Performance of Metal and Polymeric O-Ring Seals during Beyond-Design-Basis Thermal Conditions*

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Abstract

This paper summarizes the small scale thermal exposure test results of the performance of metallic and polymeric O-ring seals typically used in radioactive material transportation packages. Five different O-ring materials were evaluated: Inconel/silver, ethylene-propylene diene monomer (EPDM), polytetrafluoroethylene (PTFE), silicone, butyl, and Viton. The overall objective of this study is to provide test data and insights to the performance of these O-ring seals when exposed to beyond-design-basis temperature conditions due to a severe fire. Tests were conducted using a small-scale stainless steel pressure vessel pressurized with helium to 2 bar or 5 bar at room temperature. The vessel was then heated in an electric furnace to temperatures up to 900 °C for a pre-determined period (typically 8 h to 9 h). The pressure drop technique was used to determine if leakage occurred during thermal exposure. Out of a total of 46 tests performed, leakage (loss of vessel pressure) was detected in 13 tests.

Keywords: Cask; shipping package; fires; beyond-design-basis conditions; seals; spent fuels

1 Introduction

As described in 10 CFR Part 71.73 [1], the characterization of the performance envelop of seals used on radioactive material transportation packages are normally conducted under the hypothetical accident conditions (HAC) fire (800 °C for 30 min). However, historical non-nuclear transportation fire incidents suggest that potential thermal exposures could exceed HAC fire. Examples are the Caldecott Tunnel fire in 1982 [2], the Baltimore Tunnel fire that occurred in 2001 [3], and the MacArthur Maze fire in 2007 [4]. The performance of package seals is important for determining the potential for release of radioactive material from a package during a beyond-design-basis accident because the seals, in general, have lower temperature limits than other package components. The conservative approach for evaluating seal performance in any HAC or beyond-design-basis fire is to assume that seals fail completely if their normal operating temperature limits are exceeded at any point in the transient thermal evaluation of a given package. Such conservative and bounding approach yields the maximum possible estimates of potential for release of radioactive material from transportation packages in fire exposures.

An evaluation of the potential release of radioactive materials from three different transportation packages has been studied in detail by Adkins et al. [3]. The evaluation used predicted temperatures from a simulation of the Baltimore Tunnel fire using the NIST Fire Dynamics Simulator (FDS) [5] as boundary conditions for numerical models to determine the temperature of various components of the packages, including the seals. The model calculations predicted the seals exceeded their continuous-use rated service temperature in two of the packages evaluated, meaning a potential release of radioactive material if one assumed worst case performance (complete failure) of the seal. However, for both of those packages, the analysis determined, by a bounding calculation, that the maximum expected release was well below the regulatory limits for the release allowed during the HAC series of events in 10 CFR Part 71.

Previous work on O-ring seal performance reported in the literature has mainly focused on elastomeric seals and temperatures well below 800 °C. The test fixtures in previous work typically consisted of two flanges or two plates with two concentric O-ring grooves, one for the test seal and one for the secondary external seal, and a small cavity for helium tracer gas [6, 7]. Testing of package seals to determine their performance in beyond-design-basis fire scenarios

can provide physical data needed to understand the seal performance and likelihood of a release of radioactive materials.

The objective of this work is to provide small scale experimental seal performance data for metallic and polymeric seals for thermal exposures beyond their rated temperatures. Both materials are used in the design of seals, with metallic seals having higher allowable temperatures due to their design and material properties. The data was obtained using a test fixture consisting of a vessel body and a flange cap. The scope of the testing does not evaluate the size of the test fixture as a test parameter with no attempts of scaling up the results. The testing was performed using new seals and did not evaluate the performance of aged seals under beyond-design-thermal exposure. An electric furnace was used to provide various controlled and repeatable thermal environments since it is difficult replicate a real fire environment for testing. This paper highlights and summarizes the test results. Detailed test descriptions and data analysis can be found in Yang et al. [8].

2 Experimental method

2.1 Test vessel and apparatus

The test fixture consists of a seamless vessel body with a flange machined from a stainless steel (SS 304) cylindrical stock and a removable SS 304 flange (vessel cap) with seal groove machined to O-ring manufacturer specifications. The flange dimensions were made in conformity with the ASME Standard B16.5-2009 [9], Flange Class 2500 with a design pressure rating up to 29.2 bar at 800 °C. The vessel body and the cap were joined together using four bolts. The vessel cavity had a nominal internal volume of 100 mL.

Figure 1 shows a schematic of the experimental apparatus. A pressure transducer and two needle valves (one for vacuum and one for helium supply) were connected to the test vessel. Four thermocouples (TC) were used to record temperatures, one placed in the interior of the vessel cavity, one inside the furnace and two located close to the O-Ring groove to monitor the temperatures experienced by the test seal. The exposure of the seal to a high temperature environment was achieved using a programmable temperature-controlled electric furnace with an

internal capacity of 25.4 cm × 25.4 cm × 40.6 cm. The electric furnace has a maximum operating temperature of 1200 °C. Pressure and temperature data were recorded using a 16-bit data acquisition system at 100 Hz, with data recorded at 1 min intervals. Figure 2 shows two photographs of the experimental apparatus.

2.2 Test procedure

The vessel was assembled and placed inside the furnace. The vessel was then evacuated for at least 60 s using a vacuum pump and was filled with helium (nominally to 5 bar for metallic seals and 2 bar for polymeric seals as specified by spent fuel shipping cask manufacturer's specifications) at room temperature. The pressure was monitored for a minimum of 48 h at room temperature. Stable pressure during this period indicated "no leaks" and thermal exposure to the target test temperature was then initiated. Thermal exposure of the test vessel ranged from 150 °C to 900 °C for 8 h to 9 h, depending on the seal material being tested. Leakage from the vessel due to deterioration of seal performance was determined by monitoring the vessel pressure at isothermal test conditions using the pressure drop method in accordance with ANSI N14.5-1997 [10].

The implementation of the pressure drop technique in a harsh thermal environment proved to be less challenging than other more sensitive leak test methods [10]. Although the monitoring of pressure drop is not the most sensitive way to detect leaks, the sensitivity to detect a small pressure drop could be greatly enhanced if the vessel pressure is monitored over a very long duration. In addition, the sensitivity of the method can further be improved by using a smaller test volume since the sensitivity of a pressure drop is inversely proportional to the test volume. This work made use of these two attributes, long measurement duration and small vessel volume.

2.3 Test matrix

One metallic (Inconel 718/silver) and five polymeric (EPDM, PTFE, silicone, butyl, and Viton) O-ring seal materials were tested in two different configurations (single and double seals). O-rings were not conditioned before tests and used as-received. The O-ring nominal maximum operating temperatures are listed in Table 1. Table 2 summarizes the nominal test conditions and

parameters used. The test designation listed in Table 2 adheres to the following convention. For single O-ring tests, the seal material is followed by the test number (numeric or alphabet). For double O-ring tests, the outer O-ring is identified first, and the inner O-ring is identified second, followed by the test number. "Blank" implies an empty groove with no O-ring. For example, "EPDM-Metallic" represents the outer O-ring as EPDM and the inner O-ring as Metallic. It should be noted that the test conditions were generally more severe than the 800 °C for 30 min hypothetical accident conditions described in 10 CFR Part 71. In addition, the 800 °C and 900 °C test temperatures are much higher than would be expected in real world conditions because transportation packages generally are designed with the seals protected by being located within the package and, therefore, not directly exposed to the exterior conditions of the environment.

3 Results and discussion

Figure 3 shows a typical result obtained from a thermal exposure test. In this case, a single EPDM O-ring configuration (Test # EPDM-2) was used. The figure, which displays the measured temporal variations of vessel pressure and temperatures in the test, contain five curves, one for vessel pressure and four for temperatures measured at the vessel interior, two locations on the flange where the test O-ring was housed, and the furnace interior. There are three stages in the temperature measurements. The initial rise in temperature is due to the heating of the test vessel from room temperature to the targeted test temperature in the furnace (the heat-up period). The plateau portion of the temperature curve represents the thermal exposure duration at the test temperature (i.e. the test period), and the subsequent decrease in temperature indicates the cooling of the test vessel after turning off the electric furnace at the conclusion of the thermal exposure at the test temperature (the cool-down period).

It should be noted that only after the vessel had reached the specified test temperature was the pressure drop method applied to determine if a leak had occurred under this isothermal thermal exposure condition (the test period). During the transient heat-up phase of the vessel, the temporal variation of vessel pressure could not readily be used to determine if there was a potential leak unless a catastrophic seal failure occurred, causing a significant drop in pressure. As the vessel was heated, its pressure and temperature increased. The temporal volumetric

thermal expansion of the pressure vessel also introduced an additional parameter. The interplay among these parameters, vessel temperature, pressure, and volume, precluded the use of the transient pressure data to conclusively determine whether a leak had occurred during the heat-up phase. Another indicator for leak was to determine whether the vessel pressure could be restored to the initial pressure after the thermal exposure and cool-down. The return of the initial pre-test charged vessel pressure after cool-down indicated no leak had occurred during a test.

Following the above logic, no leak was detected in Figure 3. Figure 4 illustrates an example of a test using a double metallic O-ring configuration (Test # Metallic-Metallic-2) where leakage was observed. In this case, the pressure of the vessel was decreasing during the last part of the test period, and the initial pre-test charged pressure was never recovered. Table 2 summarizes all the test results from the program.

Peculiar results were observed in all of the single Viton O-ring tests. In the four tests conducted, the pressure was not constant but varied during the 8-h test period. In three tests, the vessel pressure increased in the early part of the 8-h test period but remained relative constant at the later part. Figure 5 shows the results of such a test (Test # Viton-3). In one test, the pressure increased continuously over the entire 8-h test period. The rate of pressure increase was irregular and not reproducible in all four tests. The increase in pressure at the isothermal test condition and the subsequent attainment of vessel pressure greater than the pre-test initial charge pressure after cool-down suggested the addition of material to the vessel interior. The origin of the material remains unknown.

Conclusions

This study provides experimental seal performance data and insights for metallic and polymeric seals typically used in radioactive material transportation packages during beyond-design-basis temperature excursions. The results showed that in most cases O-ring seals could hold pressure to almost twice their rated temperature for several hours of thermal exposure. Five polymeric (EPDM, PTFE, silicone, butyl, and Viton) and one metallic (Inconel 718/silver) O-ring seal materials were tested using two different O-ring configurations (single and double seals). Of the total 46 tests performed, leaks (loss of vessel internal pressure) were detected in 13 tests.

Acknowledgement

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Figure captions

Figure 1. A schematic illustration of the experimental apparatus.

Figure 2. Photographs of the experimental apparatus.

Figure 3. Test results using a single EPDM O-ring configuration (Test # EPDM-2).

Figure 4. Test results using a double metallic O-ring configuration (Test # Metallic-Metallic-2).

Figure 5. Test results using a single Viton O-ring configuration (Test # Viton-3).

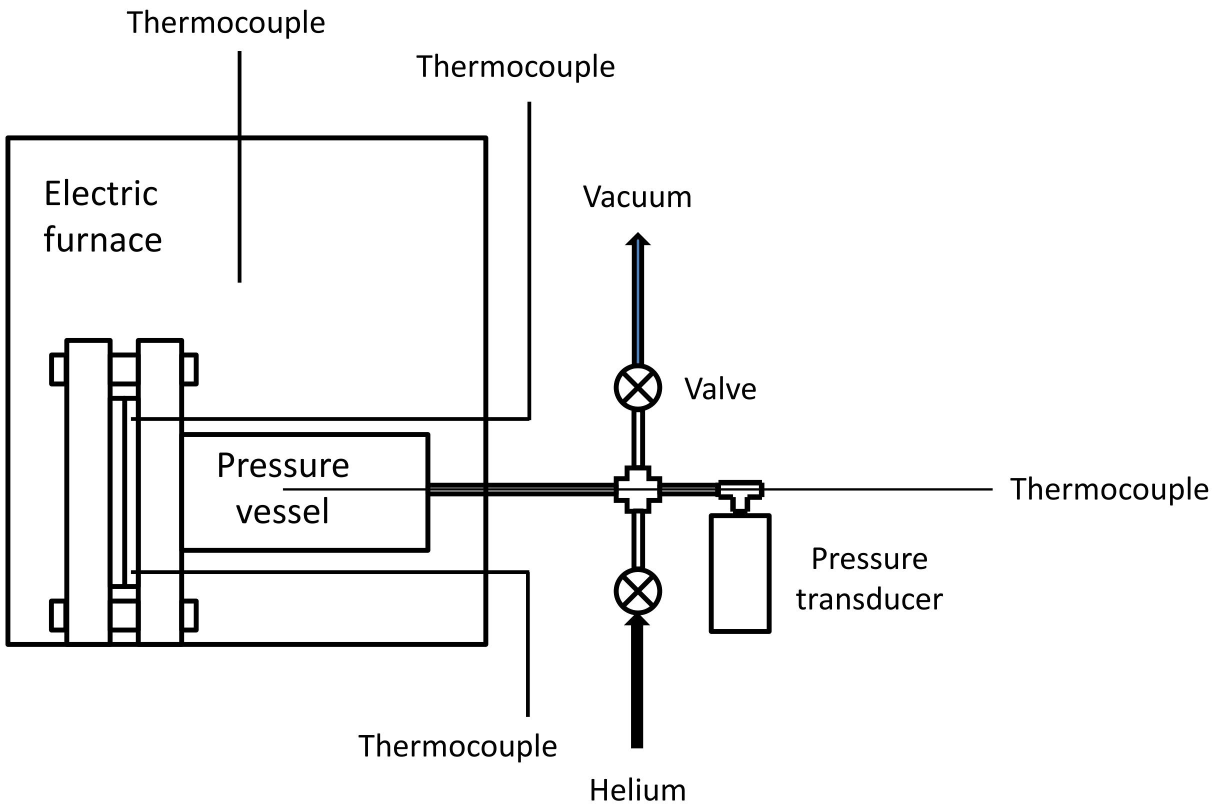

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Figure 2. Photographs of the experimental apparatus.

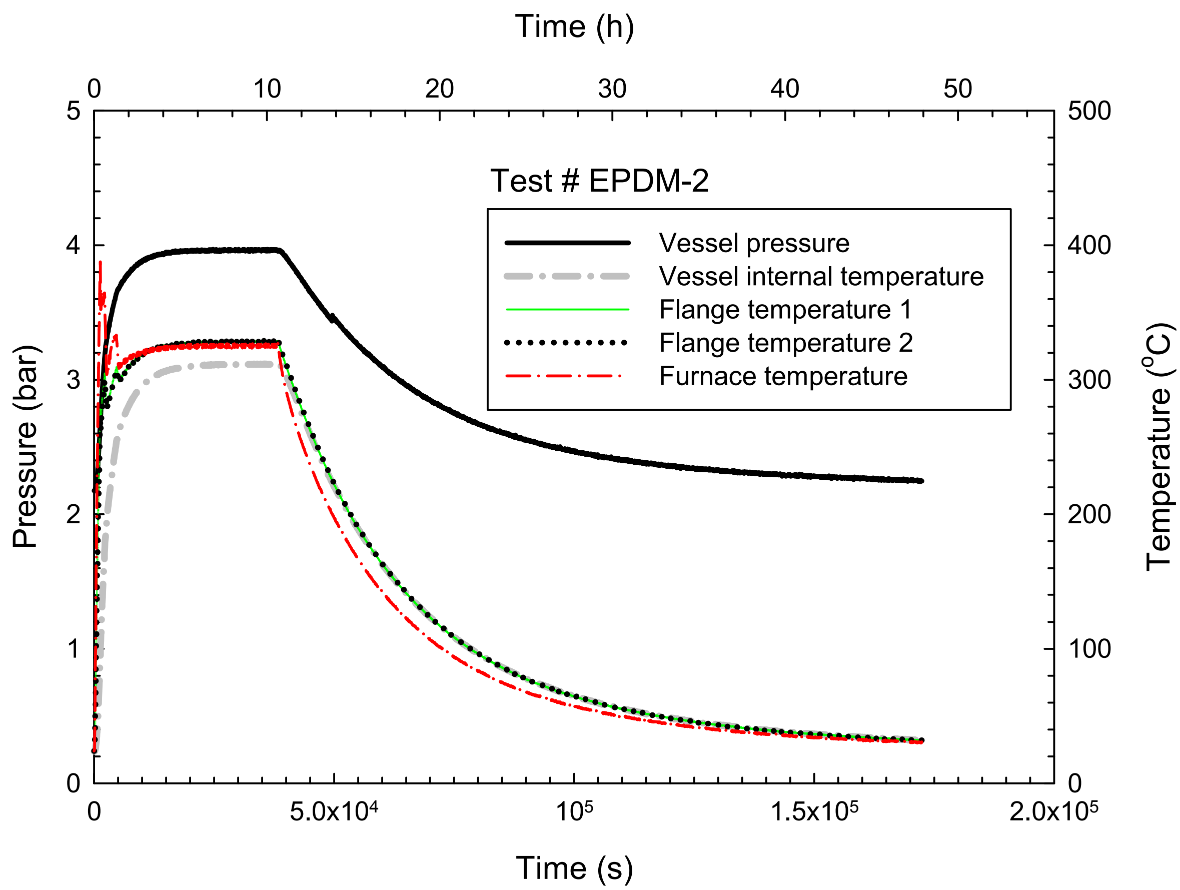

Figure 3. Test results using a single EPDM O-ring configuration (Test # EPDM-2).

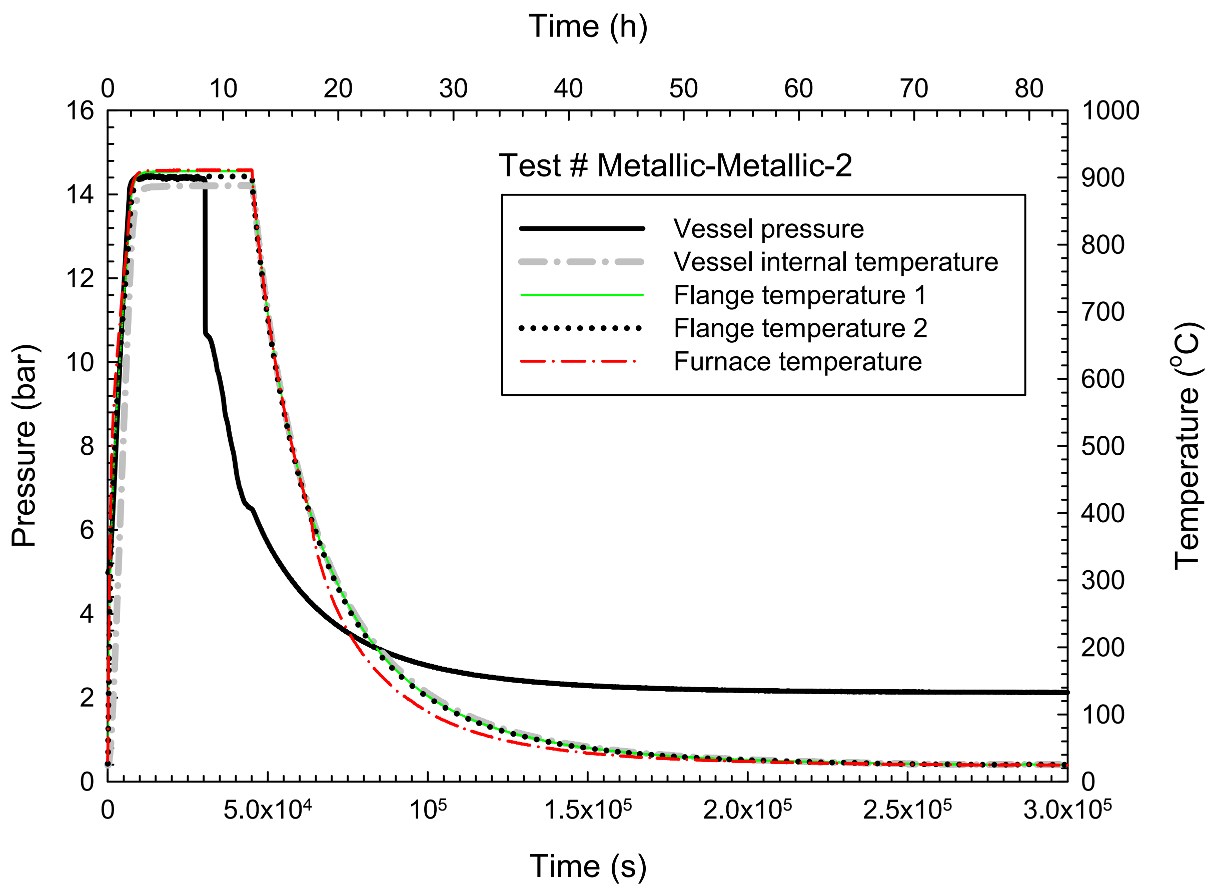

Figure 4. Test results using a double metallic O-ring configuration (Test # Metallic-Metallic-2).

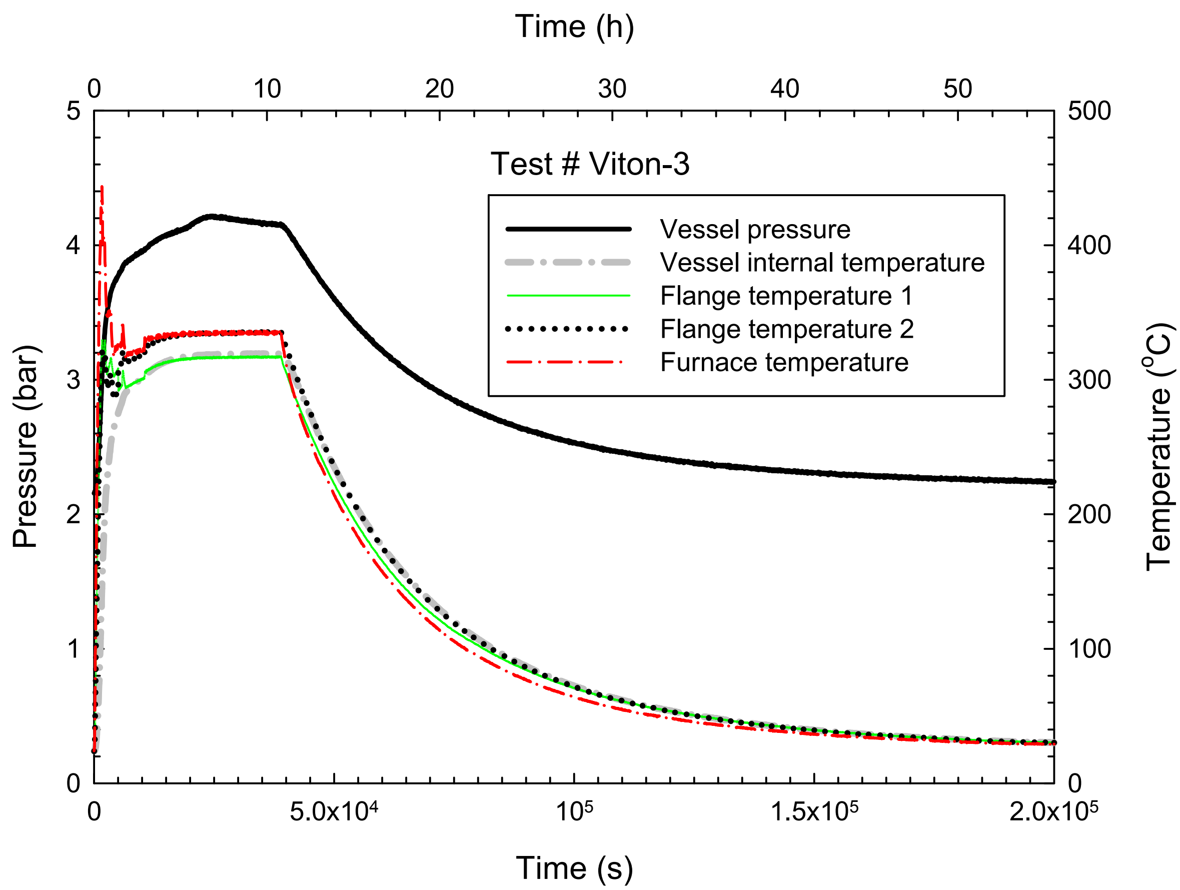

Figure 5. Test results using a single Viton O-ring configuration (Test # Viton-3).

Table captions

Table 1. Nominal maximum operating temperature of O-ring materials

O-ring material	Maximum operating temperature per manufacturer specifications
Metallic	427 °C (silver coating)
EPDM	149 °C
PTFE	260 °C
Butyl	121 °C
Silicone	232 °C
Viton	204 °C

Table 2. Nominal test conditions and parameters used

Test #	Initial vessel conditions	Exposure conditions
Metallic-1	24 °C at 5 bar	30 min at 800 °C
Metallic-2	24 °C at 5 bar	9 h at 800 °C
Metallic-3	24 °C at 5 bar	9 h at 800 °C
Metallic-4	24 °C at 5 bar	9 h at 800 °C
Metallic-5	24 °C at 5 bar	9 h at 427 °C
Metallic-6	24 °C at 5 bar	9 h at 427 °C
Metallic-7	24 °C at 5 bar	9 h at 427 °C
Metallic-8	24 °C at 5 bar	9 h at 800 °C
Metallic-9	24 °C at 5 bar	427 °C and then to 800 °C for about 4 h
Metallic-10	24 °C at 5 bar	427 °C to 627 ºC with 100 ºC increment
Metallic-11	24 °C at 5 bar	427 °C to 727 ºC with 100 °C increment
Metallic-12	24 °C at 5 bar	9 h at 800 °C
EPDM-a	24 °C at 2 bar	150 ºC to 300 °C with 50 ºC increment
EPDM-b	24 °C at 2 bar	> 24 h at 450 ºC
PTFE-a	24 °C at 2 bar	150 ºC to 300 °C with 50 ºC increment
EDPM-1	24 °C at 2 bar	8 h at 316 °C
EPDM-2	24 °C at 2 bar	8 h at 316 °C
EPDM-3	24 °C at 2 bar	8 h at 316 °C
EPDM-4	24 °C at 2 bar	8 h at 316 °C
EPDM-5	24 °C at 5 bar	9 h at 900 °C
EPDM-6	24 °C at 5 bar	9 h at 900 °C
Silicone-1	24 °C at 2 bar	8 h at 316 °C
Silicone-2	24 °C at 2 bar	8 h at 316 °C
Silicone-3	24 °C at 2 bar	8 h at 316 °C
Silicone-4	24 °C at 2 bar	8 h at 316 °C
Butyl-1	24 °C at 2 bar	8 h at 316 °C
Butyl-2	24 °C at 2 bar	8 h at 316 °C
Butyl-3	24 °C at 2 bar	8 h at 316 °C
Viton-1	24 °C at 2 bar	8 h at 316 °C
Viton-2	24 °C at 2 bar	8 h at 316 °C
Viton-3	24 °C at 2 bar	8 h at 316 °C
Viton-4	24 °C at 2 bar	8 h at 316 °C
PTFE-1	24 °C at 2 bar	8 h at 316 °C
PTFE-2	24 °C at 2 bar	8 h at 316 °C
PTFE-3	24 °C at 2 bar	8 h at 316 °C
EPDM-Metallic-1	24 °C at 5 bar	9 h at 800 °C
EPDM-Metallic-2	24 °C at 5 bar	9 h at 800 °C
EPDM-Metallic-3	24 °C at 5 bar	9 h at 900 °C
Metallic-Metallic-1	24 °C at 5 bar	9 h at 900 °C
Metallic-Metallic-2	24 °C at 5 bar	9 h at 900 °C
Metallic-Metallic-3	24 °C at 5 bar	9 h at 900 °C
Metallic-Metallic-4	24 °C at 5 bar	9 h at 900 °C
Blank-Metallic-1	24 °C at 5 bar	9 h at 900 °C
EPDM-EPDM-1	24 °C at 5 bar	9 h at 900 °C
EPDM-EPDM-2	24 °C at 5 bar	9 h at 900 °C
Butyl-Butyl-1	24 °C at 5 bar	9 h at 900 °C

Table 3. Summary of tests where constant vessel pressure was not observed

<table>
<tr><th>Test #</th><th>Comments</th><th>Exposure conditions</th><th>Nominal initial vessel condition</th><th>Seal configuration</th></tr>
<tr><td>Metallic-3</td><td>Measurable leakage occurred at approximately 6.9 h after the test temperature of 800 °C had been reached.</td><td rowspan="3">Heat-up + 9 h at 800 °C + cool-down</td><td rowspan="3">24 °C at 5 bar</td><td rowspan="9">Single</td></tr>
<tr><td>Metallic-4</td><td>Measurable leakage occurred about 2.8 h into the 800 °C exposure.</td></tr>
<tr><td>Metallic-8</td><td>Leakage was observed roughly 3 h after reaching the target temperature.</td></tr>
<tr><td>PTFE-a</td><td>Leakage was observed in the test after it had been subjected to 300 °C exposure for 22 h during the cooling phase.</td><td>8 h of incremental heating from 150 ºC to 300 ºC + more than 20 h at 300 ºC + cool-down</td><td rowspan="6">24 °C at 2 bar</td></tr>
<tr><td>EPDM-b</td><td>Leakage was observed immediately after the vessel had attained the nominal target temperature of 450 °C</td><td>Heat-up + more than 24 h at 450 ºC</td></tr>
<tr><td>Silicone-1</td><td>Leakage was observed after about 2 h at the target temperature.</td><td rowspan="5">Heat-up + 8 h at 316°C + cool-down</td></tr>
<tr><td>Viton-1</td><td rowspan="4">For all the Viton O-ring tests, the vessel pressure peculiarly increased during the thermal exposure, and the reason for the pressure increase remains unresolved.</td></tr>
<tr><td>Viton-2</td></tr>
<tr><td>Viton-3</td></tr>
<tr><td>Viton-4</td></tr>
<tr><td>EPDM-EPDM-1</td><td rowspan="3">Leakage occurred before test temperature was reached.</td><td rowspan="7">Heat-up + 9 h at 900 °C + cool-down</td><td rowspan="7">24 °C at 5 bar</td><td rowspan="7">Double</td></tr>
<tr><td>EPDM-EPDM-2</td></tr>
<tr><td>Butyl-Butyl-1</td></tr>
<tr><td>Metallic-Metallic-1</td><td rowspan="2">Leakage occurred when the bolt torque for a single metallic O-ring was used.</td></tr>
<tr><td>Metallic-Metallic-2</td></tr>
<tr><td>Metallic-Metallic-3</td><td rowspan="2">Leakage occurred even when the appropriate bolt torque was used.</td></tr>
<tr><td>Metallic-Metallic-4</td></tr>
</table>