Alternative Frequency for Periodic Leakage Rate Testing*

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ABSTRACT

This paper describes methodologies that may be used to extend the interval applied to the periodic leakage rate testing of certified Type B transportation packagings from one to up to five years. The extended intervals are predicated on the basis of acceptable results of long-term O-ring performance tests and continuous monitoring of environmental conditions of the packagings provided by the ARG-US radio frequency identification system. Extending the interval between periodic leakage rate testing of the packagings, without compromising safety, reduces radiation exposure to workers and cuts annual operating costs by $2,500–3,000 per package.

INTRODUCTION

According to Section 7.5 of the ANSI N14.5 Standard,[1] the purpose of periodic leakage rate testing of packagings of radioactive materials for shipment is to confirm that the containment capabilities of packagings built to an approved design have not deteriorated during a period of use. Periodic leakage rate testing must be performed within twelve (12) months prior to each shipment. Periodic leakage rate testing must be performed for all containment boundary seals, closures, valves, rupture disks, and other applicable components.

The basis for extending the interval applied to the periodic leakage rate testing of certified Type B transportation packagings from one year to a maximum of five (5) years has been determined, and the necessary methodologies have been developed. The extended intervals are based on acceptable results of long-term O-ring performance tests and continuous monitoring of environmental conditions of the packagings provided by ARG-US,[2] the radio frequency identification (RFID) system developed by Argonne National Laboratory for the U.S. DOE Packaging Certification Program, Office of Packaging and Transportation.

BASIS

The basis of the current frequency of periodic leakage rate testing of 12 months before each shipment can be traced to a paper by Lake[3] that deals specifically with closure designs using elastomer O-ring seals. Lake addresses both component reliability and system reliability. The reliability of a component may be defined as the probability of that component performing, as required, under specified environmental conditions over a specified period.[4, 5] Reliability of a system may be defined similarly, but the definition is expanded to encompass an interacting system of components. An example of the latter is a closure system with redundant seals and with a test port/plug. The reliability of the closure seal system has been found to be design dependent.[3]

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Component Reliability

The failure rate of a component, $\lambda(t)$, is defined as the conditional instantaneous probability of failure at time t, given that failure has not yet occurred. A mortality curve that plots the component failure rate against time (or age) has the familiar "bathtub" shape, where $\lambda(t)$ decreases initially as faulty components are eliminated by early failure. The useful life is characterized by a constant $\lambda(t)$, and the wear-out period is characterized by an increasing $\lambda(t)$. The practice that is suggested from the mortality curve is to use components that fall within the useful life period. This processing involves screening components to eliminate potential early failures and replacing components in service before the wear-out period. Component reliability, R(t), is commonly described by the Weibull distribution:[6, 7]

$$R(t) = \exp(-[t/\alpha]^{\beta}), \tag{1}$$

where α and β are the scale and shape parameters, respectively, of the Weibull distribution. The failure rate, or the hazard function, h(t), associated with the Weibull distribution is given by

$$h(t) = \beta\alpha^{-\beta}t^{\beta-1}, \tag{2}$$

where h(t) is a measure of the "proneness to failure" of a component after time t has elapsed.[7]

A special case of the Weibull distribution is the exponential distribution that occurs when $\beta = 1$ (i.e., for the flat portion of the "bathtub" where the components fail by chance alone), then Equations (1) and (2) become

$$R(t) = \exp(-t/\alpha), \tag{3}$$

$$h(t) = \alpha^{-1}, \tag{4}$$

where h(t) is a constant failure rate λ ($= \alpha^{-1}$) that reflects no aging effect on the component in service, and

$$R(t) = \exp(-\lambda t). \tag{5}$$

Using data found in the literature for static seals of a life expectancy of 3.5×10^4 h (4 yr) and a failure rate of $\lambda = 3 \times 10^{-6}$/h, Lake estimated component reliability values of 0.9999, 0.9995, and 0.9950 for periods of 1 day, 1 week, and 10 weeks, respectively.[3] Using the same failure rate of $\lambda = 3 \times 10^{-6}$/h, the component reliability would be 0.9741 and 0.8769 for a period of 1 and 5 yr, respectively.

System Reliability

Mathematical models were developed by Lake[3] for estimating the reliability of three closure designs: (1) single seal design, (2) redundant seal design without a test port, and (3) redundant seal design with a test port. The elastomer O-rings were assumed to have the same component and assembly reliabilities, and the seal plug was assumed to have its own reliability (as a product of its component and assembly reliabilities). A comparative reliability analysis of the three closure designs showed that the redundant seal design with a test port has the highest closure reliability, followed by the redundant seal design without a test port, and then the single seal design.[3] Reliability testing also showed that a closure verification test always improves the reliability of a system. For a single-seal design, a verification test results in an assembly reliability of unity, and the closure reliability is equal to the component reliability.

A number of transportation package designs have been approved by the Nuclear Regulatory Commission, on the condition that closure seals are replaced annually.[3] On the basis of life expectancy data of 4 years for static seals[8] and the possible uncertainty in the data, it was concluded that annual replacement of elastomeric seals for the more common applications in closure designs for radioactive material transportation is a reasonable approach.[3] It was also concluded that the estimates of reliability are strongly dependent on life test data, and confidence increases significantly if data for specific components under realistic transportation environments are used.

Elastomeric Viton® GLT O-ring seals are used in a number of the certified Type B transportation packages. Recent life test data for these O-rings, discussed in the next section, show that the current interval of periodic leakage rate testing of 12 months before each shipment could be extended, up to 5 years, on the basis of acceptable O-ring performance test results and continuous monitoring of environmental conditions of the packagings.

PACKAGING SURVEILLANCE PROGRAM (O-RING PERFORMANCE)

To confirm that the containment capabilities of packagings built to an approved design have not deteriorated during a period of use, a packaging surveillance program is needed to provide early detection of degradation and data that can be used to predict failure. One packaging surveillance program implemented for the Model 9975 packagings at the DOE Savannah River Site (SRS) consists of baseline characterization of Model 9975 packaging materials of construction; field surveillance tests of Model 9975 packagings; and laboratory tests on O-rings, fiberboard, and lead shield to support the storage configuration.[9] The packaging surveillance program for the Model 9975 packaging has been implemented at SRS for over 5 years and has generated a large body of data on the performance of the packaging during storage. Highlights of the Viton® GLT O-ring performance results published to date are summarized below. The Model 9975 packaging surveillance program is continuing and will provide even longer term O-ring test results in the future.

Summary Highlights of O-ring Performance[10]

- Compression stress relaxation (CSR), based on sealing force decay, is a direct measure of seal performance (ASTM D6147). Baseline CSR data from O-ring characterization activities indicates good seal performance for many years at ambient storage conditions.

- Field surveillance and non-destructive examination (NDE) of O-rings showed that they maintain shape and resiliency for 7 years. Surveillance destructive examination (DE) of package O-rings produced tensile behavior comparable to that of laboratory samples with minimal environmental aging.

- Accelerated aging studies produced CSR data and models that predicted a lifetime of ≈10–11 years for the Viton® GLT O-ring at 200°F. No failure of seals was found after 3 years of O-ring fixture testing at 200°F. No trend in leakage rates was found over time — all room-temperature leakage rates are acceptable and meet the “leaktight” criterion of ANSI N14.5.

- No trend was observed in leak-rate test data against such variables as internal atmosphere (CO_2/air), radiation dose (up to 10-yr equivalent), or the presence of grease on O-rings.

- The O-ring post-load leak tests have been conducted as part of the NDE field surveillance. Of the one hundred twenty-six (126) 9975 packages examined (as of January 2009), there were only two findings that may affect package integrity: mold on the fiberboard and a leak test that failed because pieces of extraneous fibers were on O-rings. This failed leak test was thus concluded to be caused by an assembly error, not a component (O-ring) failure.

There is no observable trend in the post-load O-ring leak tests (with tested leak rates below the ANSI 14.5 requirement) of the Model 9975 packagings stored up to 7 years, indicating that aging had a negligible effect on the rings. This finding is consistent with the DE results of the O-rings.

Statistical Analysis

Because of time and cost constraints, a surveillance testing program can only sample a relatively small number of packagings in a much larger population. As of January 2009, one hundred twenty-six (126) 9975 packagings were surveillance tested in a total population of ≈5,000, with only two aforementioned findings that may affect package integrity. On the basis of the sampling test results, the goal is to determine how many findings are likely in the remaining population that is not examined. Specifically, one would like to know the most likely number, as well as the maximum number, of "failed" packages, A and A_u, respectively, in the total population. In statistical parlance, the former quantity A is often given by the maximum likelihood estimate (MLE). The latter quantity A_u is given by the upper end of the one-sided interval estimate at a given confidence level (e.g., 95%). Knowledge of A and A_u provides guidance on how much sampling is "enough" and how to determine the quality of the estimates (i.e., how "good" the estimates are). The sampling test program is usually conducted under the protocol of random sampling without replacement (i.e., no retesting of previously tested unit). The sampling results may be analyzed by using the hypergeometric distribution approach.[11]

The data from the O-ring post-load leak tests of one hundred twenty-six (126) 9975 packages was analyzed by using this approach, yielding some valuable results, as shown in Figure 1. For example, by counting *both* findings (mold on fiberboard and fibers on O-ring) as "failed" packages in the sampling tests, the most likely and the maximum number of failed packages in the total population of 5,089 are $A = 75$ and $A_u = 247$, and the probability of $A = A_u = 247$ is only ≈3.7%. By counting only the leak test that had fibers on the O-ring as a "failed" package in the sampling tests, the most likely and maximum number of failed packages in the total population of 5,089 are $A = 35$ and $A_u = 186$, and the probability of $A = A_u = 186$ is ≈4.2%.

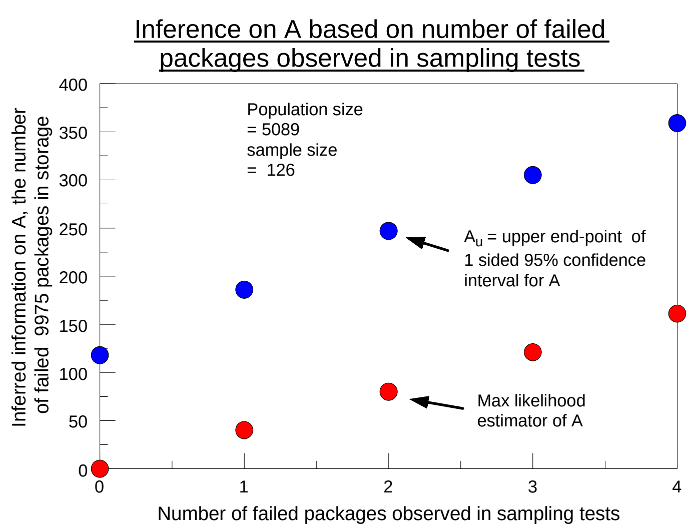

Figure 1. Inferred information from sampling tests of 9975 packages

In general, the values of A and A_u in the population increase as the number of “failed” packages observed in the sampling tests increases. The relatively large values of A_u for a small number (1 or 2) of observed failed packages in the sampling tests reflect that the sample size (126) is a small fraction of the total population (5,089).

If the finding of “failed” packages is discarded because the O-ring did not fail as a component in the sampling tests of 126 packages, the MLE is zero, which means that the most likely number A of “failed” packages in the total population is zero, an unsurprising but reassuring result. However, according to Figure 1, the maximum number of “failed” packages A_u is non-zero and equals 120, implying that one might find up to 120 “failed” packages (albeit with a relatively small probability of 5%) in the total population, even though the sampling tests of 126 packages reveal no “failed” packages so far. Conservatism suggests that one may need to take A_u into consideration in the planning and conduct of the sampling test program.

The 9975 field surveillance program is continuing with a plan to cover 258 packages: 127 packages are from the “Pressure” group, for which the contents are impure oxides without chlorides, and 131 packages are from the “Pressure and Corrosion” group, for which the contents are impure oxides containing chlorides. The field surveillance tests for the “Pressure” group of Model 9975 packages will be completed in 5 years, whereas the “Pressure and Corrosion” group of Model 9975 packages will be completed in 10 years, since corrosion is considered a slower phenomenon than the pressurization from radiolysis. The statistical analysis framework described herein allows very useful information to be extracted from the sampling test program that may help address the long-term performance of O-rings in the safe storage and transportation of the 9975 packages.

ARG-US RFID TEMPERATURE MONITORING SYSTEM

The ARG-US RFID system, which has been developed for continuous monitoring of environmental conditions, provides the data and basis for extending the interval of periodic leakage rate testing of Type B transportation packagings, such as Models 9975, 9977, and 9978. All of these packagings use Viton® GLT/GLT-S elastomeric O-rings as seals for the primary containment vessels. As discussed before, test data from the 9975 packaging surveillance program to date show acceptable, long-term O-ring performance, if the O-ring temperature can be kept below 200°F (93°C). The RFID system monitors the ambient temperature of each packaging continuously. With thermal modeling, the temperature of the O-rings of the containment vessel can be accurately correlated to the exterior surface temperature and the decay heat load of the contents. For instance, for a 9977 drum with a content heat load of 10 W, the O-ring temperature would not exceed 200°F (93°C), as long as the surface temperature of the drum is kept below 149°F (65°C). The determination of the ambient temperature thresholds as a function of content heat load will be discussed later.

The ARG-US RFID system consists of tags (transponders), readers (interrogators), and application software. The tag, with a built-in temperature sensor, is attached to the exterior of the package by using the flange bolts. The application software enables remote reading, via radio waves, of the sensor temperature. The system monitors temperature continuously, records the data periodically, and reports off-normal conditions instantly. The temperature data and event histories are stored in the tag’s internal memory, as well as in the control computer to which the reader is connected. In a large installation, the system may be linked to a server and accessible via secured Internet.

Two identical ARG-US RFID systems have been delivered to the DOE Savannah River Site (SRS) and the Nevada National Security Site (NNSS) for fielding testing and applications since March 2010. Figure 2 shows a stand-alone ARG-US RFID temperature-monitoring system on a mobile platform and an RFID tag mounted on a 9977 (or 9978) package. Each stand-alone ARG-US RFID system may be regarded as a sensor node that can be easily networked with other sensor nodes, if desired.

Figure 2. A stand-alone RFID temperature-monitoring system on a mobile platform (left) and an RFID tag mounted on a 9977 (or 9978) package (right).

RFID Tag and Reader

The MK-series RFID tag has a universal form factor that can be attached to a variety of packagings, including Models 9975, 9977, 9978, 9979, ES-3100, and DOT 7A. The tag is equipped with a suite of sensors for temperature, humidity, shock, seal integrity, and battery status, although only the temperature sensor is relevant to the current application. The back plate and the seal integrity sensor of the tag are customized to fit specific types of packages. For Model 9977 and 9978 packagings, the tag is attached to the lid of the package with a single bolt, as shown in Figure 2, whereas two bolts are used to attach a tag to the Model 9975 packaging. The non-volatile memory in the tags can store thousands of lines of records. Four (4) A-size lithium batteries (i.e., non-rechargeable primary cells), with an intelligent management circuitry, can provide up to ten (10) years of service before battery replacement is necessary. The MK-series tags communicate with the reader via 433-MHz RF and have an omni-reading range of ≈100 m.

Application Software

The application software, ARG-US OnSite,[12] is a key part of the system. The software enables the reader connected to the control computer to send instructions to, and retrieve data from, the tags. Figure 3 provides a screenshot of the software. Each round symbol depicts a tagged packaging (top view). The color coding reflects the sensor status of the package — normal, warning, or alert/alarm. The thresholds for the sensors can be adjusted according to the modes of operation. Both the current condition (right center panel) and history data (bottom panels) are displayed. The software queries the tags at preset intervals to ensure the integrity of the tags and records pertinent sensor data. When an abnormal condition is encountered, the tag reports the violation instantaneously to the application software, which, in turn, alerts facility personnel for action. All tag data can be encrypted by using an Advanced Encryption Standard with a 256-bit key (AES-256). The system's performance was verified in several demonstrations,[13–15] as well as in ongoing field testing and applications.[16]

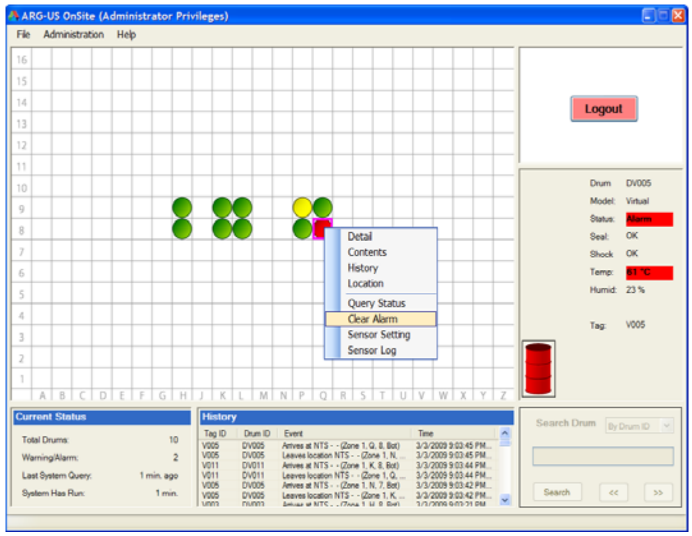

Figure 3. A sample screenshot of the ARG-US OnSite software.

<u>Quality Category</u>

The RFID tag hardware and application software are considered to be non-"Q" (i.e., not safety-related) on the basis of (1) the graded approach described in 10 CFR 71.105(b), Packaging and Transportation of Radioactive Material, and (2) the definition of quality categories described in Appendix A of the NRC Regulatory Guide (RG) 7.10, Establishing Quality Assurance Programs for Packaging Used in Transport of Radioactive Material.

Relative to the RFID hardware, the quality categories are derived from the safety significance of each item and the consequence of its failure to perform on the basis of the design and performance requirements of the item. If the failure of an item results in a loss of containment, a reduction of shielding, or an unsafe geometry that compromises criticality safety, the item is considered to be important to safety. The regulatory requirements of packaging to ensure that public health and safety are protected are addressed in 10 CFR Part 71. In accordance with 10 CFR Part 71, as long as the failure of an item does not jeopardize the packaging from performing its important-to-safety functions, the item is not considered to be important to safety. The NRC Regulatory Guide 7.10, Appendix A, embodies the same philosophy.

In application, the RFID tag is attached to the exterior of the packaging by affixing the tag's sheet-metal top plate under one or two of the drum's flange bolts. The drum lid remains closed during transport and storage, and the primary containment vessel inside the drum is never exposed. Thus, from the standpoint of configuration, the packaging is not altered in any way by the attachment of the RFID tag. Failure of the RFID hardware will not result in the loss of primary containment, the loss of shielding, or the loss of subcriticality. Therefore, on the basis of the definition of the graded approach in 10 CFR 71.105(b) and NRC Regulatory Guide 7.10, Appendix A, the RFID hardware is not considered to be an important-to-safety item for the packaging.

Quality Assurance

To ensure the quality and reliability of the RFID temperature monitoring system, two quality assurance programs were developed: one for the hardware and one for the software. The hardware quality assurance program covers the acceptance testing of the tags, calibration of the temperature sensor, durability tests of the seal sensors, and document control. The software quality assurance (SQA) program includes design control, version control, software functionality and reliability tests, user documentation, and document control. The SQA program for ARG-US meets the software QA requirements of NQA-1.

Tags destined for temperature-monitoring applications are calibrated against certified thermocouples to ensure that the temperature sensor readings are accurate in the design operating range of 32–149°F (0–65°C). The calibration of the built-in thermistors in the MK-series tags is described elsewhere. Figure 4 shows typical calibration results for a batch of 10 tags.

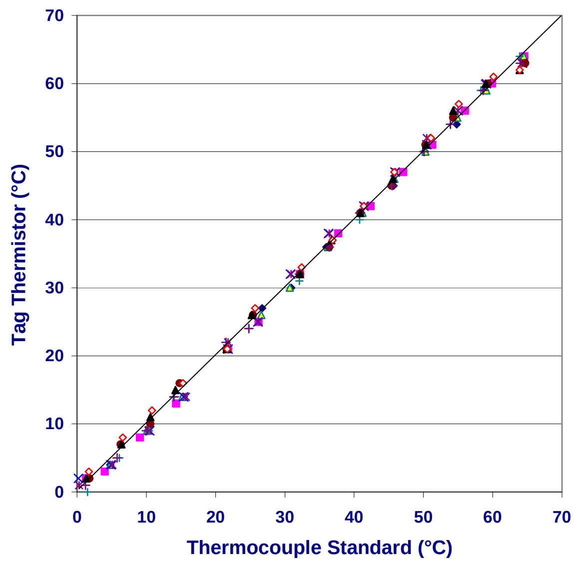

Figure 4. Typical temperature calibration results for a batch of 10 MK-series tags.

Determination of Ambient Temperature Threshold

The ambient temperature threshold is defined as the limit above which the temperature of the O-ring inside the package exceeds its permissible operating temperature (e.g., 200°F for the Viton® GLT O-ring). It is also the setting, or triggering value, for the temperature sensor (thermistor) in the MK-series RFID tag for automatic alert/alarm. The determination of the ambient temperature threshold is, therefore, a key part of using the RFID temperature monitoring system for extended periodic leakage rate testing of the Model 9975, 9977, and 9978 packages.

For the Model 9975 and 9977 packages, the O-ring temperatures have been evaluated[17, 18] under varying thermal loading and ambient temperature conditions to ensure that the maximum O-ring temperature, T_{max}, would remain below 200°F. The results were represented in the form of a regression equation, for which T_{max} depends on the thermal loading W (up to 19 W) and the ambient temperature T_a (in °F):

$$T_{max} = 2.53125 + 3.61837*W + 0.98626*T_a \leq 200^{o}F \quad (6a)$$

for the 9975 package and

$$T_{max} = -49.1 + 6.5*W + 1.236*T_a \le 200^oF \quad (6b)$$

for the 9977 package.

Rearranging Eqs. (6a) and (6b) obtain the ambient temperature thresholds $T_{a,\ threshold}$ as

$$T_{a,\ threshold} \le 200.2 - 3.669*W \quad (7a)$$

for the 9975 package and

$$T_{a,\ threshold} \le 201.5 - 5.259*W \quad (7b)$$

for the 9977 package.

Equation (7) can be used to determine the ambient temperature threshold and the alert/alarm setting of the RFID tag for the Model 9975 and 9977 packages for a given contents heat load. Alternately, the values listed in Table 1 may be used.

Table 1. Ambient temperature thresholds ($T_{a,\ threshold}$) for the Model 9975 and 9977 packages

Contents Heat Load (W)	Model 9975 °F (°C)	Model 9977 °F (°C)
0	200 (93)	200 (93)
≤ 5	181 (82)	175 (79)
≤ 10	163 (72)	149 (65)
≤ 15	145 (62)	123 (50)
≤ 19	130 (54)	101 (38)

The ambient temperature thresholds can be determined for other packages (e.g., 9978) using Viton® GLT O-rings or other elastomer O-rings provided with a well-established temperature limit. These ambient temperature limits are to be used for the settings of automatic alerts/alarms of the MK-series RFID tags on the packages. The corresponding equations for other packages are expected to be similar to Eqs. (6) and (7) for the Model 9975 and 9977 packages, except for different coefficients because of the differences in materials and geometry that affect the heat transfer of these packages.

SUMMARY

Methodologies have been established to extend the interval of periodic leakage rate testing for Model 9975, 9977, and 9978 packages from 12 months to a maximum of 5 years, on the basis of acceptable O-ring performance test results and continuous RFID monitoring of the ambient temperature conditions of the packages. Extensive data on the performance of the Viton® GLT O-ring have been accumulated in the packaging surveillance program implemented for the Model 9975 packages at the Savannah River Site. The data from both laboratory and field tests to date show that the original O-ring fixtures have maintained a leaktight seal at room temperature for over three years of exposure at 200°F. The data on the Model 9975 packages are applicable to the Model 9977 and 9978 packages because they all use the Viton® GLT O-rings for the containment vessels and have the same closure designs.

The ARG-US RFID temperature monitoring system, including the MK-series RFID tags, readers, and application software, has been developed and tested to meet the applicable quality assurance standards and requirements. The ARG-US RFID system (1) continuously monitors the ambient temperature of the packages reliably, (2) issues an alert/alarm when the ambient temperature threshold is exceeded, (3) records the event of violation, and (3) provides the basis for choosing an alternative frequency for periodic leakage rate testing. Extending the interval of periodic leakage rate testing of the packaging, without compromising safety, reduces the exposure of personnel to radiation and facility operating costs.

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