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Solvent Replacement for Hydrochlorofluorocarbon-225 for Cleaning Oxygen System Components

M.A. Mitchell
Marshall Space Flight Center, Huntsville, Alabama

N.M. Lowrey
Jacobs Technology, Inc./Jacobs ESSSA Group, Huntsville, Alabama

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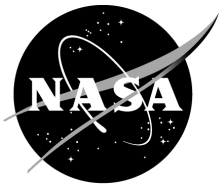

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National Aeronautics and
Space Administration

Marshall Space Flight Center • Huntsville, Alabama 35812

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LIST OF ACRONYMS

AEL	acceptable exposure limit
AIT	Autogenous Ignition Temperature
BP	boiling point
CAS	Chemical Abstract Service
DoD	Department of Defense
GOX	gaseous oxygen
HCFC-225	hydrochlorofluorocarbon-225
Kb	Kauri-butanol
LOX	liquid oxygen
MCRF	Materials Combustion Research Facility
MSFC	Marshall Space Flight Center
NBR	poly(acrylonitrile-co-butadiene) rubber
NVR	nonvolatile residue
ODS	ozone-depleting substance
PCTFE	polychlorotrifluoroethylene
PEEK	polyether ether ketone
PF	performance fluid
PFBI	perfluorobutyl iodide
PTFE	polytetrafluoroethylene
RPT	Rocket Propulsion Test
U.S.	United States
USAF	United States Air Force
VOC	volatile organic compound
WSTF	White Sands Test Facility

TECHNICAL MEMORANDUM

SOLVENT REPLACEMENT FOR HYDROCHLOROFLUOROCARBON-225 FOR CLEANING OXYGEN SYSTEM COMPONENTS

1. INTRODUCTION

This Technical Memorandum is the result of a 2-year project funded by the Defense Logistics Agency—Aviation, Hazardous Minimization and Green Products Branch, to identify and test two candidate solvents to replace hydrochlorofluorocarbon-225 (HCFC-225) for cleaning oxygen systems. The solvents were also compared to a second solvent composed predominantly of perfluorobutyl iodide (PFBI), which had received limited approval by the United States Air Force (USAF) for hand wipe cleaning of components for aviators's breathing oxygen systems. The tests performed for this study were based on those reported in AFRL-ML-WP-TR-2003-4040, "The Wipe Solvent Program,"[1] the test program used to qualify Ikon® Solvent P for USAF applications.

The study was completed in August 2014, prior to the completion of a more extensive study funded by the NASA Rocket Propulsion Test (RPT) program. The results of the RPT project are reported in NASA/TP—2015–218207, "Replacement of Hydrochlorofluorocarbon–225 Solvent for Cleaning and Verification Sampling of NASA Propulsion Oxygen Systems Hardware, Ground Support Equipment, and Associated Test Systems."[2] The test methods used in this study for novolatile residue (NVR) background, materials compatibility, and cleaning effectiveness were different than those used for the RPT project; a smaller set of materials and contaminants were tested. The tests for this study were complimentary to and provided supplementary information for the downselection process during the course of the test program reported in NASA/TP—2015–218207.[2]

2. PROBLEM DESCRIPTION

To obtain a high degree of cleanliness without risk of corrosion or hazardous reactivity, HCFC-225 is used for the cleaning and cleanliness verification of oxygen system components used on NASA's bipropellant launch vehicles and associated test stands and support equipment. HCFC-225 is a class II ozone-depleting substance (ODS) that was introduced to replace class I ODS solvents such as chlorofluorcarbon-113 that are now banned. The Montreal Protocol of 1987 and the Clean Air Act Amendments of 1990 mandated a production phaseout date for HCFCs, including HCFC-225 as of January 1, 2015.

To meet environmental regulations to eliminate the use of ODSs, a replacement solvent is required for HCFC-225 that is effective at removing oil, grease, and particulate from oxygen system components; is compatible with materials used in the construction of these systems; and is nonflammable and nonreactive in enriched oxygen environments. While aqueous cleaners such as Navy Oxygen Cleaner (NOC)[3] and flammable solvents such as cyclohexane have been qualified for cleaning some oxygen system components, many launch vehicle propulsion system components due to their size, complex configuration, or vulnerability to corrosion continue to require cleaning with oxygen-compatible solvents. Solvent cleaning is also required for field maintenance of some propulsion test stand components that cannot be moved to a location where cleaning equipment is installed.

Other services supported by this project include U.S. Army, U.S. Navy, and USAF aircraft systems. A cleaning solvent replacement is required for the aviator's breathing oxygen systems and other related equipment currently cleaned with HCFC-225. DuPont™ Ikon P PFBI solvent has been approved by the USAF as a replacement for HCFC-225 for hand cleaning where HCFC-225 is prohibited or unavailable. PFBI, however, is in limited supply and is prohibitively expensive. A replacement for both HCFC-225 and PFBI is needed to improve supportability of operational schedules for U.S. Army, U.S. Navy, and USAF aircraft systems and to reduce cost.

3. OBJECTIVES OF THE STUDY

3.1 Purpose

The purpose of this study was to evaluate the suitability of solvents for cleaning oxygen system components. Two candidate solvents were tested and compared to the performance of the baseline solvents, HCFC-225 and PFBI.

3.2 Selection of the Baseline Test Solvents

NASA typically uses purified HCFC-225, containing only the cb isomer of HCFC-225, which has a higher acceptable exposure limit (AEL) than the HCFC-225ca/cb mixed isomer form. NASA historic test data have shown that the performance of HCFC-225cb is comparable to the performance of HCFC-225ca/cb. HCFC-225cb is procured as ASAHIKLIN AK-225G, from AGC Chemicals Americas, Inc., a wholly owned subsidiary of Asahi Glass Company of Japan; Chemical Abstract Service (CAS) No. 507-55-1. PFBI (CAS No. 423-39-2) was procured as DuPont™ Capstone® 4-I, E. I. DuPont de Nemours and Company. Earlier trade names used by DuPont for this family of PFBI-based products were Zonyl® PFBI, and Ikon P. These products are no longer marketed by DuPont. Capstone 4-I is marketed by DuPont as a chemical intermediate. DuPont does not offer a product based on PFBI as a cleaning solvent.

3.3 Objectives

The objectives of this study were to:

(1) Identify potential candidate solvents to replace HCFC-225 for cleaning and verification of launch vehicle propulsion oxygen system components and associated test stands and equipment.

(2) Conduct panel and component level testing of candidate solvent alternatives for cleaning effectiveness.

(3) Test candidate solvents for compatibility with propulsion system and propulsion test stand materials.

(4) Test candidate solvents for flammability characteristics to qualify for use as cleaners for oxygen system components.

(5) Eliminate ozone-depleting emissions from cleaning applications.

(6) Recommend a candidate solvent with a lower cost and greater availability than PFBI to replace HCFC-225 for field cleaning of aviator's breathing oxygen systems.

4. TEST PLAN

4.1 Test Plan Development

Based on inputs from NASA propulsion test organizations at Marshall Space Flight Center (MSFC) and Stennis Space Center and from stakeholders at the Department of Defense (DoD), a test plan was developed to evaluate the suitability of new cleaning solvents for oxygen system applications. Stakeholders contacted at the DoD for input included representatives from the USAF—Tinker Air Force Base, Hill Air Force Base, and Wright Patterson Air Force Base; Naval Sea Systems Command (NAVSEA) Portsmouth Shipyard and Naval Surface Warfare Center Caderock Division; and Naval Air Systems Command (NAVAIR) Naval Aviation Depot FRC Southeast, Jacksonville, Florida. No stakeholders were identified from the U.S. Army.

As recommended in ASTM G127-95, Standard Guide for the Selection of Cleaning Agents for Oxygen Systems,[4] tests were selected to evaluate and compare the compatibility of the solvents with metals and nonmetals used to construct liquid oxygen (LOX) and gaseous oxygen (GOX) systems, the effectiveness of the solvents at removing contaminants commonly requiring cleaning from LOX/GOX systems, and the reactivity of the solvents in LOX/GOX. The specific test methods, metals, nonmetals, and contaminants were selected using ASTM G127-95 as a guide and based on end-user inputs regarding typical cleaning challenges for LOX/GOX systems encountered at MSFC and MSFC's Michoud Assembly Facility, and at Stennis Space Center. Materials and contaminants shown in the test report AFRL-ML-WP-TR-2003-4040, "The Wipe Solvent Program,"[1] were also considered during the selection of test parameters to reflect other potential end users. Background NVR content in the solvents as recieved was measured prior to these tests.

4.2 Selection of Candidate Solvents for Testing

Two candidate solvents were selected for testing and comparison to the baseline solvents, HCFC-225cb (AK-225G) and PFBI Capstone 4-I. Testing was limited to two candidate solvents due to funding restrictions.

Nine solvent manufacturers and solvent blenders were contacted to develop the list of solvents for consideration. This list included commercially available solvents classified as non-ODS and developmental solvents that were expected to be classified as non-ODS and made commercially available in the United States within 2 years.

Criteria used to evaluate and rank solvents for potential inclusion in the test program included: kauri-butanol (Kb) value, flammability data as an indicator of likelihood to pass oxygen compatibility tests, boiling point (BP), human toxicity data based on the vendor-reported 8-hour AEL, vendor data on compatibility with metals, and environmental factors that could restrict future usage. These environmental factors included volatile organic compound (VOC)

classification, and 100-year global warming potential (GWP). Previous NASA test data were evaluated when available. The solvents that made the short list for consideration are shown in table 1.

Table 1. Solvent candidates evaluated.

Single Component	Kb ≥ 20	Expected to Pass LOX Test	BP > 100 °F	AEL-8 hr ≥ 200	Safe With Metals	VOC Exempt	100-Year GWP*
Asahi AE3000	No	Yes	Yes	No	Yes	Yes**	Mid
Honeywell Solstice™ PF	Yes	Yes	No	Yes	Yes	Yes**	Low
Solvay Solkane® 365mfc	No	?	Yes	Yes	Yes	Yes	Mid
Azeotrope							
Asahi AE3000AT	Yes	?	Yes	No	Yes	No***	Mid
3M L-14780	Yes†	Yes‡	No	Yes	Yes	No***	Mid
DuPont™ Vertrel® MCA	Yes	?	Yes	Yes	Yes	No***	High
Solvay Solvokane®	Yes	?	No	Yes	Yes	No***	Mid

Notes:
* For any component in the solvent: High is >1,000; Mid is 10–1000; Low is <10.
** When solvent candidate selection was made, the request for VOC exemption for this solvent was in progress. The Environmental Protection Agency's approval of VOC exemption has since been received.
*** This solvent blend contains trans-1,2 dichloroethylene which is not VOC exempt.
† No Kb data available but previous industry test data showed good cleaning performance.
‡ Historical LOX mechanical impact test data showed this material to be LOX compatible.

Based on these factors, the solvents selected for testing were:

- Honeywell Solstice Performance Fluid (PF) (HCFO-1233zd(E) [Trans-1-chloro-3,3,3,-trifluoroprop-1-ene] CAS No. 102687-65-0).

- 3M L-14780 developmental solvent (22% trans-1,2 dichloroethylene CAS No. 156-60-5 / 78% HFE-347mcc3 [methyl perfluoropropyl ether] CAS No. 375-03-1 azeotrope).

Both of the selected solvent candidates have boiling points that are lower than desired (66 °F and 82–86 °F, respectively). Solvents with a lower boiling point are expected to require some special handling to limit the loss of solvent to vapor during use. While not ideal candidates, they were judged to be most likely to meet the performance requirements for safely cleaning oxygen systems. All solvent data sheets and technical data must be requested from the appropriate vendor(s).

AK-225G, Solstice PF, and L-14780 are clear liquids. Capstone 4-I as received was a pale pink liquid, but changed color. The color ranged from bright fuchsia, to deep indigo, to brownish orange during the course of testing. Capstone 4-I was reported by DuPont to be sensitive to ultraviolet light (photosensitive).

4.3 Test Performance

Following the selection of candidate test solvents and procurement of materials, tests were performed during the period of February 2013 through July 2014. Tests performed were:

(1) Background NVR in the as-received solvent per ASTM D2109–01, "Standard Test Methods for Nonvolatile Matter in Halogenated Organic Solvents and Their Admixtures,"[5] Method C, except using a solvent sample of 200 mL instead of 1,000 mL to preserve as-received solvent for the balance of the test plan.

(2) Metal corrosion by static ambient immersion for 21 days with gravimetric and visual inspection for weight loss, pitting, staining, or other evidence of incompatibility, based on ASTM F483-09, "Standard Practice for Total Immersion Corrosion Test for Aircraft Maintenance Chemicals,"[6] with modifications as noted.

(3) Compatibility with nonmetallic materials by static ambient immersion with analysis of weight loss/gain, swelling/shrinkage, cracking or other visual change, and, for elastomeric materials only, change in hardness. Duration of immersion was 30, 60, and 90 days. This test method was based on the static ambient immersion test described in AFRL-ML-WP-TR-2003-4040.

(4) Cleaning effectiveness tests, based on cleaning tests described in AFRL-ML-WP-TR-2003-4040. These were performed in two phases:

– Cleaning effectiveness test by static immersion of contaminated coupons in solvent.

– Field cleaning effectiveness test for removal of an applied contaminant mix from stainless steel tubes by internal flushing with manual agitation.

(5) LOX and GOX compatibility tests were selected to maximize comparison with tests performed in the past by NASA for selection of cleaning solvents for oxygen systems. These were performed in two phases:

– LOX mechanical impact test on the neat solvent at ambient pressure in accordance with ASTM G 86-98a, "Standard Test Method for Determining Ignition Sensitivity of Materials to Mechanical Impact in Ambient Liquid Oxygen and Pressurized Liquid and Gaseous Oxygen Environments,"[7] at 98 J (72 ft-lb) impact force. If the solvent did not pass at 98 J (72 ft-lb), impact threshold tests were performed by reduction of impact force in increments down to 27 J (20 ft-lb) or until pass.

– GOX compatibility by autogenous ignition test at two pressures in accordance with ASTM G72, "Standard Test Method for Autogenous Ignition Temperature of Liquids and Solids in a High-Pressure Oxygen-Enriched Environment."[8] Test pressures were 50 and 2,000 psi.

5. TEST RESULTS

5.1 Nonvolatile Residue in Cleaning Solvents

The solvents as received from the vendors were as follows:

- AK-225G, supplied in 1-gallon amber glass bottles, distilled. Clear liquid.
- Solstice PF, supplied in a 20-kg pressure cylinder. Clear liquid.
- L-14780, supplied in 1-gallon amber glass bottles. Clear liquid.
- Capstone 4-I, supplied in a 5-gallon can. Pale pink transparent liquid. Material in the 5-gallon can contained a large quantity of particulate that was filtered prior to the NVR test and all other tests. This material was supplemented in later tests with product contributed by the USAF Materials Laboratory, Wright-Patterson Air Force Base, supplied in sealed amber glass bottles from the manufacturer. The product in glass bottles also contained particulate that was filtered prior to use.

The four solvents used for this test program were examined as received, filtered, and tested for NVR content by evaporation and gravimetric analysis. The AK-225G was provided by the MSFC Valve and Components shop where it is routinely distilled and used for precision cleaning of oxygen system components. Over the course of testing, several batches of solvent were received for testing. Each solvent lot was tested for NVR content. Results of NVR lot tests are shown in table 2.

The NVR levels in the Capstone 4-I were high, and would require additional purification prior to use in precision cleaning.

Table 2. Solvent NVR content by lot; filtered prior to test.

Solvent	Lot	NVR Content (mg/200 mL)
AK-225G	Production stock	0.29
	Production stock	0.07
Solstice PF	1	1.79*
	BB-245B-U-50-06	0.17
	BR-130-319-50-42	0.76
L-14780	2/3/2011	0.19
	LA-M000-1478-0 2014-04-02	0.33
	LA-I000-1478-0 2014-07-16	0.08
	LA-I000-1478-0 2014-07-14	0.20
Capstone 4-I	207	63.93
	108710	1.83
	18	205.31

* Initial lot of Solstice PF contained suspected oil contamination. Replacement solvent was provided by the vendor.

5.2 Solvent Compatibility With Metals

The potential for corrosion of metals used in oxygen systems by the solvents used to clean them was tested by immersion of metal coupons in the test solvents at ambient temperature for 21 days. Component exposure to the solvent during cleaning operations, whether by vapor degreasing, solvent immersion, cold flush, or hand wiping, is typically less than 30 minutes. Extended duration exposure at ambient temperature is performed to identify potential incompatibilities when metals are exposed to solvents at elevated temperatures for short periods, or when the solvent is left as a residual due to entrapment or inadequate drying. ASTM F483-09 was used as the basis for the test protocol.

Representing the most common families of metals used in NASA launch vehicle oxygen systems, the following materials were tested with AK-225G, Solstice PF, L-14780, and Capstone 4-I:

(1) 17-4 Precipitation Hardened stainless steel.

(2) Elgiloy® (a cobalt-chromium-nickel alloy).

(3) 2219-T6 aluminum (a high copper aluminum susceptible to corrosion).

(4) Inconel® 718 (a nickel-chromium alloy).

Thirteen specimens of each metal were prepared from sheet stock, cut into 1- by 2-in (nominal) coupons, drilled for hanging, stamped with serial numbers, and cleaned prior to use. Three coupons of each metal were weighed, photographed, and then immersed in glass jars of each solvent. Figure 1 shows the test coupons suspended in solvent at the beginning of the test. The AK-225G, Solstice PF, and L-14780 were clear at the beginning of the test while the Capstone 4-I had a pale pink color. Teflon®-coated wire was used to suspend the coupons in the solvents. One coupon was maintained dry as a control.

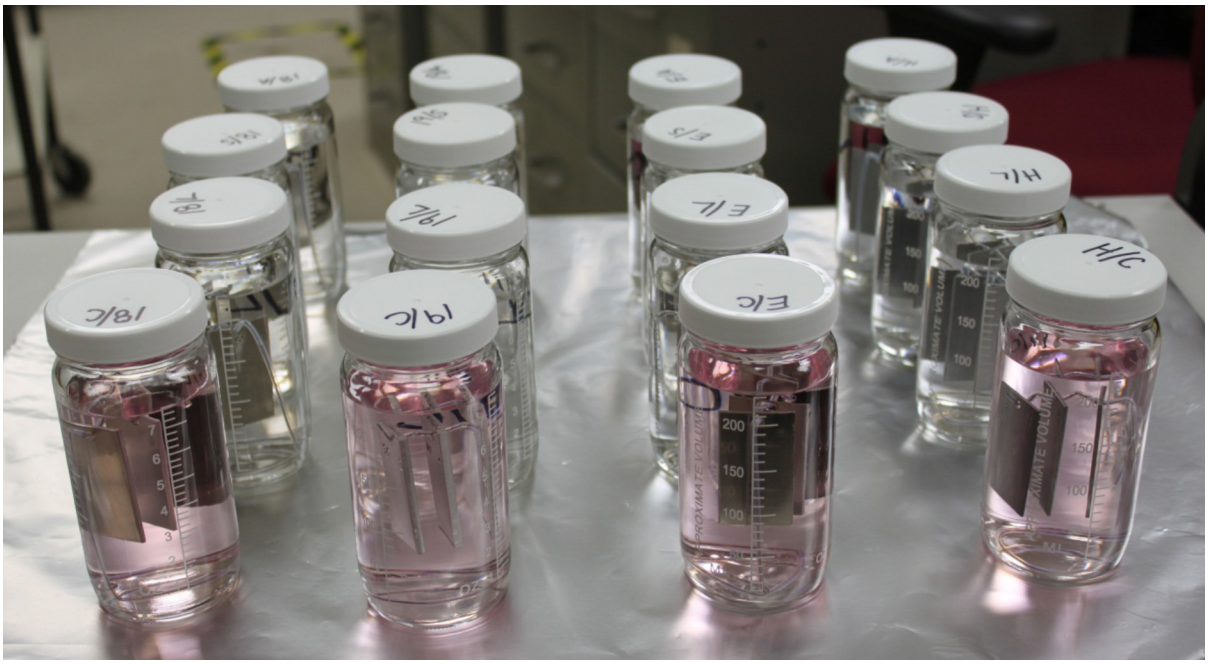

Figure 1. Metal specimens immersed in four test solvents at beginning of exposure.

At 24 hours, 7 days, and 21 days the metal coupons were removed from the solvents, air dried and desiccated for 15 minutes, weighed, visually examined, and photographed. Any visual changes compared to the control coupons were noted. After the examinations at 24 hours and at 7 days, the coupons were returned to the same solvent jars for further exposure. The jars containing Capstone 4-I, which is known to be photosensitive, were wrapped in aluminum foil during the passive exposure periods.

The AK-225G, Solstice PF, and L-14780 remained clear throughout the exposure period, and showed no evidence of precipitate. The Capstone 4-I, however, exhibited a distinct color change at 24 hours (fig. 2) and continued to darken throughout the exposure time period. The degree of color change varied between the containers containing different metals.

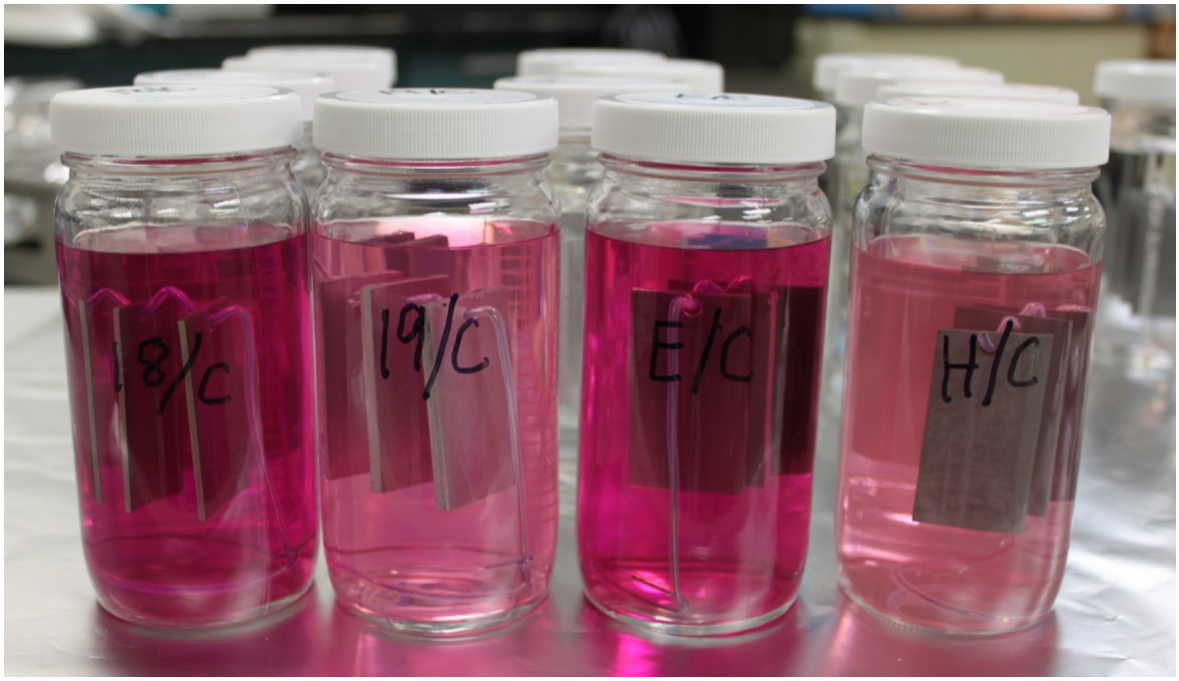

Figure 2. Metals immersed in Capstone 4-I at 24 hours.

At 24 hours, 7 days, and 21 days, the four metals immersed in the AK-225G, Solstice PF, and L-14780 showed no visible change or change in weight. All of the metals immersed in the Capstone 4-I exhibited significant evidence of corrosion. A 2005 laboratory report by a U.S. aerospace contractor noted that DuPont Zonyl PFBI, the predecessor product to DuPont Capstone 4-I, caused oxidation and pitting of aluminum substrates, so attack of the 2219-T6 aluminum in this test was not unexpected. However, the other three metals also exhibited significant weight gain and visual evidence of corrosion in Capstone 4-I. Corrosion of the stainless steel, Eligiloy, and Inconel 718, metals that are inherently corrosion resistant, was not expected and was inconsistent with previous test data reported for another predecessor product, DuPont Ikon P, a product reported by Dhooge et al.[9] to be pure perfluoro-n-butyl iodide.

Photos of the metals after immersion in AK-225G, Solstice PF, and L-14780 for 21 days are shown in figures 3–16. Photos of the metals after immersion in Capstone 4-I for 24 hours and for 21 days are shown in figures 17–22. In each photo, specimen 4 was the control that was not immersed in solvent.

Figure 3. Stainless steel after 21 days in AK-225G.

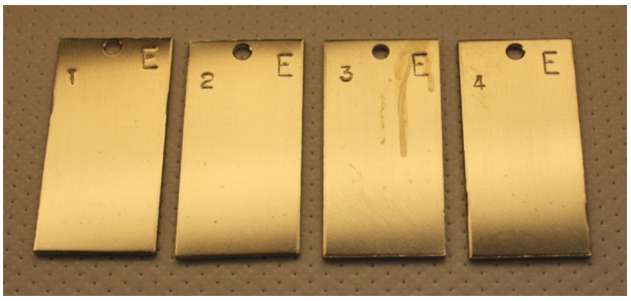

Figure 4. Elgiloy after 21 days in AK-225G.

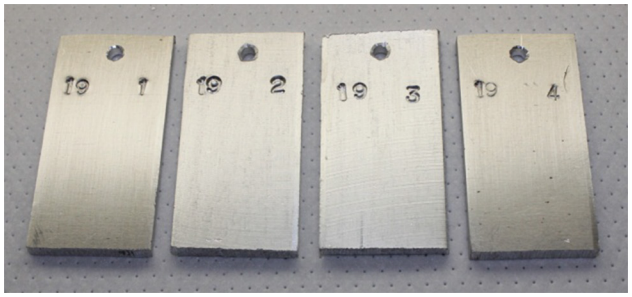

Figure 5. Aluminum after 21 days in AK-225G.

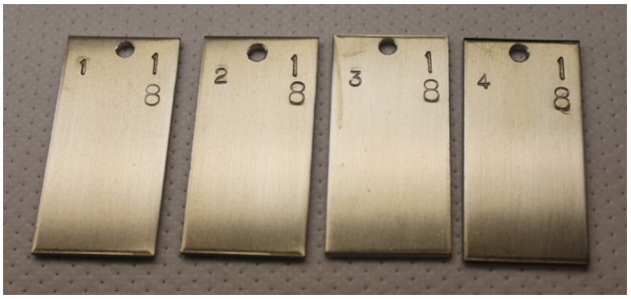

Figure 6. Inconel 718 after 21 days in AK-225G.

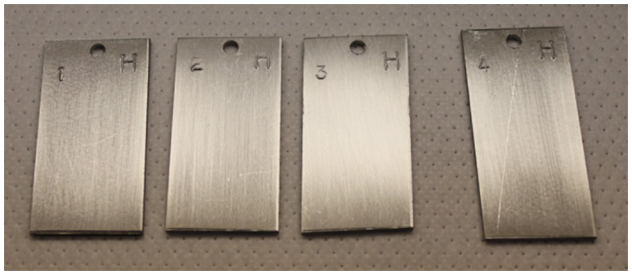

Figure 7. Stainless steel after 21 days in Solstice PF.

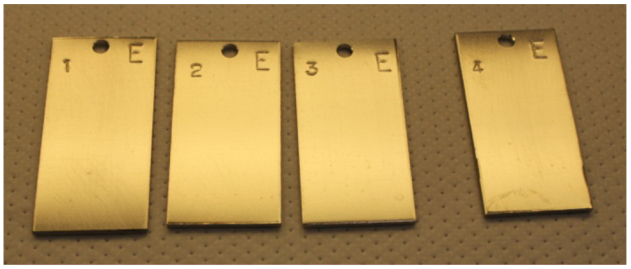

Figure 8. Elgiloy after 21 days in Solstice PF.

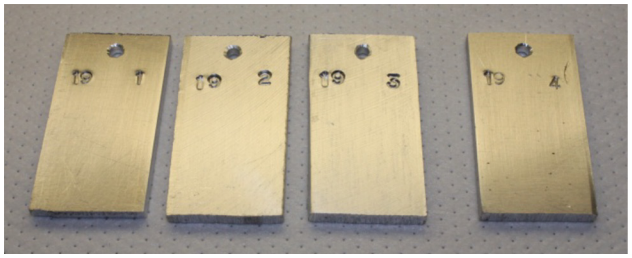

Figure 9. Aluminum after 21 days in Solstice PF.

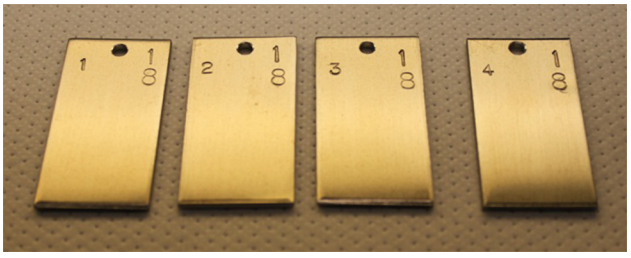

Figure 10. Inconel after 21 days in Solstice PF.

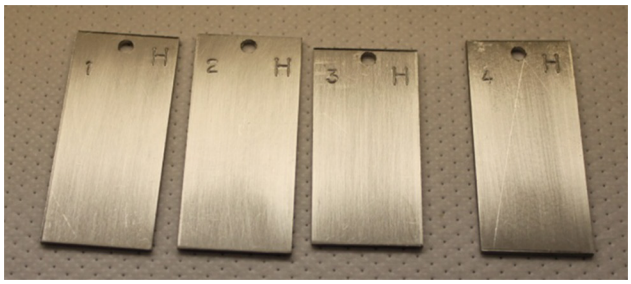

Figure 11. Stainless steel after 21 days in L-14780.

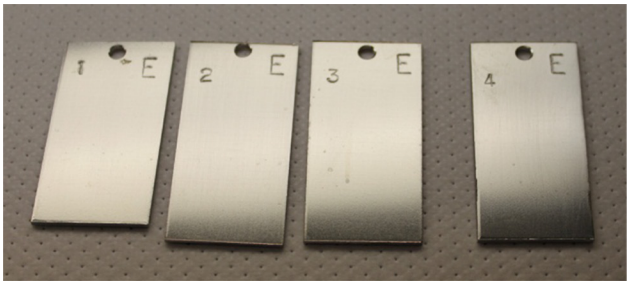

Figure 12. Elgiloy after 21 days in L-14780.

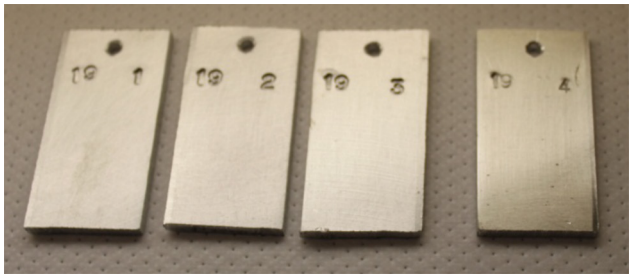

Figure 13. Aluminum after 21 days in L-14780.

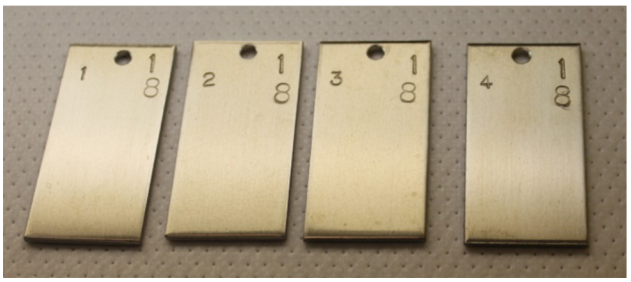

Figure 14. Inconel 718 after 21 days in L-14780.

Figure 15. Stainless steel after 1 day in Capstone 4-I.

Figure 16. Stainless steel after 21 days in Capstone 4-I.

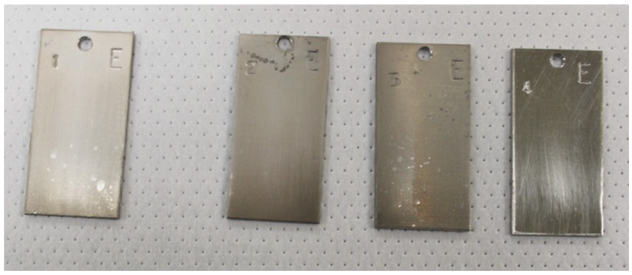

Figure 17. Elgiloy after 1 day in Capstone 4-I.

Figure 18. Elgiloy after 21 days in Capstone 4-I.

Figure 19. Aluminum after 1 day in Capstone 4-I.

Figure 20. Aluminum after 21 days in Capstone 4-I.

Figure 21. Inconel 718 after 1 day in Capstone 4-I.

Figure 22. Inconel 718 after 21 days in Capstone 4-I.

Graphs of weight gain or loss of the metal specimens over time in each solvent are shown in figures 23–26. Weight gain or loss was negligible for all of the metals in AK-225G, Solstice PF, and L-14780 so the plots for these solvents are on top of each other in the graphs. Significant weight gain was observed for all four metals in Capstone 4-I. The plots for the three coupons of each metal immersed in Capstone 4-I showed consistent weight gain over time indicating uniform attack and deposition of the corrosion product on each type of metal.

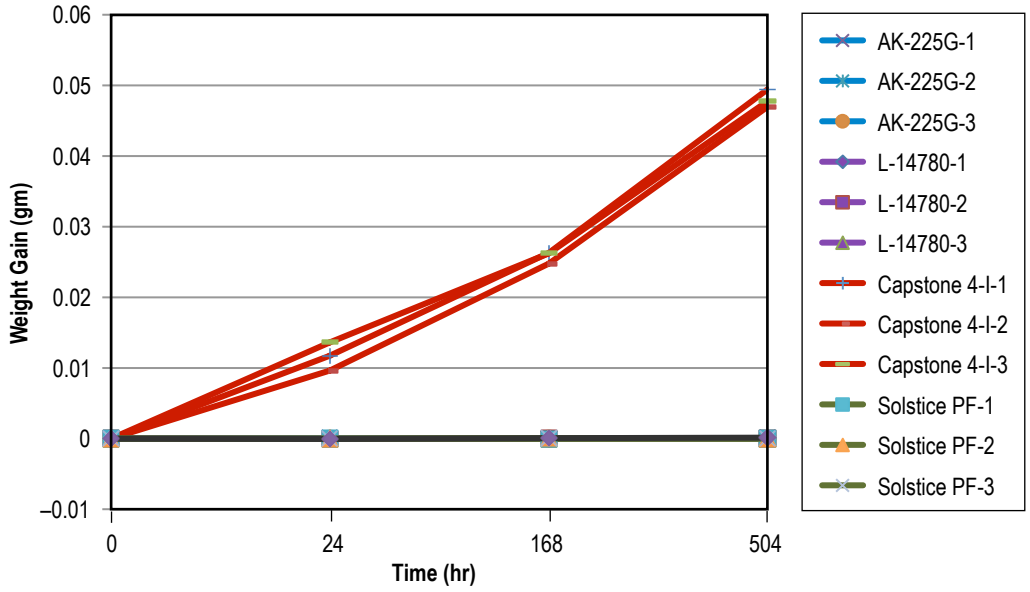

Figure 23. Weight gain or loss over time of 17-4PH stainless steel after immersion in four solvents.

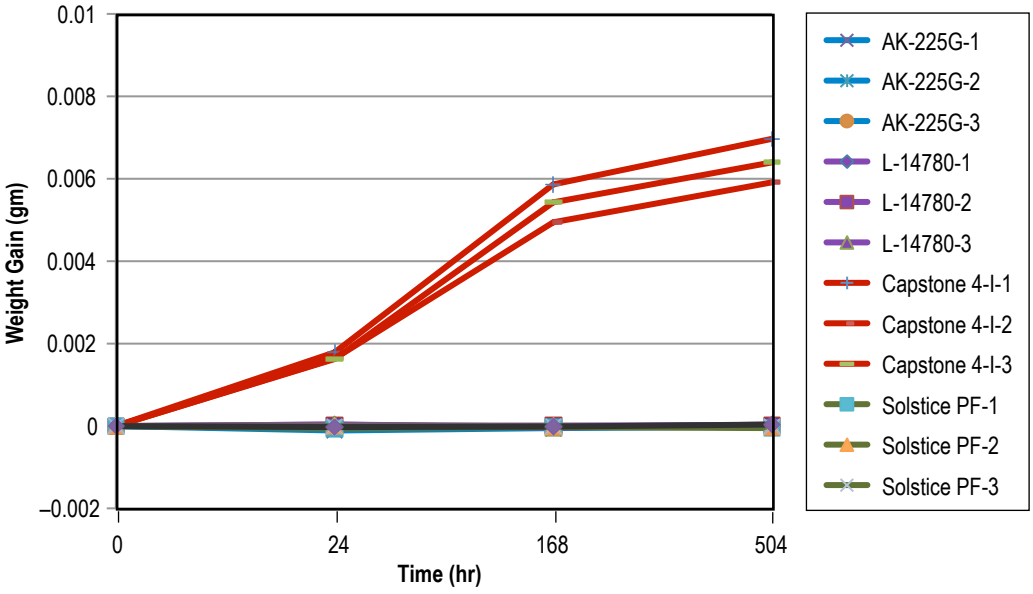

Figure 24. Weight gain over time of Elgiloy after immersion in four solvents.

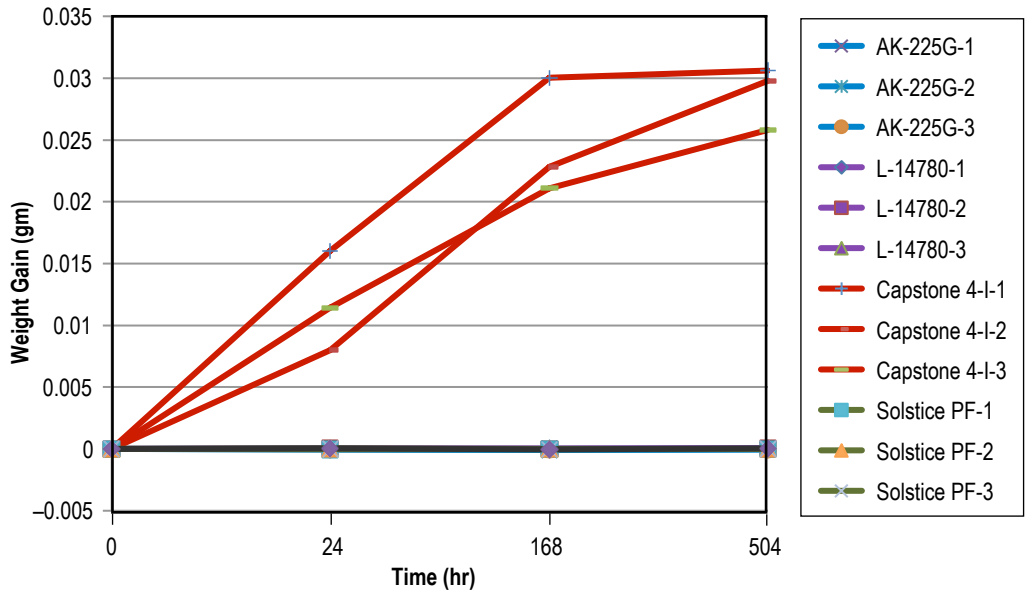

Figure 25. Weight gain over time of 2219-T6 aluminum after immersion in four solvents.

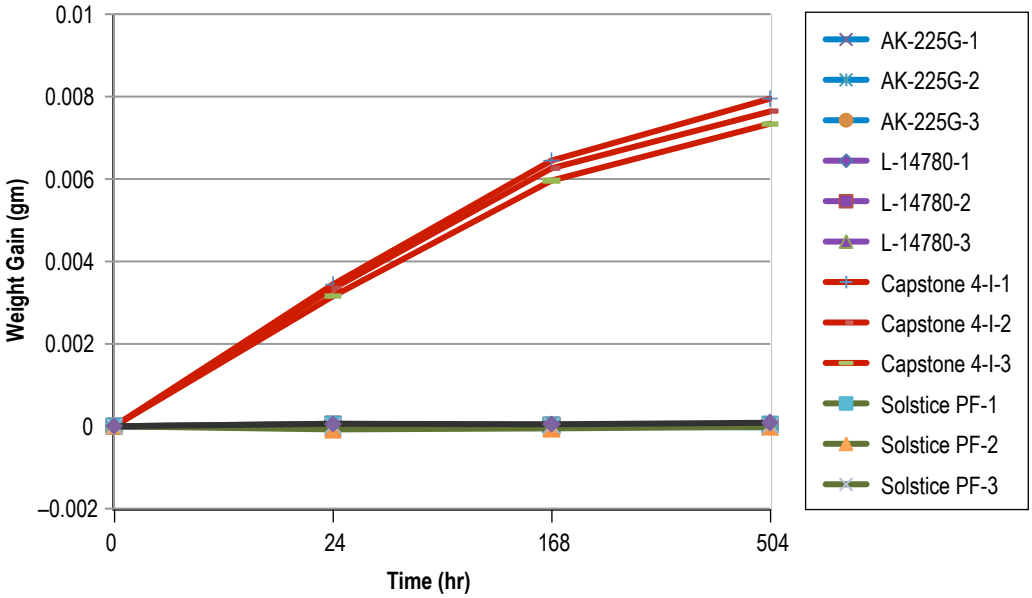

Figure 26. Weight gain or loss over time of Inconel 718 after immersion in four solvents.

Distinct darkening of all four metals was observed after exposure to Capstone 4-I. The aluminum specimens showed some pitting after 24 hours of immersion and extensive pitting after 7 days of immersion. The discoloration, pitting, and weight gain strongly indicates that Capstone 4-I is corrosive to metals used in the construction of an oxygen system, including metals that are expected to be resistant to corrosion.

It should be noted that Capstone 4-I is not pure PFBI. The Safety Data Sheet states that this product is 85%–98% PFBI. The technical data sheet for DuPont Capstone 4-I (which is classified as a chemical intermediate) states that the product is ≥90% PFBI. The other reported constituents are perfluoroethyliodide, perfluorohexyliodide, perfluorohexane, and perfluorooctane. Capstone 4-I is photosensitive and appears to break down even when stored in amber glass bottles. While it is possible that pure PFBI would not corrode metals as was seen with Capstone 4-I, a pure PFBI product was not available for testing. Furthermore, it appears that pure PFBI would require a stabilizer additive to retard chemical breakdown. Several conversations were held with DuPont during the course of this study regarding the stability of the product. DuPont indicated that there was not a strong business case for marketing this product as a cleaning solvent or development of a stabilizer additive for PFBI.

5.3 Solvent Compatibility With Nonmetals

Several types of ignition resistant nonmetals are commonly used within oxygen systems for seals and gaskets. Six common nonmetals used in oxygen systems were tested for compatibility with the candidate cleaning solvents. The materials tested were:

(1) FKM poly(hexafluoropropylene-co-vinylidene fluoride) elastomer—FKM Compound V0747-75 (Parker Hannafin) [Similar to Viton® A (DuPont)].

(2) NBR poly(acrylonitrile-co-butadiene) rubber (Buna N)—MIL-G-21569B(SHIPS)[10] Class I.

(3) Polytetrafluoroethylene (PTFE)—Avalon 01 (Parker Hannafin) [Similar to PTFE Teflon (DuPont) and Algoflon E2 (Solvay Solexis)].

(4) Polychlorotrifluoroethylene (PCTFE)—Kel-F 81® (3M) [Similar to Neoflon® PCTFE (Daiken)].

(5) Aromatic polyimide, 15% graphite enhanced—Vespel® SP-21 (DuPont).

(6) Polyether ether ketone (PEEK)—Ketron® PEEK (McMaster-Carr).

The baseline solvents AK-225G and Capstone 4-I are not compatible with all of the nonmetals tested. It is common practice to remove and replace nonmetallic parts when cleaning oxygen system components such as valves and clean these parts manually. Compatibility tests were performed with the baseline solvents alongside the candidate solvents for comparison. Compatibility of the candidate solvents with the above nonmetals was compared to the baseline solvents to determine how use of a new solvent would alter current practices when cleaning components containing nonmetallic parts.

Compatibility tests were performed by immersion of O-rings or gasket rings of each material in each solvent at ambient temperature for 30, 60, and 90 days. The test procedure was based on the nonmetal compatibility tests described in AFRL-ML-WP-TR-2003-4040. A fifth solvent,

Solvay Solvokane, was included in this test because it was being evaluated in a parallel test program as a potential backup candidate. Ten specimens of each nonmetal were fabricated for each solvent. For each solvent, the specimens were exposed as follows:

- Three specimens—immersed for 30 days.
- Three specimens—immersed for 60 days.
- Three specimens—immersed for 90 days.
- One specimen—not immersed (control).

The specimens were cleaned, stored in a desiccator for 24 hours, and then weighed on an analytical balance (fig. 27) and measured prior to immersion. The outer diameter was measured with a micrometer calipers in two perpendicular locations and averaged. The elastomers FKM V0747-75 and Buna N were measured for hardness (Shore A durometer) in three locations around the ring in accordance with ASTM D2240-05, "Standard Test Method for Rubber Property—Durometer Hardness,"[11] Type A (fig. 28).

Figure 27. Weighing specimen on an analytical balance.

Figure 28. Measurement of Shore A durometer.

The specimen rings were suspended in the solvent on stainless steel wire in wide mouth glass jars with Teflon-lined caps (fig. 29). After immersion, the specimens were suspended to air dry in a desiccator for 15 minutes and then weighed, measured, and (for the elastomers) tested for hardness. Specimens exhibiting a change in weight or linear swell of >1% were returned to the desiccator for 24 hours, and the measurements were repeated. For specimens continuing to show a change in weight or diameter of >1% from the previous measurement, desiccation was continued and measurement was repeated at 7, 14, 21, and 28 days. For the elastomers, hardness testing was repeated after the weight of the specimens stabilized.

Figure 29. O-ring specimens immersed in solvent with stainless steel wire supports.

Graphs of weight gain or loss for each set of nonmetal specimens after immersion are shown in appendix A.1. Graphs were not generated for solvent/nonmetal combinations that exhibited a weight change of <2%. Solvent/nonmetal combinations that showed a change of <3% in retained weight and linear dimension were:

- AK-225G with Vespel SP-21 and PEEK.
- Solstice PF with FKM V0747-75, PTFE, Vespel SP-21, and PEEK.
- L-14780 with PTFE, Vespel SP-21, and PEEK.
- Solvokane with PTFE, PCTFE, Vespel SP-21, and PEEK.
- Capstone 4-I with PCTFE, Vespel SP-21, and PEEK.

Bar charts were generated to compare the weight change of each nonmetal with the five test solvents at 30, 60, and 90 days (app. A.2). A change in linear dimension (swelling) of the material was generally observed when a change in weight was observed. Changes in weight were more significant than changes in linear dimension so the changes in linear dimension were not plotted.

The compatibility results for nonmetals in Solstice PF, L-14780, and Solvokane appear to be similar to or better than the baseline solvents, AK-225G and Capstone 4-I. Unlike the performance of Capstone 4-I with metals, it showed superior compatibility with PCTFE, Vespel SP-21, and PEEK. Capstone 4-I was also the only solvent in which the Buna N did not lose weight although the weight gain was sufficient for it to be considered incompatible. The Buna N also appeared to alter the color change of the Capstone 4-I. With the other five nonmetals, the Capstone 4-I turned a deep purple, but with the Buna N, the Capstone turned from a pale pink to a pale yellow-orange (fig. 30). The other four solvents remained clear with all nonmetals throughout the test.

Figure 30. Capstone 4-I after nonmetal immersion for 90 days.

Materials showing weight gain of <5% and retained weight gain after drying of <3% without significant weight loss may be considered compatible with the respective solvents but should be evaluated by each user for their particular application. Significant weight loss is an indication that the solvent is attacking the material or leaching a component from the material, and therefore should not be used with that material. The only material that exhibited significant weight loss in the test solvents was the Buna N elastomer. All of the tested solvents were compatible with Vespel SP-21 and PEEK.

The FKM V0747-75 showed a retained weight gain of <3% in Solstice PF after 7 days; however, initial swelling plus a reduction in hardness after drying of up to 15% indicate that Solstice PF should be used only with caution with FKM V0747-75 or Viton A.

5.4 Cleaning Effectiveness—Static Immersion Solvency

Cleaning effectiveness was measured by solvency alone, and was evaluated by immersion of test coupons contaminated with selected contaminants in each of the four test solvents. This test introduced no added heat or mechanical action; therefore, it was a test only of the ability of the solvent to dissolve the contaminants. Each contaminant was tested in triplicate with each solvent for an immersion period of 30 seconds, 1 minute, 2 minutes, and 5 minutes.

The contaminants used in these tests were:

- Mineral oil—CAS 8042-47-5.
- Hydraulic fluid, MIL-PRF-83282[12]—Castrol Brayco Micronic® 882.
- Fluorocarbon grease—Krytox® 240AC.
- Di-2-ethylhexyl sebacate (gauge calibration oil)—CAS 122-62-3.

Contaminants were applied to clean 2- by 1-in (nominal) stainless steel test coupons via pipette or brush (fig. 31). The contaminated coupons were suspended in a desiccator until ready for test to dry and maintain clean (fig. 32). Each coupon was weighed on an analytical balance, maintained clean inside a sealed box between use, before contaminating, after contaminating, and after immersion (fig. 33). Three beakers of solvent with four coupons each were used to test each solvent/contaminant combination (fig. 34). After suspending the contaminated coupons into the beakers, solvent was slowly poured into the center of each beaker to minimize agitation (fig. 35). One contaminated coupon was removed from each beaker at each time interval, dried in the desiccator, and weighed.

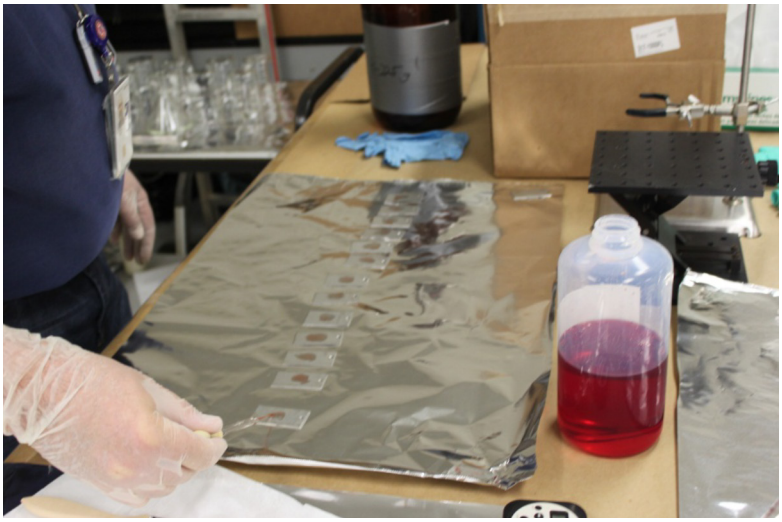

Figure 31. Application of contaminant to test coupons.

Figure 32. Coupons in desiccator.

Figure 33. Analytical balance used to weigh test coupons.

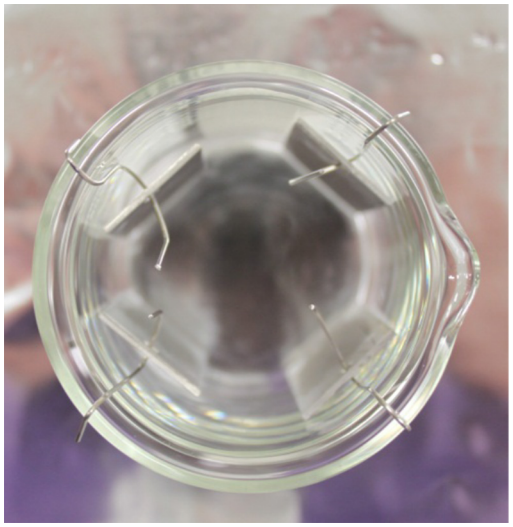

Figure 34. Coupons suspended in solvent.

Figure 35. Addition of test solvent to beakers containing suspended coupons.

The two candidate replacement solvents showed contaminant removal effectiveness (fig. 36) comparable to the baseline solvents. Removal of the mineral oil, hydraulic fluid, and sebacate was excellent. All of the solvents showed only moderate performance removing the Krytox fluorocarbon grease, with the DuPont Capstone 4-I showing slightly better (~2%) cleaning effectiveness than the other solvents. Fluorocarbon grease, which is compatible with oxygen systems, is known to be difficult to remove, generally requiring some mechanical force (spraying or wiping) with the solvent for effective removal. With the exception of the fluorocarbon grease, effective contaminant removal was achieved at 30 seconds of immersion.

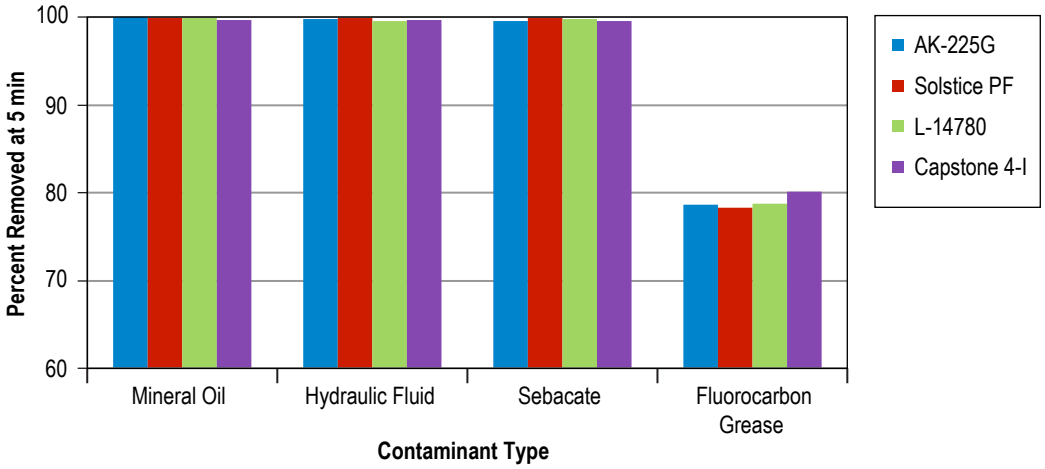

Figure 36. Comparison of contaminant removal effectiveness by static immersion.

5.5 Field Cleaning Effectiveness—Tube Cleaning

To simulate a field cleaning scenario where solvent is used to flush a part to remove surface contamination, the interiors of clean stainless steel tubes were doped with a mixture of contaminants and cleaned with each solvent to compare performance. Cleaning was performed by partially filling the contaminated tube with a measured quantity of test solvent and swishing the solvent back and forth in the capped tube with a gentle rocking motion for a set number of cycles. This test was designed to mimic a field cleaning test reported in AFRL-ML-WP-TR-2003-4040. Figure 37 shows the stainless steel tubes with end caps used for this test. Figure 38 shows the rocking motion used to clean the tubes without agitation. The four tubes were rocked simultaneously to assure consistent mechanical action for each test run.

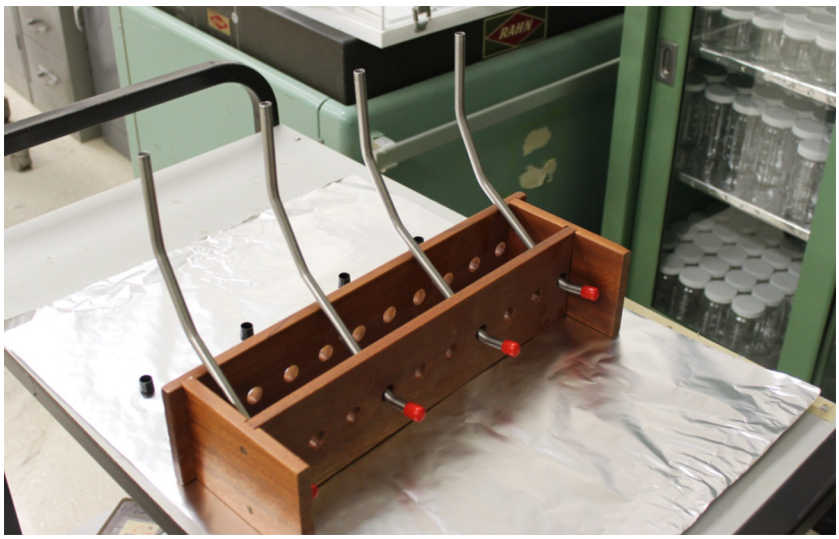

Figure 37. Stainless steel tubes with end caps used for the field cleaning test.

Figure 38. Rocking motion used to clean tubes simultaneously for the field cleaning test.

AK-225G, Solstice PF, L-14780, and Capstone 4-I were each tested with a mixture of the following contaminants in equal proportions by weight: mineral oil, Castrol Brayco Micronic 882 hydraulic fluid, di-2-ethylhexyl sebacate, and simulated fingerprint (synthetic sebum also known as modified Spangler soil, per ASTM D4265-98), "Standard Guide for Evaluating Stain Removal Performance in Home Laundering,"[13] section A2.16.2. The four contaminants blended well and a carrier solvent was not required to dispense the mixed contaminant into the tubes.

The test was performed four times, varying the quantity of contaminant applied for each set. The quantity of test solvent and the number of rocking cycles was increased after the first run, which improved the overall cleaning efficiency of the test solvents. The parameters varied for each test run are shown in table 3. Following cycling, the test solvent was poured into a tared weighing dish, the solvent was evaporated under a high-efficiency, particulate air-filtered flow bench, and the dish with dried contaminant residue was weighed. A small glass beaker was used for the Capstone 4-I rather than an aluminum weighing dish due to the incompatibility of Capstone 4-I with aluminum. To measure the amount of contaminant remaining in the tube after cleaning with the test solvent, the process was repeated with AK-225G for each tube.

Table 3. Field cleaning effectiveness test parameters varied for each run.

Run	Test Solvent Quantity (mL)	Number of Cycles	Target Contaminant Quantity (gm)	Range of Test Solvent Applied (gm)
1	7	50	0.5	0.38–0.63
2	10	100	2.0	1.91–2.45
3	10	100	1.0	1.05–1.10
4	10	100	0.8	0.75–0.81

Results of these tests are shown in figures 39 and 40. The cleaning efficiency of AK-225G and Capstone 4-I were comparable. Both Solstice PF and L-14780 appeared to benefit from additional cleaning time and additional solvent. Under heavy soil loading, the cleaning result with Solstice PF was slightly lower but met the required oxygen system cleanliness limit of <1 mg/ft^2 in all tests. The cleaning performance of L-14780 did not meet the cleanliness requirement in all cases.

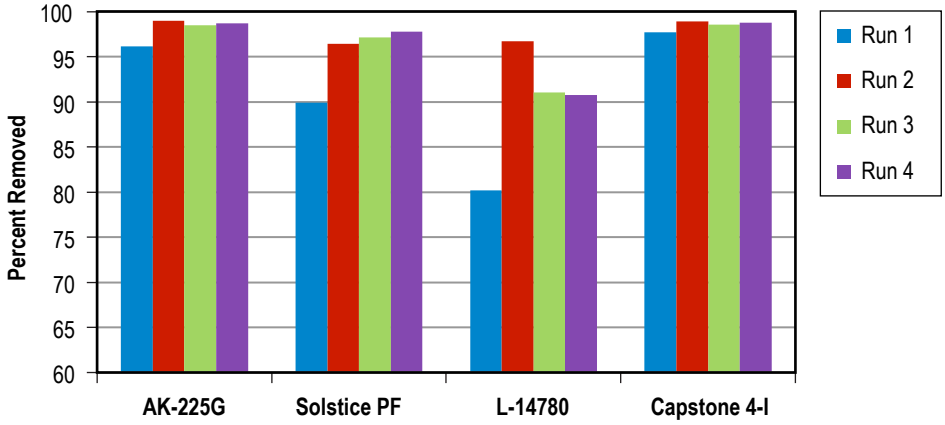

Figure 39. Field cleaning—comparison of tube cleaning efficiencies.

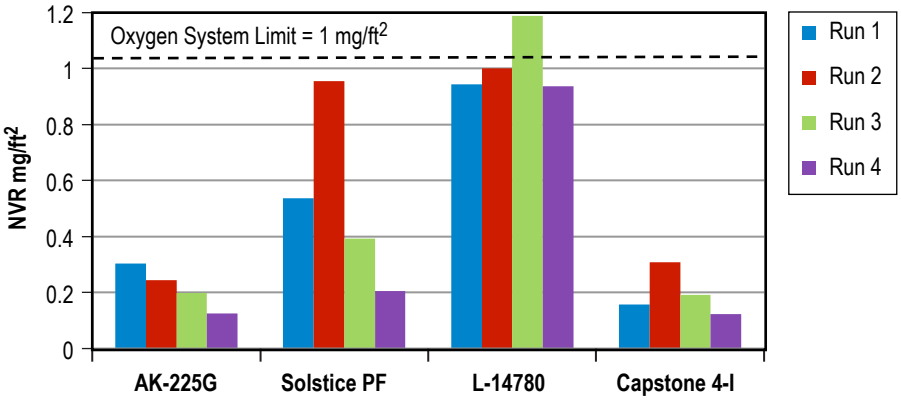

Figure 40. NVR level achieved as measured by rinsing with AK-225G.

During the tube cleaning tests, milkiness, slight foaming, and separation of the L-14780 was observed after flushing the contaminated tube, indicating that the L-14780 may have reacted with the contaminant, or the solvating capacity of L-14780 may have been exceeded. The color of the mixed contaminant is shown in figure 41. Figure 42 shows the milkiness and foaming of the L-14780 when poured from the tube after the cleaning cycles. Stratification, shown in figure 43, was seen in the L-14780 solvent rinse at higher contaminant concentrations. Some separation of the contaminant from the Solstice PF was also observed but was not as distinct and appeared to correlate with the quantity of contaminant in the vial. Given the relative quantity of separated contaminant-colored material in the L-14780 and the clarity of the lower layer, theoretically, the two components of the L-14780 azeotrope may have separated, with the contaminant dissolved in the trans-1,2 dichloroethylene portion.

Figure 41. Contaminant mix.

Figure 42. Milky L-14780 from tube cleaning.

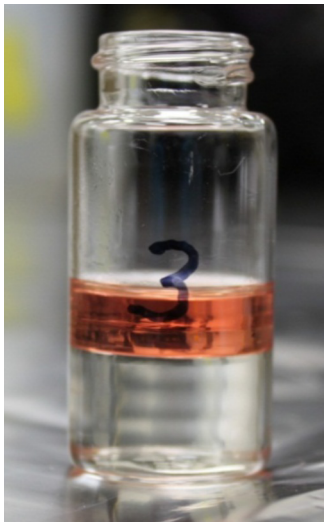

Figure 43. Separation in L-14780.

A solution of the mixed contaminant in each of the four test solvents is shown in figure 44. No separation of contaminant was observed in the AK-225G or Capstone 4-I, but some separation was seen in the Solstice PF and clear separation was seen in the L-14780. (The quantity of Solstice PF in the vial is low due to evaporation.) Separation and redeposition of contaminant is a concern for oxygen systems, as is the potential for separation of a two-component solvent blend into its flammable and nonflammable subcomponents. Additional testing was performed to determine whether 100% of the contaminant would go into solution if additional solvent is used, and whether evidence of separation would disappear. In all cases, addition of solvent showed that the contaminant will go into solution if enough of the solvent is used. Based on these tests, it is expected that these solvents will be capable of meeting oxygen system cleanliness requirements with sufficient flushing with clean solvent.

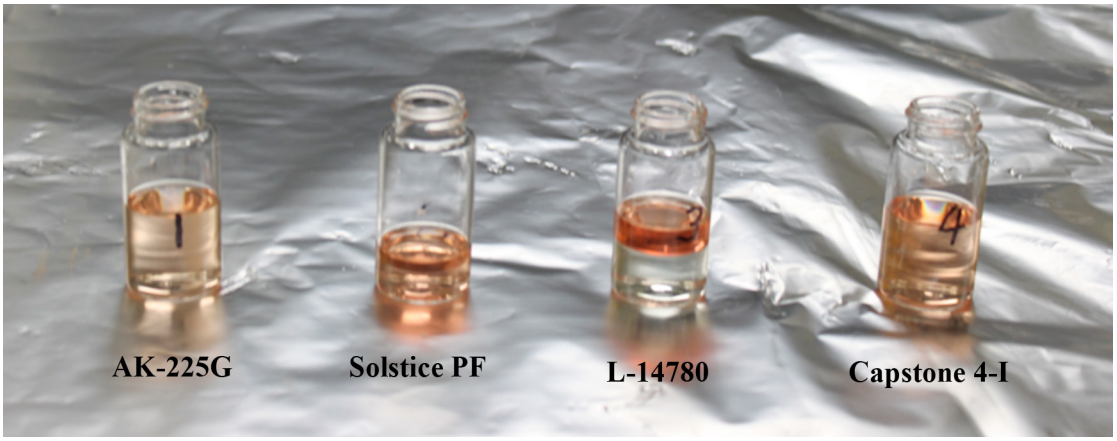

Figure 44. Contaminant mix dissolved in the test solvents showing separation in Solstice PF and L-14780.

5.6 Flammability and Reactivity of Cleaning Solvents in Oxidizers

For unrestricted use on LOX/GOX systems, cleaning solvents must be shown to be compatible with oxygen at a range of expected use temperatures and pressures. The LOX Mechanical Impact Test and the Autogenous Ignition Temperature (AIT) test in GOX have historically been used to assess the potential for ignition of residual solvent remaining within an oxygen system due to inadequate drying.

Oxygen compatibility tests were performed by the MSFC Combustion Research Facility.

5.6.1 Liquid Oxygen Mechanical Impact

The solvents were tested in LOX at ambient pressure in accordance with ASTM G86-98a, "Standard Test Method for Determining Ignition Sensitivity of Materials to Mechanical Impact in Ambient Liquid Oxygen and Pressurized Liquid and Gaseous Oxygen Environments,"[7] at 98 J (72 ft-lb) impact force.

The standard success criteria for materials to be used in the construction of oxygen systems is zero reactions in 20 impacts at 98 J (72 ft-lb) or no more than one reaction in 60 impacts at 98 J (72 ft-lb). For materials that do not meet these criteria, the test may be repeated at successively lower impact energies to establish threshold reaction energy. If no suitable materials meet the standard success criteria, data from threshold reaction energy tests as well as results from other oxygen compatibility tests, such as AIT, is used to compare alternative material choices and perform an engineering analysis of the relative hazards.

LOX mechanical impact tests were performed for the candidate solvents Solstice PF and L-14780. Tests for Solstice PF were repeated in 2014 on an additional sample provided by Honeywell after they determined that the first sample was potentially contaminated by oil on the valve. MSFC did not detect contamination in the first sample, but repeated the tests on the second sample for added assurance. Although previous test data were available for DuPont PFBI products under the trade name Ikon P, no data were available for the product marketed as Capstone 4-I so this product was tested for LOX Mechanical Impact as well. AK-225 and AK-225G were tested extensively by NASA in the past. Historical oxygen compatibility data for AK-225G were used as the basis for comparison.

Taking advantage of operational efficiencies by the Materials Combustion Research Facility (MCRF), oxygen compatibility tests were performed on three additional solvents that were considered in the initial trade study. The additional solvents tested were Vertrel MCA, Solvokane, and Solkane 365mfc. These added tests were performed as feasible within time and resource constraints.

5.6.2 Autogenous Ignition Temperature

The solvents were tested in accordance with ASTM G72-09/G72M-09, "Standard Test Method for Autogenous Ignition Temperature of Liquids and Solids in a High-Pressure Oxygen-Enriched Environment."[8] The standard (default) pressure specified in ASTM G72-09 for the AIT is 1,500 psi; however, for AFRL-ML-WP-TR-2003-4040, the solvent AITs were performed at 50 and 2,000 psi. To maximize comparability of solvent test data, the solvents in this test program were also tested at 50 and 2,000 psi.

The following catagories were used in AFRL-ML-WP-TR-2003-40401 to determine suitability of a solvent for use with gaseous breathing oxygen systems that operate at elevated pressures:

(A) AIT > 400 °F: Acceptable for use in oxygen systems.

(B) AIT 250–400 °F: May be used with caution in oxygen systems.

(C) AIT < 250 °F: Not recommended for use in oxygen systems.

Suitability of the solvent for use in GOX at pressures greater than 2,000 psi may require additional testing.

5.6.3 Oxygen Compatibility Test Results

A summary of results from the oxygen compatibility tests performed by the MCRF is shown in table 4. The Solstice PF and L-14780 performed moderately well in the AIT tests, falling into category B, "May be used with caution in oxygen systems," established in AFRL-ML-WP-TR-2003-4040. Neither of these candidate solvents performed as well as AK-225G for oxygen compatibility. The DuPont Capstone 4-I performed comparably to the predecessor, Ikon P. The performance of the additional solvents, Vertrel MCA, Solkane 365mfc, and Solvokane, in the oxygen compatibility tests was inferior to Solstice PF and L-14780, validating the initial selection of Solstice PF and L-14780 as the solvent candidates most likely to qualify as a replacement for HCFC-225cb (Asahiklin AK-225G) and PFBI (Capstone 4-I).

Table 4. Oxygen compatibility test results for solvents, MSFC, 2013–2014.

Solvent	LOX Impact (72 ft-lb)	LOX Impact Threshold for 0/20 Reactions (ft-lb)	Lowest Result AIT at 50 psi (–°F)	Lowest Result AIT at 2,000 psi (–°F)
Honeywell Solstice PF	Pass–0/20	72	501	384
Honeywell Solstice PF Sample 2, oil-free	Fail–2/28	62.9*	378	> 800
Honeywell Solstice PF Sample 3	Pass–0/20	72	–	–
3M L-14780	Pass–0/20	72	299**	318**
Asahi AK-225G***	Pass–0/20	72	> 800	> 800
DuPont Capstone 4-I***	Pass–0/20	72	†	> 800
DuPont Vertrel MCA***,‡	Fail–2/16	62.9*	†	> 800
DuPont Vertrel MCA***,§	Fail–2/5	62.9*	†	†
Solvay Solkane 365mfc***	Fail–2/4	54.6*	†	†
Solvay Solvokane***	Fail–2/6	54.6*	320	317

Notes:
* Determined by the Bruceton sensitivity test method.
** Three sequential tests at 50 psi yielded an AIT of 299 °F, 300 °F, and >800 °F. Review of the data and repeat of this test (NASA funded) by WSTF determined that the third data point (no reaction to >800 °F) was probably invalid due to loss of liquid solvent during purge. The test at 2,000 psi was later repeated with a sample size of 1 gm rather than the standard 0.2 gm and yielded an AIT of 318 °F.
*** Comparative solvent tests not required by test plan, performed on a resource available basis.
† Not required by test plan; not completed due to exhaustion of funds and commitment of the test facility to other projects during the contract period.
‡ Initial sample with unspecified stabilizer content.
§ Second sample with identified stabilizer content.

During the course of this study, additional oxygen compatibility tests were performed on these solvents at NASA's White Sands Test Facility (WSTF) as part of a parallel NASA-funded test program. Because neither of the candidate replacement solvents were shown by these initial tests to be safe for use in oxygen systems without some precautions, more extensive testing was performed.

It was noted by WSTF that an AIT result of >800 °F represents the threshold limit of the test equipment and could indicate that an inadequate amount of fuel (solvent) was present in the test vessel for a reaction to occur (table 4, note**). This would bring into question historical solvent test data where a threshold limit result was obtained, including the data for AK-225G. By increasing the initial quantity of solvent from 200 mg to as much as 1,000 mg, reactions were observed at WSTF for all solvents, including AK-225G at 2,000 psi. Also, rather than performing the LOX Mechanical Impact Threshold Sensitivity test by the Bruceton method, WSTF performed threshold sensitivity tests by repeating up to 20 mechanical impacts at each lower energy level until a level was reached at which no reactions are observed in 20 impacts. This is a much more stringent test. Both the Solstice PF and the L-14780 exhibited lower threshold reaction levels by this test method than the reaction levels observed in the MSFC Bruceton tests. Additional tests were scheduled for completion by the end of 2014, extending beyond the period of performance for this contract. The results of these additional NASA-funded tests are reported in NASA/TP—2015–218207, "Replacement of Hydrochlorofluorocarbon-225 Solvent for Cleaning and Verification Sampling of NASA Propulsion Oxygen Systems Hardware, Ground Support Equipment, and Associated Test Systems."[2]

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Cleaning Effectiveness

The candidate replacement solvents, Honeywell Solstice PF and 3M L-14780, demonstrated satisfactory performance in the metals compatibility tests and the cleaning effectiveness tests. Both of these solvents are expected to be capable of cleaning metal components used in oxygen systems to meet the cleanliness requirements of those systems.

6.2 Nonmetallic Materials Compatibility

The candidate solvents performed comparably to AK-225G in compatibility tests with nonmetallic materials. Like AK-225G, Solstice PF and L-14780 should not be used to clean Buna N (NBR) rubber as significant weight loss was observed after immersion and drying. Solstice PF and L-14780 may be used with Vespel SP-21 and PEEK. FKM Compound V0747-75 (similar to Viton A) showed the least initial weight gain when immersed in Solstice PF with minimal change in weight and dimension after drying. A change in hardness was observed with some specimens. Use of Solstice PF may be acceptable with elastomeric compounds in this family when exposure is brief and adequate time is allowed for drying; this use must be evaluated by the user. The effect of Solstice PF and L-14780 on PTFE and PCTFE was similar to that of AK-225G. Solstice PF and L-14780 may be considered for use with PTFE and PCTFE in those applications where AK-225G was determined to be acceptable given minimal exposure and adequate drying times. Capstone 4-I had significantly more effect on PTFE than the other solvents but showed negligible effect on PCTFE. Solvokane also showed excellent compatibility with PCTFE.

6.3 Flammability and Oxygen Compatibility

Although both of the candidate solvents are reported by the vendors to be nonflammable at standard atmospheric pressure and oxygen concentration, neither of these solvents performed as well in the oxygen compatibility tests as AK-225G.

Data from this test project indicated that both Solstice PF and L-14780 will be safer to use for cleaning oxygen systems than known flammable alternatives such as isopropyl alcohol and cyclohexane. However, pending further data from ongoing NASA tests, additional precautions were recommended when using these solvents to clean oxygen systems to assure that all solvent has been removed after cleaning. Such precautions may include:

- Use of sensitive hydrocarbon detection devices (also known as ‘sniffers’) shown to be effective at detecting the solvent.

- Dry gas purge of the component/system cleaned, at a temperature substantially above the boiling point of the solvent. The boiling points of both Solstice PF and L-14780 are close to common ambient temperatures so a heated drying step should be feasible without damage to oxygen system components.

6.4 Precautions Regarding Use of Capstone 4-I as a Cleaning Solvent

Test data for DuPont Capstone 4-I, a product marketed as a chemical intermediate, indicate that this product as it is currently formulated is not safe for use as a cleaning solvent for metal oxygen system components. Although it was an effective cleaner on the contaminants tested and demonstrated good oxygen compatibility, Capstone 4-I caused rapid corrosion of the four metals tested for compatibility. Capstone 4-I is not pure perfluorobutyl iodide. It was not possible to determine, based on the testing performed in this study, whether perfluorobutyl iodide or one of the other constituents found in Capstone 4-I was the cause of the observed corrosion. The dramatic and rapid color changes observed during testing appeared to indicate that Capstone 4-I is chemically unstable even under indoor laboratory conditions. Silting of particulate and deposition of what appeared to be iodine on the interiors of sealed amber bottles containing what was reported to be pure Capstone 4-I further indicate that the stability of the product is unsuitable for production use as a cleaning solvent.

Metals compatibility test results in this study were not consistent with early test data reported by Dhooge et al.[9] for Ikon P, a product reported to be pure PFBI. The PFBI-based product tested and reported in AFRL-ML-WP-TR-2003-4040 was also DuPont Ikon P, but metals compatibility testing was not reported in that study. No degradation was noted in that report on the carbon steel used as the substrate for the coupon level static immersion cleaning study. Ikon P is no longer available from DuPont. Further inquiries with DuPont indicated that there is not a sufficient business case for the vendor to market Ikon P (>99% PFBI) as a cleaning solvent, or to address the stability concerns of Capstone 4-I that would be necessary to consider this product as a potentially viable cleaning solvent alternative.

APPENDIX A—CHARTS COMPARING WEIGHT CHANGE OF NONMETALS WITH THE TEST SOLVENTS

A.1 Weight Gain (or Loss) After Immersion in Test Solvents

Figures 45–104 are graphs of weight gain (or loss) for nonmetals after immersion in test solvents for 30, 60, and 90 days.

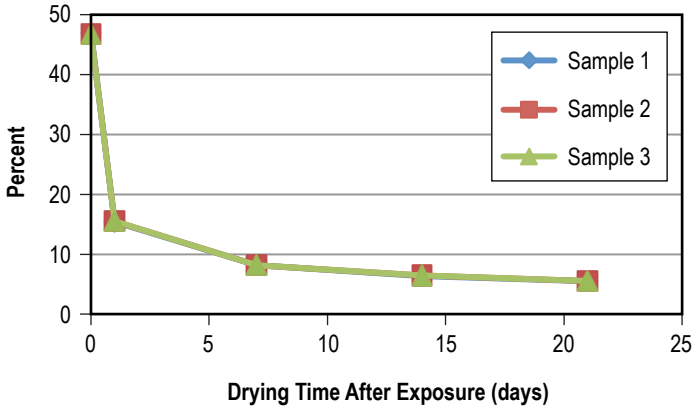

Figure 45. Weight gain of FKM V0747-75 after 30 days in AK-225G.

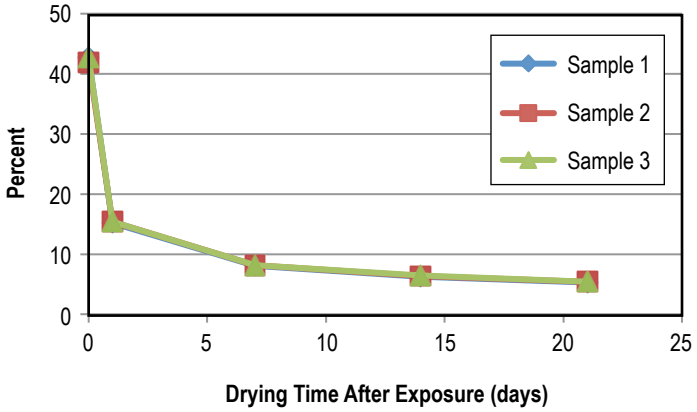

Figure 46. Weight gain of FKM V0747-75 after 60 days in AK-225G.

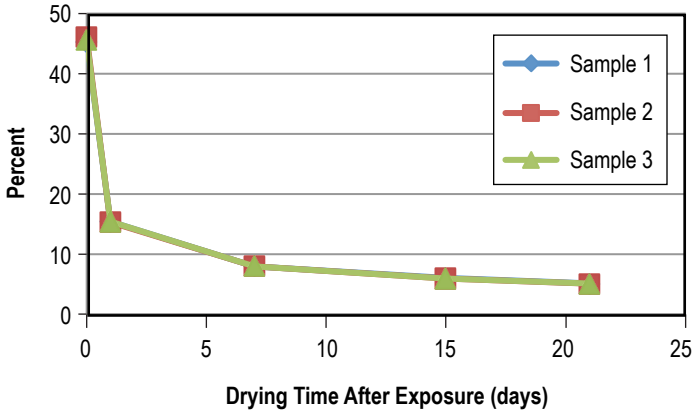

Figure 47. Weight gain of FKM V0747-75 after 90 days in AK-225G.

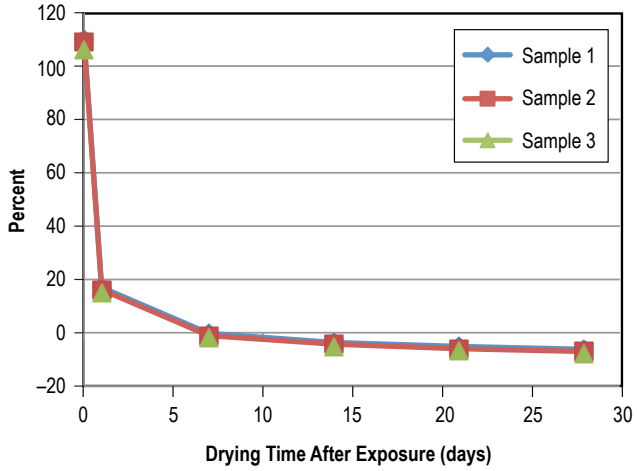

Figure 48. Weight gain (loss) of Buna N (NBR) after 30 days in AK-225G.

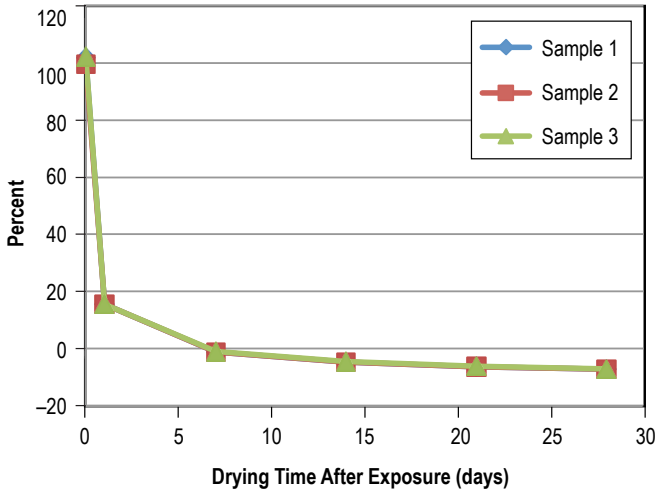

Figure 49. Weight gain (loss) of Buna N (NBR) after 60 days in AK-225G.

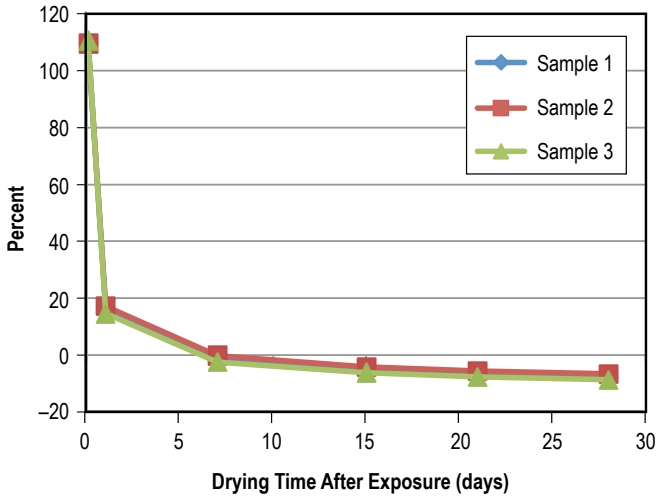

Figure 50. Weight gain (loss) of Buna N (NBR) after 90 days in AK-225G.

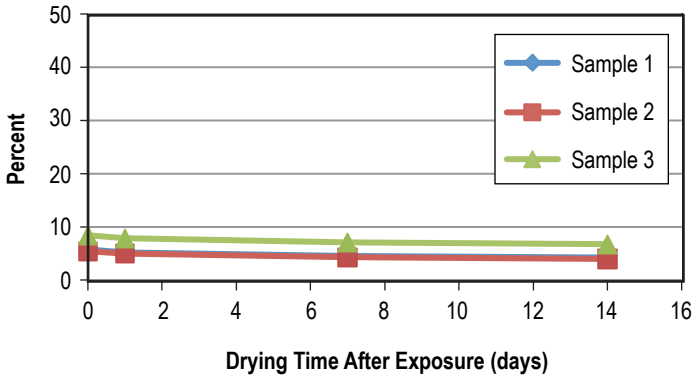

Figure 51. Weight gain of PTFE after 30 days in AK-225G.

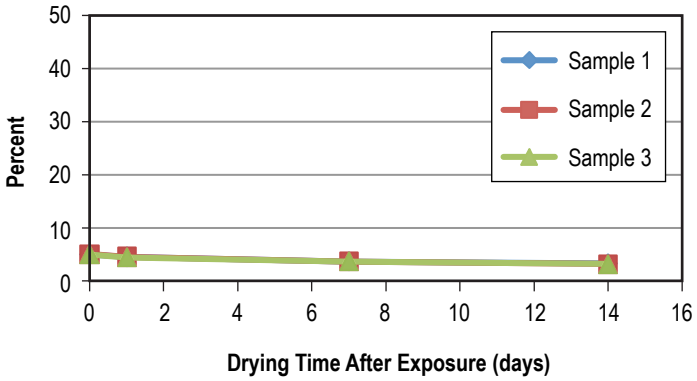

Figure 52. Weight gain of PTFE after 60 days in AK-225G.

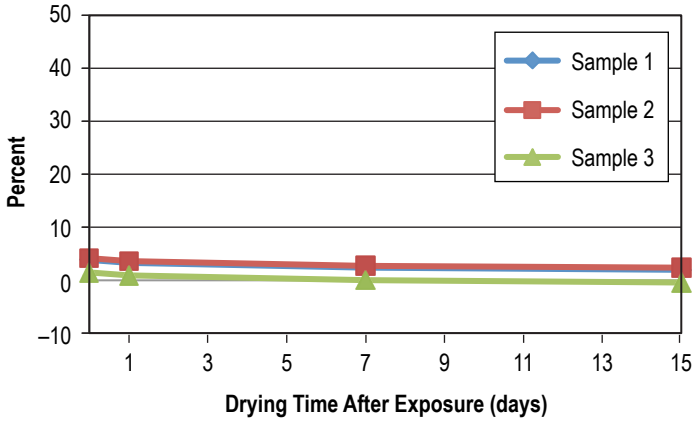

Figure 53. Weight gain of PTFE after 90 days in AK-225G.

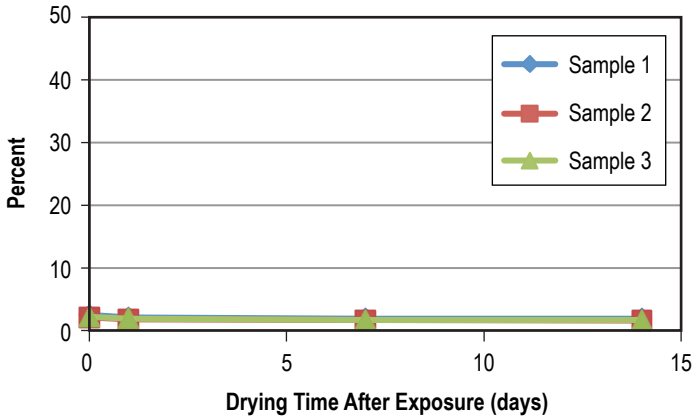

Figure 54. Weight gain of PCTFE after 30 days in AK-225G.

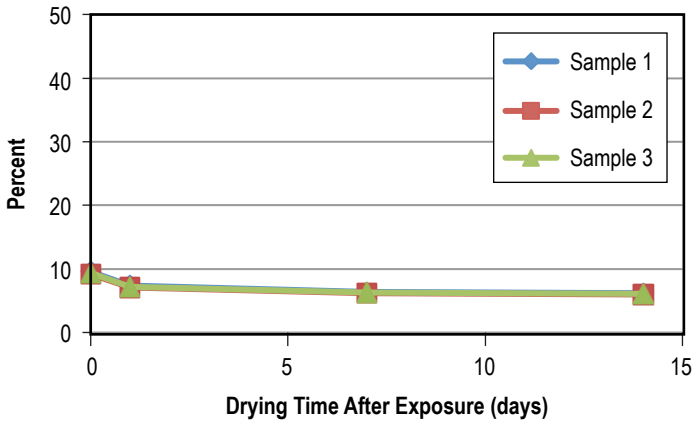

Figure 55. Weight gain of PCTFE after 60 days in AK-225G.

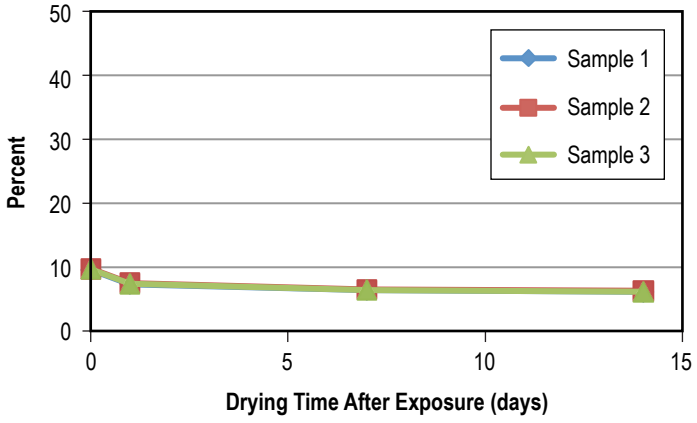

Figure 56. Weight gain of PCTFE after 90 days in AK-225G.

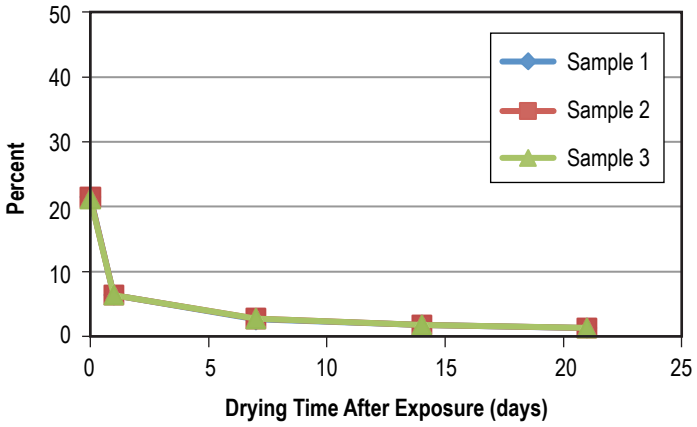

Figure 57. Weight gain of FKM V0747-75 after 30 days in Solstice PF.

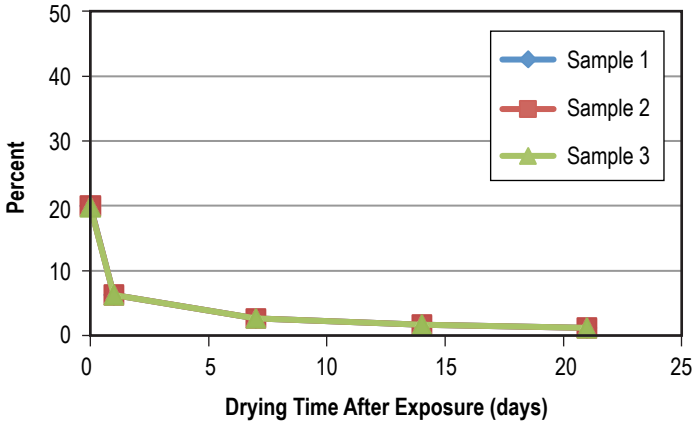

Figure 58. Weight gain of FKM V0747-75 after 60 days in Solstice PF.

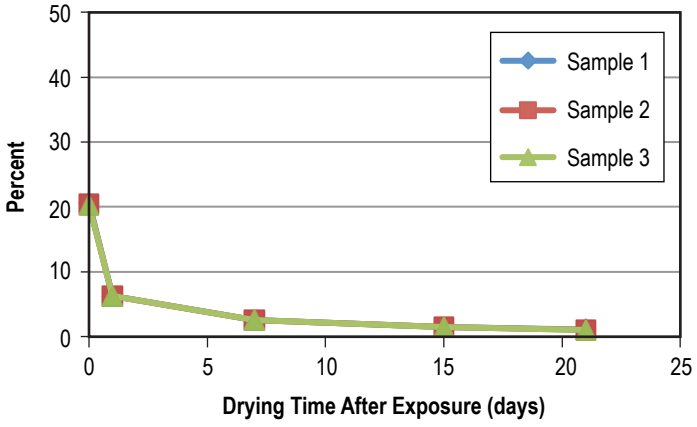

Figure 59. Weight gain of FKM V0747-75 after 90 days in Solstice PF.

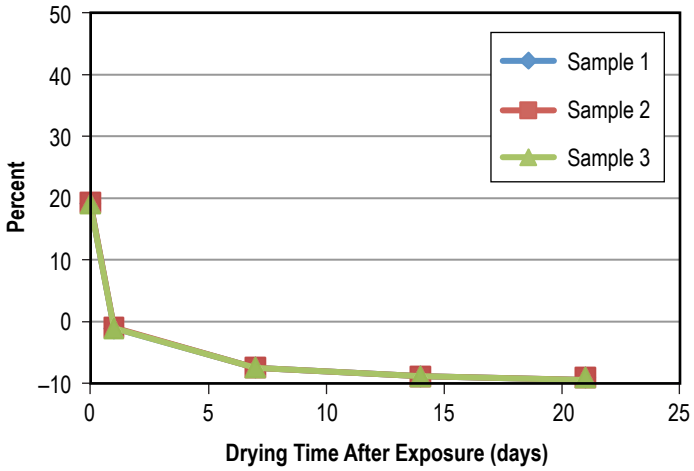

Figure 60. Weight gain (loss) of Buna N (NBR) after 30 days in Solstice PF.

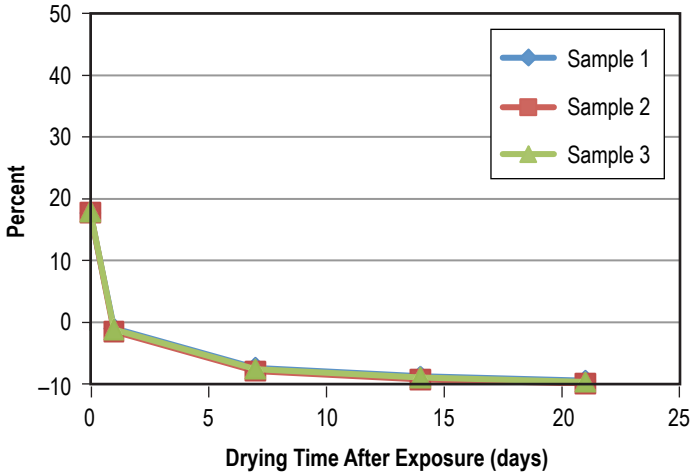

Figure 61. Weight gain (loss) of Buna N (NBR) after 60 days in Solstice PF.

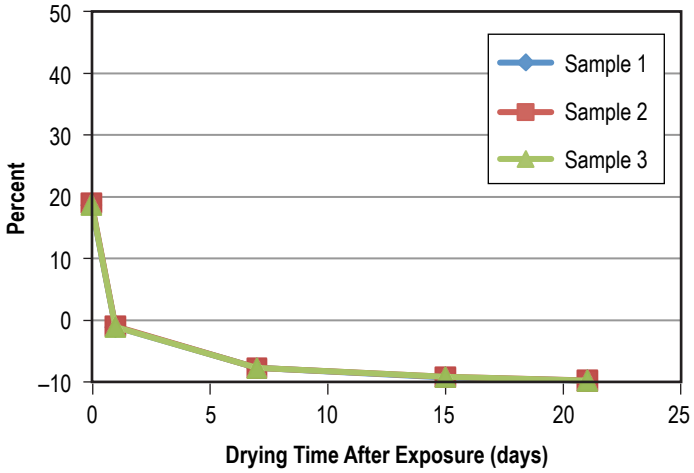

Figure 62. Weight gain (loss) of Buna N (NBR) after 90 days in Solstice PF.

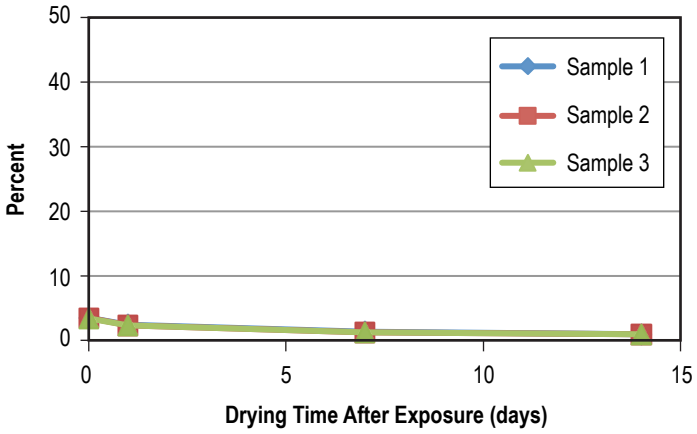

Figure 63. Weight gain of PTFE after 30 days in Solstice.

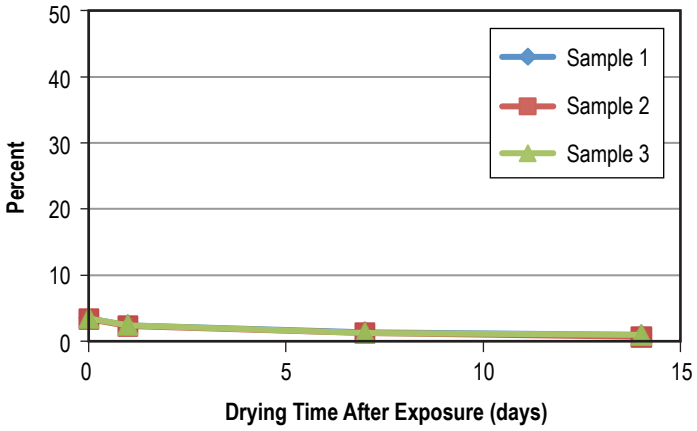

Figure 64. Weight gain of PTFE after 60 days in Solstice PF.

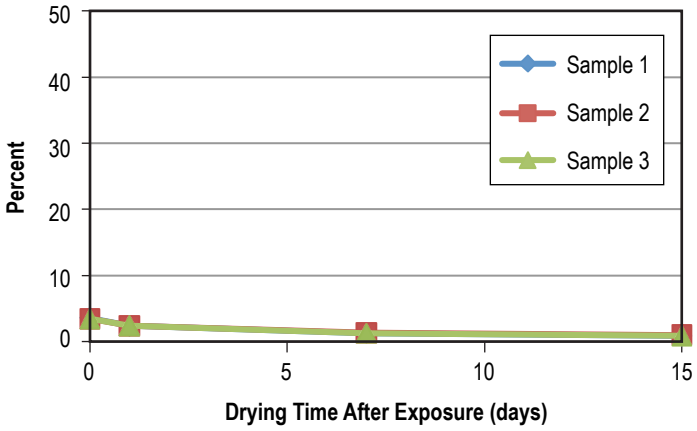

Figure 65. Weight gain of PTFE after 90 days in Solstice PF.

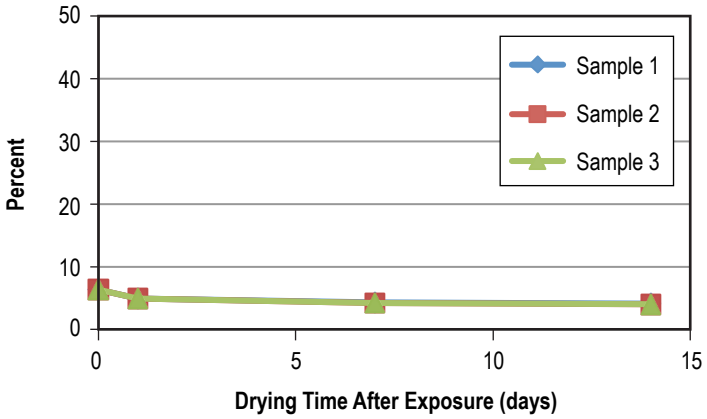

Figure 66. Weight gain of PCTFE after 30 days in Solstice PF.

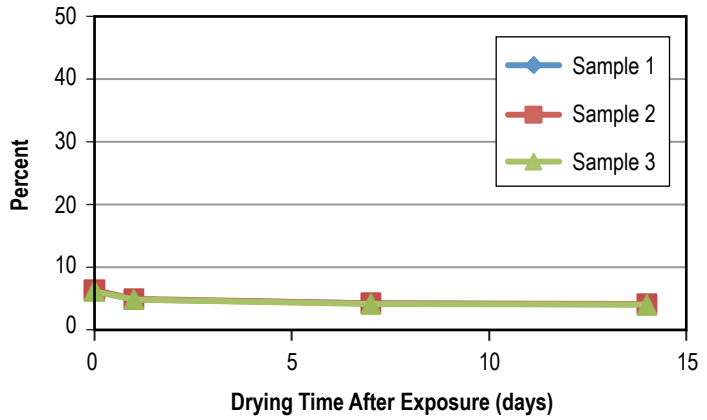

Figure 67. Weight gain of PCTFE after 60 days in Solstice PF.

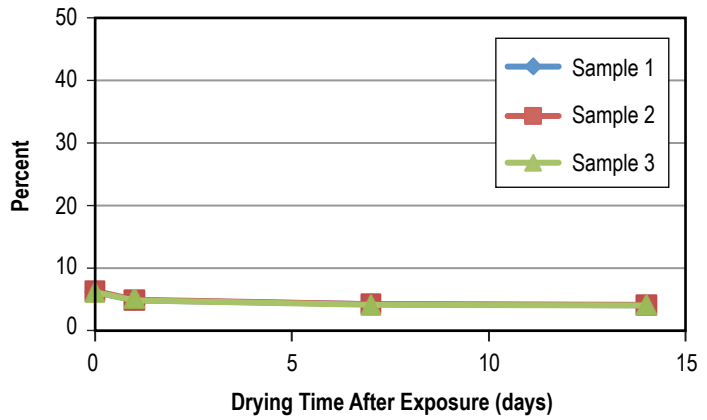

Figure 68. Weight gain of PCTFE after 90 days in Solstice PF.

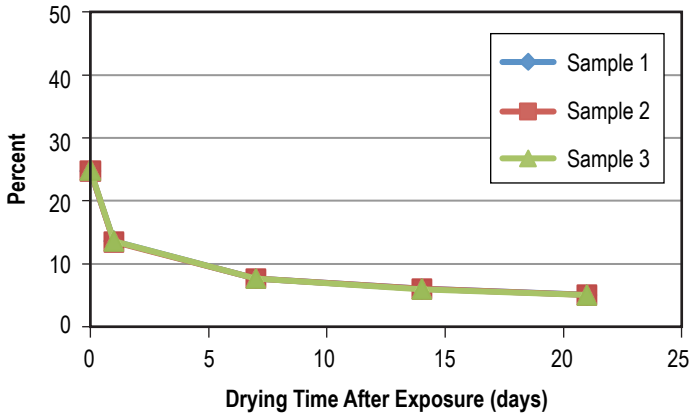

Figure 69. Weight gain of FKM V0747-75 after 30 days in L-14780.

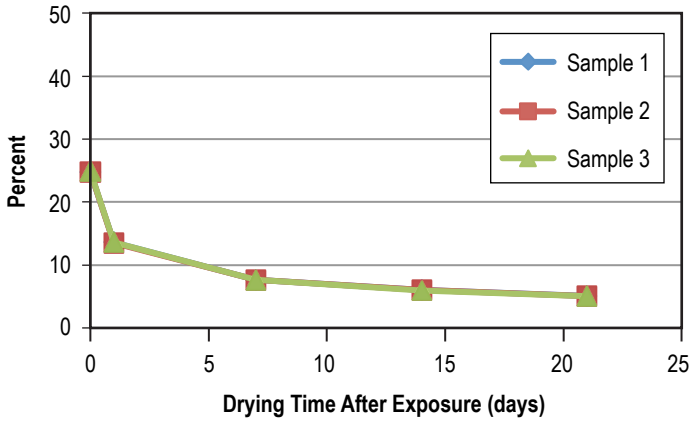

Figure 70. Weight gain of FKM V0747-75 after 60 days in L-14780.

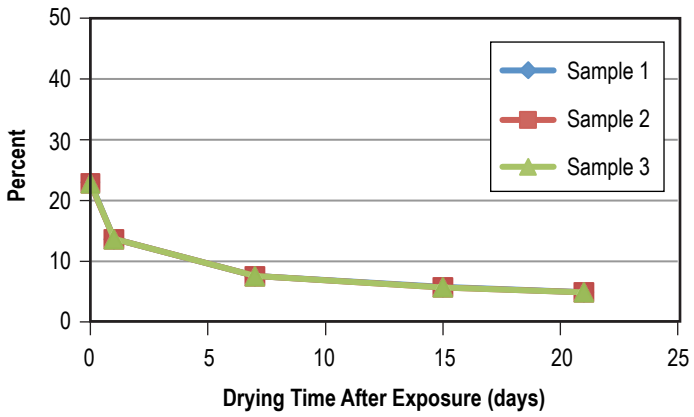

Figure 71. Weight gain of FKM V0747-75 after 90 days in L-14780.

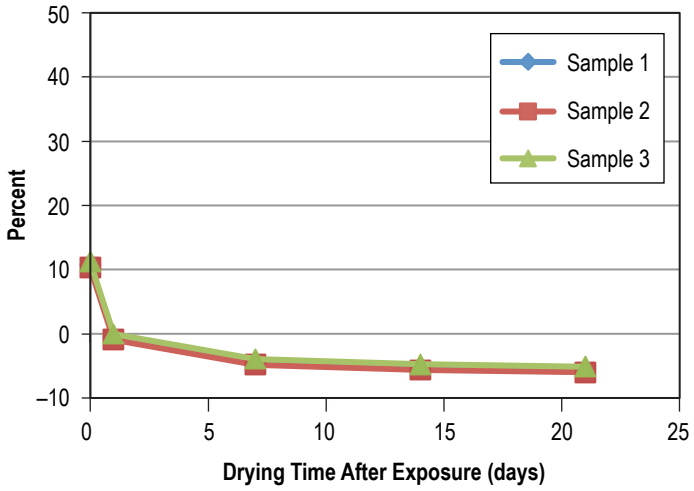

Figure 72. Weight gain (loss) of Buna N (NBR) after 30 days in L-14780.

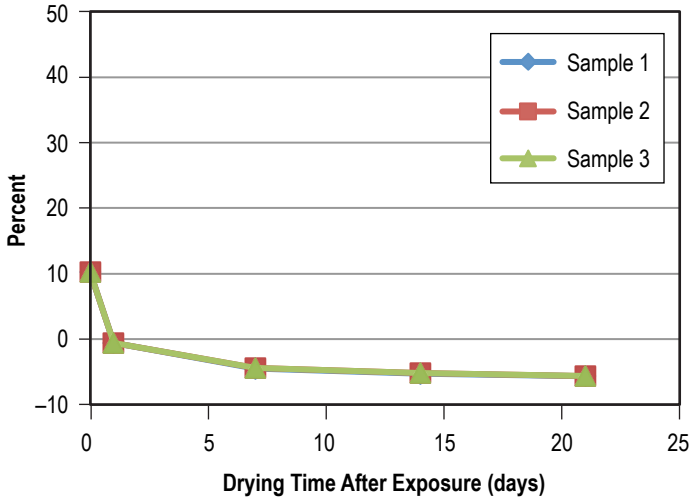

Figure 73. Weight gain (loss) of Buna N (NBR) after 60 days in L-14780.

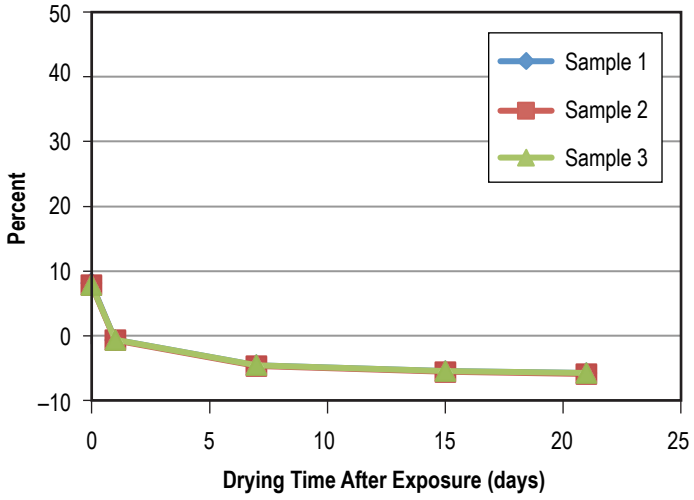

Figure 74. Weight gain (loss) of Buna N (NBR) after 90 days in L-14780.

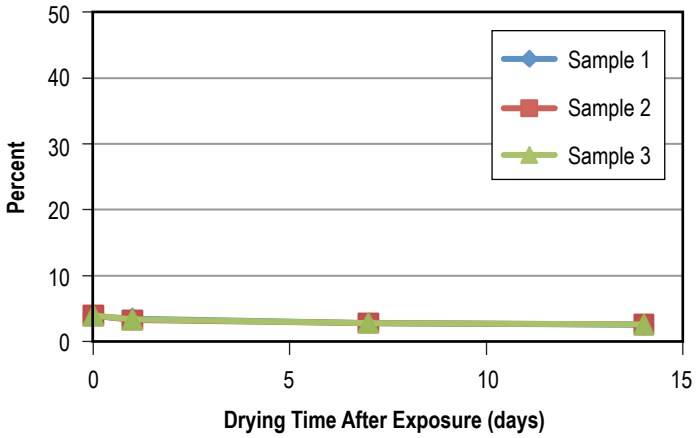

Figure 75. Weight gain of PTFE after 30 days in L-14780.

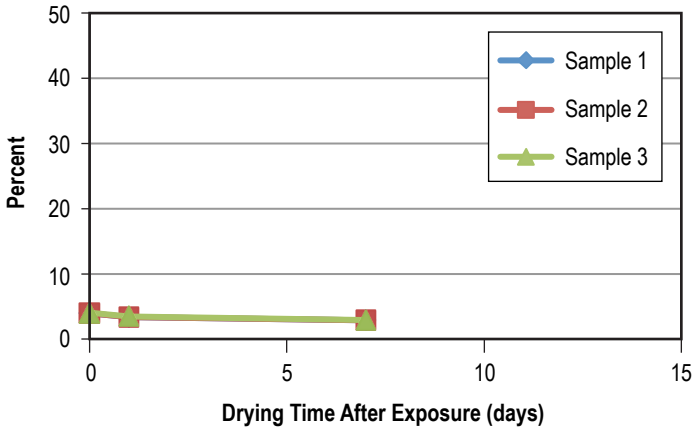

Figure 76. Weight gain of PTFE after 60 days in L-14780.

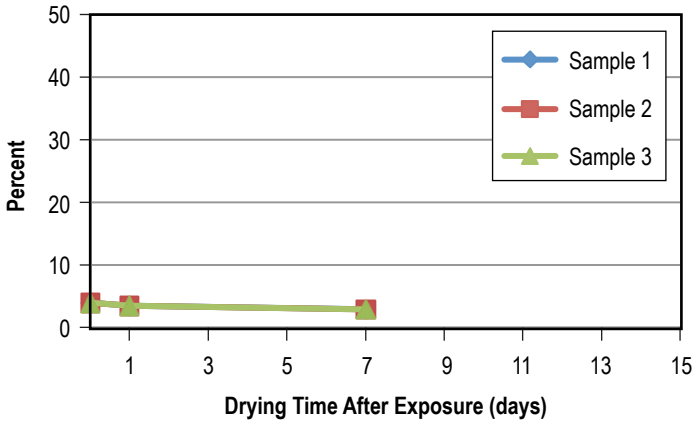

Figure 77. Weight gain of PTFE after 90 days in L-14780.

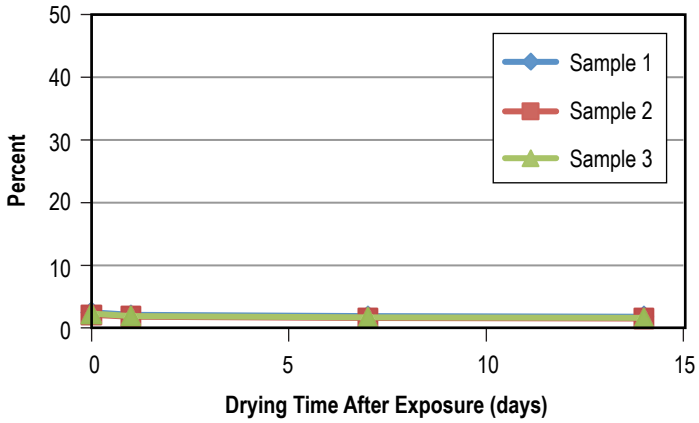

Figure 78. Weight gain of PCTFE after 30 days in L-14780.

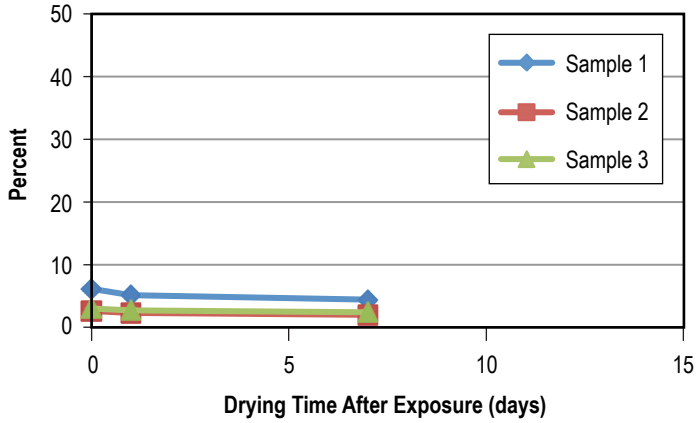

Figure 79. Weight gain of PCTFE after 60 days in L-14780.

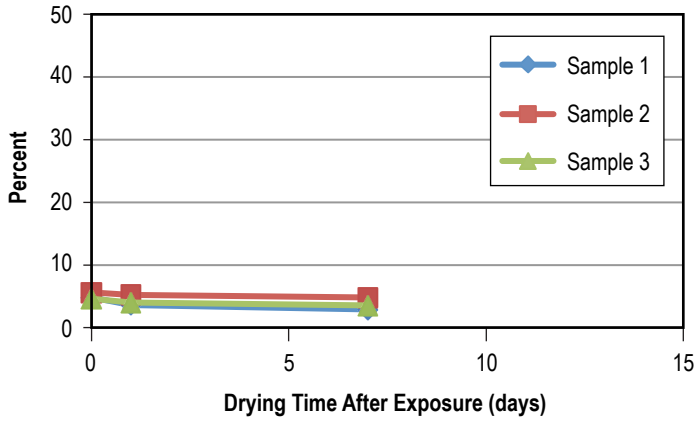

Figure 80. Weight gain of PCTFE after 90 days in L-14780.

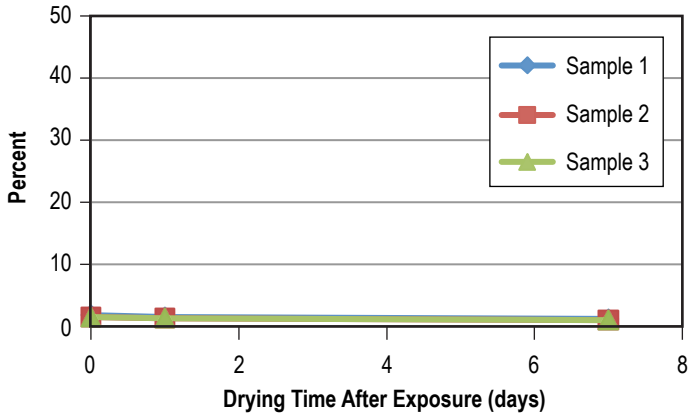

Figure 81. Weight gain of Vespel SP-21 after 30 days in L-14780.

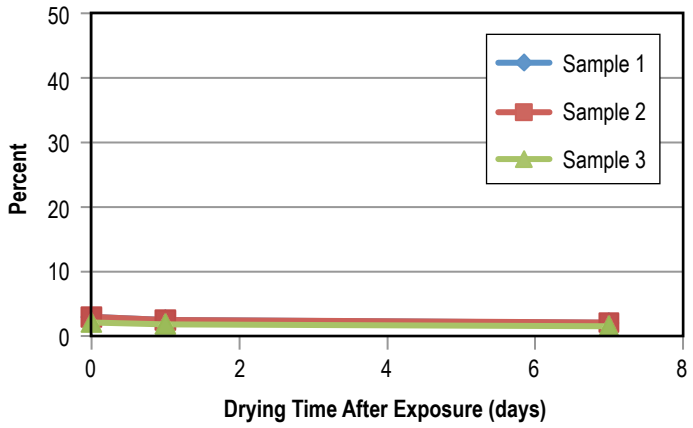

Figure 82. Weight gain of Vespel SP-21 after 60 days in L-14780.

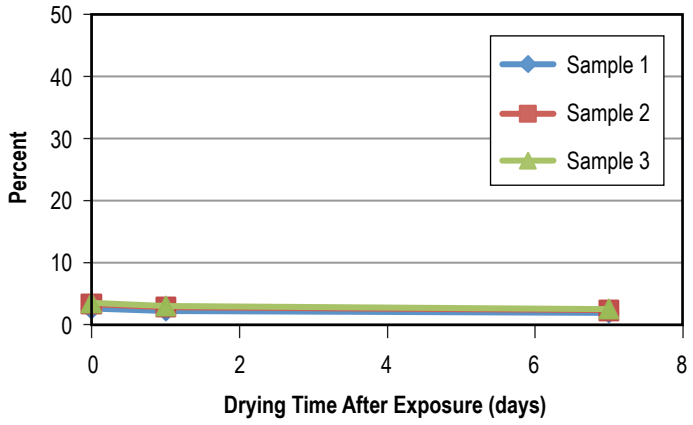

Figure 83. Weight gain of Vespel SP-21 after 90 days in L-14780.

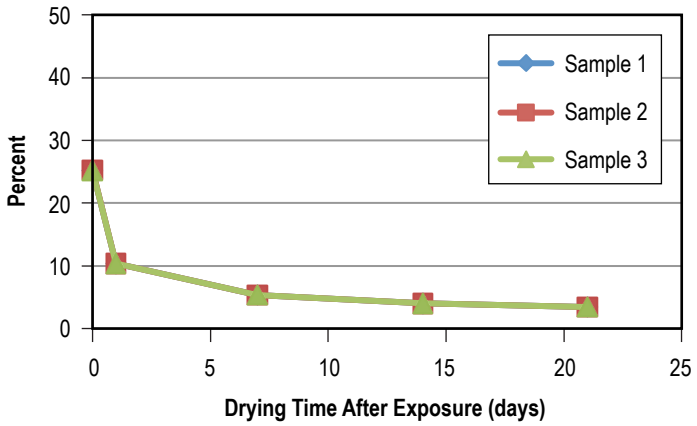

Figure 84. Weight gain of FKM V0747-75 after 30 days in Solvokane.

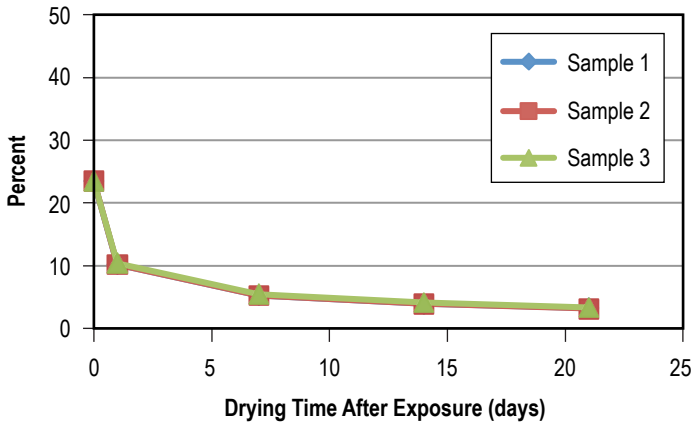

Figure 85. Weight gain of FKM V0747-75 after 60 days in Solvokane.

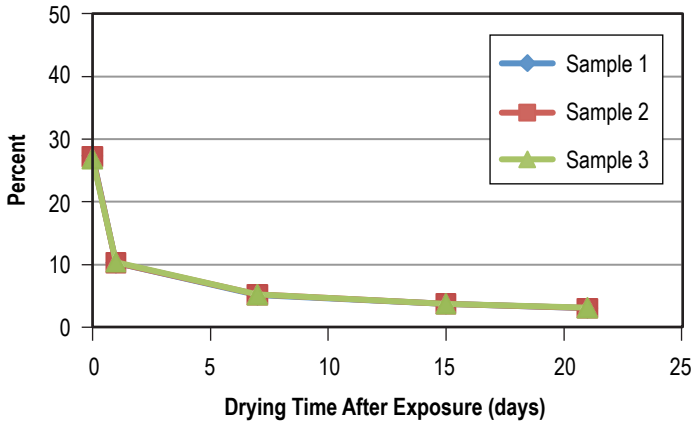

Figure 86. Weight gain of FKM V0747-75 after 90 days in Solvokane.

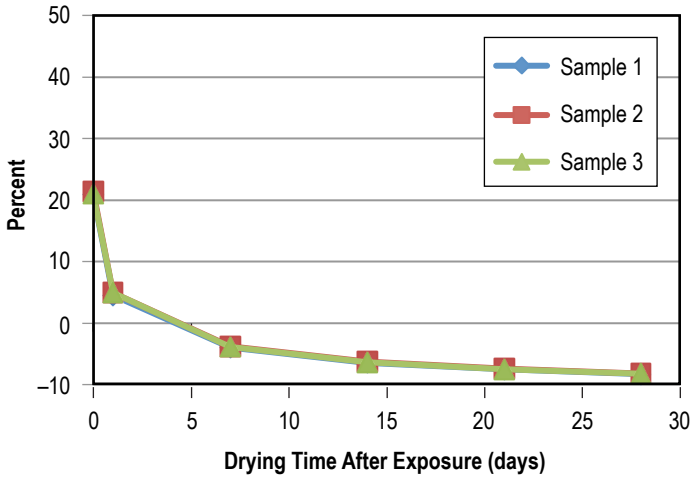

Figure 87. Weight gain (loss) of Buna N (NBR) after 30 days in Solvokane.

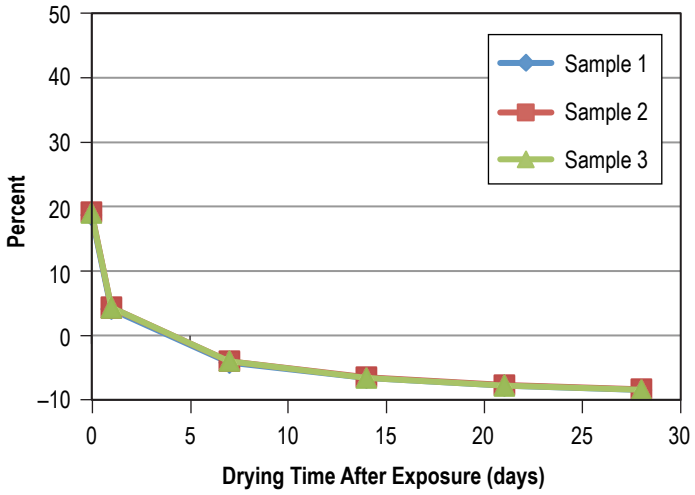

Figure 88. Weight gain (loss) of Buna N (NBR) after 60 days in Solvokane.

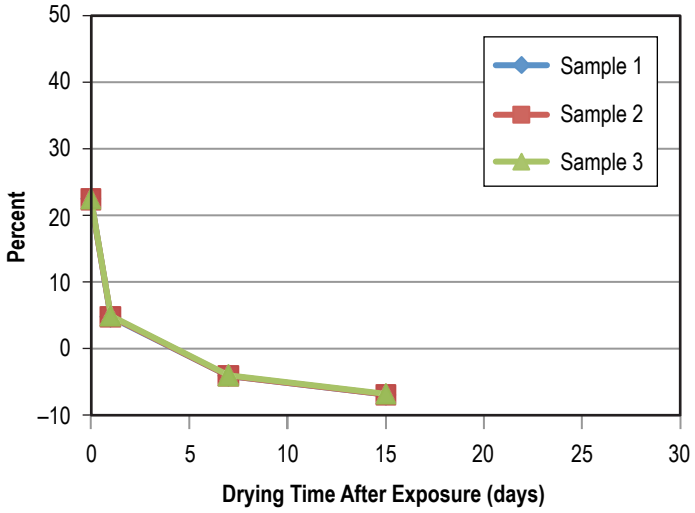

Figure 89. Weight gain (loss) of Buna N (NBR) after 90 days in Solvokane.

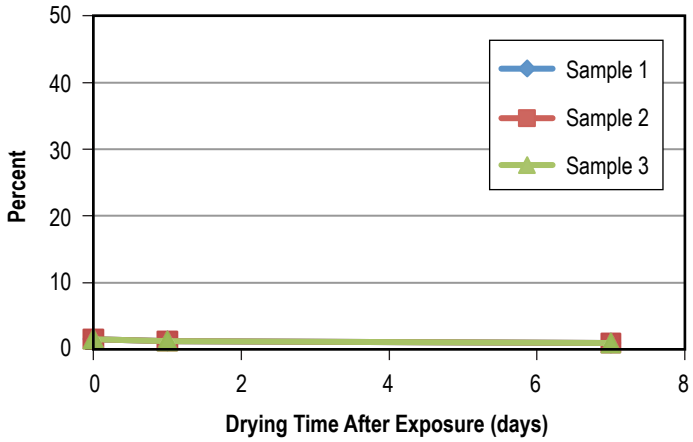

Figure 90. Weight gain of PTFE after 30 days in Solvokane.

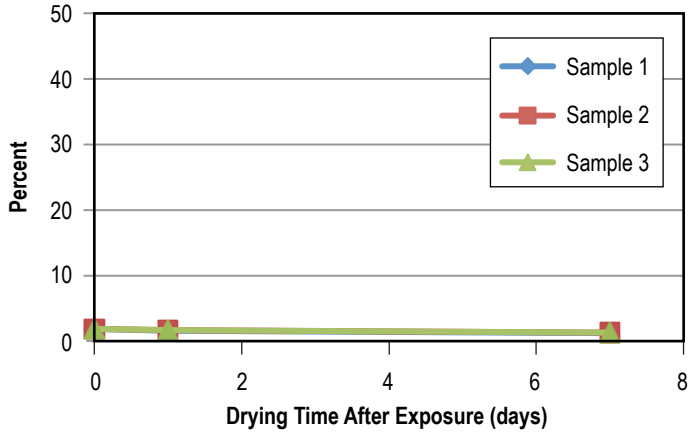

Figure 91. Weight gain of PTFE after 60 days in Solvokane.

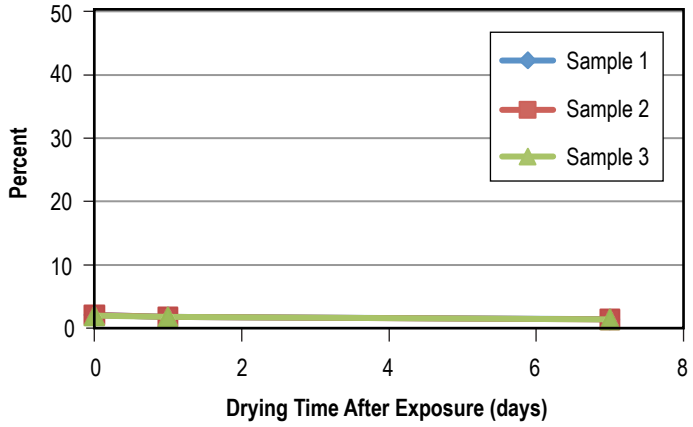

Figure 92. Weight gain of PTFE after 90 days in Solvokane.

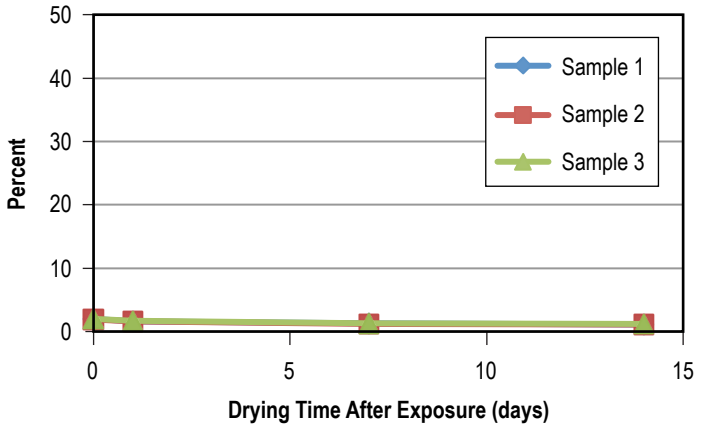

Figure 93. Weight gain of Vespel SP21 after 30 days in Solvokane.

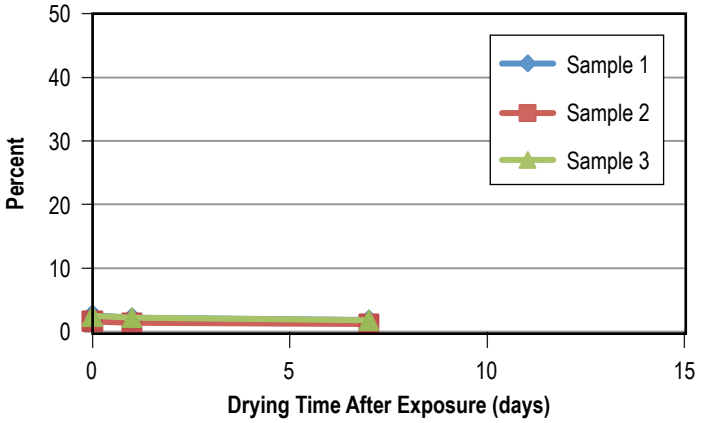

Figure 94. Weight gain of Vespel SP21 after 60 days in Solvokane.

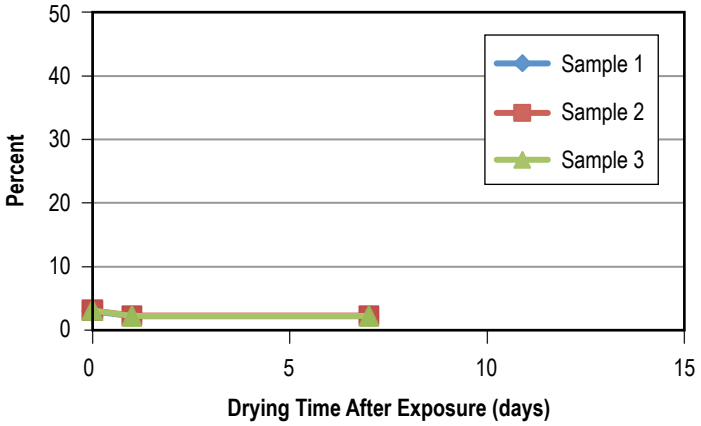

Figure 95. Weight gain of Vespel SP21 after 90 days in Solvokane.

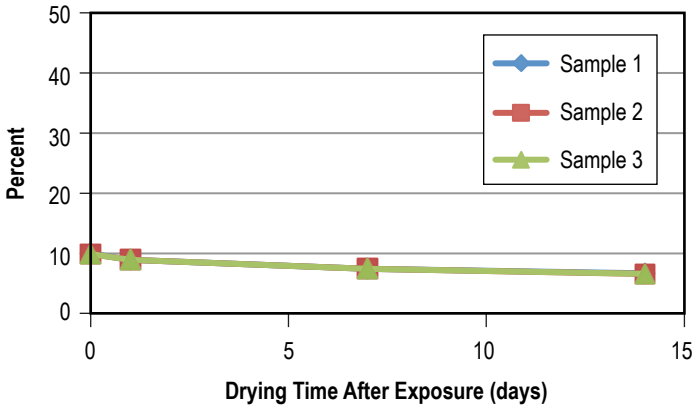

Figure 96. Weight gain of FKM V0747-75 after 30 days in Capstone 4-I.

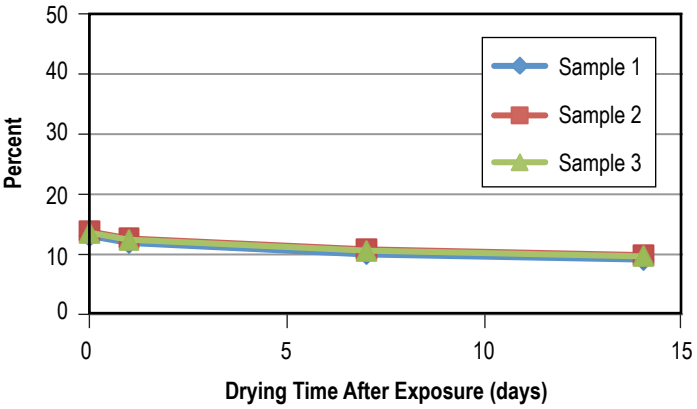

Figure 97. Weight gain of FKM V0747-75 after 60 days in Capstone 4-I.

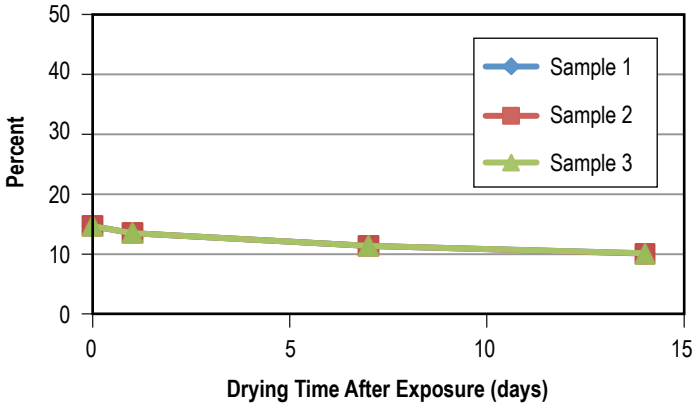

Figure 98. Weight gain of FKM V0747-75 after 90 days in Capstone 4-I.

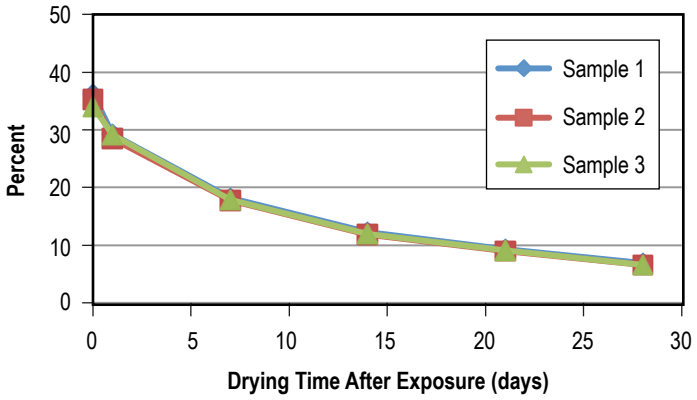

Figure 99. Weight gain of Buna N (NBR) after 30 days in Capstone 4-I.

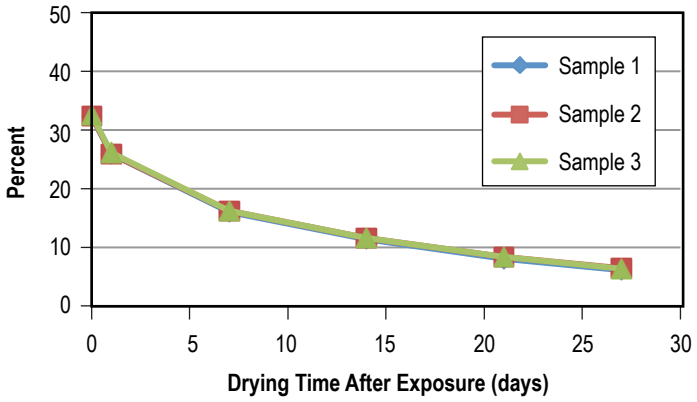

Figure 100. Weight gain of Buna N (NBR) after 60 days in Capstone 4-I.

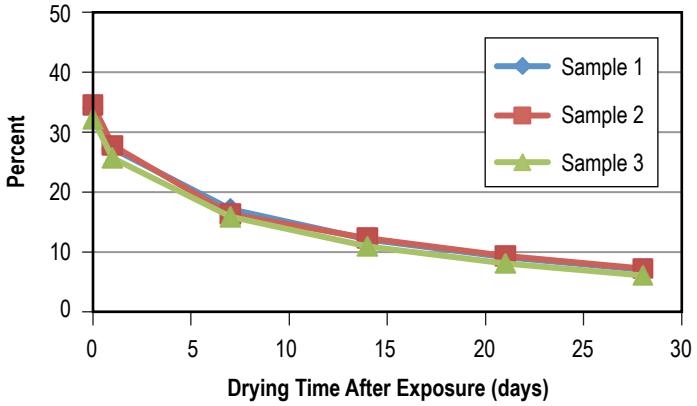

Figure 101. Weight gain of Buna N (NBR) after 90 days in Capstone 4-I.

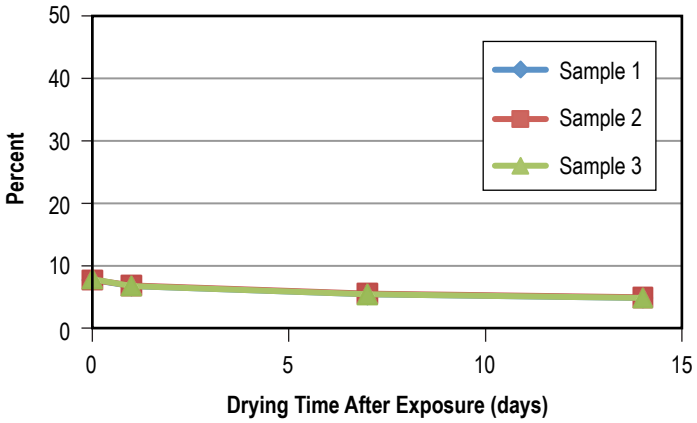

Figure 102. Weight gain of PTFE after 30 days in Capstone 4-I.

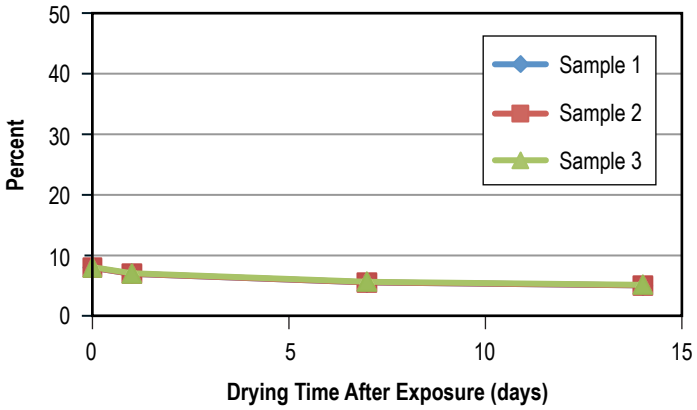

Figure 103. Weight gain of PTFE after 60 days in Capstone 4-I.

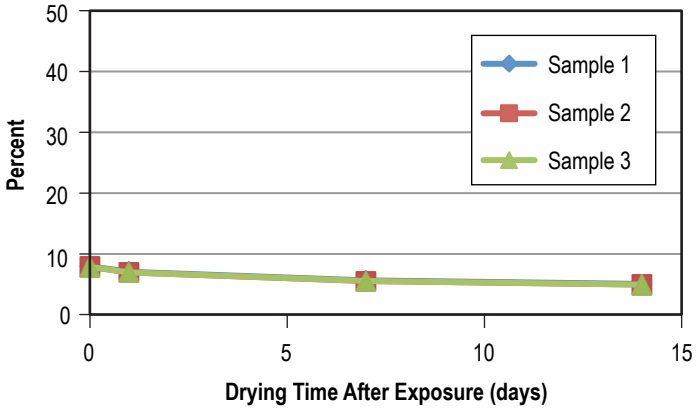

Figure 104. Weight gain of PTFE after 90 days in Capstone 4-I.

A.2 Weight Change Comparison When Exposed to Test Solvents

Figures 105–122 are bar charts comparing the weight change of nonmetals when exposed to test solvents for 30, 60, and 90 days.

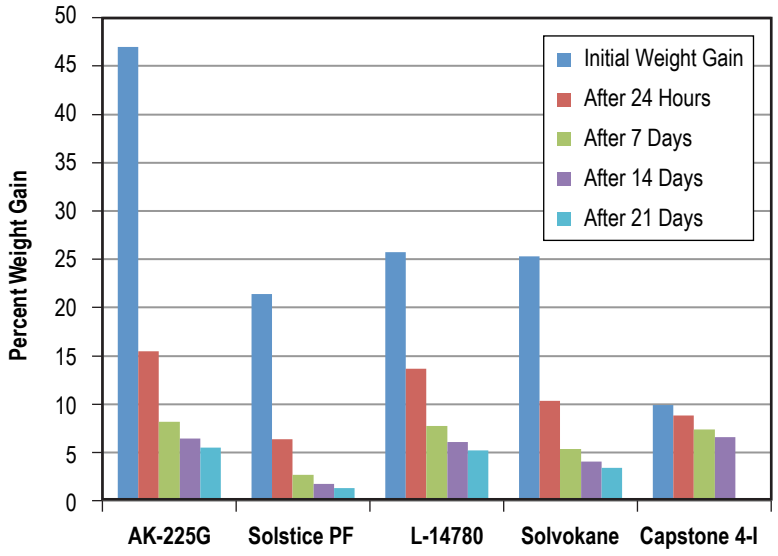

Figure 105. Weight gain of FKM V0747-75 retained after 30-day immersion in five solvents.

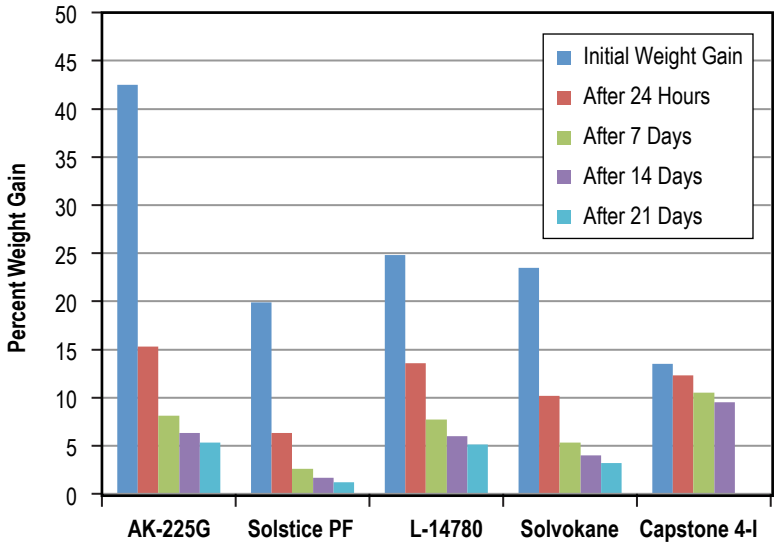

Figure 106. Weight gain of FKM V0747-75 retained after 60-day immersion in five solvents.

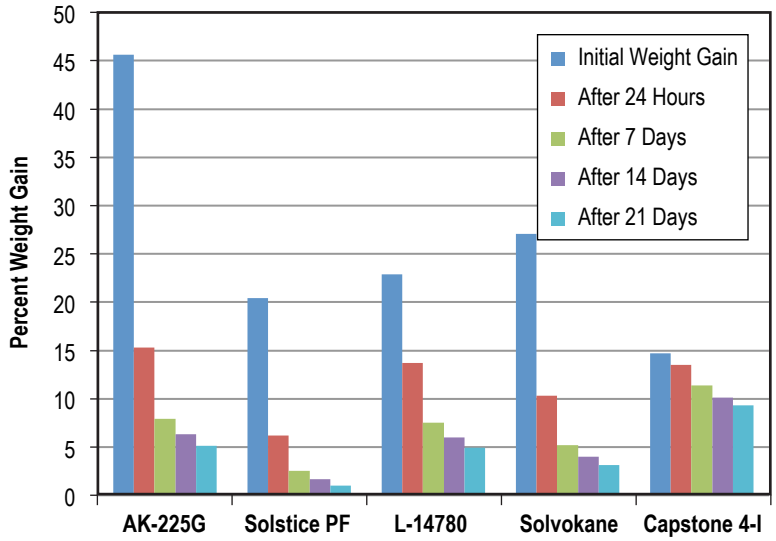

Figure 107. Weight gain of FKM V0747-75 retained after 90-day immersion in five solvents.

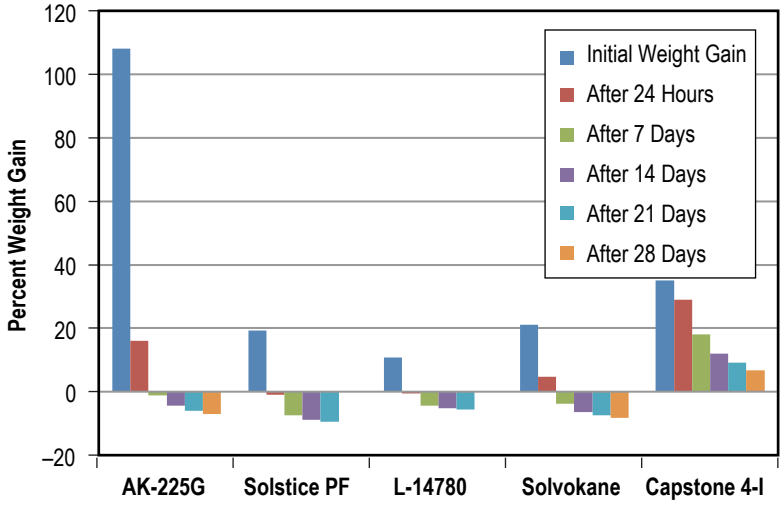

Figure 108. Weight gain (loss) of Buna N (NBR) retained after 30-day immersion in five solvents.

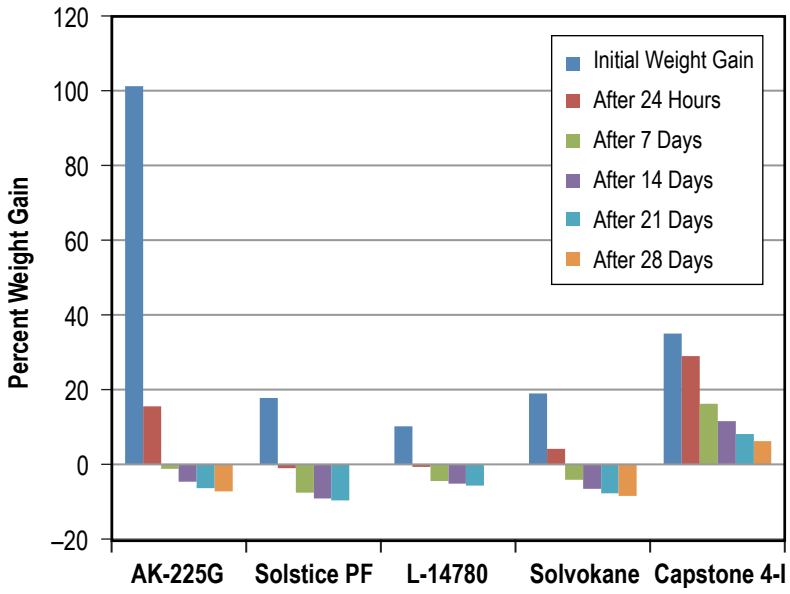

Figure 109. Weight gain (loss) of Buna N (NBR) retained after 60-day immersion in five solvents.

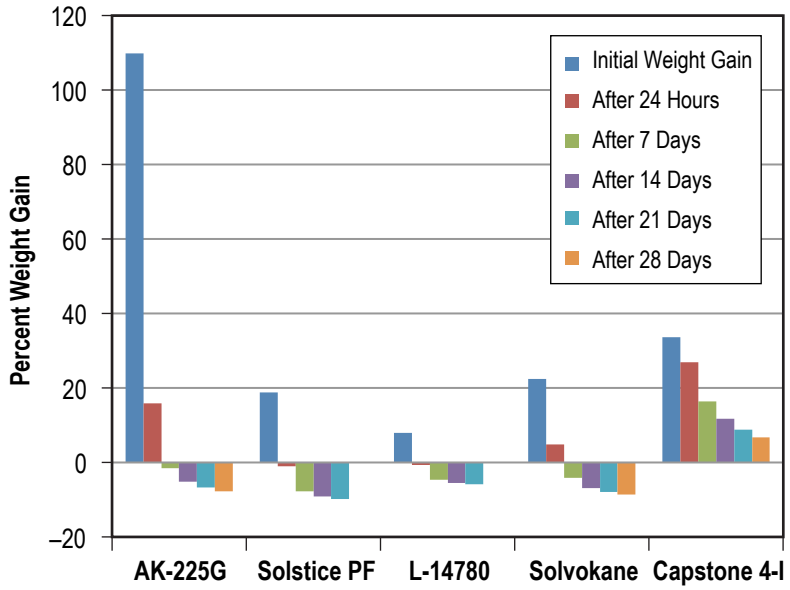

Figure 110. Weight gain (loss) of Buna N (NBR) retained after 90-day immersion in five solvents.

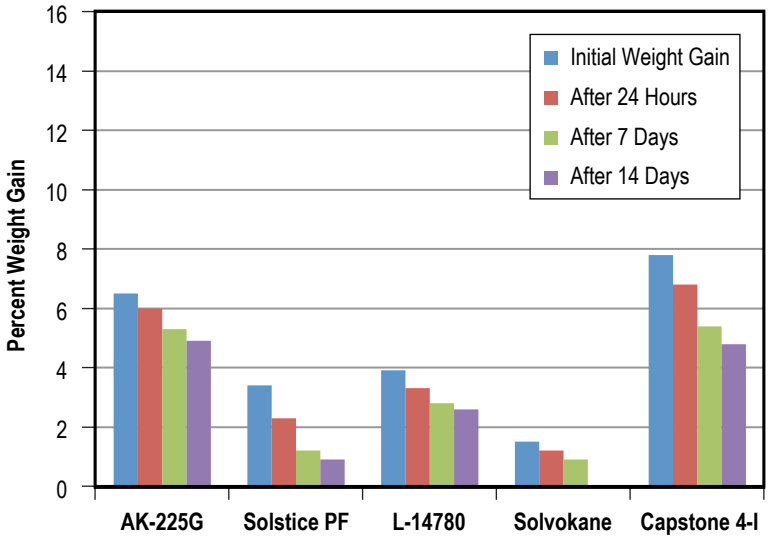

Figure 111. Weight gain of PTFE retained after 30-day immersion in five solvents.

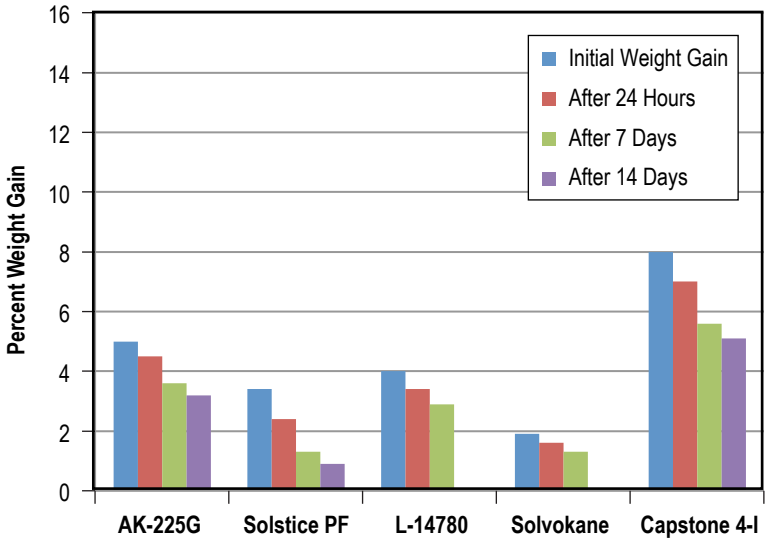

Figure 112. Weight gain of PTFE retained after 60-day immersion in five solvents.

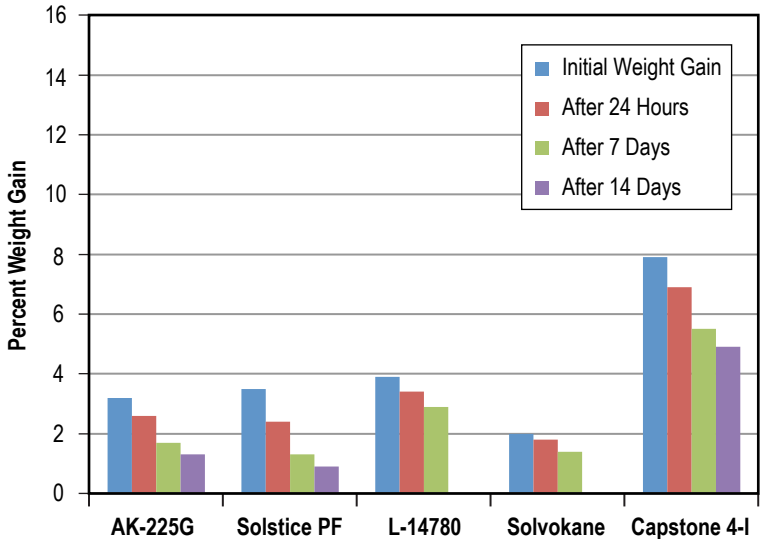

Figure 113. Weight gain of PTFE retained after 90-day immersion in five solvents.

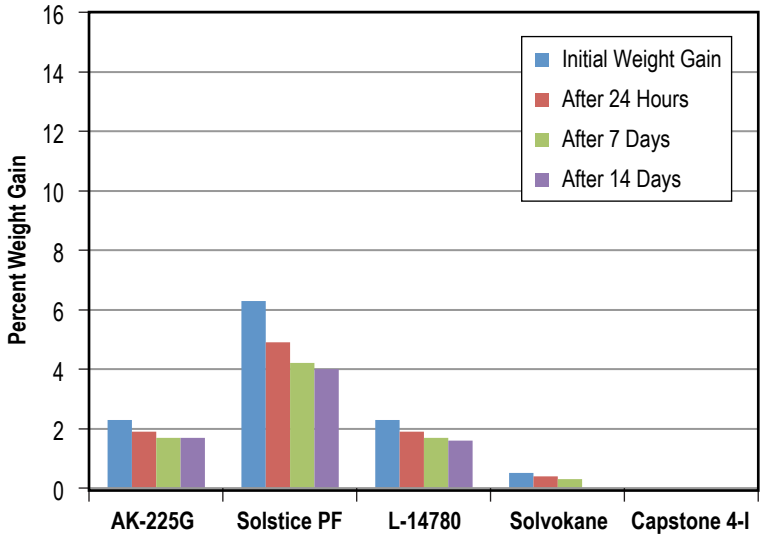

Figure 114. Weight gain of Kel-F PCTFE retained after 30-day immersion in five solvents.

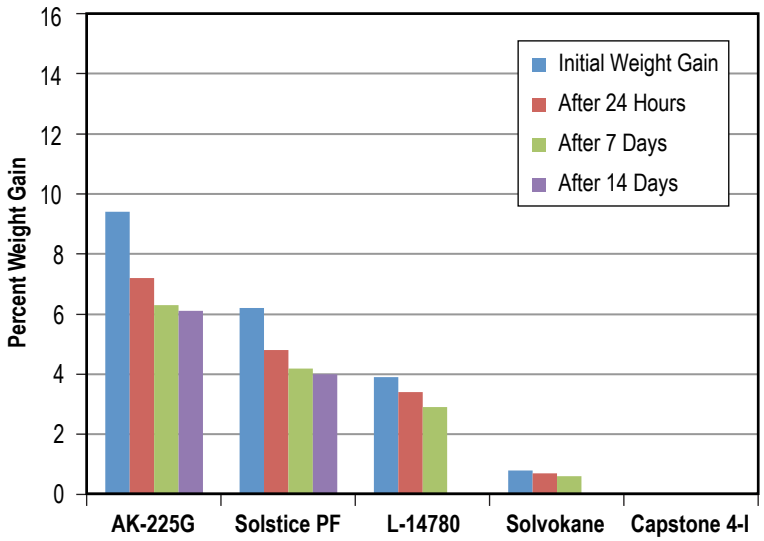

Figure 115. Weight gain of Kel-F PCTFE retained after 60-day immersion in five solvents.

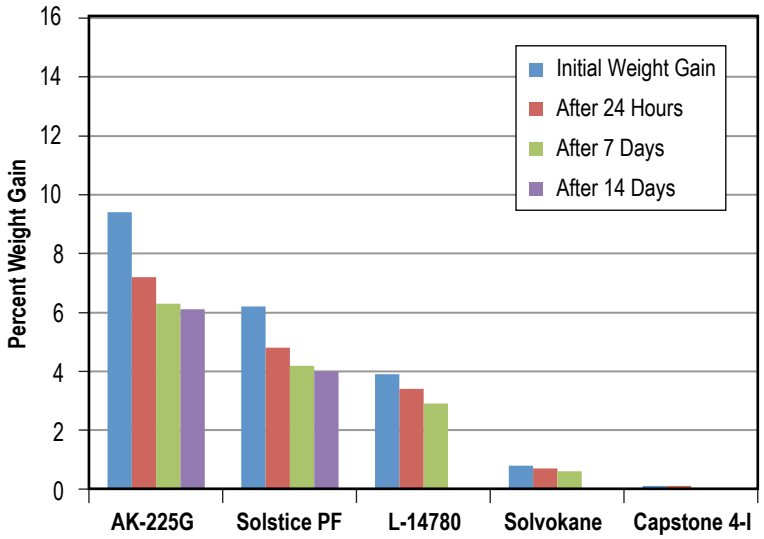

Figure 116. Weight gain of Kel-F PCTFE retained after 90-day immersion in five solvent.

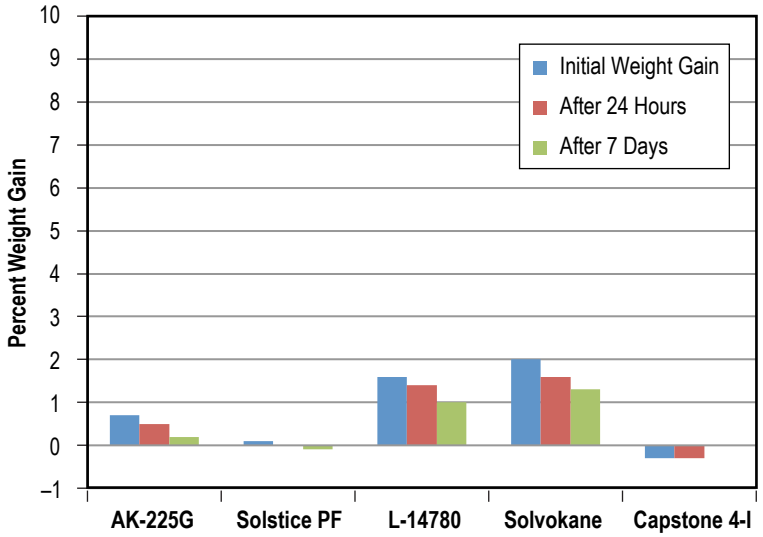

Figure 117. Weight gain (loss) of Vespel SP-21 retained after 30-day immersion in five solvents.

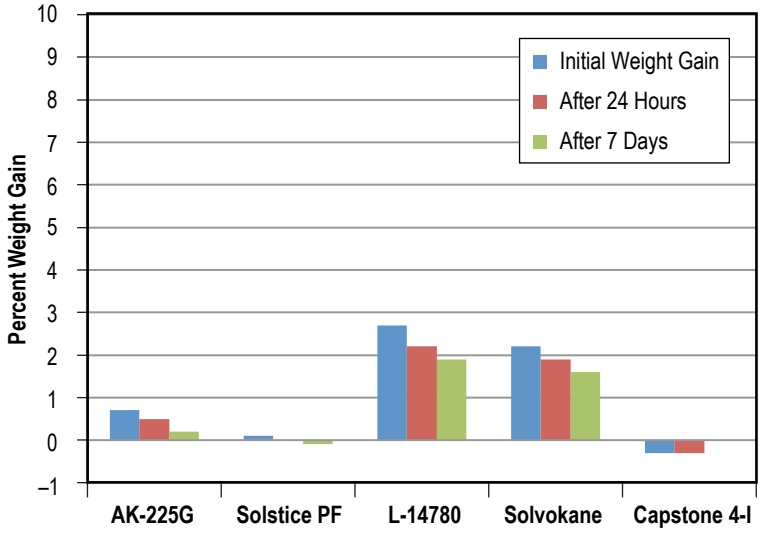

Figure 118. Weight gain (loss) of Vespel SP-21 retained after 60-day immersion in five solvents.

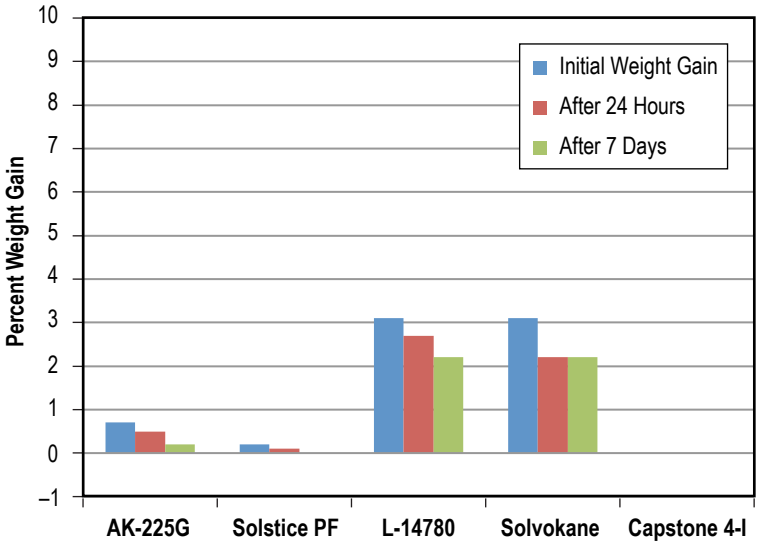

Figure 119. Weight gain of Vespel SP-21 retained after 90-day immersion in five solvents.

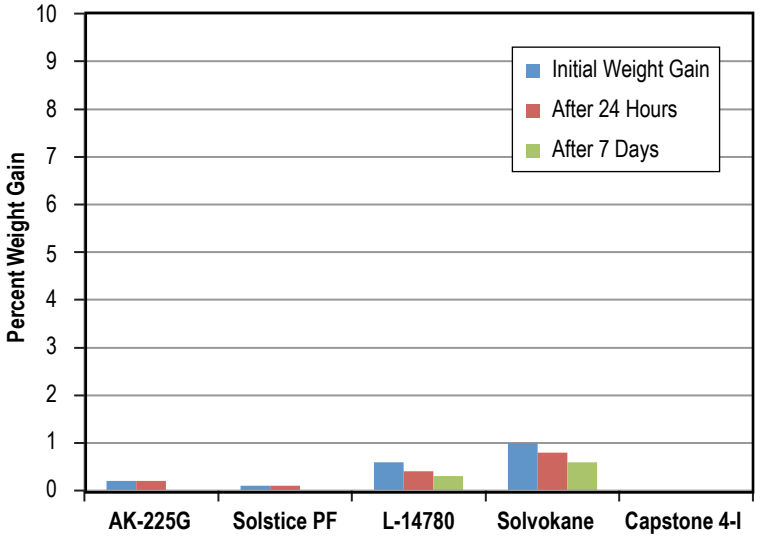

Figure 120. Weight gain of PEEK retained after 30-day immersion in five solvents.

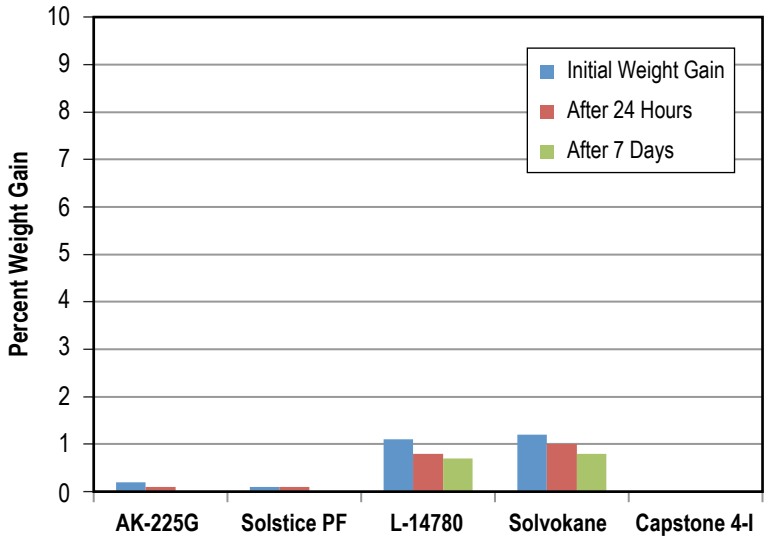

Figure 121. Weight gain of PEEK retained after 60-day immersion in five solvents.

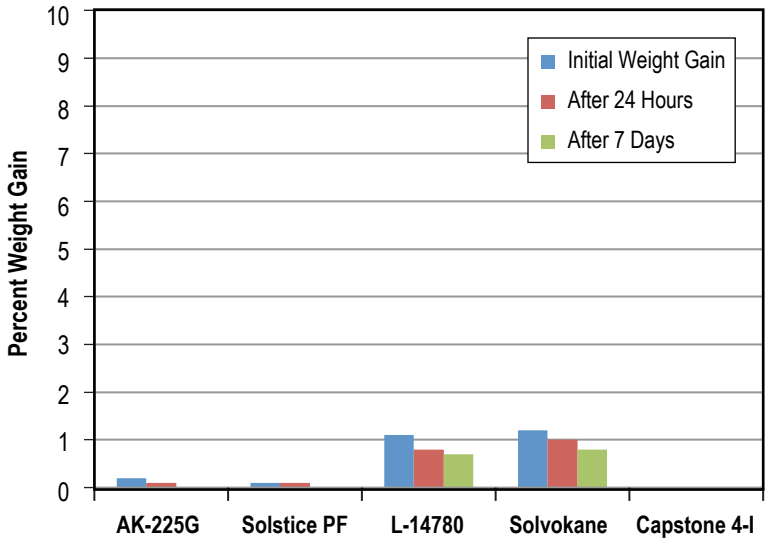

Figure 122. Weight gain of PEEK retained after 90-day immersion in five solvents.

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14. ABSTRACT

To eliminate the use of ozone-depleting substances, a replacement solvent is required for hydrochlorofluorocarbon (HCFC-225) that is effective at removing oil, grease, and particulate from oxygen system components, is compatible with materials used in construction of these systems, and is nonflammable and nonreactive in enriched oxygen systems. The purpose of this limited study was to evaluate the suitability of solvents for cleaning oxygen system components. Two candidate solvents were tested and compared to the performance of the baseline solvents HCFC-225 and perfluorobutyl iodide. Tests included metal corrosion, nonmetal compatibility, cleaning effectiveness, and oxygen compatibility.

15. SUBJECT TERMS

solvent, oxygen cleaning, ozone depletion, HCFC-225, nonvolatile residue

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