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RECENT RADIOACTIVE MATERIAL PACKAGE TESTING EXPERIENCES AT OAK RIDGE NATIONAL LABORATORY

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ABSTRACT

Oak Ridge National Laboratory (ORNL) pioneered the testing of radioactive material shipping packages and has been performing such tests for more than 50 years. Currently, except for Type B thermal tests, testing is performed at the purpose-built Packaging Evaluation Facility (PEF), located at the National Transportation Research Center (NTRC), a US Department of Energy user facility. Packages used for the transportation of Type B quantities of radioactive materials must be capable of meeting normal conditions of transportation (NCT) and hypothetical accident conditions (HAC) requirements as defined in Title 10 Code of Federal Regulations Part 71. Evaluating package designs to these criteria typically involves a combination of analysis and physical testing. Required physical tests include free drop, crush, puncture, penetration, compression, vibration, water spray, water immersion, and thermal. The ORNL Packaging Evaluation Facility at the National Transportation Research Center provides an inclusive testing capability for a wide variety of packages needed for shipment of radioactive materials. Since PATRAM 2019, ORNL has performed several sets of tests including two designs of the Defense Program Package (DPP-3 and DPP-1), one additive manufactured scale canister, and several special form capsules. This paper summarizes the testing regimes performed and the advancements made to the ORNL package testing program during that time.

INTRODUCTION

Radioactive materials widely used in many different types of industries including medicine, consumer

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This is a technical paper that does not take into account contractual limitations or obligations under the Standard Contract for Disposal of Spent Nuclear Fuel and/or High-Level Radioactive Waste (Standard Contract) (10 CFR Part 961). For example, under the provisions of the Standard Contract, spent nuclear fuel in multi-assembly canisters is not an acceptable waste form, absent a mutually agreed to contract amendment. To the extent discussions or recommendations in this paper conflict with the provisions of the Standard Contract, the Standard Contract governs the obligations of the parties, and this presentation in no manner supersedes, overrides, or amends the Standard Contract. This paper reflects technical work which could support future decision making by the U.S. Department of Energy (DOE or Department). No inferences should be drawn from this presentation regarding future actions by DOE, which are limited both by the terms of the Standard Contract and Congressional appropriations for the Department to fulfil its obligations under the Nuclear Waste Policy Act including licensing and construction of a spent nuclear fuel repository.

products, energy, and defense. Annually, there are more than 3 million shipments of radioactive material in the United States, averaging about 3,000 per day. However, most of these shipments involve low specific activity radioactive quantities. With the vast quantity of shipments of radioactive materials being transported on public roads and highways at any one time, safety and security are top priorities. Therefore, a comprehensive system of rigorous design, testing, evaluations, and packaging certification, is essential to ensure the public and environment are protected from the hazards of the radioactive materials in commerce.

Shipments of radioactive materials have been made from Oak Ridge National Laboratory (ORNL) since the 1940s [1]. This early involvement in shipment of radioisotopes placed ORNL at the forefront of transport package testing and the development of regulations pertaining to the transport of radioactive material. ORNL has continuously maintained an NQA-1 and 10 Code of Federal Regulations (CFR) Subpart H–compliant radioactive material package testing program for the past 23 years. Early tests were performed at the Tower Shielding Reactor site. Since 2001, ORNL package testing has been conducted at the Packaging Evaluation Facility (PEF) located at the National Transportation Research Center (NTRC). The NTRC is a US Department of Energy (DOE) user facility where a wide array of transportation-related research and development activities occur. The PEF facility contains indoor and outdoor drop pads as well as other equipment necessary for package testing that includes a vibration table, a compression machine, and pressure drop, pressure rise, and helium leak detectors [2]. ORNL has continuously maintained an NQA-1 and 10 Code of Federal Regulations (CFR) Subpart H–compliant radioactive material package testing program for the past 23 years.

During the past 3 years, ORNL has undertaken several different radioactive material package testing campaigns. These include testing the Pacific Northwest National Laboratory designed DPP-3 Type B shipping package, the Y-12 National Security Complex designed DPP-1 Type B shipping package, the ORNL additive manufactured scaled dual-purpose canister (DPC), and ISOTEK special form capsules. This paper describes test unit preparation, pretest conditions, conditioning of each test unit, NCT and HAC testing, and posttest damage measurements, and observations.

DPP-3

ORNL was contracted by Y-12 through Pacific Northwest National Laboratory to execute and document the performance of the DPP-3 package design when subjected to the regulatory tests. However, the DPP-3 presented a unique challenge for the ORNL testing staff. The PEF and the rest of ORNL's package testing infrastructure had been developed for fissile drum-type packages weighing up to 1,000 lb. The DPP-3 has a maximum loaded weight of just under 1,661 lbs, a height of 52 in., and a diameter of 37 in. (Figure 1). Therefore, much of the infrastructure used for testing had to either be altered or developed new.

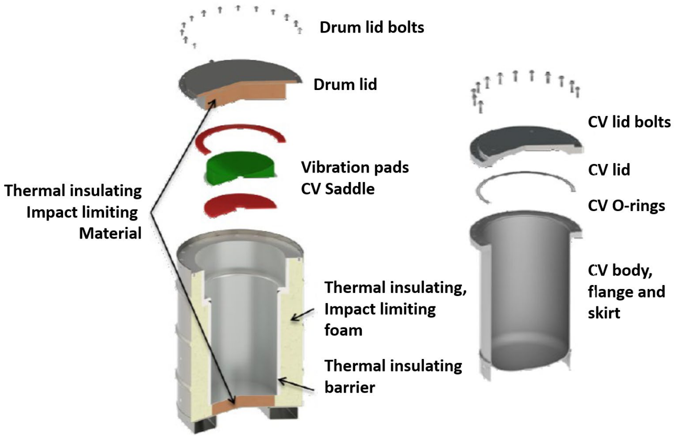


Figure 1 DPP-3 design.

Additionally, the DPP-3 prototype test units contained two unique surrogate designs: (1) basket content assembly and (2) non basket content assembly (Figure 2). Each containment vessel (CV) content assembly comprised between four and seven components. The content assembly included top and bottom foam inserts for cushioning during vibration test and structural tests. Because the foam inserts were open-cell foams, the posttest helium leak test was challenging. During the helium leak test, the CVs were connected to a vacuum pump to evacuate the internal volume in the CV to <1 Torr. The open-cell foam content resulted in various pockets of air that necessitated exposing the CV to a vacuum pump for 4 days. Because six DPP-3 prototype units were tested, the six CVs were connected in series to multiple vacuum pumps to ensure timely evacuation of all CVs to <1 Torr. Infrastructure built for the project included new manifolds for the helium leak test, a thermal test lifting/loading fixture, cooling stands for the thermal tests, a preheating chamber for the thermal test, and lifting fixtures for the drop tests. Additionally, a new furnace facility was used for this project, resulting in new thermal operating procedures, furnace loading and unloading procedures, and thermal test hardware.

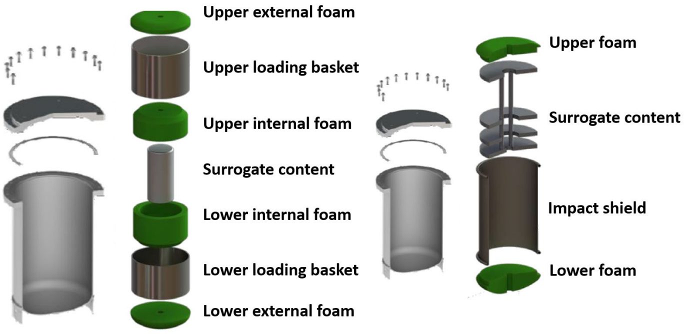


Figure 2 DPP-3 surrogate content assembly.

ORNL assembled the six test units before testing. Five test units had the non basket content assembly, and one test unit had the basket content assembly. The test unit weights ranged from 1,588 to 1,661 lb. Six of the seven units were tested to demonstrate compliance with 10 CFR 71.73 *Hypothetical Accident*

Conditions (HAC) [3]. The test series included a thermal test, so 33 temperature-indicating labels were affixed on each of these units in various locations to record the maximum temperature reached at specific locations. The seventh test unit was tested to demonstrate compliance with 10 CFR 71.73 15 m immersion test; therefore, no temperature-indicating labels were included on this unit. All seven CVs were leak tested to a pre-shipment standard before being inserted into the quad-body (drum) using a pressure-rise leak test method.

All six test units underwent the normal conditions of transportation (NCT) drop test (1 m free drop). The orientations for five impact tests included center-of-gravity over top corner (CGOC), CGOC over bottom corner, vertical on the flat top surface, vertical on flat bottom surface, and horizontal. For five of the six units, this test was followed immediately by the HAC drop test (9 m) in the same orientations. Four of these test units were subjected to the NCT water spray test, and one test unit was subjected to the NCT vibration test. After the NCT and HAC 9 m free drop tests were completed, all units were subjected to the HAC 1 m puncture. Because the test units weighed more than 1,100 lb, the steel plate crush test was not required. The orientations for the puncture tests were chosen to cause maximum damage resulting from the previous HAC and NCT drop tests. For the test units that were tested in ambient temperature conditions, damage measurements were taken between each test sequence. One test unit was chilled to −40°C before testing, and another test unit was heated to 100°F before testing. To ensure the tests was performed as fast as possible on a hot and cold test units to minimize initial temperature variations, no damage measurements were taken between tests.

Six of the DPP-3 test units were subjected to the structural HAC test then the HAC thermal test. ORNL does not have a thermal test facility on-site, so a furnace at Southwest Research Institute (SwRI) in San Antonio, Texas was used. This facility had never been used by ORNL to perform HAC thermal tests; after a site visit, ORNL determined that it met the requirements outlined in 10 CFR 71.73(c)(4). Preheating is necessary before the thermal test, and the preheat oven used previously by ORNL for this purpose was too small. Therefore, ORNL created a new preheat oven. The structure of the preheat volume was provided by aluminum "U" channels (often referred to as *unistrut*) with a 4.8 × 2.4 × 1.5 m (16 × 8 × 5 ft) volume (Figure 3). After the structure was built, ducting was placed inside the structure to allow for even heating of the entire preheat volume. The unistrut was subsequently covered by a thermal foam board and sealed with aluminium tape. An electric heater equipped with internal thermostat was used to provide a controlled heat to the chamber. During construction, several thermocouples were placed inside the preheat area. These were then attached to a control system that ensured the minimum temperature inside the preheat area was greater than 43°C (109°F). All six test units were allowed to preheat for over 48 h before thermal testing, thus ensuring the temperature throughout each tests unit was at least 38°C (100°F).

Figure 3 DPP-3 preheat chamber.

The thermal tests were all performed according to ASTM Standard E2230 *Standard Practice for Thermal Qualification of Type B Packages for Radioactive Material* [4]. In particular, the steady-state method of furnace testing, as described in Section 7.3.4.3 of ASTM E2230-13, was used for the DPP-3 test units. This method requires the external skin of the package to reach the regulatory temperature (800°C) before the 30 min clock is started. Each test unit was instrumented with six thermocouples on its skin to allow for surface temperature measurements. The test was performed by placing the test unit onto a lifting cradle and then loading the test unit into the furnace from the ceiling. Every effort was made to reduce the loading time to ensure the temperature within the furnace recovers quickly once the furnace door is closed. All surfaces within the furnace (walls, ceiling, door, and floor) were also instrumented with thermocouples. These radiating surfaces transfer most of the heat to the package; therefore, they must remain hotter than 800°C throughout the test.

The six HAC test units were successfully subjected to the thermal test. Loading each test unit into the furnace took between 30 and 45 s (furnace ceiling hatch beginning to open until furnace ceiling hatch fully closed). Total time in the furnace for the test units ranged from 33 to 35 min. That is, the skin of each test unit took between 2 and 3 min to reach 800°C, and then the 31 min test timer started. The furnace temperature set point during each test was 850°C. At the end of each test, the test unit was removed from the furnace and placed on a stand to cool. The stands were in a protected alcove to ensure that no artificial cooling occurred, as required by the regulations (Figure 4). When the thermal tests were completed and the units had fully cooled, they were packaged for transport and returned to ORNL for disassembly, inspection, and leak testing.

Figure 4 DPP-3 thermal test.

The six test units were sequentially disassembled after testing. First, the lids were removed from the drum body, allowing for removal of the intact CVs. The lid of the test unit that was subjected to the CGOC 9 m drop test and the vertical top-down test proved challenging to remove. All other drum lids were easily disassembled, and the CVs were easily removed. At this point, the temperature-indicating labels on the interior of the drum liners and on the exteriors of the CVs that were exposed to HAC tests were read and recorded. Then, each of the CVs were subjected to two separate leak tests: (1) a pre-shipment, pressure-rise leak test and (2) a helium leak test. To perform the helium leak test, each CV had to be drilled and tapped with a 0.25 in. NPT thread to enable a vacuum to be pulled on the unit's interior. Once the proper vacuum was established, a bag surrounding the CV was filled with helium. With the outside of the CV at ~760 Torr and the inside of the CV at~0 atm, this provided the pressure differential for the leak test. Any leakage pathways would result in helium entering the CV and then detection by a helium spectrometer attached to the CV. Once the CV leak testing was complete, the CVs were disassembled and the temperature-indicating labels on the interior of the CV and on the mock payloads were obtained and recorded.

A separate seventh test unit consisted of a single CV and was subjected to the 15 m water immersion test specified in 10 CFR 71.73(c)(6). This test unit was loaded with enough ballast to ensure it would not float and then assembled before a pre-shipment pressure-rise leak test was performed. Subsequently, the unit was placed in a water chamber that was then pressurized to greater than 150 kPa for more than 24 h. The unit was then removed from the water chamber and disassembled.

All test results were documented in ORNL/NTRC-087 [5].

DPP-1

The DPP-1 package (Figure 5) was designed by Y-12 and followed the same process as the DPP-3 testing campaign. The package was tested at the ORNL PEF and was subjected to the 10 CFR 71.71 and 10 CFR 71.73 sequence of tests.

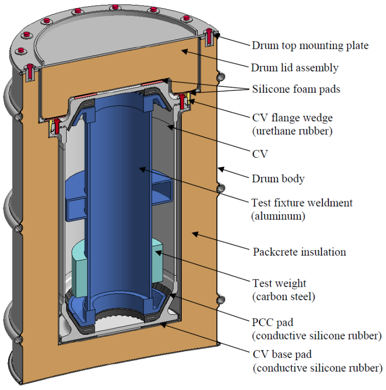


Figure 5 DPP-1 Type B design.

This testing campaign was divided into three main phases using six test units. Phase 1 was the project initiation, pretest operations. Phase 2 comprised the regulatory testing. Phase 3 included the post-test evaluations, assessments, data evaluations, and test report creation. All activities in each phase were completed by ORNL personnel, the thermal test in was completed at SwRI and a unique preheat chamber was built for this testing campaign. Unlike all previous testing campaigns, a new digital image correlation technique and 3D scan metrology was introduced to more accurately and efficiently document the test damage that resulted from his DPP-1 testing.

After the NCT and HAC tests, the test units external surfaces were scanned by the HandyScan Black Elite handheld scanner. This system provides the most effective and reliable way to acquire accurate 3D surface measurements of physical objects. The HandyScan features *dynamic referencing*: both the scanner and the part can move during measurement and still provide an accurate and high-quality scan. The accuracy of the scanner is 0.025 mm (0.0009 in.) with a 310 × 350 mm (12.2 × 13.8 in.) scan area and has a measurement rate of 1,300,000 measurements/s (Figure 6).

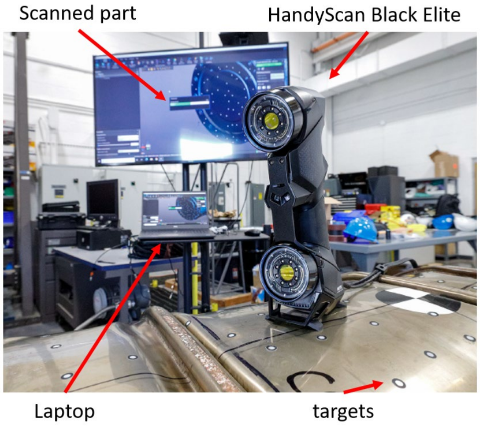


Figure 6 HandyScan Black Elite 3D scanner.

The final scanned model was postprocessed using the VXmodel software provided by the HandyScan vendor. The VXmodel is a posttreatment software module designed to optimize the scanned part and prepare 3D scans for additive manufacturing (AM), CAD analysis, structural analysis, and reverse engineering operations. In the VXmodel, the scanned test unit data points were post processed to remove all slivers, gaps, and holes. Then, the model was aligned with a global coordinate system, and entities such as section cuts and dimensional measurements were extracted from the final scanned model. Initial height and diameter measurements were extracted from the undamaged test unit (Figure 7). The test unit was then subjected to the prescribed NCT or HAC test. After the prescribed tests, the test unit was scanned and postprocessed for damage evaluation. A contour map of each drum body outer surface deformation was created and enabled quantification of the maximum penetration depth of the drum outer shell when subjected to the NCT and HAC tests. For example, the sixth test unit was subjected to the penetration test, and the contour map indicates that the maximum penetration damage depth on the outer shell was 0.1837 in. (4.6 mm) and the penetration length was 0.24 in. (6 mm) (Figure 8).

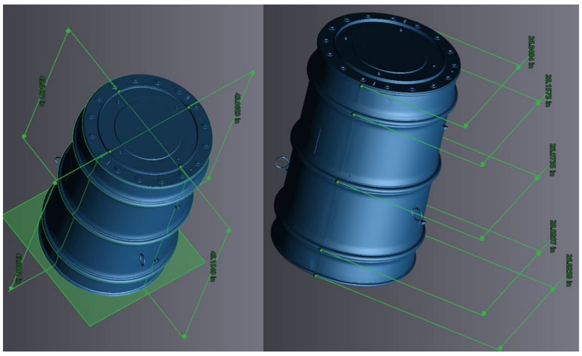


Figure 7 Initial 3D metrology scan.

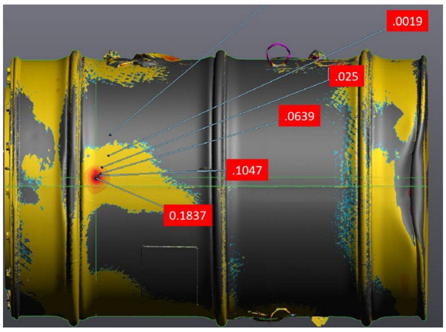
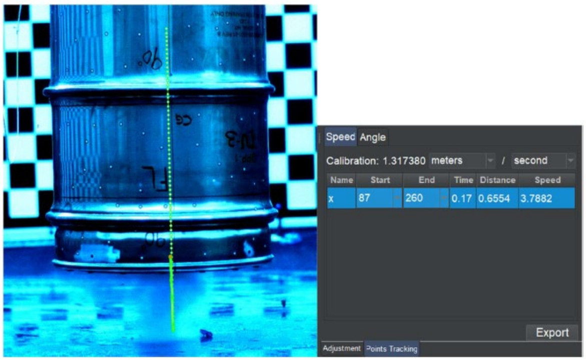


Figure 8 3D scan posttest evaluation.

Digital image correlation and tracking is an optical method that employs image registration techniques for accurate 2D and 3D measurements of changes in images. This technique was used during the DPP-1 testing campaign's free-drop testing campaign to acquire position, velocity, and acceleration. The impact data were acquired using Mega Speed [6] object-tracking software. Using those data, acceleration and maximum gravitational loads were calculated. This method was compared with the accelerometer data and theoretical values. Using 3D scans, this technique was also used to find the total deformation of the test unit after all testing was completed. Each high-speed digital video was postprocessed using the Mega Speed object-tracking software. This postprocessing required correlating the number of pixels in the video to a known measurement. The video pixels were calibrated to scale all movement in the high-speed video. Calibration was achieved by drawing a virtual line that measures an object of known length that exists in the same plane of motion as the package. For this study, no object fulfilled those criteria other than the package itself. The virtual line was drawn either along the length of the package or along the diameter of the package, depending on the package orientation. Figure 9 shows an example of a high-speed video being calibrated. Setting the known length prompts the software to set each pixel to that calibrated length as a ratio or pixels to length. This ratio was used during the object-tracking phase. The virtual line must be placed as accurately as possible since the software calculates based on pixels and any uncalibrated pixel contributes to error in the final calculations.



Calibration: 1.317380 meters / second

Name	Start	End	Time	Distance	Speed
x	87	260	0.17	0.6554	3.7882

Figure 9 Digital image correlation object tracking.

Self-adhesive white dots were tracked to find the displacement in each frame. The software follows these dots through each image and calculates each dot’s travel distance. For consistency, the same dot was used to post-process each object tracking in the high-speed digital videos. The data obtained via this method include position, time, and velocity. All data was exported to an Excel file for further calculations. The finite difference method was used to calculate the second derivative of the position with respect to time. Specifically, this method used to calculate maximum deceleration loads of the impact events of the test units.

These test results were documented in ORNL/NTRC-095 [7].

ADDITIVE MANUFACTURED DUAL-PURPOSE CANISTERS

Dual-purpose canisters (DPCs) provide confinement for spent nuclear fuel (SNF) while in storage and subsequent material handling and transportation. As the volume of SNF steadily increases, individual sites will increase their use of DPCs for long term dry storage systems. Therefore, having a comprehensive aging management plan in place to ensure long-term DPC confinement is essential to ensuring the safe storage of SNF. Chloride-induced stress corrosion cracking of welded stainless-steel structures has been identified as a potential degradation mechanism for DPCs. Therefore, an aging management plan is required, and potential advanced manufacturing techniques must be investigated to reduce the potential for chloride-induced stress corrosion cracking near the heat-affected zone of welded canisters. Fabricating DPCs via AM is a proposed method to largely reduce high-tensile residual stresses caused by welding.

In 2022, ORNL's Nuclear Materials, Packaging, Testing, and Systems Analysis group demonstrated the dynamic response of a canister with an integrated basket assembly using wire arc AM (WAAM). The additive manufactured canister was subjected to a select set of the Type B NCT and HAC tests specified in 10 CFR 71.71, *Normal conditions of transport*, and 10 CFR 71.73, *Hypothetical accident conditions of transport*.

A 316L stainless steel additive manufactured canister was printed by the ORNL Manufacturing Demonstration Facility. A canister design, representative of a commercially available SNF canister, was chosen (Figure 10). However, the limitations of the welding robotic arms in the Manufacturing Demonstration Facility rendered a full-scale SNF canister unachievable. Therefore, a canister with a length of 36 in. and a diameter of 17.25 in. with an integrated basket design was printed using the WAAM method (Figure 11).

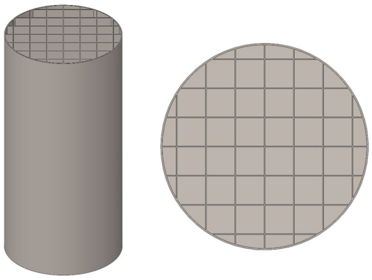


Figure 10 Additive manufactured test unit design.

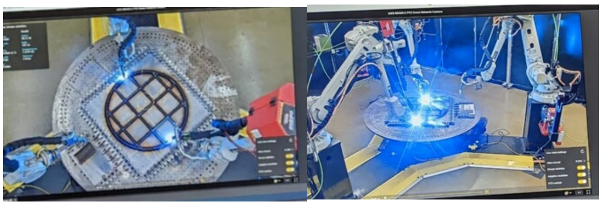


Figure 11 WAAM print.

The additive manufactured test unit underwent three tests: (1) the NCT 1.2 m free drop, (2) the HAC 9 m free drop, and (3) the HAC 1 m puncture test at the ORNL PEF. The additive manufactured test unit was scanned using the HandyScan scanner to obtain a pretest 3D model. The 1.2 m free drop test resulted in minimal deformation of package dimensions. Other than a very small flat segment being created in the test unit, no other discernible damage was noted from the 1.2 m free drop. The 9 m drop test and the 1 m puncture test resulted in minimal damage to the canister, except for scuff marks on the impact area and a relatively small flat segment on the impact side of the test unit (Figure 13). To document the damage, dimensional measurements were recorded by scanning the canister using the HandyScan scanner after each structural test.

HAC 30-ft free drop

HAC 1-m puncture test

Figure 12 - Additive manufactured test unit HAC test.

Upon completion of the four NCT and HAC tests, it was noted that although the packaging sustained minor permanent deformation, no cracking, brittle, or catastrophic shattering failure of the additive manufactured stainless-steel outer shell occurred. Because the canister remained structurally intact throughout the most severe of the NCT and HAC tests, further exploration of the potential use of additive manufactured 316L stainless steel is warranted. The additive manufactured canister could reduce fabrication costs as well as provide opportunities to design canisters that optimize shielding layers and shapes that could not be created using traditional fabrication methods.

The test results were documented in PVP2023-105981 [8].

SPECIAL FORM TESTS

Tests were performed on several different capsule designs to earn these designs special form certification. These designs include an ISOTEK capsule as well as neptunium-237 and americium-241 ORNL ZipCans. Each of these test protocols consisted of a 9 m drop test, a percussion test, and a 10 min 800°C thermal test. For each design, a single unit was used for the drop test and the percussion test, and a separate unit was used for the thermal test. For all designs, a helium leak test and a bubble leak test were performed after each test to meet regulatory requirements. The bubble leak test was used to detect gross leaks, and the helium leak test was used to detect fine leaks. Various additive manufactured lifting fixtures were designed and used to ensure each test unit impacted at the location that created the most damage. Additionally, the drop tests were supplemented with explicit dynamic finite element analysis to help guide the test process. Finally, a newly built thermal data acquisition system was used for the thermal tests. The system provides 224 data channels that continuously log to a data file (Figure 14). The thermocouples are connected to a portable thermocouple connector box, which is then connected to the data acquisition unit. This unit then transfers data to a laptop via a

USB cable. During the thermal test, the system is set to log data every 15 s from each data channel. The results of the special form testing process are detailed in the literature [9,10].

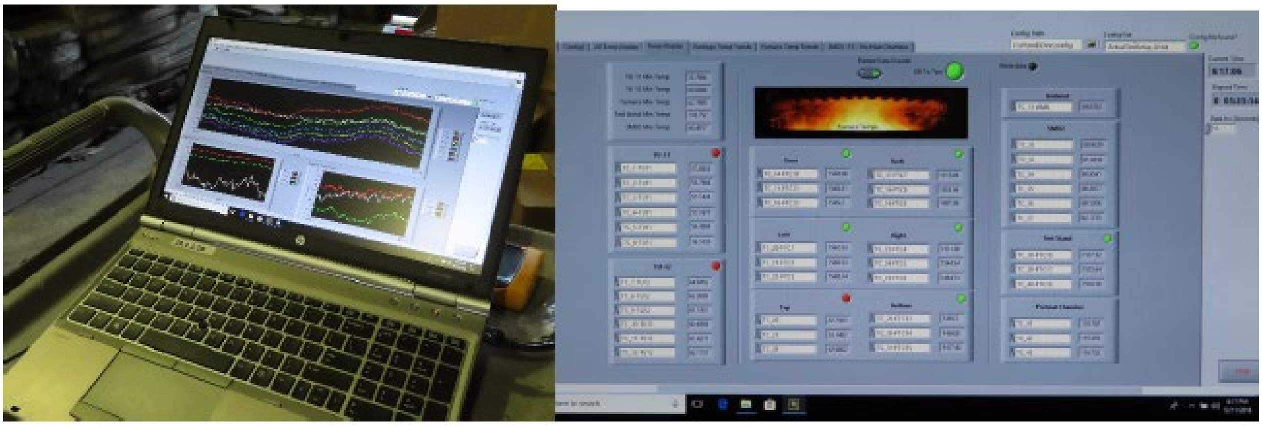


Figure 13 Package testing program thermal data acquisition.

SUMMARY

ORNL has performed radioactive material package tests for more than 50 years. Recently, ORNL tested several different radioactive material packages, including Type B packages (DPP-1, DPP-3), additive manufactured DPC designs for SNF, and special form capsules. The testing process includes test plan and test report documentation with corresponding digital media (pictures and video) as well as performance data and leak test results of all required and/or requested testing. Digital image correlation and 3D metrology were introduced as posttest damage evaluation and data gathering techniques to improve the accuracy of posttest evaluations.

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REFERENCES

1. Shappert, L. B., S. B. Ludwig, “44 Years of Testing Radioactive Materials Packages at ORNL,” *Proceedings of 14th International Symposium on Packaging and Transportation of Radioactive Materials* (PATRAM2004), Berlin, Germany, 2004.
2. ORNL *Design and Certification of Targets for Drop Testing at the NTRC Package Research Facility*, ORNL/NTRC-001 Rev. 0, Oak Ridge, Tennessee: Oak Ridge National Laboratory,

2003.

3 US Nuclear Regulatory Commission, *Packaging and Transportation of Radioactive Material*, 10 CFR Part 71, Washington, D.C., January 2013.

4 ASTM International, *Standard Practice for Thermal Qualification of Type B Packages for Radioactive Material*, E2230-13, West Conshohocken, Pennsylvania, 2008.

5 Martinez, O., P. Nogradi, A. Adeniyi, B. Loftin, B. Van Hoy, *Test Report for DPP-3 Regulatory Compliance Testing*, ORNL/TM-2020/1807, Oak Ridge, Tennessee: Oak Ridge National Laboratory, 2020.

6 Mega Speed, www.megaspeedusa.com.

7 Nogradi, P., Martinez, O., Adeniyi, A., Van Hoy, B., *Test Report for DPP-1 Regulatory Compliance Testing,* ORNL/TM-2022/2399, April 2022, Oak Ridge, Tennessee: Oak Ridge National Laboratory.

8 Martinez, O., D. Giuliano, W. Tang, P. Nogradi, A. Adeniyi, L. Lowe, "Additive Manufacturing and Regulatory Testing of Canister for Spent Fuel Management," *Proceedings of the ASME 2023 Pressure Vessels and Piping Conference*, Atlanta, Georgia, July 16–21, 2023.

9 Adeniyi, A., O. Martinez, *Test Report for the Qualification Testing of the ORNL-SFC-Am-ZipCan Special Form Capsule,* ORNL/SPR-2021/2264, Oak Ridge, Tennessee: Oak Ridge National Laboratory, 2021.

10 Adeniyi, A., O. Martinez, *Test Report for the Qualification Testing of the ORNL-SFC-Np-ZipCan Special Form Capsule,* ORNL/TM-2020/1840, Oak Ridge, Tennessee: Oak Ridge National Laboratory, 2020.