Joyce L. Connery, Chair
Thomas A. Summers, Vice Chair

DEFENSE NUCLEAR FACILITIES SAFETY BOARD
Washington, DC 20004-2901

July 17, 2024

The Honorable Jennifer Granholm
Secretary of Energy
Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585-1000

Dear Secretary Granholm:

The Department of Energy (DOE) sponsored testing to determine the confinement integrity of containers designed according to DOE Standard 3013, *Stabilization, Packaging, and Storage of Plutonium-Bearing Materials*. A team of DOE contractors exposed containers to simulated fire conditions, observed whether the containers failed, and measured the pressure at which the containers failed. The failure pressures are used to determine the airborne release fraction (ARF), which is a parameter that describes how much radioactive material could be released from the containers during accidents. The ARF is used to help determine the need for safety controls to protect workers and the public from accidents at facilities that use these containers for plutonium storage.

The Defense Nuclear Facilities Safety Board's (Board) staff review team evaluated the fire testing documents and held discussions with representatives from DOE, the Savannah River Site, Los Alamos National Laboratory, and Sandia National Laboratories. The Board determined that the results of the fire testing were not conservatively bounding for credible fire scenarios, as discussed in further detail in the enclosed report. The DOE Savannah River Operations Office also documented concerns with the testing. The Board's staff review team discussed the test methods and results with DOE and its contractors, who added safety conservatism to the ARFs planned for use at the Savannah River Site. The resulting ARFs are conservatively bounding for application in the Savannah River Site's safety basis documents.

The Board is providing the enclosed report outlining technical issues with the development and conduct of the tests. The Board encourages DOE to consider the limitations indicated by these issues when its contractors use the test results in safety analyses, or when its contractors develop future test protocols in this area.

High-quality research can improve nuclear safety. Twenty years ago, the Board highlighted the importance of nuclear safety research in Recommendation 2004-1, *Oversight of Complex, High-Hazard Nuclear Operations*. The Board recommended that DOE take steps to "ensure the continued integration and support of research, analysis, and testing in nuclear safety technologies.” The Board continues to encourage such research and testing and will evaluate DOE plans for and conduct of those activities.

Sincerely,

Joyce L. Connery

Joyce L. Connery
Chair

Enclosure

c: The Honorable Jill Hruby, Administrator, National Nuclear Security Administration (NNSA)
Ms. Candice Robertson, Senior Advisor, Office of Environmental Management
Mr. Michael Mikolanis, Manager, NNSA Savannah River Field Office
Mr. Michael Budney, Manager, Savannah River Operations Office
Mr. Theodore Wyka, Manager, NNSA Los Alamos Field Office
Mr. Daryl Hauck, Manager, Sandia Field Office
Mr. Joe Olencz, Director, Office of the Departmental Representative to the Board

DEFENSE NUCLEAR FACILITIES SAFETY BOARD

Staff Report

April 19, 2024

Plutonium Storage Container Fire Testing

Summary. The Department of Energy (DOE) sponsored fire testing of containers that comply with DOE Standard 3013, *Stabilization, Packaging, and Storage of Plutonium-Bearing Materials* [1] with the goal of removing perceived excess conservatism in the safety basis for the Surplus Plutonium Disposition (SPD) project at the Savannah River Site (SRS). The tests involved exposing containers to simulated fire conditions, observing whether the containers failed, and measuring the failure pressures. Analysts can use failure pressure to estimate the airborne release fraction (ARF), which is a parameter used in safety analyses to characterize the amount of radiological material released from containers in accidents. They can then use ARF to help determine the need for safety controls to protect workers and the public from accidents at facilities that use these containers for plutonium storage.

The Defense Nuclear Facilities Safety Board's (Board) staff review team evaluated the 3013-container fire testing through a series of interactions in 2023 with DOE, the National Nuclear Security Administration (NNSA), and the management and operating contractors Savannah River Nuclear Solutions (SRNS) at SRS, Triad National Security, LLC (Triad) at Los Alamos National Laboratory, and National Technology and Engineering Solutions of Sandia, LLC at Sandia National Laboratories. This report refers to the involved contractor personnel collectively as the experiment team.

The staff team concluded that the development and conduct of the 3013-container fire testing resulted in measured pressures that are not bounding for credible fire scenarios at defense nuclear facilities. DOE's Savannah River Operations Office (DOE-SR) also expressed safety concerns with the testing. SRNS responded to these safety concerns by adding safety conservatism to its planned ARF. The staff team evaluated the resulting ARF and concluded that it would be bounding for credible fire scenarios.

Background. DOE sponsored the fire testing to evaluate the performance of 3013-containers in postulated fire scenarios. A fire could cause a 3013-container to pressurize and rupture, releasing the plutonium stored within the container. In accordance with DOE standards, DOE contractors analyze the potential consequences of such events to determine whether safety controls are needed to protect workers or the public. The ARF is an important parameter in this consequence analysis. DOE Handbook 3010-94, *Airborne Release Fractions/Rates and Respirable Fractions for Nonreactor Nuclear Facilities*, provides ARF values [2]. Handbook 3010-94 specifies a bounding ARF value of 0.1 for the release of powders (such as plutonium oxide) from containers that fail at pressures between 25 psig and 500 psig. The handbook does not address release pressures above 500 psig. Prior to the fire testing, SRNS had estimated that 3013-containers could fail at pressures far above 500 psig, and thus extrapolated the data described in Handbook 3010 to calculate ARF values. In an analysis for the SPD project, SRNS calculated an ARF of 0.237 based on an estimated release pressure of 1715 psig [3, 4]. SRNS pursued the fire testing to potentially justify a lower release pressure, and thus a lower ARF value.

The test objectives identified by the experiment team included the following [5]:

- To increase understanding of the pressure and temperature conditions at which failure occurs;
- To increase understanding regarding the effects of salts on the pressurization, corrosion, and potential failure of the container.

DOE sites use different models of containers to meet the 3013 packaging requirements. When evaluating which models of containers to test, the experiment team determined that two container configurations were representative of the inventory of containers used by DOE sites. These configurations use either the Westinghouse Engineered Products Division or Dynamic Flowform, Inc., outer containers. The experiment team's testing plans [5] [6] identified 10 tests varying the following parameters: (a) the two types of 3013 configurations, (b) 6, 12, or 18 g of water, (c) 0, 464, or 928 g of a salt mixture, and (d) the heating profile imposed on the container, with peak temperatures of either approximately 815°C or between 1,010 and 1,180°C.

Upon completion of the testing, Triad experiment team members recommended [7] excluding three tests involving Engineered Products Division containers that reached unexpectedly low pressures and did not breach. They hypothesized that water not bound to salt migrated out of some containers into the attached test manifold during transport and storage prior to conducting the tests. Water vapor is the major contributor to the elevated pressure in the heated containers, so a loss of water would reduce that pressure. SRNS used the remaining test results for breached 3013-containers to determine ARFs using a Nuclear Regulatory Commission correlation from NUREG/CR-6410, *Nuclear Fuel Cycle Facility Accident Analysis Handbook* [8] that uses pressure, mass, and volume as inputs.

Initially, NNSA's Savannah River Field Office (SRFO) approved [9] the safety design strategy for SPD that would apply ARFs directly calculated from these pressures. NNSA's chief of defense nuclear safety issued a memorandum [10] on November 28, 2023, supporting the use of these ARFs by the SPD project with appropriate coverage of the testing limits and assumptions in the safety basis. The DOE-SR manager expressed concern [11] with the development and use of these ARFs in the K-Area Complex. After additional consideration, SRFO and DOE-SR agreed on the common use of a more conservative ARF value of 0.1258 in the next versions of the safety analyses for K-Area and the SPD project. SRNS personnel arrived at that value by extrapolating the measured data to account for the maximum water content allowed in a 3013-container (25 g) and adding margin to account for uncertainties. Appendix A provides additional details on the testing.

Discussion. The staff team's evaluation of the testing is summarized below and discussed in more detail in Appendix A, which also includes additional observations.

Water Migration—Triad experiment team members recommended discarding the results from three experiments because they believed that some water migrated from the test container into the attached pressure measurement manifold where it did not vaporize and therefore did not contribute to the pressure inside the container. The manifold extended beyond the furnace and was colder than the container. The lower temperature allowed incomplete vaporization. This issue occurred even though the experiment team took steps to avoid water condensation in the manifold.

The test plan [6] states: "The pressure tap and manifold are external to the heater assembly and are separately heated and held to approximately 200°C to avoid condensation of the payload water content in the pressure measurement system." However, the temperature needed to fully vaporize water increases as the pressure increases. At the manifold temperature of 200°C, some water would condense if the pressure exceeded approximately 225 psia, a pressure reached in several tests. Avoiding water condensation would have required a higher temperature in the manifold. Because the device used to heat the manifold did not cover the entire manifold assembly, portions of the manifold were at temperatures below 200°C, potentially allowing further condensation.

Condensation in the manifold could have occurred in all the tests, including those that the Triad experimenters did not discard. Accordingly, DOE contractors need to carefully evaluate all the tests before using the results in safety analyses.

Test Temperatures—The first of the 10 tests involved heating a container using the lower temperature profile. The measured container pressure was lower than the experimenters expected [12], and the container did not fail. As a result, the experiment team used the higher temperature profile for all but one of the remaining tests, even though the test plan called for at least eight tests with the lower temperature profile [6] [12]. After the tests were completed, Triad experiment team members determined that the first test should be discarded because of possible water migration and condensation, as discussed above [7].

Thus, testing anomalies led the experiment team to conduct most of the tests using the higher temperature profile, with peak furnace temperatures between 1,010 and 1,180°C. At those higher temperatures, the strength of the stainless-steel container is significantly reduced compared to its strength at the lower temperature heating profile (815°C peak furnace temperature). This lower container strength reduces the pressure that can be reached inside a container before it fails.

If the experiment team had performed more testing at lower temperatures, with sufficient water content to drive significant pressurization, it could have measured higher container failure pressures. Testing at lower temperatures such as 815°C would be informative, even though the containers subjected to the higher temperature profile did momentarily pass through such lower temperatures during the heat-up at the start of the test. In the tests with the higher temperature profile, the exterior temperature of the outer container was hotter than 815°C by the time the container breached. If the experiment team had held the furnace temperature at about 815°C for longer, the containers could have eventually failed at that temperature, where the metal is stronger, potentially resulting in a higher failure pressure and higher ARF.

Staff Team's Analysis of Final ARF Value—Despite these experimental and analytical concerns, the ARF of 0.1258 that SRNS is now using for the SPD project [13] is bounding. SRNS's derivation of this value demonstrates a conservative safety approach. SRNS selected the peak measured pressure, added the uncertainty of the pressure transducer to the measured pressure, extrapolated the test results to a bounding water content of 25 g, and added about 12 percent margin to account for other test uncertainties. This ARF value should bound the failure pressures expected for the lower test temperatures, as could have been validated if more testing had been conducted in that range.

Conclusion. The ARF of 0.1258 that SRNS derived for the SPD project is conservative for 3013-containers. SRNS added safety conservatism through extrapolation and by adding margin to account for test uncertainties. Without adding such safety conservatism, the test results would not lead to a bounding estimate of the pressure in a 3013-container in a fire, and thus the test results would not lead to a bounding ARF.

The staff team concludes that other DOE contractors need to consider these issues if they use the test results in safety analyses, or if they develop any future testing in this area.

Appendix A: Additional Detail on Plutonium Storage Container Fire Testing

Background. The Department of Energy (DOE) sponsored a three-phase series of fire tests to evaluate the performance of plutonium storage containers in postulated fire scenarios. The Defense Nuclear Facilities Safety Board's (Board) staff review team evaluated the third phase, which involved containers designed to requirements in DOE Standard 3013, *Stabilization, Packaging, and Storage of Plutonium-Bearing Materials* [1].

The tests involved exposing the 3013-containers to simulated fire conditions in a furnace, observing whether the containers failed, and measuring the failure pressures of the containers. Analysts can use the failure pressures to estimate the airborne release fraction (ARF), which they can then use in safety analyses when determining the radiological consequences of postulated accidents. DOE Standard 3009-2014 [14], *Preparation of Nonreactor Nuclear Facility Documented Safety Analysis*, defines ARF as "the coefficient used to estimate the amount of a radioactive material that can be suspended in air and made available for airborne transport under a specific set of induced physical stresses." The experiments did not measure ARF directly, but analysts can use existing correlations to relate the failure pressure to ARF. Higher release pressures tend to lead to higher ARFs and thus higher accident consequences.

The testing involved multiple organizations. The National Nuclear Security Administration (NNSA) funded the testing. Savannah River Nuclear Solutions (SRNS), the management and operating contractor for the Savannah River Site (SRS), developed the initial testing objectives, requirements, and plan [6]. Triad National Security, LLC (Triad), the management and operating contractor for Los Alamos National Laboratory (LANL), planned how the 3013-containers should be loaded, and then loaded them [5, 15, 16].

Triad shipped the containers to SRS where the test manifolds used to measure container pressure during the test were installed. SRNS shipped the finished test assemblies to National Technology and Engineering Solutions of Sandia, LLC, the management, and operating contractor for Sandia National Laboratories, which performed the tests and documented the test results [17]. Triad subsequently conducted an additional forensic study of the containers to interpret and characterize container failure mechanisms [7, 18, 19, 20]. This report refers to the involved personnel from these contractors collectively as the experiment team.

A 3013-container set includes an outer container, an inner container, and in some cases, an innermost convenience can. DOE sites use different models of containers to meet the 3013 packaging requirements. The experiment team selected two container sets to represent the inventory of containers in use at DOE sites.

The first container set included the Westinghouse Engineered Products Division (EPD) outer container, in which the manufacturer machined the container to size, then welded the container base to the cylindrical shell. This test configuration also included an inner container and a vented convenience container that held aluminum oxide, which the experimenters used as a surrogate for plutonium oxide. Figure A-1 shows this configuration.

Figure A-1. *EPD container configuration, example from SRS.*
From left to right, these are the outer, inner, and convenience containers.

The second container set included an outer container manufactured by Dynamic Flowform, Inc. (Flowform). The manufacturing process plastically deforms a metal blank around a mandrel to achieve the final container dimensions. The process forms the container base and walls from the same metal blank. The inner container in this container set is the type used in LANL's advanced recovery and integrated extraction system. The convenience container is a crimped lid canister. Figure A-2 shows this configuration.

Figure A-2. *Flowform container configuration, example from LANL.*
From left to right, these are the outer, inner, and convenience containers.

The test objectives identified by the experiment team included the following [5]:

- To increase understanding of the pressure and temperature conditions at which failure occurs;

- To increase understanding regarding the effects of salts on the pressurization, corrosion, and potential failure of the container.

In these tests, the experiment team considered that a container failed if it breached. If a breach occurred, gases would vent, and the surrogate material could escape.

The experiment team performed 10 tests, varying the parameters for container type, water content, salt content, and heating profile as shown in Table A-1. The experiment team used two different heating profiles. It modified one profile from American Society for Testing and Materials (ASTM) Standard E119, *Standard Test Methods for Fire Tests of Building Construction and Materials* [21], to have a sustained peak temperature of about 815°C (ASTM E119m).[1] The experiment team selected the other heating profile from ASTM Standard E1529, *Standard Test Methods for Determining Effects of Large Hydrocarbon Pool Fires on Structural Members and Assemblies* [22], with sustained peak temperatures between 1,010 and 1,180°C.

Initially the test plan [6] called for most of the tests to be conducted using the lower heating profile (ASTM E119m). However, when the initial test with 18 g of water resulted in unanticipatedly low container pressures, and the container did not fail, the experimenters changed the plan to focus primarily on the higher heating profile (ASTM E1529) to ensure container failures [12].

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[1] The Sandia test report uses “ASTM E119m” to refer to the modified temperature profile [17]

Table A-1. *3013-container test loading conditions and test results.*

Test Sequence[a]	Outer Container Type[a]	Water Content (g)[a]	Salt Content (g)[a]	Planned Heat Profile[b]	Actual Heat Profile[a]	Peak Pressure +/-25 (psig)[a]	Container Breach[a]
1	EPD	18	0	ASTM E119m	ASTM E119m	169	No
2	EPD	12	0	ASTM E119m	ASTM E1529	123	No
3	EPD	12	929	ASTM E119m	ASTM E1529	284	Yes
4	Flowform	12	0	ASTM E119m	ASTM E1529	324	Yes
5	Flowform	12	929	ASTM E119m	ASTM E1529	332	Yes
6	EPD	6	0	ASTM E119m or ASTM E1529 (see Reference [6])	ASTM E1529	186	No
7	EPD	6	464	ASTM E119m	ASTM E1529	229	Yes
8	Flowform	6	0	ASTM E1529	ASTM E1529	244	Yes
9	Flowform	6	464	ASTM E119m	ASTM E1529	253	Yes
10	Flowform	6	0	ASTM E119m	ASTM E119m	262	No

[a] Information taken from Reference [17].
[b] Information taken from Table 7-1 of Reference [6].

Upon completion of the testing, Triad personnel recommended [7] that the tests involving EPD containers without salt (sequences[2] 1, 2, and 6) be omitted from further consideration. They hypothesized that water from the vented convenience containers used in that configuration migrated to the pressure measurement manifold during transport and storage, prior to the fire testing. Such migration would have lowered the pressure that could be reached inside the 3013-container during testing. Triad personnel also hypothesized that the salt in the other EPD containers prevented water migration, so the tests with salts yielded usable results. In addition,

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[2] When referring to specific tests, the experiment team uses 'sequence' numbers to denote the order in which they performed the tests.

the experiment team could not use sequence 10 to determine an ARF because the Flowform container did not breach, so the test did not yield a failure pressure.

SRNS used the remaining six test results to determine ARFs using a Nuclear Regulatory Commission (NRC) correlation from NUREG/CR-6410, *Nuclear Fuel Cycle Facility Accident Analysis Handbook* [8] that uses pressure, mass, and volume as input parameters. SRNS also extrapolated the test data (both container pressure and volume) to obtain ARFs for 3013-containers with higher water content. The extrapolation was necessary because the tests that were not discarded had a maximum water content of 12 g, while DOE Standard 3013 allows as much as 25 g. Table A-2 lists the resulting ARFs [23]. Using these values, SRNS proposed using an ARF value of 0.0614 for the SPD project and a higher ARF value for other locations in the K-Area Complex at SRS.

Table A-2. *ARFs calculated by SRNS from the 3013-container testing. Adapted from Table 6 of Reference* [23].

Container	Salts	Water (g)	ARF	Notes from SRNS
EPD	Yes	12	0.0465	Bounds current K-Area Complex inventory except 12 containers
EPD	Yes	18	0.0532	Bounds current K-Area Complex inventory
EPD	Yes	25	0.0609	Bounding value for EPD
Flowform	No	6	0.0548	Bounds current LANL inventory
Flowform	Yes	6	0.0614	Bounds projected LANL inventory
Flowform	Yes	25	0.1116	Bounding value for Flowform

Different DOE entities reviewed the tests and how SRNS was proposing to incorporate the results into safety analyses at the site. The NNSA chief of defense nuclear safety issued a memorandum [10] on November 28, 2023, supporting the use of these ARFs by the SPD project with appropriate coverage of the testing limits, assumptions, and bounds with technical safety requirements. Meanwhile, the manager of the Savannah River Operations Office (DOE-SR) issued a letter of direction [11] to SRNS on December 19, 2023, to address DOE-SR concerns about incorporating ARFs based on the testing into the documented safety analysis of the K-Area Complex.

In response, SRNS modified the ARF analysis [13]. It proposed an updated ARF for the SPD project and other parts of the K-Area Complex. SRNS based the new ARF on the extrapolated failure pressure for Flowform containers with 25 g of water, and added some margin, to result in an ARF of 0.1258.

Discussion. The development and conduct of the 3013-container fire testing resulted in measured pressures that are not bounding for credible fire scenarios at defense nuclear facilities.

Water Migration to the Manifold Causes Experimental Issues—A variety of gases and vapors contributed to the pressure in the 3013-containers during the fire testing. The major contributor was water vapor that formed as the furnace heated liquid water that the experimenters had loaded into the container. The test conditions inadvertently could have allowed some water to exist as liquid (not vapor) during the tests, resulting in lower container pressures during the testing [7].

In each test, a 3013-container (the large cylinder in Figure A-3) was connected to an instrumented pressure manifold. The manifold extended outside the furnace, which raised the possibility that water vapor could condense in the manifold during the tests due to lower temperatures in that location. The experiment team recognized this possibility and took steps to avoid condensation of water in the manifold. One of the test plans [6] states: “The pressure tap and manifold are external to the heater assembly and are separately heated and held to approximately 200°C to avoid condensation of the payload water content in the pressure measurement system.”

However, at the pressures observed during most of the tests, a temperature of 200°C is too low to fully vaporize water.[3] Exacerbating this issue, experimenters used a heat trace that did not cover the entire manifold, so parts of the manifold were at temperatures even lower than 200°C. Liquid water in the manifold reduced the amount of water vapor available to contribute to pressure in the 3013-container. This reduced pressure likely led to 3013-containers not failing during tests in which they would have failed otherwise. Further, if a container did fail, the failure could have occurred at a lower pressure than it otherwise would have.

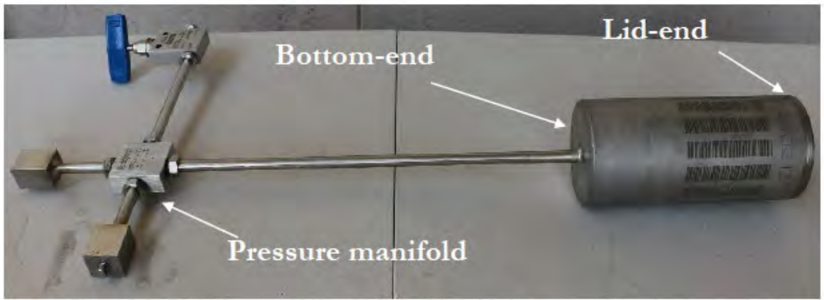

Figure 2-3. Typical tested 3013 container with welded pressure tap on bottom-end.

Figure A-3. *Test configuration showing 3013-container (cylinder on right) with instrument manifold. The manifold extended outside the furnace (not shown). Image taken from Figure 2-3 of Reference [17].*

Triad discarded the results of sequences 1, 2, and 6 (EPD containers without salt) from further use, due to the possibility of liquid water in the manifold [7]. Triad’s decision to discard three of the five EPD tests was based on the following factors:

- Pressures in the containers were far below what would be expected from vaporization of water and heating of the gas.
- Inner surfaces of the outer containers showed little or no signs of steam oxidation.

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[3] The saturation pressure of water at 200°C is approximately 225 psia. The pressure in the manifold exceeded this pressure for most tests, so water would condense.

The staff team concurs with Triad's decision to discard sequences 1, 2, and 6 for these reasons. However, condensation of water in the manifold may have also affected the pressures of the other tests. Triad provided the following reasoning to support the validity of the remaining seven tests:

- The pressures in these seven tests were closer to the expected pressures, and the ratio of observed to expected pressure was comparable to that seen in small-scale testing.
- The five tests with Flowform containers were less prone to water loss to the manifold because the convenience cans used with these containers were sealed by crimping, which could have inhibited water loss prior to the furnace test.
- The two remaining EPD tests included salt, which would have bound the water in place prior to the furnace test.
- The experimenters observed some steam oxidation on the containers.

However, Triad's reasoning does not eliminate the possibility of liquid water in the manifold during the remaining seven tests. For example, Triad stated that ratios of the observed peak pressure to the expected peak pressure in these full-scale tests were comparable to that seen in small-scale testing. This ratio is relevant because it compares the observed pressure to the theoretical pressure that would be expected if all the water vaporized. If the observed pressure is substantially lower than the theoretical pressure (i.e., a low ratio), it could be a sign that not all the water vaporized. Triad used the results of small-scale testing, where condensation would not have been an issue, to determine what might be a reasonable range for this ratio.

In some cases, the ratio of observed peak pressure to expected peak pressure was low, compared to what Triad observed in small-scale testing. In the small-scale testing, Triad reported ratios between 0.73 and 0.84 [24], whereas Triad reported ratios of 0.53 and 0.54 respectively for sequences 3 and 7. The ratio could also be low if the container failed before the pressure had a chance to increase further, but that does not appear to be case for sequences 3 and 7, where container failure occurred after the pressure had peaked or plateaued [17]. Thus, pressures in sequences 3 and 7 were lower than expected, which may be an indication of lower water content in the two EPD tests that Triad considered valid.

The review team concurs with Triad's judgment that three tests should be discarded. However, the validity of at least two more tests is uncertain. Performing new experiments designed to avoid water condensation in the test manifold would eliminate this uncertainty.

Insufficient Tests Performed in the Temperature Range that Could Produce the Highest Failure Pressure—For eight out of the ten tests, the experiment team used a heating profile with peak furnace temperature between 1,010 and 1,180°C. However, a lower temperature heating profile (representing less severe exposure in a building fire) could have led to higher failure pressures than seen in those eight tests. The strength of stainless steel, used to fabricate the 3013-containers, decreases with increasing temperature. Thus, at lower temperatures, a container could withstand higher pressures before ultimately failing, assuming enough water was present to generate those higher pressures.

SRNS previously performed calculations that illustrate this effect. These calculations used a Monte Carlo method to estimate the internal pressure that would cause a 3013-container to fail [25]. SRNS repeated the method for different temperatures to build capacity curves that predict minimum, median, and maximum failure pressures. In addition, SRNS calculated demand curves [25], which represent the pressure that could be generated at different temperatures, given an initial loading of water. The theoretical maximum failure pressure would be where the capacity curve (which decreases as temperature increases) intersects with the increasing demand curve. For a container loaded with 25 g of water, the SRNS calculation found that this theoretical maximum failure pressure would occur at about 815°C (see Figure 6-5 of Reference [25]).

This temperature (about 815°C) corresponds to the lower heating profile (ASTM E119m) from the experiments. As shown in Table A-1, the experiment team only used this profile for two out of ten tests (sequences 1 and 10), although they originally planned to use it for more tests [6, 12]. Triad discarded sequence 1, leaving sequence 10 as the only test using the lower heating profile that Triad considered valid. Sequence 10 involved a Flowform container with 6 g of water, and it did not fail, so no failure pressure was obtained from the test.

The staff team generated Figure A-4 to examine the conditions of sequence 10. Figure A-4 shows the capacity curves[4] calculated by SRNS [25], as well as demand curves[5] calculated by the staff team. Figure A-4 also shows the measured peak pressures for the tests with Flowform containers. As shown, the theoretical demand pressure in a container with 6 g of water (red line) at about 815°C is well below the capacity curves. Thus, these calculations show that sequence 10 should not lead to container breach, which is indeed what was observed. In contrast, the demand pressure would be higher in a container with between 12 g and 25 g of water. This pressure could have exceeded the container capacity in the range of 800–900°C, leading to a container breach.

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[4] The staff team did not review the calculation of the capacity curves.

[5] The staff team generated demand curves because the SRNS calculation did not include curves for the 6 g water content of sequence 10. Like SRNS, the staff team used the ideal gas law and assumed full vaporization of water, but unlike SRNS, the review team did not predict container bulging. The staff team used free volumes of 1,349 cubic centimeters and 1,611 cubic centimeters for the EPD and Flowform container sets, respectively, based on averages of the test containers [5, 13]. The staff team assumed the containers were initially loaded with 8.1 psig of fill gas at 21.1℃ [17].

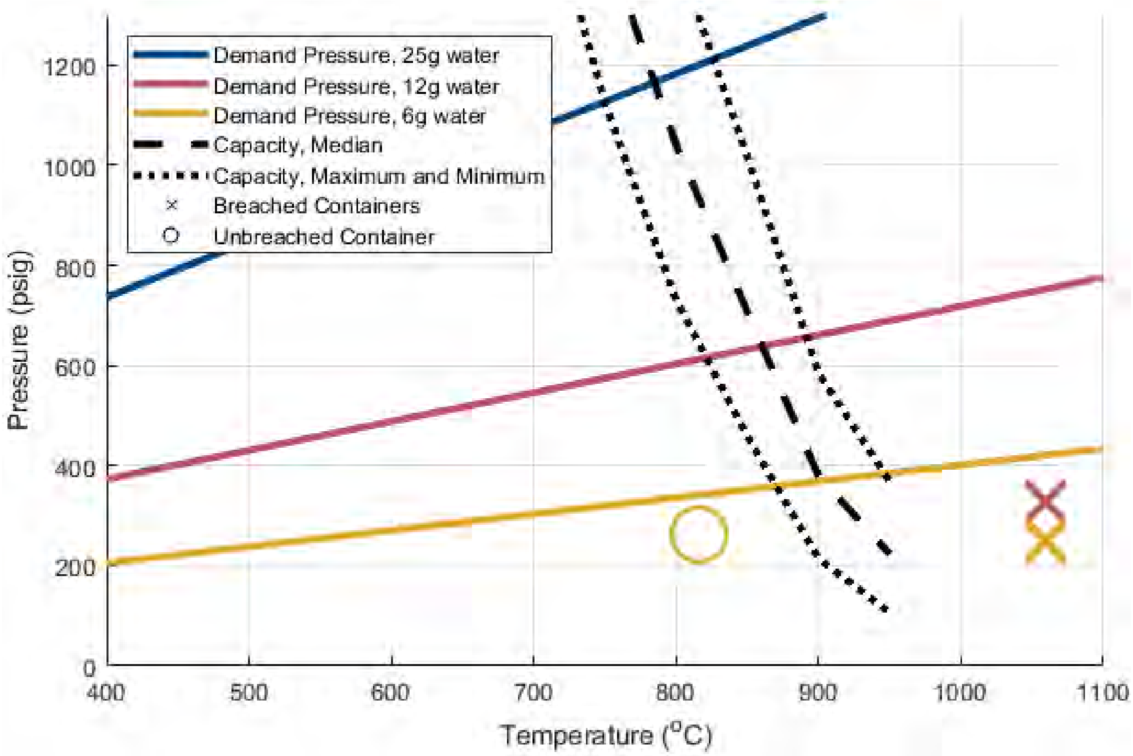

Figure A-4. *Plot of capacity and demand curves, and maximum pressures observed during Flowform container tests. Sequence 10 is shown by the yellow circle. Sequences 4 and 5 (12 g water) are both shown by red crosses and overlap on the graph. Sequences 8 and 9 (6 g water) are both shown by yellow crosses and overlap on the graph.*[6]

Accordingly, it is possible that additional experiments in the 800–900°C range could have led to container breaches, and at higher pressures than those the experiment team measured at higher temperatures. For containers with 12 g of water, the experiment team measured peak pressures[7] between 284 to 332 psig. For containers with 25 g of water, SRNS used extrapolation to estimate peak pressures of 403 and 507 psig for EPD and Flowform containers, respectively [23]. These observed and extrapolated peak pressures are lower than the pressures that theoretical calculations suggest are possible at lower temperatures.

New experiments would be needed to conclusively determine the behavior of containers in the 800–900°C range, given that there are several reasons why the actual behavior would not match the theoretical calculations. One challenge is that, as a container heats up, the temperature of the steel of the outer container (corresponding to the capacity curve) will increase faster than the temperature of the gas inside the container (corresponding to the demand curve). As a result, the theoretical maximum failure pressure indicated by the intersection of the demand and capacity curves may not be reached, but there is still a potential for failure at higher pressures at lower test temperatures. SRNS personnel acknowledged the potential for higher failure

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[6] The container breaches on Figure A-4 are plotted at the nominal peak furnace temperature. The temperature of the container's outer surface varied with location and also changed over the course of each test. The internal temperature was not measured in the tests.

[7] In several runs, the container pressure peaked, and then the container breached at a lower pressure.

pressures at lower temperatures but suggested that the impact on ARF would be counteracted by less container bulging at the lower temperatures, given that SRNS used a correlation that relates ARF to both failure pressure and container volume (see Figure A-5 for photographs of bulging). This hypothesis would also have to be confirmed by additional testing.

Figure 4-19. Post-test conditions of test vessel for Sequence 8. Angle positions refer to the visible portion of the vessel (see Figure 2-4). Angular positions, in clockwise direction, starting from upper left quadrant: 0°, 90°, 180°, and 270°.

Figure A-5. *Bulged condition of 3013-container after test sequence 8. Image taken from Figure 4-19 of Reference* [17].

Additional testing at lower temperatures such as 815°C would be informative, even though the containers exposed to the higher temperature profile did momentarily pass through lower temperatures during heat-up. In the tests with the higher temperature profile, the exterior temperature of the outer container was hotter than 815°C by the time the container breached (see the graphs in the Sandia test report [17]). If the experiment team had held the furnace temperature at about 815°C for longer, the containers could have eventually failed at that temperature, where the metal is stronger. The interior pressure within the 3013-container is dependent on the interior temperature. As stated above, the container interior would have heated up more slowly than the exterior. Holding the furnace at a temperature like 815°C for longer would have allowed the interior temperature and thus pressure to reach their steady-state values for that furnace temperature. If the container was initially loaded with sufficient water, that interior pressure may have been enough to fail the container.

Staff Team's Analysis of Final ARF Value—As mentioned above, SRNS ultimately responded to concerns on the testing program by adopting an ARF value of 0.1258. This ARF value is substantially more conservative than the value of 0.0614 that SRNS had previously proposed for the SPD project. The staff team evaluated the safety conservatism of this value by determining what failure pressure is implied by this ARF value, and evaluating whether this failure pressure could be exceeded under credible conditions.

SRNS used a correlation published by the NRC [8] to determine ARF [13]. That correlation is provided below (combining Equations 3.15 and 3.17 of Reference [5]):

$$ARF = (2.74E-4)\left[\frac{2(\Delta P)V}{m}\right]^{0.7}$$

In this correlation, ΔP is the pressure difference between the container contents and ambient (in Pascals), V is the free volume inside the container (in cubic meters), and m is the mass of the container contents (in kg).[8] Using this correlation, ARF increases with both free volume and failure pressure.

The staff team considered various cases, including EPD and Flowform containers (which had different free volumes inside the containers and bulged to different extents in the fire tests). For example, the staff team considered an EPD container that hypothetically did not bulge during the fire exposure. Such a container would have a free volume of 1,349 cubic centimeters (or 0.001349 cubic meters, in the units required by the correlation). Applying the maximum container payload of 5 kg, the NRC correlation for this case results in a failure pressure of 1,707 psig (or pressure difference at failure of 1.18E7 Pascals). Based on graphs such as Figure A-4, such a failure pressure could not credibly be reached for stainless steel 3013-containers at the tested temperatures, even with the maximum allowed water loading of 25 g. Accordingly, the ARF of 0.1258 should conservatively bound credible accident scenarios. Additional experimentation could further refine the ARF, but the experiment team informed the staff team that it was not planning new experiments.

Experimental Variability Not Fully Considered—SRNS's analysis does not explicitly account for experimental variability. While SRNS did account for the instrument uncertainty of the pressure transducers (+/- 25 psig for the transducers used for most of the test results) [17] [23], this only accounts for the accuracy of the transducer. When conducting experiments, experimenters can evaluate variability by performing additional tests with the same conditions.

The tests did not include such duplicates; each of the 10 tests had different experimental conditions. In addition to only having one test for each experimental condition, Triad discarded three tests. These discarded tests comprised most tests on the EPD container type, which further impacted the confidence that the test data could adequately represent the behavior of 3013-containers in actual fire situations.

Uncertainty Introduced by Extrapolation—DOE Standard 3013 allows as much as 25 g of water in a 3013-container [1]. DOE's current inventory includes containers with moisture levels between 12 g and 18 g of water.[9] However, in the 3013-container tests, the highest moisture level in a test considered valid by Triad was 12 g. Thus, SRNS extrapolated the experimental results beyond 12 g to 18 g and 25 g water [13]. SRNS extrapolated both the peak pressure and container volume (after bulging). These extrapolations did not take the physical properties of the container into account, so the extrapolated pressure and volume could be higher than what is physically possible at that temperature (i.e., SRNS conducted the extrapolation in a conservative fashion). In some cases, SRNS performed this extrapolation with only a single data point. Not testing to the full range of allowed moisture content and relying on few data points

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[8] SRNS assumed 5 kg [13]. DOE Standard 3013 also uses 5 kg as the limit for 3013 containers [1].

[9] Flowform containers in the current inventory have less than 6 g water.

for extrapolation adds considerable uncertainty to the ARF (although as noted above, the ARF of 0.1258 should be conservatively bounding). Including well-controlled experiments at higher moisture levels would have avoided this uncertainty.

Applicability of ARF Correlation—The tests provided values for release pressure and container volume expansion but did not directly measure ARF. SRNS related release pressure to ARF using a method published by NRC in NUREG/CR-6410, *Nuclear Fuel Cycle Facility Accident Analysis Handbook* [14], instead of using methods published by DOE. DOE has published its methods in DOE Handbook 3010-94, *Airborne Release Fractions/Rates and Respirable Fractions for Nonreactor Nuclear Facilities* [2], and DOE Standard 5506-2021, *Preparation of Safety Basis Documents for Transuranic (TRU) Waste Facilities* [26]. DOE Standard 3009-2014 allows departure from ARFs in Handbook 3010 if "a different value is provided in an applicable standard or is otherwise technically justified." The review team thus examined the applicability of the method from NUREG/CR-6410.

The methods in NUREG/CR-6410, DOE Handbook 3010-94, and DOE Standard 5506-2021 are all based on the same set of ARF measurements from the 1980s [27, 28, 29]. However, each of the three methods yields different ARF values for given scenarios. DOE Handbook 3010-94 specifies the same ARF value (0.1) for all release pressures between 25 and 500 psig. Equation E-3 of DOE Standard 5506-2021 allows the ARF value to vary with release pressure, with an ARF of 0.1 at 500 psig and lower ARF values at lower pressures. NUREG/CR-6410 introduces a correlation where ARF is a function of release pressure, the mass of the container contents, and the container volume.

One limitation for all these methods is that the 1980s data only included release pressures up to 500 psig. Analyzing failure pressures in 3013-containers that exceed 500 psig necessitates extrapolation beyond the original data set. Ideally, DOE should consider performing new ARF experiments to cover release pressures above 500 psig.

SRNS's use of the NUREG/CR-6410 correlation also involved extrapolation beyond the 1980s data with respect to payload mass and container volume. For example, the 1980s experiments involved masses of 100 g and 350 g, whereas SRNS assumed the maximum payload of a 3013-container of 5 kg (over 10 times higher) when using the correlation. In contrast, the DOE methods lack any dependence of ARF on mass or volume. The DOE methods involve the conservative assumption that the ARFs originally measured at 350 g will be directly applicable to larger payload masses such as 5 kg. While SRNS's extrapolation with mass reduced the ARF, its extrapolation with volume tended to increase the ARF. Overall, SRNS's use of the NUREG/CR-6410 correlation in this case did not present a safety concern, but additional ARF experiments could reduce the uncertainty associated with extrapolations.

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