16.36	10.27
		σ	435.98	26.75		
53	PFE-VF	Mean	1005.00	178.60	1.79	20.17
		σ	304.90	23.99		

Table 40. O-ring Tensile Data – 28 Days in JP-8 @ 225° F

Material ID	Material Type		Unaged		Fluid Aged	
			Tensile Strength (psi)	Elongation @ Break (%)	ΔTensile Strength (%)	ΔElongation @ Break (%)
0	**NBR-L**	**Mean**	2626.49	383.29	-78.36	-94.74
		σ	236.94	46.91		
3	FKM	Mean	1529.35	312.72	-18.26	0.25
		σ	104.56	18.70		
5	FKM	Mean	1034.83	159.36	-62.33	-38.73
		σ	405.08	38.69		
6	FKM	Mean	1556.15	318.89	-26.36	-4.30
		σ	302.66	29.47		
8	NBR	Mean	2397.03	331.44	-17.50	-45.18
		σ	55.85	6.15		
10	FVMQ	Mean	1222.49	149.07	-23.45	-6.45
		σ	98.25	10.53		
12	ECO	Mean	1564.54	294.67	-31.13	-21.93
		σ	93.99	20.05		
13	HNBR	Mean	3121.32	362.09	-26.03	-22.51
		σ	388.98	40.30		
18	HNBR	Mean	2777.24	233.85	-27.47	-12.54
		σ	483.79	30.76		
20	HNBR	Mean	2678.80	224.00	-29.73	-49.05
		σ	805.98	55.40		
21	FKM	Mean	1294.47	189.62	-33.80	-1.52
		σ	63.33	8.01		
22	HNBR	Mean	3178.24	263.89	-28.31	-17.05
		σ	169.38	21.21		
25	FKM	Mean	1401.41	226.28	-2.83	-5.99
		σ	114.77	19.52		
29	FVMQ	Mean	727.33	290.31	-34.32	-9.07
		σ	104.87	36.80		
30	NBR	Mean	1528.10	149.72	-51.37	-11.61
		σ	314.89	20.71		
32	NBR	Mean	1808.38	127.27	-31.48	-12.56
		σ	77.69	5.85		
37	FKM	Mean	1672.44	273.26	-36.00	-22.11
		σ	22.62	7.91		
38	PFE	Mean	1518.66	336.71	-33.18	-13.32
		σ	163.31	29.42		
39	PFE	Mean	933.34	417.48	-18.86	-39.81
		σ	239.46	25.81		
40	PFE	Mean	1102.09	149.02	-34.62	-17.47
		σ	100.55	18.79		
41	PFE-VF	Mean	1486.20	144.64	-14.83	-9.20
		σ	69.96	3.41		
42	PFE	Mean	1090.36	171.62	27.89	-5.90
		σ	58.13	9.55		
51	X-FKM	Mean	1393.14	195.34	-15.71	-23.63
		σ	148.53	14.15		
52	PFE-VF	Mean	1997.32	138.90	-2.89	5.55
		σ	435.98	26.75		
53	PFE-VF	Mean	1005.00	178.60	nd	nd
		σ	304.90	23.99		

Table 41. O-ring Tensile Data – 28 Days in JP-8+100 @ 225° F

Material ID	Material Type		Unaged Tensile Strength (psi)	Unaged Elongation @ Break (%)	Fluid Aged ΔTensile Strength (%)	Fluid Aged ΔElongation @ Break (%)
0	**NBR-L**	**Mean**	2626.49	383.29	-81.57	-87.92
		σ	236.94	46.91		
3	FKM	Mean	1529.35	312.72	-25.71	52.26
		σ	104.56	18.70		
5	FKM	Mean	1034.83	159.36	-47.91	-18.93
		σ	405.08	38.69		
6	FKM	Mean	1556.15	318.89	-49.86	3.40
		σ	302.66	29.47		
8	NBR	Mean	2397.03	331.44	-28.16	-58.87
		σ	55.85	6.15		
10	FVMQ	Mean	1222.49	149.07	-37.06	-6.15
		σ	98.25	10.53		
12	ECO	Mean	1564.54	294.67	-50.14	-40.57
		σ	93.99	20.05		
13	HNBR	Mean	3121.32	362.09	-22.73	-26.10
		σ	388.98	40.30		
18	HNBR	Mean	2777.24	233.85	-34.32	-9.10
		σ	483.79	30.76		
20	HNBR	Mean	2678.80	224.00	-47.85	-25.24
		σ	805.98	55.40		
21	FKM	Mean	1294.47	189.62	-61.13	-34.82
		σ	63.33	8.01		
22	HNBR	Mean	3178.24	263.89	-33.61	-15.32
		σ	169.38	21.21		
25	FKM	Mean	1401.41	226.28	-14.84	-6.82
		σ	114.77	19.52		
29	FVMQ	Mean	727.33	290.31	-27.21	0.80
		σ	104.87	36.80		
30	NBR	Mean	1528.10	149.72	-48.97	-12.96
		σ	314.89	20.71		
32	NBR	Mean	1808.38	127.27	nd	nd
		σ	77.69	5.85		
37	FKM	Mean	1672.44	273.26	-40.22	-21.99
		σ	22.62	7.91		
38	PFE	Mean	1518.66	336.71	-43.90	-6.90
		σ	163.31	29.42		
39	PFE	Mean	933.34	417.48	-11.46	-31.89
		σ	239.46	25.81		
40	PFE	Mean	1102.09	149.02	-42.44	3.84
		σ	100.55	18.79		
41	PFE-VF	Mean	1486.20	144.64	-35.13	-2.69
		σ	69.96	3.41		
42	PFE	Mean	1090.36	171.62	nd	nd
		σ	58.13	9.55		
51	X-FKM	Mean	1393.14	195.34	nd	nd
		σ	148.53	14.15		
52	PFE-VF	Mean	1997.32	138.90	-42.10	-10.04
		σ	435.98	26.75		
53	PFE-VF	Mean	1005.00	178.60	-15.40	7.27
		σ	304.90	23.99		

4.2.3 O-ring Compression Set Measurements

O-ring compression set measurements were performed at room temperature, -40º F and -65º F, both before and after fluid aging by methods previously described. All compression set measurements were performed in triplicate using size 214 o-rings. Compression set was determined 30 minutes after removing the o-rings from the compression set test jig for each test condition described. The ASTM provides for median or average data to be reported, depending on the number of measurements taken. Average data and standard deviations are presented in this report. As previously stated, the compression set data reported in this section were determined based on averaged thickness data for o-rings before and after compression set experiments without respect to the specific measurement location.

Room temperature compression set values were determined after 22 and 70 hours of compression for all unaged materials and after 70 hours of compression in each of the fluid aging conditions. For consistency, only the 70 hour data are reported in this section to support direct comparison to the 70 hour fluid aged samples. Low temperature compression set values for unaged samples were determined after compressing the o-rings to 75% of their initial thickness (25% deflection) at room temperature and then allowing the compressed o-rings to equilibrate at -40° F and -65° F for 70 hours before measuring the amount of compression set. Low temperature compression set values for fluid aged samples were determined after (1) compressing the o-rings to 75% of their initial thickness at room temperature, (2) fluid aging the compressed o-rings for 70 hours under each of the fluid aging conditions, (3) allowing the samples to cool to room temperature before removing the compression test jigs from the test fluids, and then (4) allowing the compressed o-rings to equilibrate at -40° F and -65° F for 22 hours before (5) measuring the amount of low temperature compression set. The o-ring compression set data are presented in the following tables:

- Table 42. Room Temperature Compression Set for Aged and Unaged O-rings
- Table 43. -40° F Compression Set for Aged and Unaged O-rings.
- Table 44. -65° F Compression Set for Aged and Unaged O-rings.

A complete set of data are not presented for the o-ring compression set measurements for several reasons: (1) a number of o-ring materials were down-selected during the program effort; (2) materials availability changed during the course of the program efforts; (3) in some instances, material formulations evolved during the course of the program so newer, refined material formulations were substituted for previous versions of materials; and (4) JP-8 testing efforts were curtailed during the final part of the program due to fuel availability. Materials substitution was most common among the advanced fluoroelastomers tested under the program (particularly the PFE materials) as these materials were new to the market and materials development efforts were ongoing.

The room temperature o-ring compression set data was all very positive, both before and after 3-day fluid aging with a few notable exceptions. The NBR-L control samples performed very poorly after fluid aging, with the test o-rings often exhibiting some degree of plastic flow during compression at the high temperature aging conditions (the plastic flow accounts for the compression set values in excess of 100%). 6-FKM demonstrated poor compression set resistance after fluid aging, with 25-FKM demonstrating moderate performance relative to the other materials tested, but still exceeding the performance requirements. 12-ECO, which was included for relative performance comparison, performed very poorly after fluid aging in MIL-PRF-83282, and poorly in MIL-PFR-87257 and JP-8+100. With the exception of 13-HNBR in MIL-PRF-87252, the HNBR and NBR samples performed within specification at room temperature compression before and after fluid aging. The PFE and PFE-VF o-rings all performed very well before and after high temperature fluid aging. PFE samples

94 and 95, representing more recent advances in PFE chemistry, demonstrated excellent room temperature compression set resistance.

The low temperature compression set measurements demonstrated that relatively few materials could actually meet the performance requirement of the specifications. At -40° F, the better performing materials demonstrated lower compression set after fluid aging in fuel, with higher compression set values after aging in hydraulic fluid. This trend was not as prevalent in the -65° F compression set data. 10-FVMQ exhibited relatively good compression set resistance after fuel aging at -40°F and hydraulic fluid aging at -65° F. Some of the NBR materials tested (30 and 34) actually demonstrated relatively good -40° F compression set resistance after fuel aging. The HNBR samples did not test well, exhibiting cold flow under compression during high temperature fluid aging. As a group, the PFE samples demonstrated very good performance at -40° F after high temperature fuel aging and relatively good performance at -65° F after high temperature fuel aging. PFE samples 94 and 95 exhibited moderate performance at -40° F after high temperature aging in hydraulic fluids and PFE samples 38, 39 and 42 exhibited excellent compression set resistance at -65° F after high temperature aging in MIL-PRF-83282 and MIL-PRF-87257. -40° F compression set data for these samples are not available due to lack of material availability.

Table 42. RT Compression Set (%) for Aged and Unaged O-rings

Material ID	Material Type		Unaged	MIL-PRF-83282	MIL-PRF-87257	JP-8+100
0	NBR-L	Mean	32.59	114.77	97.98	90.30
		σ	2.75	3.13	3.44	0.47
6	FKM	Mean	33.89	69.83	65.97	nd
		σ	3.62	10.32	1.97	
10	FVMQ	Mean	13.27	35.81	12.91	8.62
		σ	2.30	1.74	3.27	2.77
12	ECO	Mean	21.22	93.10	65.23	48.99
		σ	0.29	3.43	1.00	5.01
13	HNBR	Mean	38.36	19.76	60.64	33.31
		σ	3.90	1.08	11.56	5.52
21	FKM	Mean	17.24	35.05	12.98	5.21
		σ	2.41	5.95	2.50	2.51
22	HNBR	Mean	26.98	nd	nd	5.67
		σ	5.57			3.76
25	FKM	Mean	40.03	52.04	50.53	38.78
		σ	2.64	2.66	1.44	1.60
29	FVMQ	Mean	8.87	nd	13.26	31.73
		σ	4.57		7.03	15.00
30	NBR	Mean	nd	32.61	33.57	4.759834
		σ		5.88	1.35	2.286751
33	NBR	Mean	19.13	nd	nd	8.69
		σ	2.31			2.17
34	NBR	Mean	28.38	45.48	22.96	nd
		σ	3.56	0.26	2.88	
37	FKM	Mean	29.39	17.55	16.13	13.79
		σ	4.49	3.54	0.45	1.89
38	PFE	Mean	nd	17.77	nd	nd
		σ		0.28		
39	PFE	Mean	nd	20.94	nd	nd
		σ		2.082		
40	PFE	Mean	nd	42.20	nd	nd
		σ		1.28		
42	PFE	Mean	nd	27.85	nd	nd
		σ		5.62		
52	PFE-VF	Mean	26.99	22.19	14.48	16.26
		σ	0.10	9.67	2.37	2.40
53	PFE-VF	Mean	36.44	26.65	30.68	23.29
		σ	4.94	8.19	7.07	3.00
94	PFE	Mean	nd	18.57	18.95	14.00
		σ		0.48	0.80	1.71
95	PFE	Mean	nd	18.08	19.92	11.14
		σ		1.03	4.98	1.78

Table 43. -40° F Compression Set (%) for Aged and Unaged O-rings

Material ID	Material Type		Unaged	MIL-PRF-83282	MIL-PRF-87257	JP-8	JP-8+100
0	NBR-L	Mean	124.99	123.60	123.90	106.44	110.34
		σ	5.95	3.79	2.10	4.85	3.08
6	FKM	Mean	116.28	117.20	123.01	123.58	106.58
		σ	1.76	4.76	3.00	2.62	6.52
10	FVMQ	Mean	63.62	94.23	71.17	38.43	31.18
		σ	4.74	3.98	14.13	4.43	2.53
12	ECO	Mean	77.44	108.87	108.20	94.27	82.78
		σ	2.28	4.06	5.52	6.40	5.38
13	HNBR	Mean	124.42	121.61	119.95	119.49	111.00
		σ	1.81	12.58	3.94	7.49	4.55
21	FKM	Mean	nd	nd	nd	nd	89.18
		σ					15.41
22	HNBR	Mean	135.49	126.25	134.16	115.11	nd
		σ	11.81	8.88	2.14	8.20	
25	FKM	Mean	nd	nd	nd	nd	100.17
		σ					9.53
30	NBR	Mean	125.15	87.35	78.90	46.22	46.79
		σ	4.47	4.88	6.55	1.71	7.67
34	NBR	Mean	nd	nd	nd	nd	55.76
		σ					9.38
37	FKM	Mean	nd	122.78	124.99	nd	122.73
		σ		3.13	5.68		3.43
38	PFE	Mean	nd	nd	nd	nd	20.71
		σ					0.69
39	PFE	Mean	nd	nd	nd	nd	18.37
		σ					1.71
40	PFE	Mean	nd	nd	nd	nd	41.83
		σ					1.89
42	PFE	Mean	nd	nd	nd	nd	24.70
		σ					1.74
52	PFE-VF	Mean	80.90	86.88	89.91	93.53	75.00
		σ	13.46	4.73	3.01	0.92	7.81
94	PFE	Mean	73.43	85.99	53.58	21.78	30.12
		σ	9.38	3.00	7.01	1.78	3.01
95	PFE	Mean	63.38	64.02	50.33	34.03	32.89
		σ	6.67	2.96	5.05	11.84	2.32

Table 44. -65° F Compression Set (%) for Aged and Unaged O-rings

Material ID	Material Type		Unaged	MIL-PRF-83282	MIL-PRF-87257	JP-8+100
0	NBR-L	Mean	119.35	120.52	117.52	127.09
		σ	2.28	2.92	2.04	4.37
6	FKM	Mean	122.53	115.39	105.29	124.11
		σ	9.05	8.47	4.28	4.33
10	FVMQ	Mean	nd	48.23	68.24	nd
		σ		14.90	15.07	
12	ECO	Mean	117.95	93.33	108.96	124.51
		σ	3.10	10.54	4.54	10.96
13	HNBR	Mean	118.51	114.32	124.91	126.71
		σ	8.29	7.58	2.84	13.91
22	HNBR	Mean	132.35	100.18	117.46	114.99
		σ	7.77	15.56	9.92	31.28
30	NBR	Mean	124.75	70.86	79.97	103.87
		σ	9.59	7.85	7.97	5.85
37	FKM	Mean	121.96	124.98	120.62	119.81
		σ	3.00	6.44	12.36	8.39
38	PFE	Mean	64.94	30.64	32.32	nd
		σ	10.67	6.42	4.55	
39	PFE	Mean	78.84	36.05	44.49	62.00
		σ	5.20	7.72	6.29	1.49
40	PFE	Mean	99.68	51.38	71.98	91.19
		σ	5.23	6.85	4.43	6.30
42	PFE	Mean	70.39	40.72	42.05	55.95
		σ	7.65	1.60	5.31	7.68
52	PFE-VF	Mean	131.43	80.12	98.76	130.32
		σ	5.75	5.77	3.30	6.01
94	PFE	Mean	100.58	99.48	87.86	79.46
		σ	2.60	8.02	6.92	5.47
95	PFE	Mean	93.80	88.14	84.49	71.08
		σ	5.32	6.43	6.26	4.49

4.2.4 CSR Testing

Two sets of compression stress relaxation measurements were performed to determine the best way to use CSR testing to support the program objectives. In the first set of CSR experiments, unaged o-rings and o-rings that were aged for 3 days in MIL-PRF-83282 and JP-8+100 (at 275° F and 225° F respectively; o-rings were not aged in compression) were placed in the CSR device and compressed to 25% deflection at room temperature, and then cooled to -40°F at a controlled rate over a period of 1 hour. CSR measurements were taken for 48 hours at -40°F prior to reheating the samples to room temperature. The CSR measurements were continued at room temperature for an additional 48 hours to evaluate compression set recovery. The CSR data for this set of experiments are presented in Figures 7, 8 and 9 for un-aged, hydraulic fluid aged, and fuel aged samples respectively. Duplicate size 214 nitrile (0) and PFE (68) o-rings were used in each test. Individual replicate data are presented in the figures presented in this section. The CSR data are normalized with respect to the initial sealing force exerted by the o-rings under 25% deflection at room temperature.

The CSR data for the unaged samples demonstrates a significant decrease in elasticity (80% reduction in sealing force) for NBR control samples at -40° F, while the PFE samples demonstrated an average decrease in sealing force of approximately 45% (Figure 7). Upon heating to room temperature after low temperature exposure, the PFE samples recovered 100% of their initial sealing force and the nitrile o-rings recovered about 90% of their initial sealing force. A similar response was demonstrated for the samples aged in hydraulic fluid (Figure 8).

Interestingly, the response of the o-rings aged in JP-8+100 (Figure 9) was significantly different, as there is virtually no difference between the normalized response of the nitrile and PFE o-rings. This affect may be attributed to the difference in aging temperatures between the hydraulic fluid aged (275° F) and fuel aged (225° F) samples. Furthermore, the nitrile o-rings demonstrate significantly more volume swell during a 3-day exposure to JP-8+100 (20% for NBR vs. 6% for PFE), so the apparent improved low temperature performance of the nitrile o-rings (or some portion thereof) may also be attributed to plasticization effects or to the fact that the aged (swollen) nitrile o-rings would be subjected to less compressive force at the same 25% deflection relative to the unaged nitrile o-rings and the PFE o-rings, which are less susceptible to fuel swelling. Based on the last argument, the difference in response may be an artifact of the experimental procedure used in this sequence of CSR testing and not a good measure of relative performance.

A second set of experiments was designed to more closely mimic the thermal and mechanical stresses imparted on static o-ring during service. In these experiments, nitrile and PFE o-rings were compressed to 25% deflection (at room temperature) in the CSR device and then aged *in situ* while under compression in the CSR unit. Thermal aging was conducted for a period of 3 days in air at 275°F, in MIL-PRF-83282 at 275° F, and in JP-8+100 at 225° F. After aging, the o-rings were cooled to -40° F to determine the low temperature sealing capacity of the o-rings after high temperature aging under compression.[15] The exact temperature profile was presented in Section 3.2.4, CSR Profile 2. The response (sealing force) of the o-rings was constantly monitored during the course of the entire thermal program. The CSR data for these experiments are presented in Figures 10, 11, and 12 for o-rings aged in air, hydraulic fluid and JP-8+100,

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[15] With the exception of the data presented for JP-8+100. The low temperature data presented for this experiment is at -20° F as equipment issues encountered during the run affected low temperature cooling capacity. As noted, this issue affected several other data sets. These experiments could not be repeated due to contract limitations.

Note - CSR data sets presented in this document are not necessarily presented in the order of execution of experiments. Equipment modifications were required to support JP-8+100 experiments and additional data sets were acquired near the end of the program to support reporting efforts.

respectively. Once again, the data are normalized with respect to the initial sealing force exerted by the o-rings under 25% deflection at room temperature.

The response of the nitrile o-rings under *in situ* aging is significantly different than the response of the PFE o-rings. After an initial increase in sealing force due to volume expansion, the nitrile o-rings exhibit a constant decrease in sealing force during high temperature aging (in all test environments) as the o-rings soften and begin to flow under the 25% deflection force (the o-rings are not constrained laterally). Once again, however, the nitrile o-rings aged in situ in JP-8+100 perform better than the nitrile o-rings aged in air and hydraulic fluid, retaining a greater percentage of their initial sealing force for the duration of the test sequence. The sealing force for the nitrile o-rings aged in air continues to decrease in a linear fashion during the entire 3-day period, while the sealing force of the o-rings aged in fluid decreases in a more exponential manner. The difference in response in air and fluid would indicate possible competing mechanisms for force retention as a function of the thermal and chemical influences. When the nitrile o-rings are cooled back down to room temperature after 3 days of aging in air and hydraulic fluid, they retain only 10 to 25% of their initial sealing force. The nitrile o-rings aged in JP-8+100 retain 70-75% of their initial sealing force. When cooled further to the low temperature extreme of -40° F, the sealing force of the nitrile o-rings falls to zero in air and hydraulic fluid due to volume contraction. The fuel aged samples retain 60% of their low temperature sealing force but, as previously noted, the low temperature data for this set were collected at -20° F and not -40° F. The PFE o-rings exhibit a significant increase in sealing force due to thermal expansion during initial heating, followed by a slight decrease in sealing force as a function of time during high temperature aging in all environments, with all samples continuing to exhibit more than 120% of their initial sealing force during the entire 3-day exposure periods.[16] After the 3-day aging cycle, the PFE samples retain 60 to 85% of their initial sealing force after cooling to room temperature, and approximately 30-40% of their initial sealing force at -40°F, in air and hydraulic fluid, respectively. The JP-8+100 samples retained 70% of their initial sealing force at -20° F.

The *in situ* aging test procedure clearly demonstrates the low temperature performance limitations of the nitrile o-rings tested. The difference in CSR response during thermal aging is also significant, clearly demonstrating the potential benefit of using the PFE o-rings to replace nitrile o-rings in hydraulic fluid applications, especially where low temperature sealing requirements are critical.

Based on the results of the initial *in situ* CSR experiments, additional testing was performed in MIL-PRF-83282 and JP-8+100 to see if this specific CSR test sequence could be used to demonstrate and evaluate the relative performance differences between other program materials, including 23-FKM, 32-NBR and 22-HNBR. These specific materials represent some of the best performing o-ring materials within each of the other major classes of materials evaluated under the program, but they are not part of the group of best performers. The FKM material is actually a Viton® material. The results of these CSR experiments are presented in Figures 13 and 14. The temperature profile for these experiments is the same as that presented for CSR Profile 2 in Section 3.2.4.

All three of the candidate materials selected for *in situ* CSR measurements demonstrate about the same level of resistance to high temperature hydraulic fluid aging (Figure 13) and about the same level of sealing force retention after the 3 day aging period. Interestingly, 32-NBR demonstrated good high temperature stability and the best low temperature sealing capacity after hydraulic fluid aging, whereas the NBR-L control sample tested previously (Figure 11) demonstrated significant reduction in sealing force during high temperature aging and retained none of its sealing force after hydraulic fluid aging. This particular NBR (32), characterized by the supplier as a low temperature nitrile rubber, performed

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[16] Note - In Figure 10, the test cell for PFE sample 2 hung up during heating. This accounts for the constant, lower sealing force values exhibited by this sample. This problem was corrected in other experiments.

very well throughout the test program, exceeding the performance of all other NBR and HNBR samples tested.

The high temperature data trends were similar for these same samples when aged *in situ* in JP-8+100 (Figure 14). However, the low temperature trends were inconclusive as the samples were only cooled to -20° F. The 22-HNBR is clearly the poor performer at this temperature, but 23-FKM and 32-NBR exhibit the same -20° F sealing performance after high temperature aging. It is unclear from this data whether the FKM material will continue to demonstrate good sealing performance at -40° F after fuel aging or if the sealing performance of 23-FKM and 22-HNBR will fall to zero at -40° F as they did after aging in hydraulic fluid.

4.2.5 Corrosion and Adhesion Testing

Corrosion and adhesion testing was performed in accordance with methods previously described. The best performing o-ring materials were evaluated along with some additional materials representing the various classes of materials evaluated under the program. None of the best performing materials demonstrated a propensity to adhere to or corrode any of the substrate metals under the conditions tested. 12-ECO, which was tested for comparative purposes, did demonstrate a tendency to adhere to bronze and magnesium when tested in JP-8+100 (testing in JP-8 was not performed for these metals).

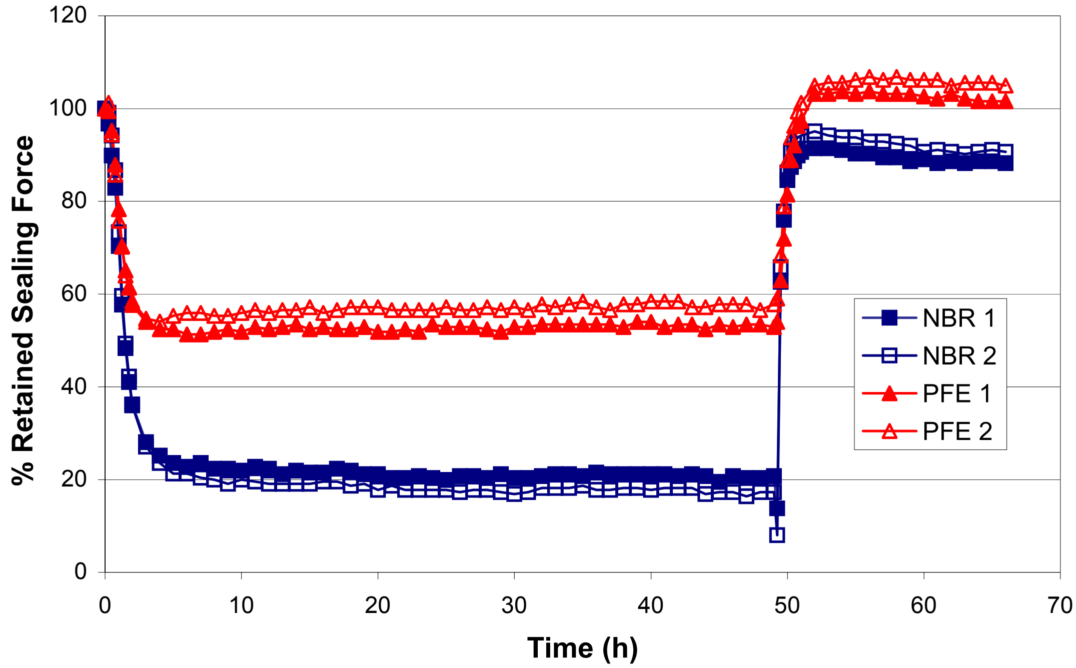

Figure 7. Normalized CSR data for low temperature experiments (unaged).

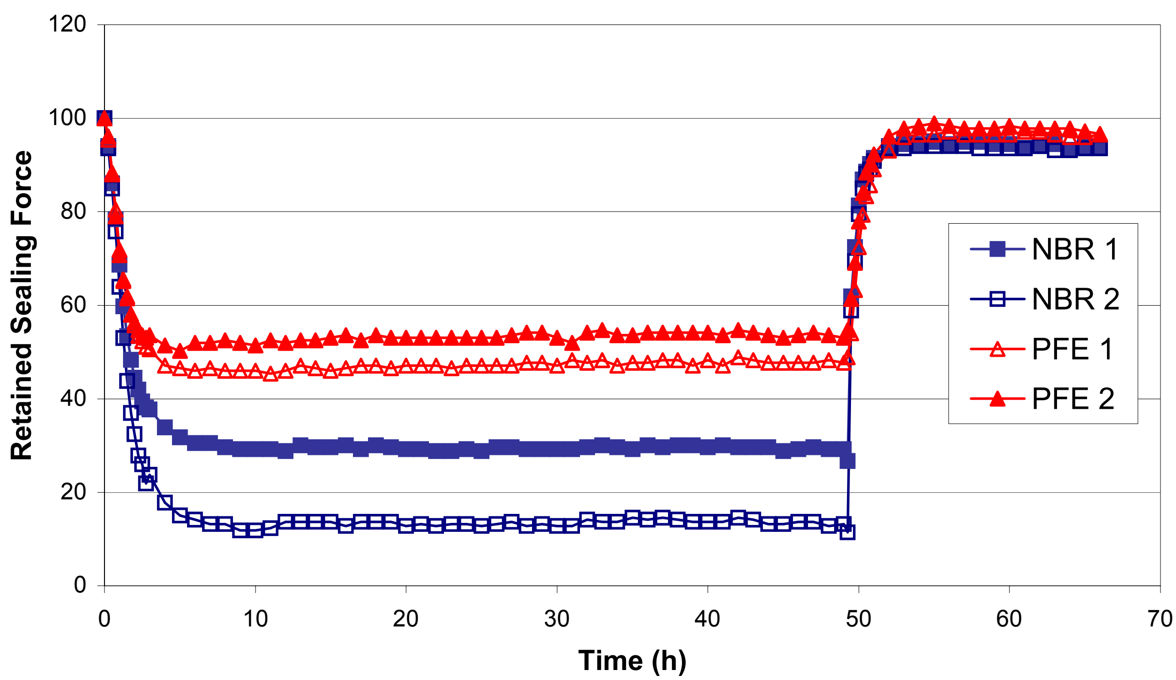

Figure 8. Normalized CSR data for low temperature experiments (aged in MIL-PRF-83282).

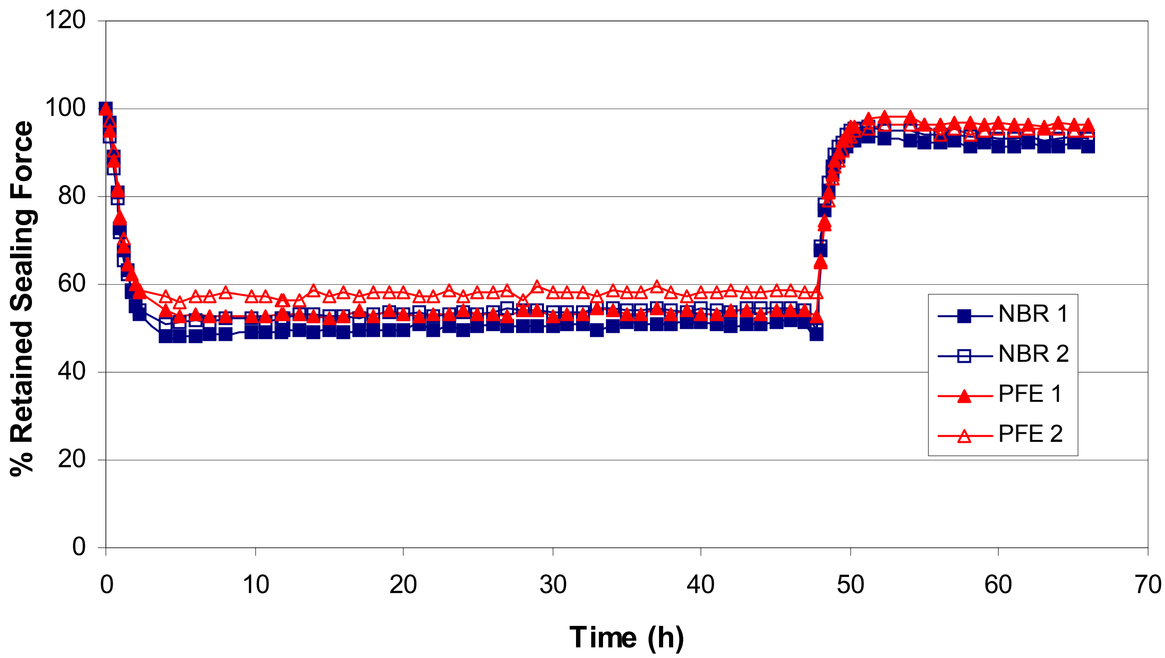

Figure 9. Normalized CSR data for low temperature experiments (aged in JP-8+100).

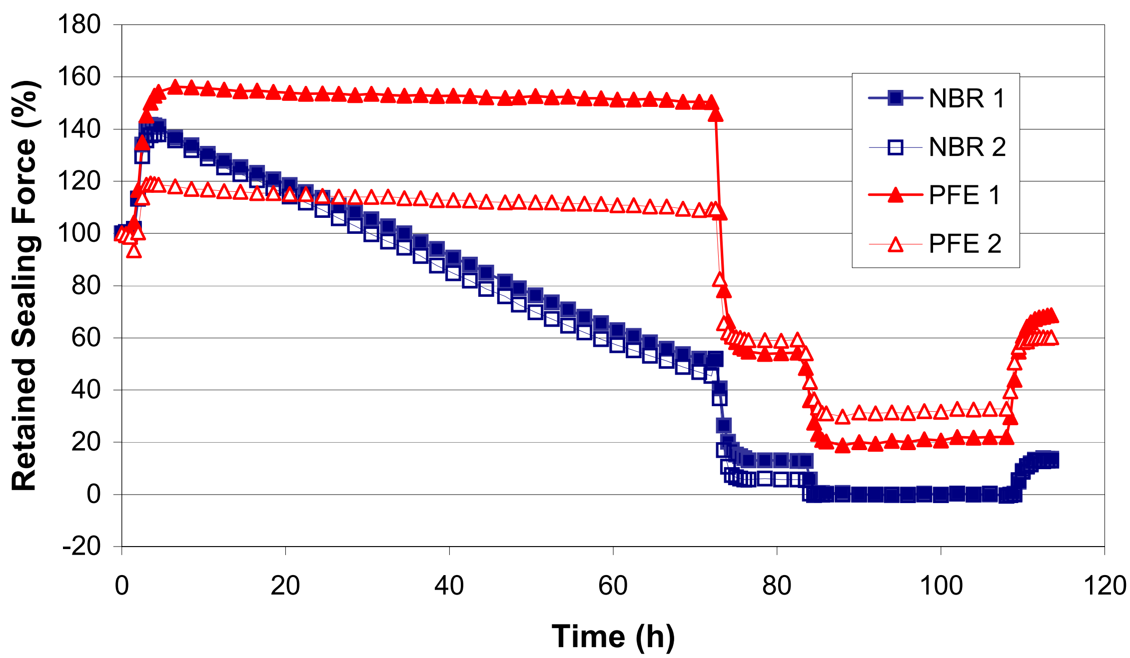

Figure 10. Normalized CSR data for *in situ* air aging experiments.

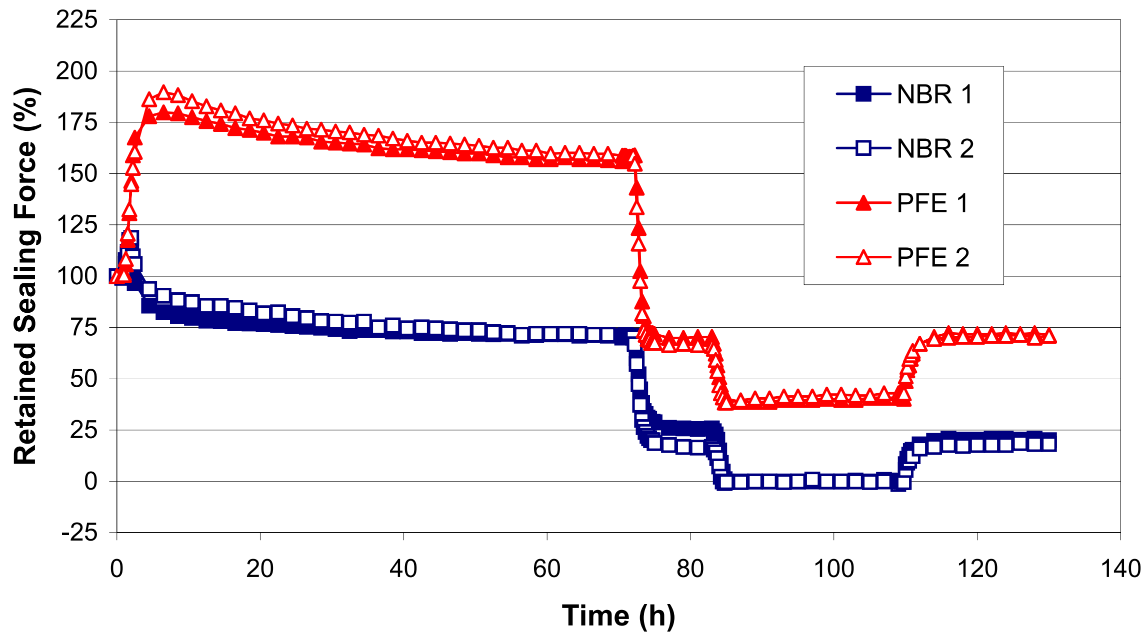

Figure 11. Normalized CSR data for *in situ* MIL-PRF-83282 fluid aging experiments.

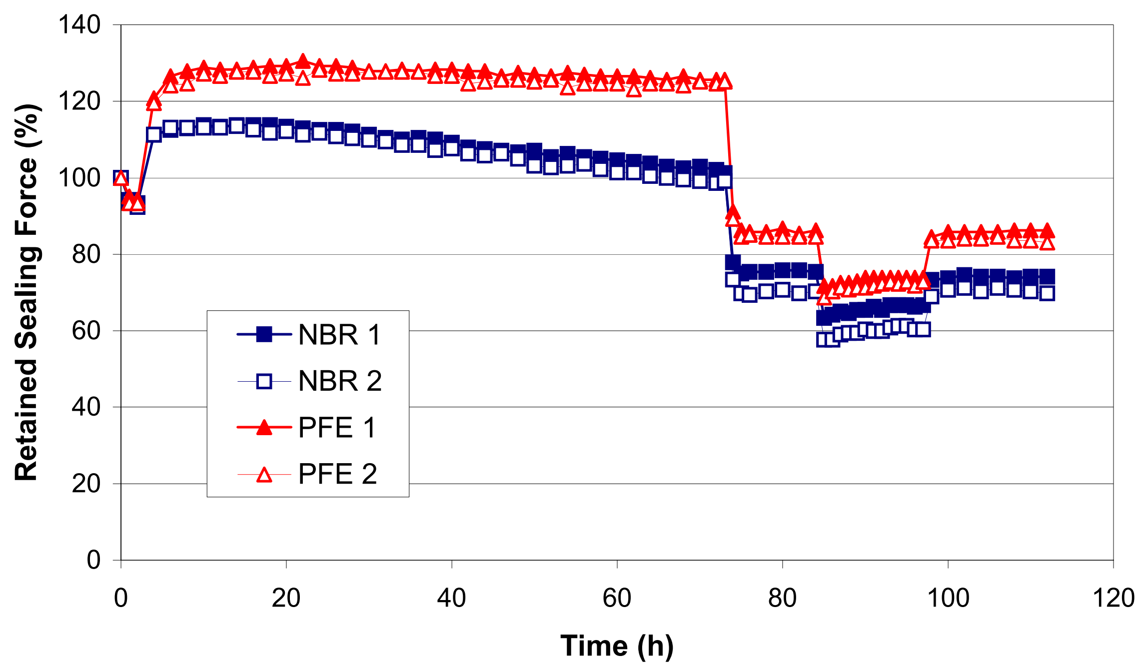

Figure 12. Normalized CSR data for *in situ* JP-8+100 fluid aging experiments.[17]

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[17] Low temperature segment of program only cooled to -20°F due to equipment failure.

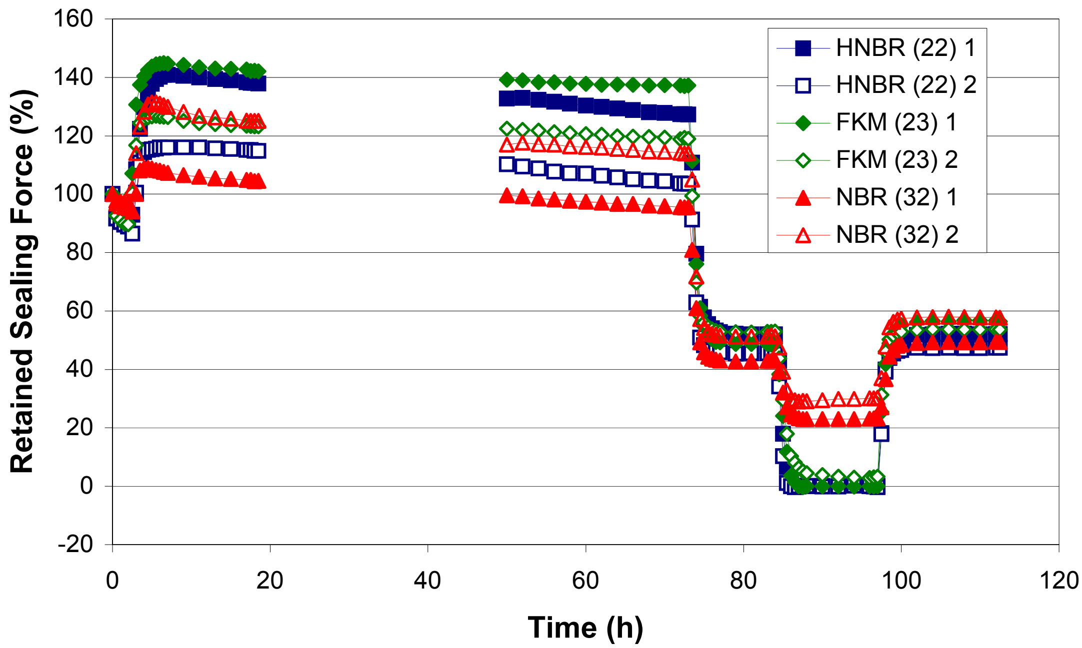

Figure 13. Normalized CSR data for *in situ* MIL-PRF-83282 fluid aging experiments.[18]

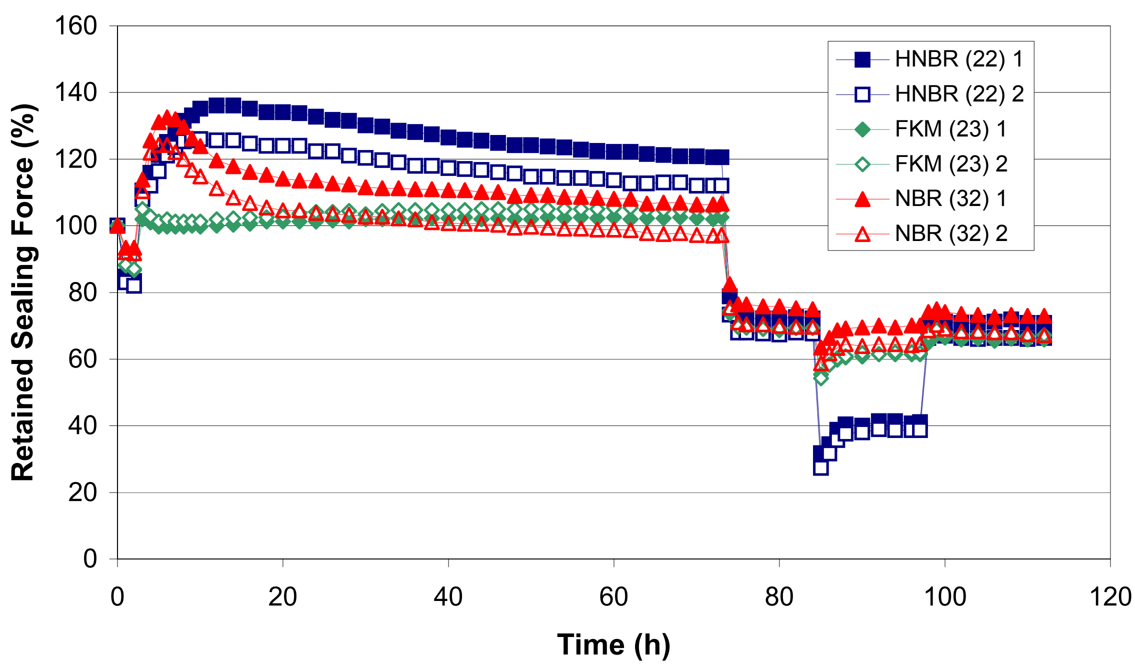

Figure 14. Normalized CSR data for *in situ* JP-8+100 fluid aging experiments.[19]

[18] Date missing during portion of 3-day aging due to data acquisition error.

4.3 FINAL TESTING AND EVALUATION

The best performing materials were selected based on the results of the testing and evaluation efforts conducted during the course of the program and subjected to a final series of tests. In addition to 3-day fluid aging in JP-8, JP-8+100, MIL-PRF-83282 and MIL-PRF-87257, final testing and evaluation efforts included additional fluid aging experiments in JRF, MIL-PRF-5606, and MIL-PRF-23699. Fluid aging in JP-8 was limited due to problems sourcing additional fluid at the end of the program. A series of room temperature, 60-day fluid and air aging experiments were added to the final test sequence. Volume swell, weight gain and physical property changes were determined on all o-rings before and after aging experiments. Volume swell was determined volumetrically to provide more accurate results. Room temperature and low temperature (-40° F) compression set measurements were also repeated before and after fluid aging, also using more precise measurement methods. More extensive CSR testing was performed to evaluate sealing force retention during high temperature aging and low temperature exposure. Finally, samples of the best performing materials were sent out for third party testing and evaluation to verify program results and evaluate dynamic sealing performance capability.

4.3.1 Selection of Best Performers

During the course of the program, some materials were eliminated from further testing based on obvious performance limitations. Others were eliminated based on issues of materials availability, which may have been contributed to several factors including: (1) loss of program support by material suppliers; (2) elimination of materials from production; (3) materials not available as o-rings; (4) sample duplication; or (5) the development and substitution of replacement materials for prior versions (replacement materials were given new identification numbers and treated as new samples).

Program considerations used to identify the best performing o-ring materials for hydraulic fluid and fuel system applications are summarized in Chart 1 and Chart 2, respectively. Materials were evaluated with respect to MIL-PRF-83461 and MIL-PRF-5315 requirements separately, leaving open the possibility that a given material may be suited for hydraulic fluid application but not fuel systems, and visa versa. Generous allowances were given with most performance criterion to make sure no materials were prematurely eliminated from final consideration and to provide a more complete body of data to support final material selection efforts. Hardness requirements were relaxed for both fuel and hydraulic applications, with the range of Shore A 60 to 80 used as the governing requirement for program consideration. Minimum tensile property requirements were relaxed to include one standard deviation (1σ) of the averaged data. Changes in o-ring physical properties after fluid aging were reasonable in most instances, so this criterion was not used extensively in the final down-selection process. In some instances, materials remained in the test sequence for comparative purposes. Materials may be mentioned more than once in Charts 1 and 2 if there were multiple reasons for elimination.

While a substantial amount of nitrile data is included in this report, all nitrile (NBR) materials were eliminated from ongoing program consideration based on previous field experience. The data in this report confirms previous experience with nitrile materials. All of the NBR materials exhibited a relatively high amount of extractable materials during fluid aging; an indication of the amount of low molecular plasticizers needed to impart low temperature flexibility. However, within the group of nitrile rubbers, the exceptional performance of 32-NBR should be noted. While more resistant to high temperature fluid aging, the HNBR samples demonstrated similar performance in this regard. As such, both of these classes of materials exhibited high compression set and loss of sealing force after high temperature fluid aging. Relative to the better performing materials, the NBR and HNBR samples also tended to

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[19] Low temperature segment of program only cooled to -20° F due to equipment failure.

demonstrate a greater loss in physical properties after fluid aging. Furthermore, with the exception of 32-NBR, the nitrile-based materials performed very poorly in the CSR experiments, demonstrating no retained low temperature sealing force after high temperature fluid aging.

Conventional FKM materials were also not emphasized in the final testing and evaluation efforts due to known limitations in the low temperature performance properties of these materials. Mixed results were obtained on the FKM materials tested during the course of the program, even when considering some of the more advanced Viton® formulations. While the overall ability of these materials to resist the effects of high temperature fluid aging was good, the low temperature transition temperatures demonstrated by these materials were generally higher than most of the better performing materials tested, leading to relatively poor low temperature performance. The limited CSR data collected on FKM materials confirmed the low temperature sealing capacity limitations of FKM materials after high temperature fluid aging.

Chart 1. Down-Selection of O-ring Materials for Hydraulic Fluid Systems

O-ring materials eliminated based on materials availability issues, excluding substitution of replacement materials:

- 3-FKM
- 5-FKM
- 9-FKM
- 11-FKM
- 17-HNBR
- 19-HNBR
- 21-FKM
- 25-FKM
- 36-HNBR

O-ring materials with Shore A hardness less than 60 or greater than 80 (± 2.5 for experimental error), or materials exhibiting excessive change in hardness after fluid aging (noted with *):

- 9-FKM
- 10-FVMQ
- 12-ECO*
- 18-HNBR
- 19-HNBR
- 20-HNBR
- 22-HNBR
- 54-X-FKM
- 55-X-FKM

O-ring materials not meeting minimum tensile strength requirements (less than 1350 psi - 1σ):

- 4-ECO
- 11-FKM
- 29-FVMQ
- 39-PFE
- 40-PFE
- 42-PFE
- 54-X-FKM
- 55-X-FKM

O-ring materials exhibiting excessive compression set (>50%) after fluid aging:

- 6-FKM (RT, -40° F, -65° F)
- 10-FVMQ (-40° F, -65° F)
- 12-ECO (RT, -40° F, -65° F)
- 13-HNBR (-40° F, -65° F)
- 22-HNBR (-40° F, -65° F)
- 35-HNBR (molded, -40° F)
- 37-FKM (-40° F, -65° F)
- 40-PFE (-65° F)
- 52-PFE-VF (-40° F, -65° F)
- 94-PFE (-40° F, -65° F)
- 95-PFE (-40° F, -65° F).

Remaining (Best) Candidates:

- **38-PFE**
- **41-PFE-VF**
- **51-PFE-VF**
- **53-PFE-VF**

Chart 2. Down-Selection of O-ring Materials for Fuel Systems

O-ring materials eliminated based on materials availability issues, excluding substitution of replacement materials:

- 3-FKM
- 5-FKM
- 9-FKM
- 11-FKM
- 17-HNBR
- 19-HNBR
- 21-FKM
- 25-FKM
- 36-HNBR

O-ring materials with Shore A hardness less than 60 or greater than 80 (± 2.5 for experimental error), or materials exhibiting excessive change in hardness after fluid aging (noted with *):

- 5-FKM*
- 9-FKM
- 10-FVMQ
- 12-ECO*
- 18-HNBR
- 19-HNBR
- 20-HNBR
- 22-HNBR
- 54-X-FKM
- 55-X-FKM

O-ring materials not meeting minimum tensile strength requirements (less than 1000 psi - 1σ):

- 4-ECO
- 11-FKM
- 29-FVMQ
- 55-X-FKM

O-ring materials exhibiting excessive compression set (>50%) after fluid aging:

- 6-FKM (-40° F, -65° F)
- 12-ECO (RT, -40° F, -65° F)
- 13-HNBR (-40° F, -65° F)
- 22-HNBR (-40° F, -65° F)
- 35-HNBR (molded, -40° F)
- 37-FKM (-40° F, -65° F)
- 40-PFE (-65° F)
- 52-PFE-VF (-40° F, -65° F)
- 94-PFE (-65° F)
- 95-PFE (-65° F).

Remaining (Best) Candidates:

- **38-PFE**
- **39-PFE**
- **42-PFE-VF**
- **51-PFE-VF**
- **53-PFE-VF**

A review of the data indicates two classes of materials that demonstrated exceptional performance in all four test fluids evaluated under the primary program: PFE and PFE-VF. Differences in PFE and PFE-VF performance among the samples evaluated under the program can be largely attributed to variations in product formulations. These materials represent a significant advancement in fluoropolymer o-ring materials, demonstrating exceptional high temperature resistance to hydraulic fluids and aircraft fuels, as well as good low temperature performance.

4.3.2 Final Testing (METSS)

The suppliers of the best performing materials were contacted after the down-selection process and asked to submit a final series of o-ring samples to support the final testing and evaluation efforts. At this time, the material providers were asked to submit samples representing the final commercial versions of the o-ring materials that would be made available for commercial introduction. Because of this, new numbers were assigned to the PFE materials. The number for the PFE-VF material included in the final series of testing remained the same. In addition to the NBR-L control sample, one additional material was included in the final series of tests. This material was a more advanced version of the X-FKM materials evaluated under earlier program efforts but was not included in the final series of tests due to material availability issues. Testing under another government program effort demonstrated this material to be a comparatively good performer in aircraft hydraulic fluid applications, so o-ring samples were requested for inclusion in the final round of testing under the current program.

Based on the results of the program efforts, the following o-ring materials were selected for the final testing and evaluation efforts:

- 0-NBR-L
- 52-PFE-VF
- 68-PFE
- 100-PFE
- 200-X-FKM.

Size 214 o-rings were obtained for all of the best performing materials. With the exception of 200-X-FKM, o-ring properties were characterized before and after three days of fluid aging in JP-8+100 and JRF at 225° F, and three days of fluid aging in MIL-PRF-83282, MIL-PRF-87257, MIL-PRF-5606, and MIL-PRF-23699 at 275° F. 200-X-FKM was only evaluated in JP-8+100 and MIL-PRF-83282 due to o-ring sample availability. Volume swell, weight gain and physical property changes were determined on all o-rings before and after fluid aging. Volume swell was determined volumetrically to provide more accurate data for the final data set. Room temperature and low temperature (-40° F) compression set measurements were performed before and after 3-day fluid aging at high temperature, as well as after 60 days of fluid and air aging at room temperature. In the final set of compression set experiments, o-ring measurement locations were marked so thickness measurements could be made in exact locations before and after the compression set experiments. In addition, experimental verification indicated actual o-ring deflection to be of the order of 33% during compression set experiments rather than the 25% reported in earlier testing.

The results of the final testing and evaluation efforts before and after the 3-day fluid aging experiments are presented in the following tables:

- Table 45. Final Test Data (0-NBR-L) w/3-Day Data
- Table 46. Final Test Data (52-PFE-VF) w/3-Day Data

- Table 47. Final Test Data (68-PFE) w/3-Day Data
- Table 48. Final Test Data (100-PFE) w/3-Day Data
- Table 49. Final Test Data (200-X-FKM) w/3-Day Data.

As expected, the NBR-L control o-rings demonstrated the worst performance. Room temperature and low temperature compression set values were excessive in almost all cases and the loss in tensile properties after high temperature fluid aging was exceptionally high in all fluids except JP-8+100 and MIL-PRF-83282.

52-PFE-VF demonstrated exceptional stability during the high temperature aging experiments in all of the test fluids. However, while the room temperature compression set values were far better than those exhibited by the nitrile control samples, the -40° F compression set performance was only marginally better. The physical properties of this material are in compliance with both the MIL-P-5315 and MIL-P-83461 performance specifications for fuel system and hydraulic fluid o-rings respectively.

The PFE o-rings (68 and 100) performed exceptionally well in the 3-day fluid aging experiments. Volume change was minimal in all fluids, with the exception of JRF, which resulted in a volume swell of just less than 15% for both materials. Room temperature compression set was minimal before and after fluid aging and the -40° F compression set values were excellent, especially for 100-PFE material. Retention of tensile properties after fluid aging was very good for both of the PFE materials; however, neither of the materials meets the existing tensile strength requirement of 1350 psi for hydraulic fluid applications, and tensile elongation values fall short of the existing 200% requirement for fuel system applications. While the impact on the test results is not quantified, it is worth noting that approximately 10% of the PFE o-rings tested in tension (which were liquid injection molded instead of compression molded) had internal defects (bubbles) at the point of failure. This is obviously an artifact of the manufacturing process that will need to be addressed for quality assurance. However, this is not an uncommon task for new materials development efforts and should not be deemed as a critical flaw as the inherent properties of this material are obviously very good.

While only a limited amount of 3-day testing was conducted with the 200-X-FKM o-rings, the performance exhibited by this material is worth noting. Volume change was minimal during fluid aging and compression set performance was exceptional at room temperature and -40° F. Physical properties were comparable to 100-PFE, except elongation at break is in excess of 200% (as required), and retention of properties after aging was very good in both of the fluids tested.

As previously noted, additional room temperature and low temperature (-40° F) compression set measurements were performed after 60 days of room temperature aging in air, JP-8+100 and MIL-PRF-83282. The results of the 60-day room temperature aging experiments are reported in Table 50 for 52-PFE-VF, 100-PFE and 200-X-FKM. MIL-P-83461 limits for compression set (at room temperature) after 60 days of room temperature aging are 25% for air and 20% for fluid aging. Limits for 60-day room temperature compression set are not defined in MIL-P-5315.

All of the best performers meet the 60-day requirements for room temperature compression set. The compression set values for 100-PFE and 200-X-FKM were negligible. While 52-PFE-VF, demonstrated 8-11% compression set after air and fluid aging. At –40° F, 52-PFE-VF exhibited approximately 80% compression set after 60 days of air and fluid aging. The -40° F compression set values for 100-PFE and 200-X-FKM were considerably better. Both materials demonstrated exceptional compression set performance in JP-8+100, with 200-X-FKM demonstrating the best overall performance in the 60-day room temperature aging test.

Table 45. Final Test Data (0-NBR-L) w/3-Day Data

Test Condition		Weight Gain	Volume Change	RT C-Set	-40° F C-Set	Break Stress	ΔBreak Stress	Elong @Break	ΔElong @Break
		%	%	%	%	psi	%	%	%
Control	Mean	[redacted]	[redacted]	9.8	81.0	2442.66	0.0	324.29	0.0
	σ	[redacted]	[redacted]	0.9	4.2	356.62		42.98	
JP-8+100	Mean	14.0	19.0	73.5	86.8	1600.86	-34.5	267.40	-17.5
	σ	0.2	0.0	1.8	6.2	122.81		7.05	
JRF	Mean	10.7	16.4	52.4	59.0	664.66	-72.8	191.31	-41.0
	σ	0.2	0.3	1.8	5.7	77.96		13.28	
83282	Mean	7.3	9.3	87.5	101.7	1761.76	-27.9	237.20	-26.9
	σ	0.1	0.2	3.4	1.5	91.13		10.60	
87257	Mean	9.8	12.6	82.6	99.3	623.89	-74.57	113.85	-4.9
	σ	0.1	0.2	3.7	1.5	6.16		3.60	
5606	Mean	11.7	15.6	44.6	82.9	793.64	-67.5	164.40	-49.3
	σ	0.1	0.1	4.4	7.2	301.82		37.90	
23699	Mean	22.9	26.4	28.7	59.5	884.21	-63.8	185.57	-42.8
	σ	0.4	0.6	2.1	1.1	231.98		31.97	

Table 46. Final Test Data (52-PFE-VF) w/3-Day Data

Test Condition		Weight Gain	Volume Change	RT C-Set	-40° F C-Set	Break Stress	ΔBreak Stress	Elong @Break	ΔElong @Break
		%	%	%	%	psi	%	%	%
Control	Mean	[redacted]	[redacted]	11.1	73.8	1588.49	0.0	209.21	0.0
	σ	[redacted]	[redacted]	0.7	9.3	197.39		15.41	
JP-8+100	Mean	1.7	4.8	22.4	77.1	1378.44	-13.2	205.84	-1.6
	σ	0.1	0.1	0.2	0.9	139.94		21.14	
JRF	Mean	4.1	10.8	15.7	67.1	1273.91	-19.8	197.91	-5.4
	σ	0.2	0.3	1.5	0.9	103.97		7.78	
83282	Mean	1.1	3.2	30.9	77.3	1633.94	2.9	206.71	-1.2
	σ	0.1	0.3	6.0	1.0	95.25		12.03	
87257	Mean	1.4	4.3	29.3	79.2	1283.23	-19.2	200.93	-4.0
	σ	0.1	0.3	11.7	3.5	208.43		23.39	
5606	Mean	1.8	4.7	28.7	78.3	1594.91	0.4	205.97	-1.5
	σ	0.0	0.4	2.3	4.6	7.47		24.07	
23699	Mean	1.3	3.7	28.6	76.3	1454.20	-8.5	207.05	-1.0
	σ	0.0	0.1	1.8	5.4	17.42		3.48	

Table 47. Final Test Data (68-PFE) w/3-Day Data

Test Condition		Weight Gain	Volume Change	RT C-Set	-40° F C-Set	Break Stress	ΔBreak Stress	Elong @Break	ΔElong @Break
		%	%	%	%	psi	%	%	%
Control	Mean			3.4	30.4	982.88	0.0	186.22	0.0
	σ			1.1	5.8	87.64		28.54	
JP-8+100	Mean	2.3	6.4	3.6	15.4	661.32	-32.7	137.28	-26.3
	σ	0.0	0.2	2.5	2.4	84.54		8.23	
JRF	Mean	5.1	14.4	-3.3	3.4	604.48	-38.5	136.79	-26.5
	σ	0.2	0.6	0.9	1.5	200.14		23.34	
83282	Mean	0.5	2.2	10.3	41.7	924.96	-5.9	167.56	-10.0
	σ	0.0	0.3	0.3	8.2	122.99		13.29	
87257	Mean	1.1	3.7	9.2	30.4	965.99	-1.7	176.40	-5.3
	σ	0.1	0.3	0.8	1.7	100.63		10.43	
5606	Mean	2.3	6.7	5.9	30.4	746.05	-24.1	149.55	-19.7
	σ	0.2	0.3	0.6	2.3	108.77		11.64	
23699	Mean	0.3	1.9	10.6	47.8	927.30	-5.7	165.55	-11.1
	σ	0.0	0.1	0.8	8.2	59.70		8.98	

Table 48. Final Test Data (100-PFE) w/3-Day Data

Test Condition		Weight Gain	Volume Change	RT C-Set	-40° F C-Set	Break Stress	ΔBreak Stress	Elong @Break	ΔElong @Break
		%	%	%	%	psi	%	%	%
Control	Mean			2.3	14.8	1137.28	0.0	147.69	0.0
	σ			0.3	1.6	205.04		15.29	
JP-8+100	Mean	2.7	6.1	1.2	5.9	957.19	-15.8	132.60	-10.2
	σ	0.0	0.2	1.4	1.0	186.70		15.47	
JRF	Mean	6.0	14.9	-4.9	-2.3	870.99	-23.4	129.38	-12.4
	σ	0.0	0.4	1.0	1.1	36.16		5.15	
83282	Mean	0.5	2.0	6.9	22.5	1228.85	8.1	156.05	5.7
	σ	0.0	0.1	0.3	3.3	138.66		7.80	
87257	Mean	1.0	3.3	5.5	15.3	1226.51	7.8	156.59	6.0
	σ	0.0	0.2	0.6	1.0	26.90		3.77	
5606	Mean	2.5	6.6	4.4	11.1	871.22	-23.4	128.20	-13.2
	σ	0.0	0.2	3.2	0.3	176.14		13.61	
23699	Mean	0.4	1.7	12.8	22.5	1064.64	-6.4	140.02	-5.2
	σ	0.0	0.2	2.5	2.7	75.80		6.07	

Table 49. Final Test Data (200-X-FKM) w/3-Day Data

Test Condition		Weight Gain	Volume Change	RT C-Set	-40° F C-Set	Break Stress	ΔBreak Stress	Elong @Break	ΔElong @Break
		%	%	%	%	psi	%	%	%
Control	Mean	[redacted]	[redacted]	2.5	19.2	1123.74	0.0	230.37	0.0
	σ	[redacted]	[redacted]	0.1	0.5	80.85		1.54	
JP-8+100	Mean	2.6	6.5	2.5	10.9	797.85	-29.0	187.01	-18.8
	σ	0.0	0.5	0.1	4.5	106.09		17.86	
83282	Mean	0.6	1.8	11.3	26.5	877.67	-21.9	203.19	-11.8
	σ	0.0	0.5	0.4	0.2	2.70		1.04	

Table 50. Compression Set After 60-Day Aging @ RT

Test Condition		Air		JP-8+100		MIL-PRF-83282	
		RT C-Set	-40° F C-Set	RT C-Set	-40° F C-Set	RT C-Set	-40° F C-Set
		%	%	%	%	%	%
52-PFE-VF	Mean	11.3	84.5	8.8	83.1	11.1	76.2
	σ	0.8	3.1	0.2	4.5	0.9	5.9
100-PFE	Mean	1.4	32.1	-1.7	6.3	1.9	24.7
	σ	0.3	2.3	0.3	0.7	0.2	1.5
200-X-FKM	Mean	2.3	21.0	0.4	7.6	2.3	19.1
	σ	0.6	0.3	0.7	2.1	0.6	4.7

4.3.3 Third Party Verification Testing

At the end of the program, samples of the best performing o-rings (52-PFE-VF, 100-PFE and 200-X-FKM) were sent to ARDL for final performance verification testing, including initial properties and change in properties after three days of high temperature aging in air, JP-8+100 and MIL-PRF-83282. The test methods used by ARDL were the same as those used by METSS to support internal testing and evaluation efforts except ARDL used a New Age Microhardness Tester (IRHD) to test the hardness of the o-rings. The results of the ARDL testing are summarized in Table 51.

The trends in the ARDL test data are in general agreement with the data collected at METSS. However, the METSS tensile data are typically higher in value and there are some discrepancies in the data for changes in tensile properties after aging. In addition, METSS consistently reported higher compression set values for 52-PFE-VF o-rings and, in most cases, slightly lower values of compression set for 100-PFE and 200-X-FKM o-rings. However, both sets of data demonstrate the 100-PFE and 200-X-FKM o-rings to have better resistance to compression set, especially at low temperatures. Volume swell data are well in line with one another. While the initial tensile strength of the 100-PFE and 200-X-FKM materials is lower than would be preferred, the changes in tensile properties exhibited by all of the best performers with high temperature fluid aging are acceptable and demonstrate a good mechanical stability after fluid aging. The microhardness measurements demonstrate the 200-FKM o-rings do not meet the Shore A 70 to 80 hardness requirement of MIL-P-83461 and falls to the low side of the 60-70 hardness requirement of MIL-P-5315. Pre-cursors to this material exhibited hardness values from Shore A 71 (see Table 2, 51-X-FKM) to greater than 90 (see Table 2, 54-X-FKM and 55-X-FKM), so there may be enough flexibility in the formulation to bring hardness values to within specification. However, the tensile values of these samples were still less than the 1350 psi requirement for the existing MIL-P-83461 specification, and are marginal for the 1000 psi requirement of MIL-P-5315.

4.3.4 Dynamic Sealing Performance

Dynamic seal testing was conducted by UDRI on 100-PFE and 200-X-FKM o-rings in accordance with methods outlined in MIL-P-83461. The details of the test were described in Section 3.3.3. One of the 200-X-FKM duplicate o-rings failed after 192,538 cycles; the other failed after 17,441 cycles. The 100-PFE o-rings failed after 3,445 and 5,228 cycles. To be MIL-P-83461 compliant, o-rings must survive at least 110,000 cycles prior to failure. The test results indicate that these materials are not suited for dynamic sealing applications.

Table 51. Third Party (ARDL) Verification Data - Best Performers

Property	52-PFE-VF	100-PFE	200-X-FKM
Initial Properties			
• Hardness	70	71	58
• Tensile Strength (psi)	1405	1010	908
• Tensile Elongation (%)	134.4	119.3	163.9
• Compression Set (RT)	16.7	10.3	4.4
• Compression Set (-40° F)	35.7	25.0	36.8
• Compression Set (-65° F)	51.5	41.2	44.2
After 3 Days in Air @ 275° F			
• Compression Set (RT)	27.2	8.8	5.9
• Compression Set (-40° F)	35.7	22.1	10.3
• Compression Set (-65° F)	70	54.4	35.3
After 3 Days in MIL-PRF-83282 @ 275° F			
• Volume Swell (%)	2.6	1.7	1.1
• Change in Hardness (%)	0	2	0
• Change in Tensile Strength (%)	-1.9	+13.6	+38.9
• Change in Tensile Elongation (%)	+4.8	+2.9	+15.9
• Compression Set (RT)	14.7	10.3	13.3
• Compression Set (-40° F)	52.9	17.7	25.0
• Compression Set (-65° F)	73.6	47.1	36.8
After 3 Days in JP-8+100 @ 225° F			
• Volume Swell (%)	3.9	7.2	6.1
• Change in Hardness (%)	-1	-5	-4
• Change in Tensile Strength (%)	-6.4	+6.5	+7.1
• Change in Tensile Elongation (%)	-8.3	+4.3	+4.2
• Compression Set (RT)	10.3	5.9	7.4
• Compression Set (-40° F)	64.7	25.0	22.1
• Compression Set (-65° F)	76.5	31.0	27.9

4.3.5 Final CSR Testing

In a final series of CSR experiments, o-rings of the best performing materials (52-PFE-VF, 100-PFE and 200-X-FKM) were compressed to 25% deflection (at room temperature) in the CSR device and aged *in situ* in air, MIL-PRF-83282, MIL-PRF-87257, MIL-PRF-5606 and MIL-PRF-23699 hydraulic fluids for Three days at 275° F and then cooled to -40° F to determine the low temperature sealing capacity of the o-rings after high temperature fluid aging under compression. METSS was unable to repeat the test sequence in JP-8+100 due to experimental problems. The temperature profile for the final set of CSR experiments was presented in Section 3.2.4. The response (sealing force) of the o-rings was constantly monitored during the course of the thermal program.

The CSR data for this thermal sequence are presented in Figures 15 to 19. The data are normalized with respect to the initial sealing force exerted by the o-rings under 25% deflection at room temperature. The trends in the CSR data are remarkably consistent under all five test conditions. All of the best performing materials exhibited relatively constant sealing force during high temperature aging, demonstrating good high temperature thermal stability in air and the test fluids. Upon cooling to -40° F, the 200-X-FKM o-rings consistently retained more sealing force (40 to 60%) than the 100-PFE o-rings (20 to 40%), which consistently retained sealing more force than the 52-PFE-VF o-rings (10 to 20%). The room temperature sealing force values after thermal aging followed the same general trend, with the 200-X-FKM o-rings consistently retaining more sealing force (70 to 85%) than the 100-PFE o-rings (60 to 70%), which consistently retained more sealing force than the 52-PFE-VF o-rings (40 to 60%).

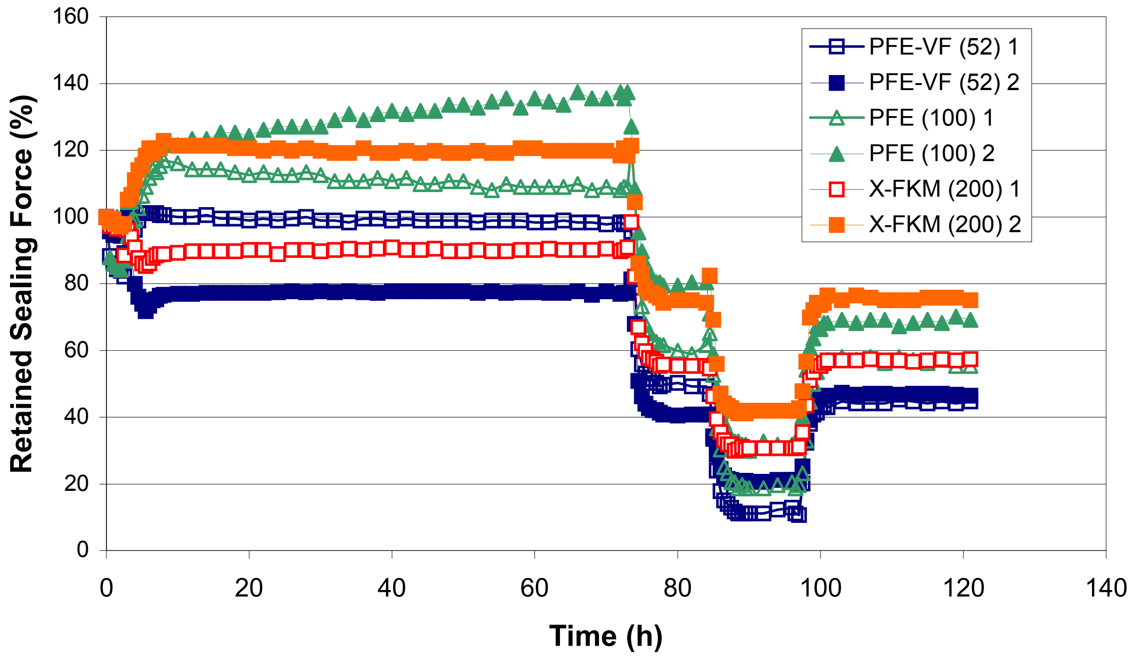

Figure 15. Normalized CSR data for *in situ* air aging of best performers.

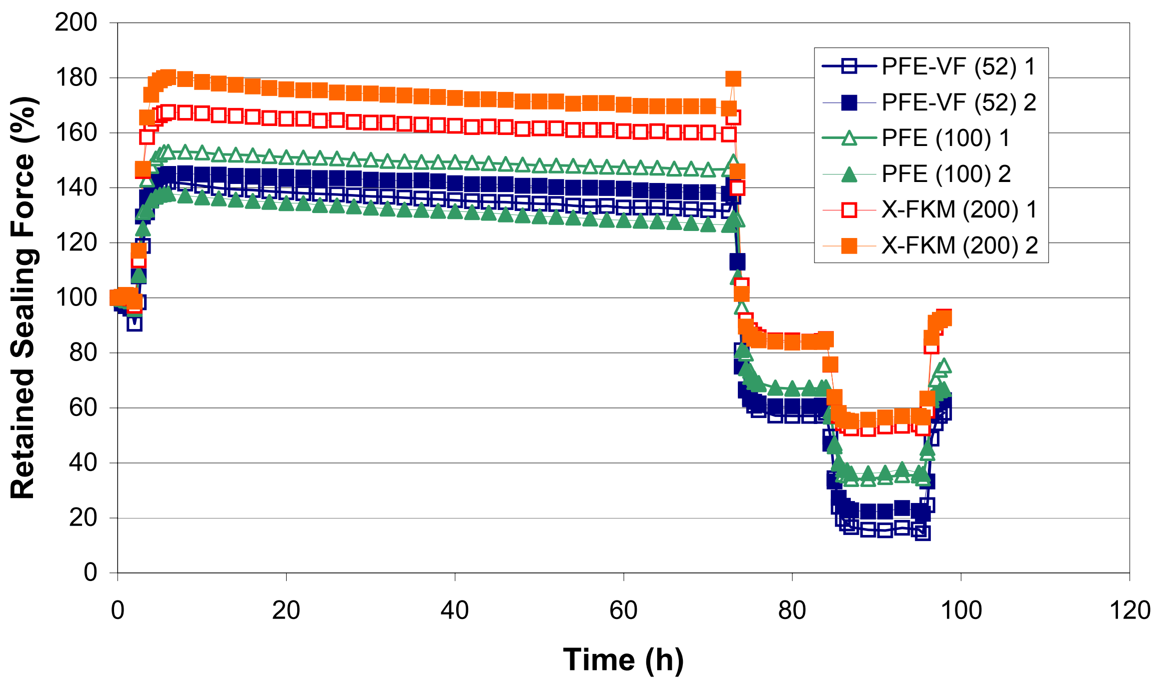

Figure 16. Normalized CSR data for *in situ* aging of best performers in MIL-PRF-83282.

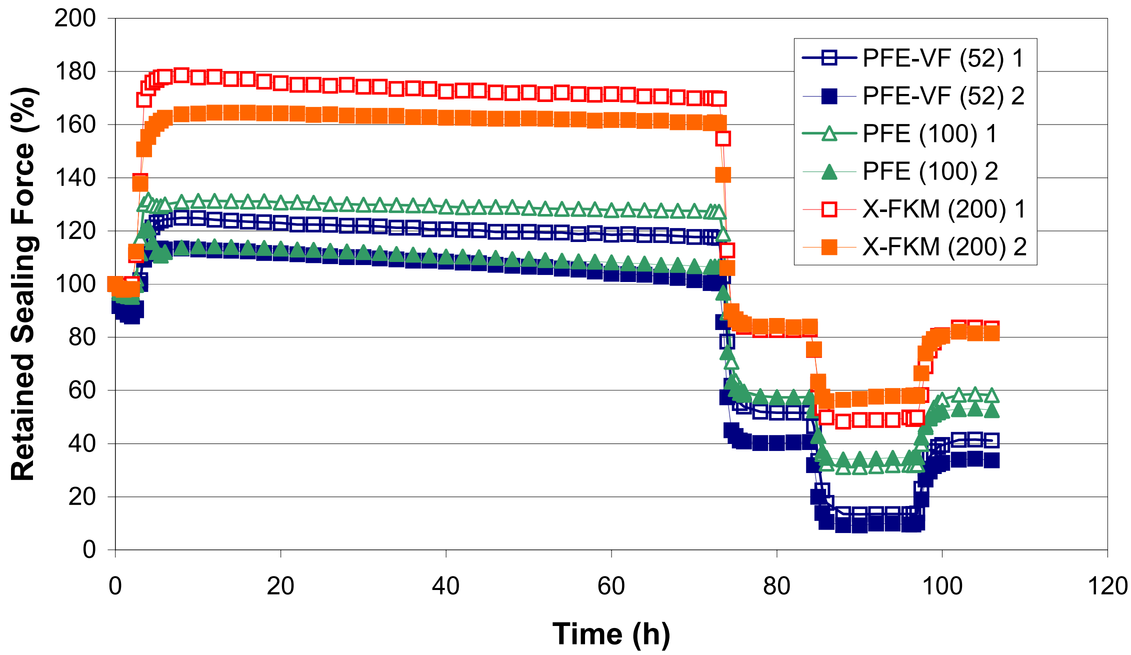

Figure 17. Normalized CSR data for *in situ* aging of best performers in MIL-PRF-87257.

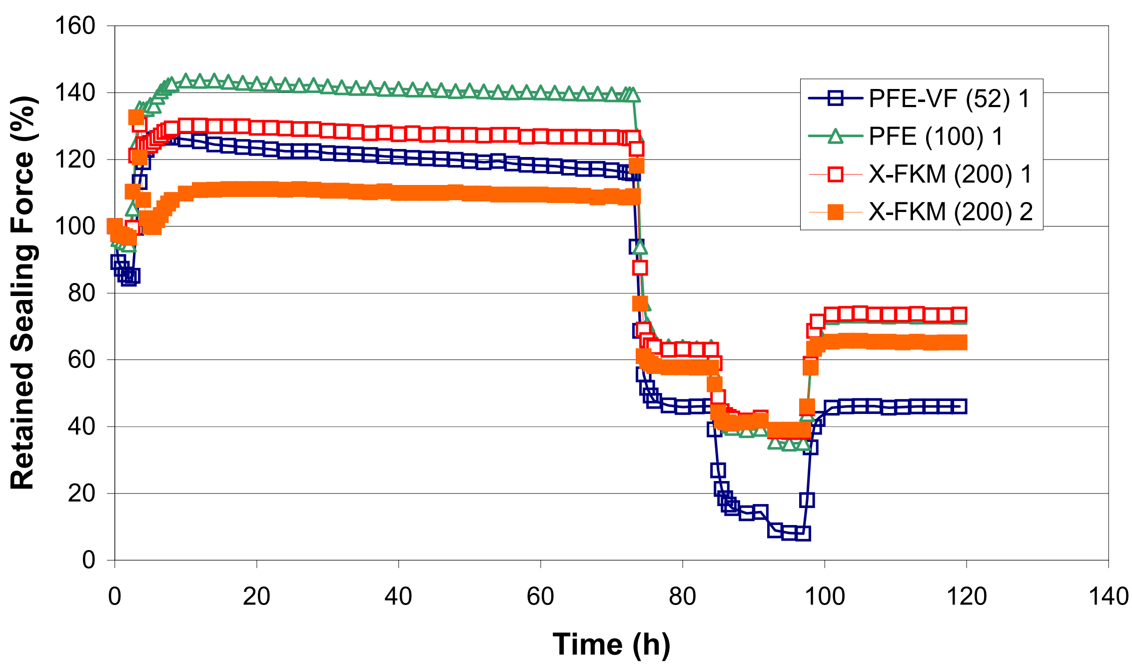

Figure 18. Normalized CSR data for *in situ* aging of best performers in MIL-PRF-5606.[20]

[20] Duplicate data for PFE-VF (52) and PFE (100) terminated due to load cell failure.

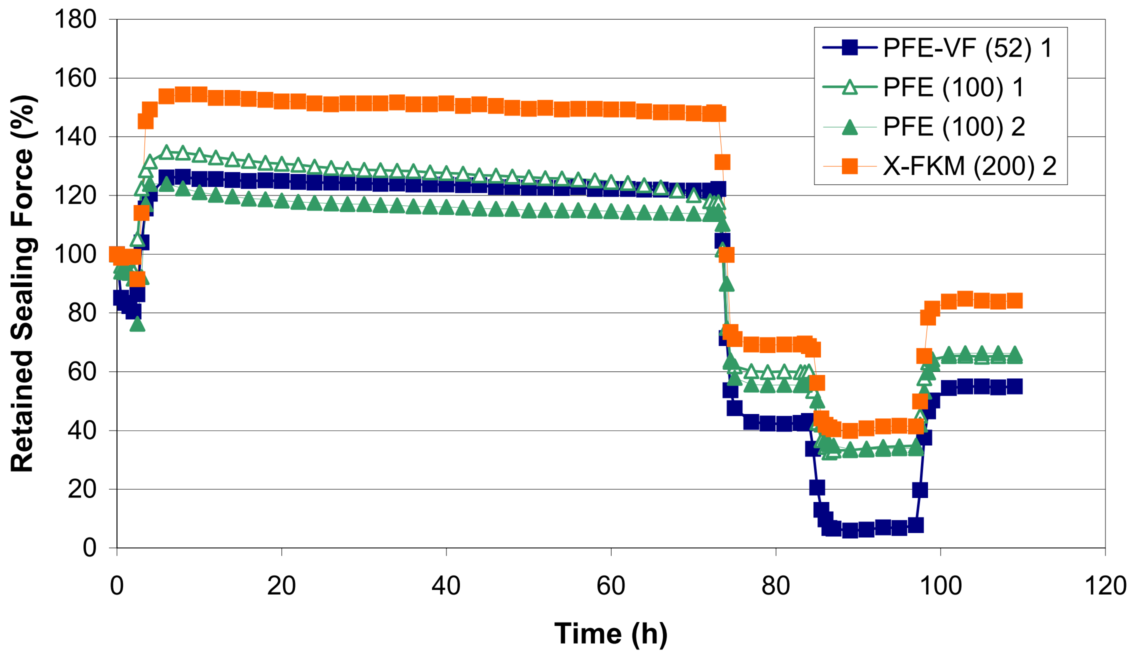

Figure 19. Normalized CSR data for *in situ* aging of best performers in MIL-PRF-23699.[21]

[21] Duplicate sample data for PFE-VE (52) and X-FKM (200) were lost due to experimental error.

5.0 SUMMARY

During the course of this program, materials representing eight different classes of rubber chemistries were systematically evaluated for high temperature resistance to aircraft hydraulic fluids and jet fuels, and low temperature sealing performance before and after 3- and 28-days high temperature fluid aging. The performance requirements and test methods used to support the program efforts were derived from MIL-P-83461 - *Packing, Preformed, Petroleum Hydraulic Fluid Resistant, Improved Performance at 275 °F* and MIL-P-5315 - *Packing, Preformed, Hydrocarbon Fuel Resistant.*

The advanced performance requirements targeted under this program included:

- Hydraulic fluid o-ring candidates must demonstrate high temperature (275° F) resistance to MIL-PRF-83282, MIL-PRF-87257 and MIL-PRF-5606 aircraft hydraulic fluids, as well as MIL-PRF-23699 engine oil;
- Fuel system o-ring candidates must demonstrate high temperature (225° F) resistance to JP-8, JP-8+100 and JRF; and
- Importantly, candidate o-ring materials must demonstrate low compression set values and the ability to seal at low temperatures (-65° F/-40° F) before and after high temperature fluid aging.

Volume swell, weight gain and physical property changes were measured on all candidate o-ring materials before and after 3- and 28-day fluid aging experiments. These measurements were used as a primary source of screening to identify the most chemically resistant materials. Standard compression set measurements were performed at room temperature, -40° F and -65° F before and after fluid aging to provide the first measure of low temperature sealing capability. Additional testing included a series of room temperature, 60-day fluid and air aging experiments. CSR testing was used to measure the sealing force of candidate o-ring materials during *in situ* high temperature fluid aging and low temperature sealing experiments. The CSR experimental work conducted under this program clearly demonstrates the utility of using continuous sealing force measurements to evaluate the stability and performance of o-ring materials as a function of time, temperature and chemical environment. Finally, samples of the best performing materials were subjected to third party testing and evaluation to verify program results and to screen the best performing materials for dynamic sealing performance capability.

The results of this program provide substantial support for the use of emerging material technologies based on advanced fluoroelastomer chemistries to support aircraft sealing applications where high temperature chemical stability and low temperature performance is required. These newer materials, which have been generally characterized in this report as PFE, PFE-VF rubbers, and X-FKM, represent recent advances or new classes of materials based on fluoropolymer chemistry that have been developed to support high performance sealing applications. While the performance among these materials varies to some degree, these materials, in general, all demonstrate excellent resistance to high temperature fluid exposure (including the target hydraulic fluids and fuels) and good to excellent low temperature sealing performance.

The results of the specific testing conducted under this program indicate that 200-X-FKM and 100-PFE o-rings provide better low temperature sealing performance than 52-PFE-VF o-rings. However, the PFE-VF o-ring materials are physically stronger and, of the best performing materials, PFE-VF is the only material capable of meeting the existing tensile strength requirements of both MIL-P-83461 and MIL-P-5315. In addition to potential tensile property limitations, additional effort may be required to support the production of o-rings of consistent quality and form using the 200-X-FKM and 100-PFE o-ring materials. Improvements in tensile performance may be realized through ongoing product formulation development efforts. The need to address manufacturing quality issues is not an uncommon task for new materials development efforts. Importantly, none of these advanced materials were developed with dynamic sealing applications in mind and, while limited dynamic testing was part of the original program plan, this potential issue was not emphasized until very late in the program cycle. As such, the use of the recommended materials in aircraft hydraulic or fuel systems should be limited to static sealing applications until more extensive dynamic characterization of these materials can be performed.

LIST OF ACRONYMS

ARDL	Akron Rubber Development Laboratory
CSR	Compression Stress Relaxation
DMA	Dynamic Mechanical Analysis
ECO	Epichlorohydrin Rubber
FKM	Fluoroelastomer
FS	Fluorosilicone
FVMQ	Fluorosilicone
HNBR	Hydrogenated Nitrile Rubber
IRHD	International Rubber Hardness Degrees
JRF	Jet Reference Fluid
LNCA	Liquid Nitrogen Cooling Accessory
METSS	Materials Engineering and Technical Support Services
NBR	Nitrile Rubber
NBR-L	Standard L-Stock Nitrile Rubber
PAO	Polyalphaolephin
PFE	Perflouronated Elastomer
PFE-VF	Perflouronated Elastomer -Vinylidene Fluoride
PNF	Polyphosphazine Fluoroelastomer
RT	Room Temperature
X-FKM	Experimental Fluoroelastomer