Spent Nuclear Fuel Transportation Package Seal Performance in Beyond Design Basis Thermal Exposure Scenarios - 11391

Christopher Bajwa, Earl Easton, Felix Gonzalez,
U.S. Nuclear Regulatory Commission, Washington, DC 20005

Jiann Yang, Edward Hnetkovsky,
National Institute of Standards and Technology, Gaithersburg, MD 20878

ABSTRACT

The Nuclear Regulatory Commission (NRC) technical report, NUREG/CR-6886, "Spent Fuel Transportation Package Response to the Baltimore Tunnel Fire Scenario," describes, in detail, an evaluation of the potential for a theoretical release of radioactive material from three different spent nuclear fuel (SNF) transportation packages, had they been exposed to the Baltimore tunnel fire that occurred in July of 2001. This evaluation determined the temperatures of various components of the packages, including the seals, using temperatures resulting from models of the Baltimore tunnel fire (as boundary conditions) and finite element models of the SNF packages. For two of the packages evaluated, the analyses indicated that the seals used would have exceeded their continuous-use rated service temperatures, meaning the release of radioactive material could not be ruled out with available information; However, for both of the packages evaluated, the analysis determined, by a bounding calculation, that the maximum potential release was well below the regulatory requirements for releases from a SNF package during the hypothetical accident condition (HAC) sequence of events in 10CFR Part 71.

The NRC is investigating the performance of seals in SNF transportation packages exposed to fires that could exceed the HAC fire described in 10CFR Part 71, such as the Baltimore Tunnel Fire that occurred in 2001. The performance of package seals is important for determining the potential release of radioactive material from a package during a beyond-design-basis accident. The seals have lower temperature limits than other package components and are the containment barrier between the environment and the cask contents.

The NRC Office of Nuclear Regulatory Research contracted the National Institute of Standards and Technology (NIST) to conduct small-scale thermal testing to obtain experimental data of the performance of seals during extreme temperature exposures.

The experimental testing consisted of several small-scale pressure vessels fabricated with a modified ASME flange design and used metallic seals from a selected manufacturer, similar to those that might be used on an actual SNF transportation package. The vessels were heated in an electrical oven at temperatures as high as 800°C, which far exceeded the rated temperature of the seals in question.

This paper will provide a summary of the testing completed to date, specifically the metallic seal thermal testing, as well as the present preliminary results and conclusions.

NOMENCLATURE

ASME – American Society of Mechanical Engineers
CFR – Code of Federal Regulations
CRUD – Chalk River Unknown Deposit[1]
DAQ – Data Acquisition
HAC – Hypothetical Accident Condition
NIST – National Institute of Standards and Technology
NRC – United States Nuclear Regulatory Commission
SNF – Spent Nuclear Fuel

[1] Generic term for various residues deposited on fuel rod surfaces, originally coined by Atomic Energy of Canada, Ltd. (AECL) to describe deposits observed on fuel removed from the test reactor at Chalk River.

INTRODUCTION

The Nuclear Regulatory Commission (NRC) is collecting data to better characterize the performance envelope of seals used on spent nuclear fuel (SNF) transportation packages during fire exposures that exceed the hypothetical accident condition (HAC) fire described in 10CFR Part 71 Section 73 [2]. An example of an accident that could produce this type of exposures was the Baltimore tunnel fire that occurred in 2001. 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.

NUREG/CR-6886, "Spent Fuel Transportation Package Response to the Baltimore Tunnel Fire Scenario" [1], describes in detail an evaluation of the potential theoretical release of radioactive material from three different spent fuel transportation packages. This evaluation determined the temperatures of various components of the packages, including the seals, using temperatures resulting from models of the Baltimore tunnel fire (as boundary conditions) and finite element models of the SNF packages. For two of the packages evaluated, the model-estimated temperatures of the seals exceeded their continuous-use rated service temperature, meaning a release of radioactive material, such as Cobalt 60 (from CRUD) or Cesium 137 (from fission products), could not be ruled out with available information. 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 a release during the HAC series of events in 10CFR Part 71.

Testing of the types of seals used in SNF packages to determine their performance in beyond-design-basis thermal exposures can provide the physical data needed to understand the potential for a release of radioactive material during a severe fire accident. Previous work on the thermal performance of package seals has focused on temperatures well below 800°C, [3][4]. The test fixture typically consisted of two flanges or two plates with two concentric O-ring grooves, one for the test seal and one for the containment seal, and a small cavity for helium tracer gas.

Experimental Apparatus and Test Method

The test vessels were composed of a cylindrical shell and a flange fabricated from Stainless Steel 304 (SS 304). The flange dimensions were made in conformity with the ASME Standard B16.5-2009, flange class 2500 with a design pressure rating up to 29.2 bar (Table 2-2.1, ASME Standard B16.5-2009) [5]. The vessel cavity had a nominal internal volume of 100 mL. The seal was a metal O-ring made from Inconel 718 and silver with an outer diameter of 6.35 cm (2.5 in) and a cross section of 0.32 cm (0.125 in).

The vessel body and the flange were joined together using four bolts (SS 304 1-1/8 in. 7TPI), each tightened with a torque of 416 N·m (307 ft·lb) ± 2 N·m using a micrometer torque wrench. A 24 cm long SS tubing with an inside diameter of 0.48 cm (0.189 in) and an outside diameter of 0.953 cm (0.375 in) was inserted into the bottom of the vessel body flush through a straight-hole with a bevel-groove and was all-around fillet welded to the vessel. The exposed end of the tubing was connected to a union cross equipped with two needle valves or bellow valves for filling and evacuating the test vessel and a tee connection for mounting a pressure transducer and a thermocouple to monitor the vessel pressure and temperature.

The exposure of the seal to high temperature environment was achieved using a programmable temperature-controlled electrical furnace with an internal capacity of 25.4 cm x 25.4 cm x 40.64 cm (10 in x 10 in x 16 in). Four Type K grounded thermocouples were used to monitor the transient temperature distribution of the test fixture.

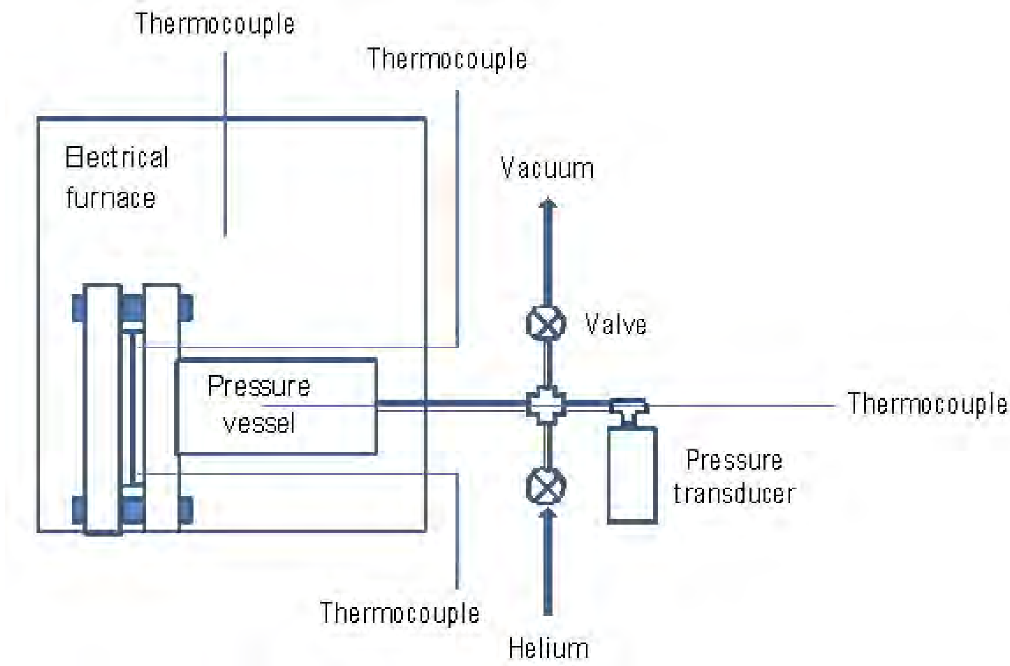

Figure 1: Schematic of experimental apparatus

The test series involved the thermal exposure of a test vessel with a metallic seal in an electric furnace to determine the seal performance at elevated temperatures. The test vessel with the test seal in place was first evacuated and then filled with helium at room temperature to nominal pressure of 5 bar. The vessel was immediately tested for leaks using soapy water. The vessel pressure was then monitored for more than 48 hrs to further monitor for leaks. The vessel was placed in the electrical furnace and heated from room temperature to either 800°C or 427°C. The heating process typically took about 4 hrs. Once the flange temperature had reached the pre-set temperature, the vessel was heated for an additional 9 hrs at this temperature. The furnace was then turned off, and the vessel was allowed to cool to room temperature inside the furnace. The internal temperature and pressure of the vessel, the furnace temperature, and the flange temperatures were recorded during the heat-up and cool-down phases using a LabVIEW-based 16-bit DAQ (Data Acquisition) system with an input/output connector block.

Table 1: Test conditions and parameters

Test #	Vessel #	Nominal initial vessel conditions	Exposure Duration[1]
1[2]	1	24°C at 5 bar	30 min at 800°C[3]
2	2		9 hrs at 800°C
3	3		9 hrs at 800°C
4	4		9 hrs at 800°C
5	5		9 hrs at 427°C
6	2[4]		9 hrs at 427°C
7	1[4]		9 hrs at 427°C

[1] Heat-up and cool-down were done for all tests and are **not** included in the times noted

[2] Shakedown test; during this test DAQ malfunctioned, and no temporal data was collected

[3] The tests conducted at 800°C are considered "beyond-design basis" as the seals were tested to a temperature beyond their rated temperature.

[4] Flange and groove surfaces refurbished

Figure 2: Test rig: test vessel inside the furnace with thermocouple and pressure transducer in place

Test Results and Discussion

During the 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, the vessel pressure and temperature increased. If there was a very small leak, the reduction in pressure due to the reduction in helium in the vessel from the leak could easily be compensated for by the increase in pressure due to increasing temperature. The net effect would still indicate an increase in pressure, thus masking the leak. The use of the temporal variation of vessel pressure as a means to detect potential leakage is best applied to conditions where the vessel is at a constant temperature.

The thermal exposure test using Vessel #1 was intended to be a shakedown experiment. The entire heating process took about 4.5 hrs for the flange temperature to reach the equilibrium furnace temperature of 800°C. The vessel was then maintained at this temperature for an additional 30 min before turning off the electrical furnace. During this shakedown test the DAQ readings from the pressure transducer and thermocouples became erratic, but the DAQ was diagnosed and repaired for subsequent tests. The readings from the pressure transducer and the thermocouples were recorded manually using a voltmeter and a thermocouple reader, respectively. At 800°C, the vessel pressure reached 14.6 bar and was holding at 14.5 bar for an additional 30 min of heating. After the vessel was cooled to room temperature, the vessel pressure recovered to its initial pressure of 5.0 bar, which indicated the absence of a leak.

A postmortem inspection of the tested vessel revealed that the metallic seal was soldered to the flange of the vessel body and a silver-colored coating was imprinted on the surface of the O-ring groove, as shown in Figure 3. The high-temperature exposure also discolored the test fixture.

Figure 3: Postmortem photographs showing the O-ring bonded to the tested vessel body (left) and showing silver from the metallic O-ring deposited on the O-ring groove (right)

Figure 4 shows the temporal variations of the vessel internal pressure and temperature, two flange temperatures and furnace temperature during the heat-up, the constant-temperature heating (isothermal), and the cool-down phases for Test #2. The entire cool-down phase is not shown in Figure 4 because it normally takes more than several days to naturally cool the test vessel inside the powered-down furnace from 800°C to room temperature.

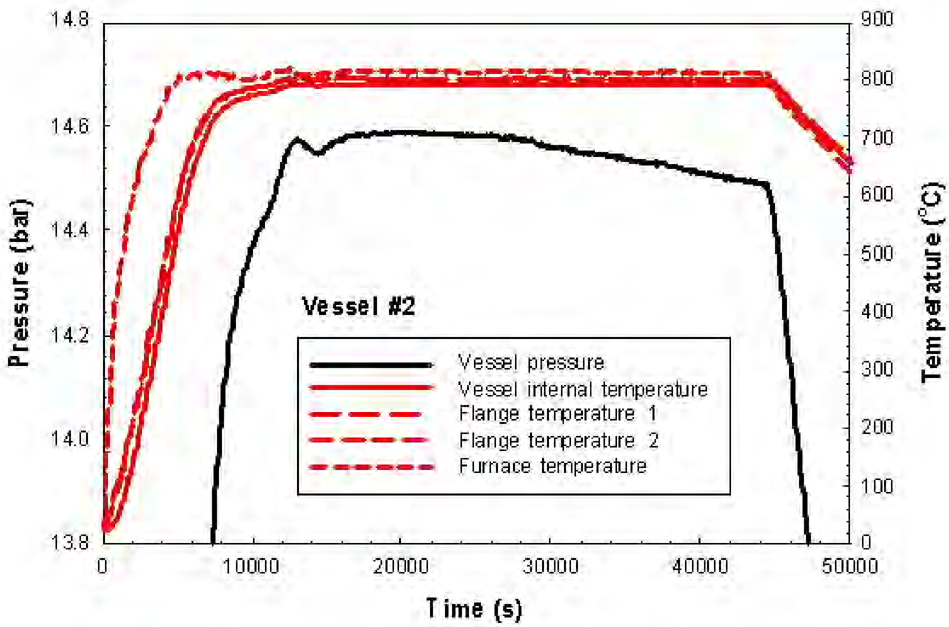

Figure 4: Temporal variations of vessel pressure and temperature in Test #2 (note: y-axis [pressure] has been magnified to show the small pressure decrease)

The scale of the ordinate for pressure in Figure 4 is magnified to show that the pressure starts to decrease shortly after the vessel temperature has reached 800°C and continues to decrease during the rest of the 9 hour constant-temperature heating phase. Although the decrease in pressure, which is within the expanded measurement uncertainty of the pressure transducer, is not significant in this test, the continuous downward trend does seem to imply the occurrence of a very small leak.

Test #3 and #4 are the repeats for Test #2. Figure 5 and Figure 6 are the test results and also show the occurrence of a leak during the 9 hour constant-temperature heating phase at 800°C. In Test #3, the vessel pressure decreases slowly initially and then significantly after about 25000 sec at 800°C. Since the leakage rate is directly proportional to the time rate of change of pressure, this two-stage decrease in pressure indicates a slower leak rate at first and then a faster leak rate at the end. In Test #4, the pressure remains relatively constant for about 10000 sec initially during the 9-hour constant-temperature heating phase, begins to drop significantly for about 15000 sec, and decreases slowly for the remaining duration.

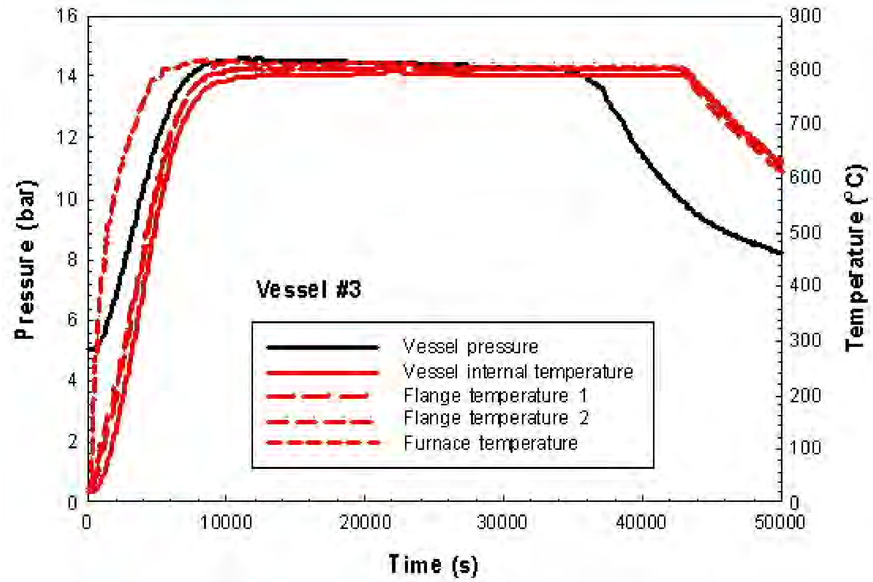

Figure 5: Temporal variations of vessel pressure and temperature in Test #3

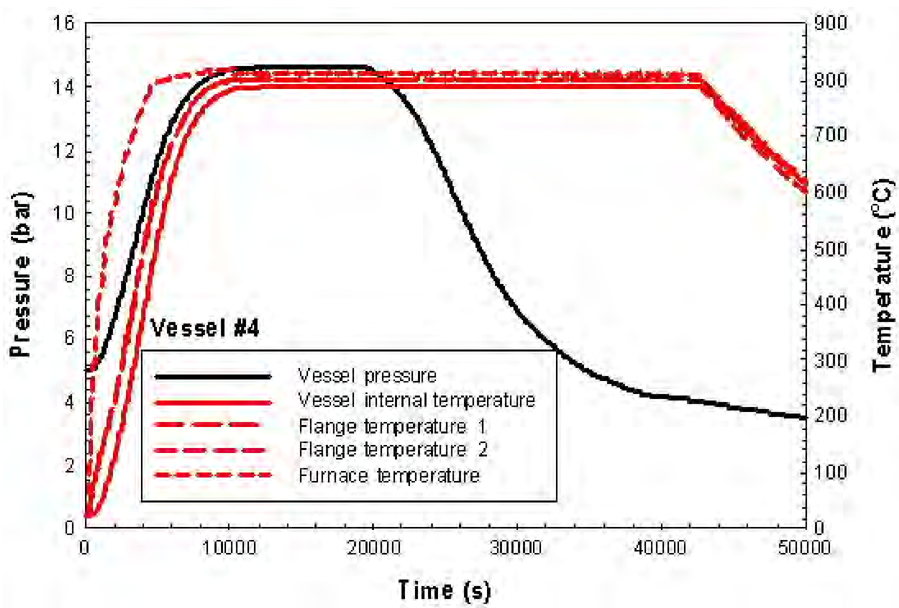

Figure 6: Temporal variations of vessel pressure and temperature in Test #4

It is interesting to note that despite the consistent occurrence of a leak in these three tests, the vessel pressure remained above atmospheric pressure at the end of the cool-down-phase, which took several days. This seems to indicate the possibility that during the heat-up phase, the silver coating on the metallic seal (with a melting point of 962°C) softened and "flowed" in the O-ring groove. At that point it may not have been able to hold the system pressure and a slow leak commenced. During the cool-down phase, the softened silver hardened, bonded to the flange surface, and left a silver coating on the O-ring groove surface. The re-hardening of silver might have re-sealed the vessel. While it cannot be verified experimentally, the test results discussed below appear to indicate the possibility of re-sealing. The ability of the vessel to maintain pressure following the exposures provides further support, in addition to the photographic evidence described above, to the possibility that re-sealing could potentially occur as the silver in the seal cools.

For Test #5, the vessel pressure remains constant during the entire 9-hour constant-temperature heating period at 427°C. The seal held vessel pressure. This was further confirmed by the fact that the initial pressure of 5 bar was recovered after the cool-down phase. A postmortem inspection revealed that the metallic O-ring seal was not soldered to either flange surface and no silver coating from the seal was transferred to the O-ring groove.

The results for Test #6 using the refurbished Vessel #2 are shown in Figure 7. The refurbishment only involved the re-facing of the surfaces of the flanges and the O-ring groove to the specified tolerances. For this test, the vessel pressure started to decrease very slowly during the constant-temperature heating period. The scale of the ordinate pressure is magnified in Figure 7 to elucidate the small pressure drop, which is within the expanded measurement uncertainty of 0.11 bar; however, the continuous decrease in pressure does seem to imply that a very small leak might have occurred during the test.

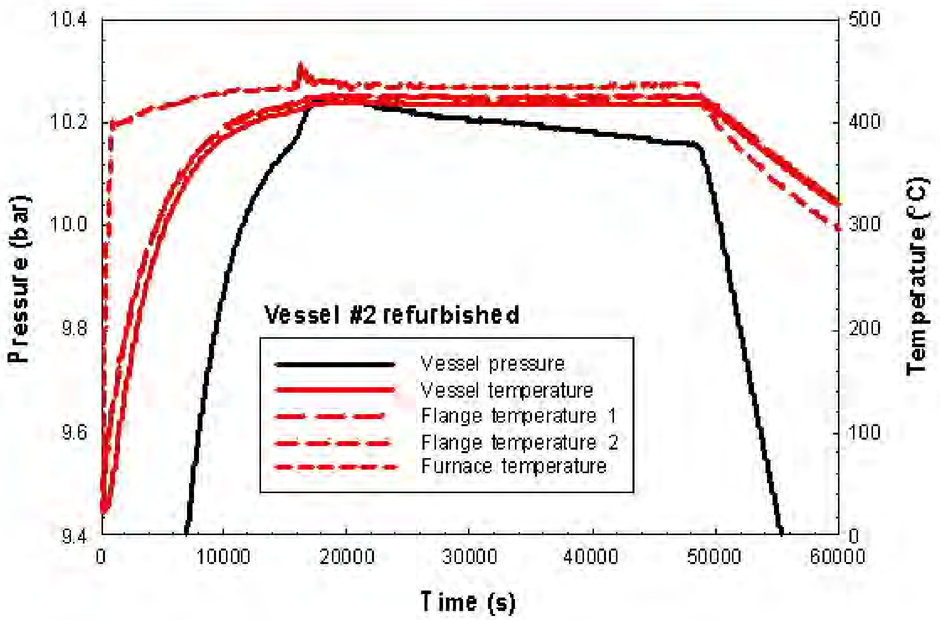

Figure 7: Temporal variations of vessel pressure and temperature in Test #6

Test #7 was performed using the refurbished Vessel #1. The same refurbishing process used in Vessel #2 was applied to Vessel #1. The vessel pressure remained unchanged during the 9-hour constant-temperature heating period. No leak was observed during Test #7.

It is not known if the leak in the refurbished Vessel #2 was caused by a different thermal response of the vessel, which had previously been exposed at 800°C for 9 hrs. Although Vessel #1 was also refurbished, the previous exposure time at 800°C was much shorter than that of Vessel #2 (30 min vs. 9 hrs).

CONCLUSION

Seven tests were performed to acquire experimental data of metallic seals, similar to those used in transportation packages, to determine a performance envelope for these seals in beyond-design-basis fire exposures. The data obtained in these tests will be used to determine the leakage rate of the system. Further performance testing on elastomeric type seals is planned.

REFERENCES

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