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Application of O-Ring Studies to the Extended Maintenance Cycle of Type B Radioactive Material Packages

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ABSTRACT
Type B radioactive material package elastomeric O-rings have, historically, been replaced annually to satisfy inspection requirements of ANSI N14.5[1]. The recently approved ANSI N14.5-2014[2] allows for an alternative inspection frequency with appropriate justification. This paper examines the available data, evaluates potential failure mechanisms, and recommends a reduced inspection frequency based on characteristics of transportation and storage environments.

INTRODUCTION
American National Standards Institute Standard ANSI N14.5-2014 specifies methods for leak testing Type B radioactive material packages which satisfy Code of Federal Regulation, Title 10, Part 71.51. ANSI N14.5, Table 1, requires the packaging containment boundary be confirmed 12 months prior to use to ensure that no degradation of components subject to wear has occurred. Historically, the most demanding aspect of the required periodic inspection has been the testing of the elastomeric O-rings that form the replaceable closure portion of the package containment boundary.

The annual inspection/replacement schedule required by ANSI N14.5 is based on early probabilistic analysis of O-ring manufacturing data and recommendations.[3] The recently adopted ANSI N14.5-2014 standard continues to specify periodic annual leak testing but provides for approval of an alternate inspection frequency if justified and approved by the applicable regulatory authority. Aging studies of H1616 Shipping package EPDM O-Ring material, performance testing of Model 9975 FKM O-Rings and emerging studies being performed by BAM Federal Institute for Materials Research and Testing on EPDM, FKM and HNBR material provide a sound technical basis for adoption of a decreased inspection interval for packages used in transportation with similar seals and transportation environments.

REGULATORY REQUIREMENTS
Radioactive material packaging must meet the quality assurance requirements for design, purchase, fabrication and maintenance, and other aspects of package development specified in 10 CFR 71.101(a). Quality assurance is defined as “all those planned and systematic actions necessary to provide adequate

confidence that a system or component will perform satisfactorily in service". 10 CFR 71.101 part (a) further states that "The licensee shall apply each of the applicable criteria in a graded approach, i.e., to an extent that is consistent with its importance to safety". The Quality Assurance maintenance requirements of Subpart H, 10 CFR 71.101(a) are implemented in Chapter 8 of the associated Safety Analysis for Radioactive Material Packaging (SARP) in accordance with guidance from NRC Regulatory Guide (RG) 7.4.[4] RG 7.4,originally published to endorse ANSI N14.5-1973, currently advises that maintenance and periodic practices be based on ANSI N14.5-1997. The ANSI Standard states that each package must be subjected to tests and inspections "annually". Annual requirements include a leakage test to ensure that no deterioration of containment boundary components has occurred. The underlying purpose for this test is to provide control over activities affecting the quality of the packaging material and components that make up this boundary and to ensure that no failure or malfunction exists as a result of nonconformance with the approved package design, even following a period of repeated use.

Throughout the evolution of ANSI N14.5, various maintenance cycles have been cited for qualification (leak-testing) of the package containment boundary. Some cycles, such as periodic shake-down tests and single-trip containment system verification,[5] have been retired from the standard as packaging designs, materials, and quality assurance have improved. Evolution of the standard continues with the 2014 revision which provides for an extension to the established maintenance cycle when justification is provided.

PACKAGE PERFORMANCE REQUIREMENTS

Type B packaging performance requirements for Normal Conditions of Transport and Hypothetical Accident Conditions are specified by 10 CFR 71.51. The performance requirements, with regulatory reference, are summarized below. Tests and conditions that are considered to impact elastomeric seal performance are highlighted and are being addressed at Savannah River National Laboratory through conduct of extended elastomeric O-ring studies of H1616 and 9975 packagings. Similar studies of cask packages are being performed by BAM Federal Research Institute.[6]

Normal Conditions of Transport *		Hypothetical Accident Condition	
Vibrations	10 CFR 71.71(c)(5)	30-ft drop	10CFR 71.55(f)(1)(i)/71.73(c)(1)
Water Spray	10CFR 71.71(c)(6)	Crush, 1100-lb plate	10CFR 71.55(f)(1)(ii)/71.73(c)(2)
4-ft Free Drop	10CFR 71.71(c)(7)	Puncture	10CFR 71.73(c)(3)
1-ft Drop	10CFR 71.71(c)(8)	Thermal 1,475°F	10CFR 71.73(c)(4)
Compression	10CFR 71.71(c)(9)	3-ft Immersion	10CFR 71.73(c)(5)(6) (3-ft and 50-ft Immersion)
Penetration	10CFR 71.71(c)(10)		
*NCT/HAC conditions are evaluated at temperatures -40°F to 100°F, with Insolation			

PACKAGE SEAL CONFIGURATION DESCRIPTION

The H1616 is a Type B Radioactive Material Package designed to transport tritium filled reservoirs. The H1616 seal configuration is a standard static face seal gland design as outlined by the Parker Seals Handbook.[7] This is in contrast to conventional radioactive material packaging designs which typically employ two concentric seal glands, one seal being credited as the packaging containment boundary and a second seal serving only as a boundary for testing the containment seal. The 9975 is a Type B Package designed principally to transport plutonium and uranium and it includes two concentric seals, though the

face seal design is made on mated 10-degree conical surfaces. The 9975 design incorporates a Primary Containment Vessel Closure (PC) and Secondary Containment Vessel (SCV). Seal testing has been performed on the primary vessel. The 9975 PCV seal uses a Parker AS-568-244 O-ring. Figure 1 illustrates the two face seal configurations. The compressive loads applied to the seals by the H1616 design are typical of the design specified by the Parker Handbook, whereas the 9975 conical configuration has greater compressive loading.

Standard Face Seal – H1616 Conical Face Seal - 9975

Figure 1 Static Face Seal Configurations – (NTS)

EARLY SEAL PROBABILISTIC ANALYSIS – ANSI N14.5

The current periodic section of N14.5 specifies that leakage rate testing shall be performed within 12-months prior to each shipment. This requirement has been met by the removal and replacement of the elastomeric seals that comprise the containment boundary between the vessel and vessel closure. Though other boundaries are referenced, e.g., closures, valves, rupture disks, etc., only seals have been identified for routine replacement. The periodic leakage rate testing specifies a leakage rate less than the reference air leakage rate, L_R . Typical for Type B packages, L_R is defined as "leaktight". The 12-month verification is based on a seal life Mortality Curve (sometimes referred to as a "bathtub" curve) as depicted in Figure 2. The curve depicts an early life failure of seals which was initially denoted as "shake-down" in early ANSI N14.5 editions.

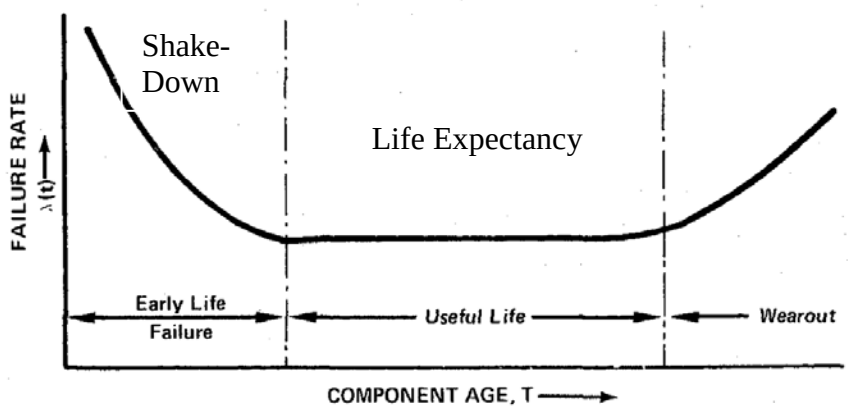


Figure 2 Mortality "Bath-Tub" Curve (Bill Lake, PATRAM 1978)[3]

The useful life, or normal life expectancy, of a seal, presented in Figure 3, is based on engineering reliability data and USNRC safety study reports from 1962 and 1975, respectively. Based on this data,

seal life expectancy was reported to be 4 years. Due to limitations of available manufactures data, a safety factor of 3 was applied and the resulting ANSI N14.5 12-month inspection criteria was established (Lake). It was noted by Lake that "reliability estimates are strongly dependent on life test data, and confidence increases significantly if data for specific components under realistic transportation environments is used." Current evaluations performed on the 9975 and H1616 packages by Savannah River National Laboratory discussed in this paper provide additional confidence of extended life expectancy for the seals and provide a basis for extending the ANSI N14.5 periodic inspection cycle.

Parameter	Value	Reference
Life Expectancy, T	3.5×10^4 hr = 4 years	8 (1962)
Failure Rate, λ	3×10^{-6} / hr	9 (1975)

Figure 3 Seal Life Expectancy

PACKAGING PERFORMANCE DURING NORMAL USE

The H1616-1 Package design was certified in 1992 and the package has been in use for approximately 20 years. Since that time, approximately 2,300 H1616 containers have been fabricated to support NNSA mission shipments. Thus, more than 20 years of quality assurance data, collected for a substantial population of packages, is available to support seal inspection performance evaluation. During this extended period of in-service performance, no cases of O-ring hardware rejection related to CV sealing were observed. Visual inspection and testing have identified no damage to the CV or its sealing surfaces. Similarly, thousands of 9975 packages have been placed in service since certification in the late 1990s and no cases of O-ring hardware rejection have occurred. A variety of other packagings which employ the 9975 sealing configuration, including the 9965, 9968, 9977, 9978 and H1700, have demonstrated comparable hardware performance.

Package O-ring Sealing Studies

A series of packaging seal aging studies has been ongoing for more than 10 years at SRNL and, for a shorter period of time, at BAM Federal Institute for Materials Research. These aging studies are designed to derive an estimate of seal Life Expectancy ("Time to Failure") based on the experimental activation energies that are derived from extrapolating seal CSR behavior in response to test temperatures indicative of packaging transport and storage conditions. The time to failure (t) is assumed to be defined by the Arrhenius relationship:

$$t = A \exp(-E_a / RT)$$

A = constant
E_a = activation energy, J/mol
R = ideal gas constant, 8.3145 J/K-mol
T = absolute temperature (K)

The material component and package evaluations include Fluorocarbon (FKM), Ethylene Propylene Diene Monomer (EPDM) and Hydrated Acrylonitrile Butadiene rubber (HNBR) O-rings. The specific FKM compounds are Viton® GLT, GLT-S and TTN Flex® and EPDM compounds are EPDM 30H E-0740-75 and Royalene® 580HT. The material component evaluations include:

- Compression Stress Relaxation (CSR)
- Thermal Aging 160 ºF to 450 ºF
- Environmental conditions inert gas and air
- Mechanical properties (hardness, thickness, tensile strength, elongation, etc.)
- Radiation exposure
- Diffusion-Limited Oxidation (DLO)
- Thermo Gravimetric Analysis (TGA)
- Leakage rate measurements

Package evaluations include:

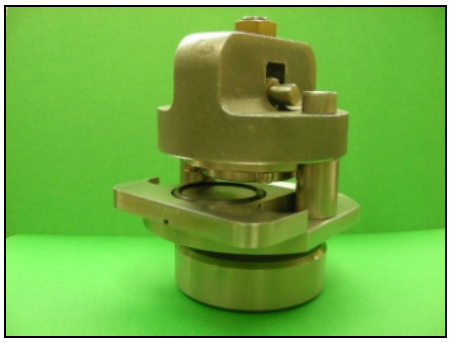
- In-situ Transport and Storage Environments
- Packaging opening and closing cycle
- Vibration and shock

EXTENDED AGING O-RING STUDIES – H1616

A series of experiments addressing performance of H1616 Package EPDM O-rings was initiated by Savannah River National Laboratory in April 2012.[10] The study was designed to assess H1616 sealing performance under worst case extended (greater than one year) maintenance conditions by collecting and evaluating physical aging data on the performance of the EPDM seals specified for the H1616-1. The study included both full scale package and material sample testing.

In the full scale evaluation, three H1616-1 containment vessels (CVs) were removed from SRS Tritium inventory, EPDM O rings specified for use with the H1616-1 were installed, and the CVs were closed in accordance with the SARP procedure. The packages were heated to three temperatures, 160°F, 235°F, and 300ºF, to determine the effect of a chronic temperature environment on the ability of the O ring seals to remain leaktight in accordance with ANSI N14.5. The CVs were removed from the heated environments after one month for inspection and leak testing. Following cooling, the CV seals and sealing surfaces were inspected. Hardness testing was performed on the seals and the CVs were then closed, leak tested and returned to the heated environments. The test cycle was subsequently repeated for additional periods. Geometric configuration of the tested packages was identical to service conditions. Full scale testing of the H1616-1 production CVs facilitated determination of age effects on actual packaging seals. Opening and closing of the packages during the test simulated actual service conditions.

Three material sample tests were performed. In each test, temperatures exceeded the calculated maximum expected during normal conditions of transport, 152°F. All testing was performed in the inert environment (argon) required for the H1616-1. In the first material sample test, EPDM O-ring material was cut into ¾” segments and subjected to five chronic temperatures, 175°F, 235°F, 270°F, 300°F and 350°F. Three segments were tested at each temperature. Each set of three segments was placed in a compression stress relaxation (CSR) jig as shown in Figure 4. Approximately monthly, the O-ring segments were removed from the jig and placed as close to test temperature as possible in a relaxometer for measurement of sealing force. The CSR results were used to develop an O-ring aging model based on sealing force decay. In the second material sample test, twelve O-rings were destructively examined to verify tensile strength, elongation and hardness. Results of this test were compared to published vendor data. The final material sample test involved the heating of O-ring segments to temperatures of 175°F, 235°F, 270°F, 300°F in air and argon environments for approximately one year. The segments were periodically removed and tested for hardness, tensile strength and elongation. This test was performed to verify that thermo-oxidation is a primary degradation mechanism for the EPDM material.



Full Scale H1616 In-situ Seal Thermal Aging CSR Jig for Sample Testing

Figure 4 H1616 Containment Vessel Seal Testing

During the course of the full size package test, CVs were cycled (opened and closed) more than twenty times. Those heated to 160°F and 235°F remained leaktight per ANSI N14.5 no sign of degradation of the seals was observed during the two year period. Material sample testing produced comparable results at the lower test temperatures. CSR testing preformed at 175°F demonstrated that the O-ring retains 80% of its sealing capacity and projections based on those tests results predict O-ring life of 4.8 years for the bounding normal environment temperature of 152°F. Elongation, tensile strength, and material hardness testing confirmed published vendor data and demonstrated undiminished properties for samples exposed to temperatures of 175°F and 235°F.

The H1616-1 studies consistently demonstrated that EPDM O-rings retain significant mechanical properties and sealing force after 2-years of testing at or below bounding normal service temperatures. Following repeated opening and closing cycles, the tested H1616-1 CVs remained leaktight per ANSI N14.5. Interpretation of available data demonstrates that a service life of 2 years is readily achievable and suggests that service life of 4 to 6 years is possible for the intended service temperatures.

EXTENDED AGING O-RING STUDIES FOR THE 9975

Since approximately 2002, SRNL has been conducting performance testing of O-rings used in the 9975, 9977 and H1700 radioactive material shipping packages. The objective of these O ring tests has been to correlate the projected O-ring life to CSR data under specific storage conditions (i.e., K-Area Materials Storage (KAMS) facility). The results from these studies can be used to predict seal performance under transport conditions. Eighty-four PCV fixtures assembled with GLT/GLT-S seals in PCV fixtures that replicate the package seal design have been tested under temperatures ranging from 200 ºF to 450 ºF. Figure 5 illustrates the typical test fixture used to environmentally test 9975 PCV seals. The peak temperature observed for the PCV under NCT is 202 ºF. Performance testing of the 9975 O-ring demonstrated that degradation of the O-ring material at temperatures up to 200°F for the reported durations is negligible.[11] Data gathered from the 9975 O-ring testing has been used to support extension of packaging maintenance beyond 1-year for the 9975, 9977 and H1700 packages that have identical or similar seal configurations.

Figure 5 9975 Primary Containment Vessel Seal Thermal Aging Test Fixture

No failures have yet been observed in GLT O-ring fixtures exposed to 200 °F for durations of 72 to 96 months. GLT-S O-ring fixtures have remained leaktight for more than 60 months (5 years) at 200 °F, 250 °F and 300 °F. No significant changes to material properties have been reported.

O-RING FAILURE MODES EVALUATION

Consideration of potential failure modes and their applicability to radioactive material packaging containment vessel performance under conditions of normal use, storage and normal and accident conditions of transport (time, environment, temperature, and pressure) provides additional insight into the viability of an extended maintenance period. The failure modes for O-rings are well established and discussed in the Parker O-Ring Handbook for Seals.[12] Additional information on common modes of failure are also presented in SAE Aerospace Information Report AIR1707. [13] Failure modes considered applicable to RAM packages are summarized below. Modes judged to be inapplicable to radioactive material packaging, e.g., abrasion, spiral failure, nibbling, etc., are not included.

<u>Normal Conditions of Transport and Design</u>

- Radiation, Chemical and Galvanic Reactions/Exposures

Damage to an O-ring can occur when the O-ring has been exposed to high levels of radiation or incompatible fluids. Radiation rates in excess of 10^7 rad are typically required before significant changes to physical properties of the O-ring are observed.[14] The dose effects from tritium, a beta emitter, and depleted/natural uranium, a low energy alpha emitter, are negligible for the H1616. The dose from highly enriched uranium and plutonium for the 9975 is well below 10^7, therefore no changes to the mechanical properties of the EPDM or FKM seals are expected.

EPDM and FKM seals are compatible with the gases that may be in contact with the O-rings, including H_2, He, Air, CO_2, N_2 and Argon. No chemical or galvanic reaction that may affect changes in mechanical properties is predicted. Thermo-oxidation is considered to be the primary degradation mechanism for the O-ring when in air. Argon, the required backfill for the H1616-1, limits thermos-oxidation, significantly extending the EPDM material service life.[10] Air and CO_2 containment vessel gases in the 9975 have been similarly demonstrated to prevent elastomer degradation due to thermos-oxidation.

- Vibration, 4-ft Drop

NCT impact to the CV is characterized by 4-ft drop shock conditions and transport vibration. An analysis was performed to assess the potential for inertial loads, associated with the NCT impact and vibration, to result in a loss of O-ring compressive sealing force. Vibration levels were assumed to be no greater than 4G while shock was evaluated at 500G.[15] Calculations, performed for the H1616 but considered to be applicable to the 9975as well, show that the inertial loads acting on the O-rings are an order of magnitude less than the reduced compressive force acting on the sealing surface resulting from thermal aging. These loads are insufficient to separate the O-rings from their sealing surfaces.

- Heat and Cold

The maximum calculated O-ring temperatures for the H1616 and the 9975 under NCT is 152°F and 202°F, respectively. When in storage, loaded H1616 packages are maintained indoors, protected from insolation. The maximum calculated seal temperature is 116°F under the NCT regulatory condition of a 100°F ambient temperature. Storage requirements (for a loaded package) restrict the maximum ambient temperature to 120°F, which would result in seal temperature of less than 140°F. Actual physical conditions are expected to be less than these values as packages would generally be stored in environmentally controlled structures and not loaded at the maximum quantity of material authorized by the SARP. Based on years of test data at chronic temperatures for the 9975 and H1616-1, the vessels remained leak tight per ANSI N14.5.It is, therefore concluded that, at less severe maximum calculated temperatures, their CVs will remain leaktight.

EPDM and Viton seals have a glass transition temperature much less than the required -40°F regulatory evaluation point. The elevated aging temperatures equivalent to NCT for the 9975 and H1616 did not result in any appreciable difference in the elastomer properties of hardness, tensile strength and elongation or significant loss of compression as measured by CSR. Therefore, low temperature performance is not expected to be impacted.

- Pressure

The gland designs are based on the Parker Seals Industrial O-Ring Static Face Seal Gland design for a maximum 1500 psi specified in the Parker O-ring Handbook. This established design has been recommended by Parker seals for decades and has been demonstrated to be sufficient to prevent failure since the packages have been placed in service. The maximum calculated pressures for each packaging design is significantly less, therefore, loss of sealing under elevated pressure conditions is not considered to be credible, e.g., through extrusion, swelling, etc.

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- Repetitive opening and closing of the CV

Historically, H1616-1 CV are opened and closed 8-10 times per year. Experimental study by SRNL of EPDM seals used in the H1616-1 does not specifically address repetitive assembly or its effect on seal performance. However, it may be inferred from observations made following inspection disassembly and test reassembly that low assembly cycles do not affect the sealing performance of the packaging when seals are exposed to maximum normal in service temperature. Elevated temperature testing performed at SRNL since April of 2012 has resulted in more than 21 opening and closing cycles for the H1616 with no observed reduction in EPDM O-ring ability to meet leak tight performance as defined by ANSI N14.5.

For the 9975, the CV design was subject to repeated opening and closing cycle testing (>150x). The design was leakage tested per ANSI N14.5 and remained leaktight in all instances. Repetitive opening for RAM packages are few and it may be concluded that there is no effect on seal performance.

Hypothetical Accident Conditions of Transport

- Free Drop and Thermal

HAC impact on the CV is characterized by 30-ft free drop shock and elevated temperature reflective of the hypothetical thermal event. An analysis was performed to assess the potential for inertial loads, associated with impact, to result in a loss of O-ring compressive sealing force. Shock was evaluated at 500G. Calculations demonstrate that the inertial loads acting on the O-rings are an order of magnitude less than the reduced compressive force acting on the sealing surface as a result of the elastomer thermal aging studies. These loads are insufficient to separate the O-rings from their sealing surfaces.

Elevated aging temperatures equivalent to NCT for the packages (9975 and H166) did not result in any appreciable difference in the properties of hardness, tensile strength and elongation or in significant loss of compression as measured by CSR. Therefore, a single temperature excursion is not expected to affect the sealing performance under the HAC of fire.

- Crush, Puncture and Immersion

These conditions do not subject the packages to loading conditions that would affect the ability to remain leaktight.

CONCLUSIONS

The annual inspection of radioactive material packages involves substantial labor resources and, more importantly, is a potential source of worker exposure. Prudent resource allocation and the pursuit of 10 CFR 20, As Low As Reasonably Achievable (ALARA) exposure goals suggests the adoption of longer inspection intervals where supporting justification can be developed. The ANSI N14.5 basis for annual inspection is rooted in 1960s reliability data. The recently adopted ANSI N14.5-2014 standard provides for approval of increased inspection intervals for situations in which adequate technical basis is documented. O-ring material testing, leak testing on H1616 and 9975 containment vessels, and actual service performance observations all indicate seal performance is not degraded under routine conditions. Testing, along with advances in polymer science, support the conclusion that the inspection interval for these packages may be extended to two years or more without affecting the safety performance of the package under both NCT and HAC. These conclusions are applicable to other packages with similar seal design and elastomeric materials.

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REFERENCES

1. American National Standard for Radioactive Materials - Leakage Tests on Packages for Shipment, ANSI N14.5-1997 and earlier releases.

2. American National Standard for Radioactive Materials - Leakage Tests on Packages for Shipment, ANSI N14.5-2014.

3. William H. Lake, Reliability in Maintenance and Design of Elastomer Sealed Closures, Proceedings of the Fifth International Symposium Packaging and Transportation of Radioactive Materials, Las Vegas, NV, May 7-12, 1978.

4. U.S. Nuclear Regulatory Commission, Regulatory Guide 7.4, Leakage Tests on Packages for Shipment of Radioactive Material, Revision 1, March 2012.

5. American National Standard for Radioactive Materials - Leakage Tests on Packages for Shipment, ANSI N14.5-1977.

6. Anja Kömmling, Matthias Jaunich, Dietmar Wolff, Aging of Elasotmer Seals for Storage Casks, BAM Federal Institue for Materials Research and Testing, Berlin, Germany, WM2015 Conference, Mach 15-19, Phoenix, Arizona.

7. Parker O-Ring Handbook, Design Chart 4-2,Parker Hannifin Corporation, O-Ring Division, Cleveland, OH, Copyright 2001.

8. D.R. Earles and M.F. Eddins, Reliability Engineering Data Series Failure Rates, AVCO Corp., MA, April 1962.

9. USNRC, Reactor Safety Study, WASH-1400 (NUREC-75/014) Appendix III, October 1975.

10. T.M. Stefek, W.L. Daugherty, T.E. Skidmore, Final report for Aging Studies of EPDM O-ring Material for the H1616 Shipping Package (U).

11. W.L. Daugherty, Eight Interim Status Report: Model 9975 PCV O-Ring Fixture Long-Term Leak Performance (U), SRNL-TR-2013-00151, Savannah River National Laboratory, Aiken, SC, (August 2013)

12. Parker O-Ring Handbook, Parker Hannifin Corporation, Cleveland, OH, Copyright 2001.

13. Patterns of O-Ring Failures, SAE Aerospace Information Report AIR1707, Revision A, (December 2003).

14. T.E. Skidmore, Radiation Resistance of Viton® GLT O-Rings for model 9975 Packaging Assemblies (U), Westinghouse SRTC Memo, SRT-MTS-98-4117, (September 1998).

15. C. Mckeel, Evaluation of H1616-1 Seal During Vibration and Impact Events, M-CLC-A-00465, Savannah River National Laboratory, Aiken, SC, (August 2014).