Proceedings of the 19th International Symposium on the Packaging and Transportation of Radioactive Materials
PATRAM 2019
August 4-9, 2019 New Orleans, LA, US

Thermal Analysis of the Model 9602 Type B Packaging Design for Disused Radiological Sources

J. Li,[1] Z.H. Han,[1] Y.Y. Liu,[1] and J.M. Shuler[2]

[1] Argonne National Laboratory, Lemont, IL 60439
[2] U.S. Department of Energy, Washington, DC 20585

ABSTRACT

A new compact Type B transportation packaging, designated as Model 9602, is being designed by Argonne National Laboratory researchers for storage, transport and disposal of disused radiological sources. This paper describes the thermal analysis of the Model 9602 packaging design that was performed as part of the preparation of a Safety Analysis Report for Packaging (SARP), which is to be submitted to the regulatory authority for an application of a Certificate of Compliance for the packaging design. The thermal performance of Model 9602 under the normal conditions of transport (NCT) and hypothetical accident conditions (HAC), prescribed in Title 10 of the *U.S. Code of Federal Regulations* (10 CFR 71), “Packaging and Transportation of Radioactive Material,” were evaluated using the Oak Ridge Isotope Generation (ORIGEN) code for the decay heat load of the disused CsCl sealed sources and the finite-element code ANSYS/Mechanical. The results of the thermal analysis indicate that the calculated maximum temperature of all packaging components (e.g., basket, containment vessel, cask) are within their allowable temperature limits under NCT. For HAC, the thermal analysis results showed that the peak temperatures of the packaging components are all well below the allowable temperatures limits of corresponding construction materials. Thus, the thermal analysis demonstrated that the thermal performance of the Model 9602 packaging design provides reasonable assurance that the regulatory requirements of 10 CFR 71 have been met.

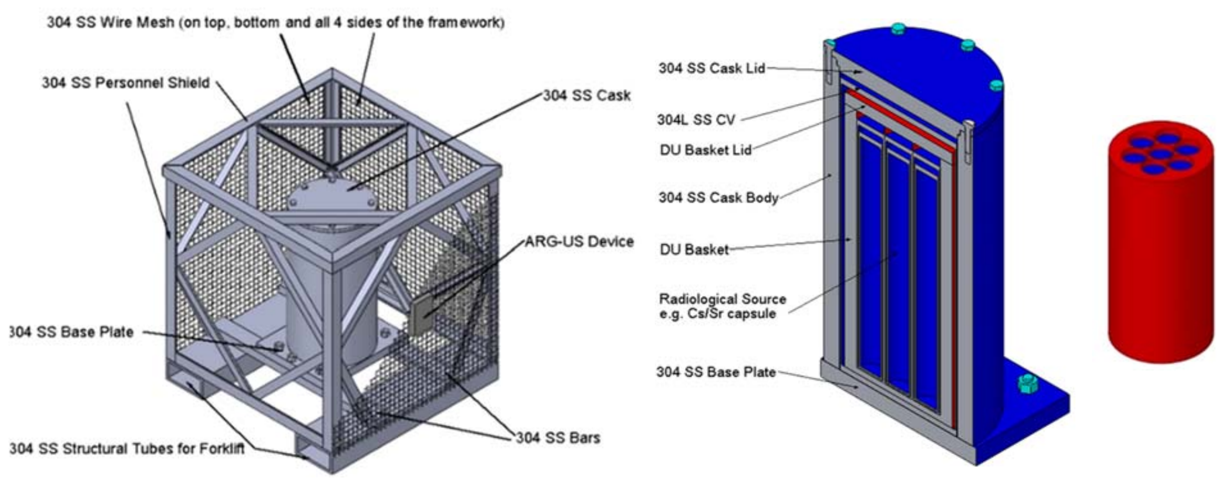
INTRODUCTION

Many countries use radiological sources for their beneficial applications in medicine and industry. Some radioisotopes used in these radiological sources have relatively short half-lives—for example, 73.8 days for Ir-192 and 5.27 years for Co-60—while others have much longer half-lives—30.17 and 28.79 years, respectively, for Cs-137 and Sr-90. These radioisotopes are all high-energy β-γ emitters, and the lack of a disposition pathway for the disused radiological sources poses significant risk in terms of inadvertent or deliberate misuse of the material and other problems [1].

Since the mid-1980s, the U.S. Department of Energy (DOE) has planned to dispose of all high-level waste (HLW) and spent nuclear fuel (SNF), regardless of commercial, defense, or research origin, in a common mined geologic repository. A separate mined repository was proposed in 2015 for DOE-managed SNF and HLW, in addition to an option for deep borehole disposal of “small” waste forms, such as the cesium Chloride (CsCl) capsules currently stored in the pool cells at Hanford’s Waste Encapsulation Storage Facility. However, space restrictions and other limits (e.g., heat load, radioactivity, floor loading) imposed on the adjacent hot cells would permit only a limited number of disused CsCl source capsules to be brought from the pool cells into the hot cells for packaging and transfer to an onsite facility for dry storage. This paper describes a new compact Type B packaging design and thermal analysis for packaging and transfer of the CsCl capsules from wet to dry storage, followed by transportation for direct disposal at a mined geological repository, or a deep borehole, without repackaging the capsules. The compact Type B packaging design should also be readily applicable to other disused commercial radiological sources found in the United States and other countries. The conceptual design of this work originated from a project supported by the DOE Office of Environmental Management, which was described in “Groundwork for Universal Canister System Development” [2].

COMPACT TYPE B PACKAGING DESIGN

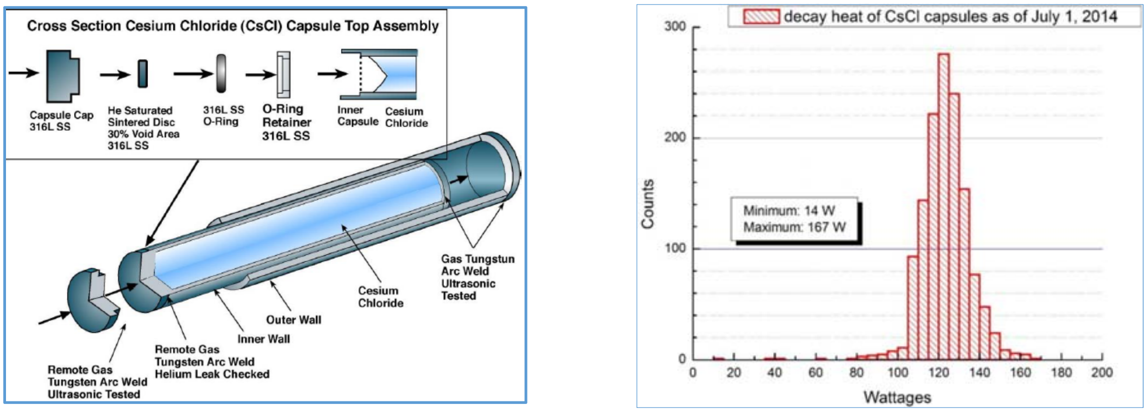
Figure 1 shows the compact Type B packaging design for Model 9602, which consists of a personnel shield with wire mesh, a bolted-closure cask containing a containment vessel (CV), and a depleted-uranium (DU) basket that can hold up to seven CsCl capsules, with a total heat load limit of up to 1,000 W. The packaging is ~0.91 m (3 ft) long, 0.91 m (3 ft) wide, and 1.07 m (3.5 ft) high overall. All packaging components, except for the basket, are made of 304 stainless steel (SS) or 304L SS (CV only). The basket can be made of SS, lead (Pb), aluminum, or DU, depending on the radioactivity of the contents. (DU is shown for the basket here because of its excellent performance as a shielding material for high-energy gammas.) Each component of the compact Type B packaging design serves one or more important-to-safety functions. For example, the 304 SS personnel shield provides protection for radiation from the cask during normal operation, while the space between the personnel shield and the cask enables heat dissipation by natural convection. The 304 SS framework of the personnel shield also serves as an excellent impact limiter in a hypothetical accident (HAC), such as a 9-m (30-ft) drop followed by impact on a puncture bar, as prescribed in 10 CFR 71.73. Structural analyses conducted to date showed that the structural performance of the packaging design meets all the requirements specified in 10 CFR 71 [3].



(a) (b) (c)

Figure 1. (a) Schematic of the compact Type B packaging design for Model 9602; (b) cask and CV; and (c) DU basket accommodating up to 7 CsCl capsules for a total heat load of up to 1,000 W.

Figure 2 shows a schematic of the CsCl capsule (a) and its population distribution according to decay heat as of July 1, 2014 (b). Over 260 CsCl capsules had decay heat ~120 W, and a significant number had decay heat above and below 120 W. The entire population of CsCl capsules would shift to the left in Figure 2(b), because their decay heat drops with time based on the Cs-137 half-life of 30.17 years. CsCl salt has a phase transition temperature of 330°C (626°F), which is accompanied by volume expansion, and a melting temperature of 430°C (806°F). The authors of the Hanford reports [4, 5], used 317°C (603°F) and 600°C (1,112°F) as the allowable temperature limits for the salt–metal interface, respectively, for NCT and HAC. The melting point of pure CsCl is 645°C (1,193°F), which is higher than the salt–metal interface temperature limit of 600°C (1,112°F); however, CsCl capsules that are overheated above the phase transition temperature can potentially cause the capsules to rupture due to volume expansion.



(a) (b)

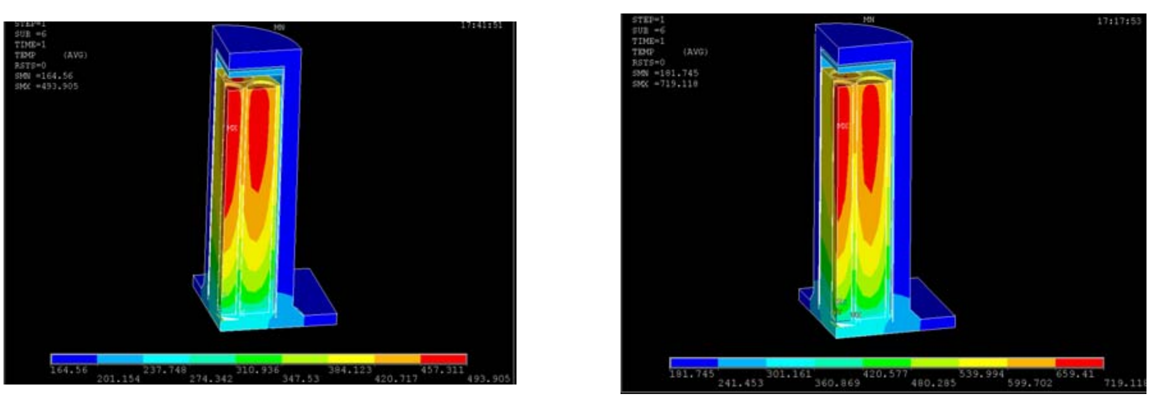
Figure 2. (a) Schematic of a CsCl capsule and (b) its population distribution according to decay heat.

THERMAL PERFORMANCE EVALUATION

We used the ANSYS/Mechanical code to evaluate the thermal performance of the Model 9602 packaging design during NCT and HAC. Only the cask, the CV, the basket, and the CsCl capsules are included in the ANSYS/Mechanical geometrical model, at a quarter scale, due to radial symmetry. The physical dimensions and thermal properties of the CsCl capsules were taken from references [4] and [5], and standard thermal physical properties were used for other materials. Conduction and radiation are the predominant heat transfer mechanisms included in the ANSYS/Mechanical analyses, for which fill gas (air, or helium) in the CV, basket material (SS, Pb, Al-1100 or DU), and the combinations thereof, were investigated for a range of total decay heat loads of 500, 840, and 1,000 W. Appropriate ambient boundary conditions, such as the NCT solar insolation and the HAC fire, as specified in 10 CFR 71, were imposed in all of the above ANSYS/Mechanical analyses of the Model 9602's thermal performance.

Normal Conditions of Transport (NCT)

Figure 3 shows the calculated temperature profiles of the Model 9602 cask with seven CsCl capsules in an SS basket inside an *air-filled* SS CV, with a total decay heat load of (a) 500 W and (b) 840 W. The corresponding decay heat load for each CsCl capsule was assumed to be uniform at 71.4 and 120 W, respectively.

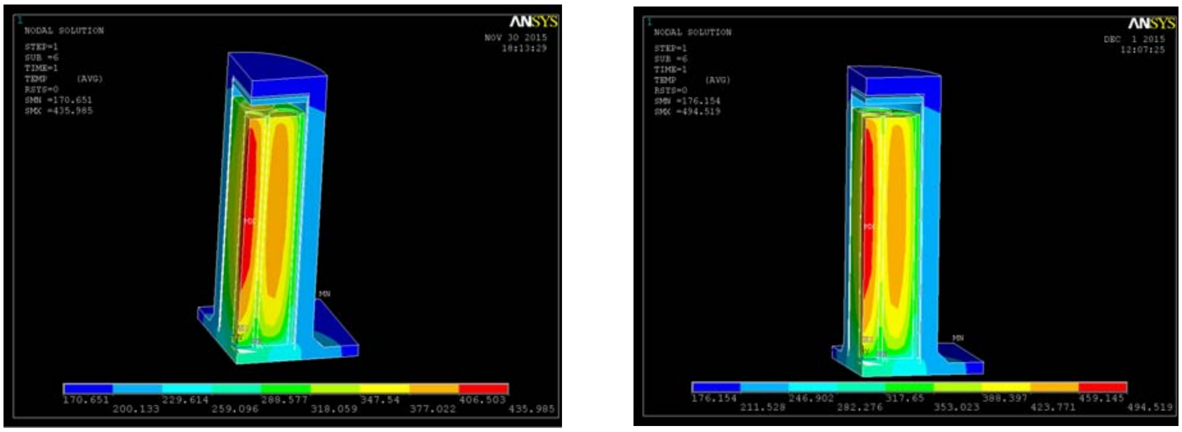


(a) (b)

Figure 3. Temperature profiles of the Model 9602 cask with seven CsCl capsules in an SS basket inside an air-filled SS CV, with total heat load of (a) 500 W and (b) 840 W.

The calculated peak temperatures for the CsCl capsules are 257°C (494°F) and 382°C (719°F), respectively, for decay heats of 500 and 840 W, compared to the salt–metal interface temperature limit of 317°C (603°F). An SS basket inside an air-filled SS CV of the Model 9602 cask, therefore, can accommodate up to seven CsCl capsules for a total decay heat load of 500 W, but not 840 W.

Figure 4 shows the temperature profiles of the Model 9602 cask with seven CsCl capsules in an SS basket inside a *helium-filled* SS CV, with a total heat load of (a) 840 W and (b) 1,000 W. The corresponding decay heat load for each CsCl capsule was assumed uniform at 120 and 143 W, respectively.

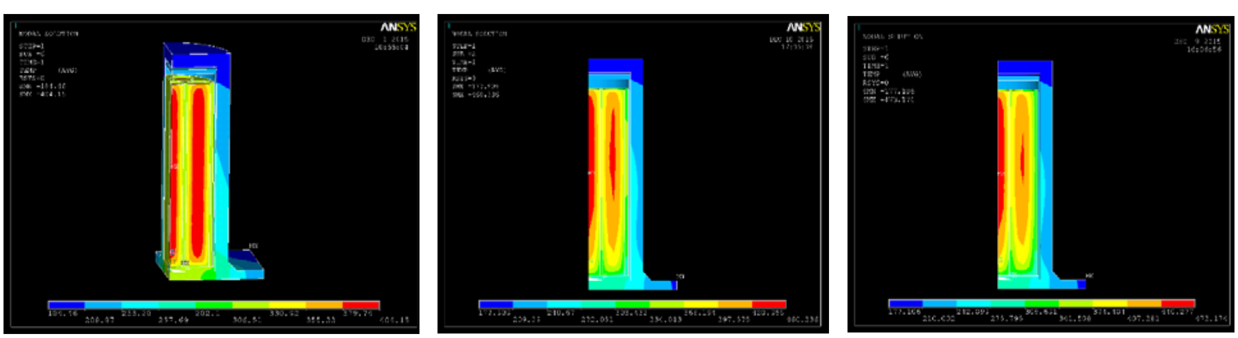


(a) (b)

Figure 4. Temperature profiles of the Model 9602 cask with seven CsCl capsules in an SS basket inside a helium-filled SS CV, with a total heat load of (a) 840 W and (b) 1,000 W.

The calculated peak temperatures for the CsCl capsules are 224°C (436°F) and 257°C (495°F), respectively, for decay heats of 840 and 1,000 W. These are drastically lower than the peak temperatures calculated for an air-filled SS CV in Figure 3, and both are lower than the salt–metal interface temperature limit of 317°C (603°F). The color scales in these temperature profiles do not match exactly; however, the patterns clearly indicate the superior thermal conductivity of helium fill gas compared to that of air.

Figure 5 shows the temperature profiles of the Model 9602 cask with seven CsCl capsules in (a) Al-1100, (b) Pb, and (c) DU baskets inside a helium-filled SS CV, with a total heat load of 1,000 W. The corresponding decay heat load for each CsCl capsule was assumed to be uniform at 143 W.



(a) (b) (c)

Figure 5. Temperature profiles of the Model 9602 cask with seven CsCl capsules in an (a) Al-1100 basket, (b) Pb basket, or (c) DU basket inside a helium-filled SS CV, with a total decay heat load of 1,000 W.

The calculated peak temperatures for the CsCl capsules are 207°C (404°F), 238°C (460°F) and 245°C (473°F), respectively, for a basket of Al-1100, Pb or DU inside a helium-filled SS CV for a total decay heat load of 1,000 W. All of the calculated peak temperatures for the CsCl capsules are lower than the salt–metal interface temperature limit of 317°C (603°F); the lowest obtained was for the Al-1100 basket, which is made of aluminum with embedded ceramic nanoparticles to significantly enhance its thermal conductivity. The colors in the temperature profiles in Figure 5(a) indicate that the calculated temperatures for CsCl capsules are much more uniform in the Al-1100 basket than those in the Pb or DU basket in Figures 5(b) and 5(c). For comparison, room-temperature thermal conductivity values are 0.717, 133, 35 and 27.5 W/m-K, respectively, for 304 SS, Al-1100, Pb, and DU.

Table 1 summarizes the calculated peak temperatures for the CsCl source capsules under NCT for various combinations of fill gas and basket material. The design temperature limit is that at the salt–metal interface of 317°C (603°F), which is conservatively lower than the CsCl phase transition temperature of 330°C (626°F).

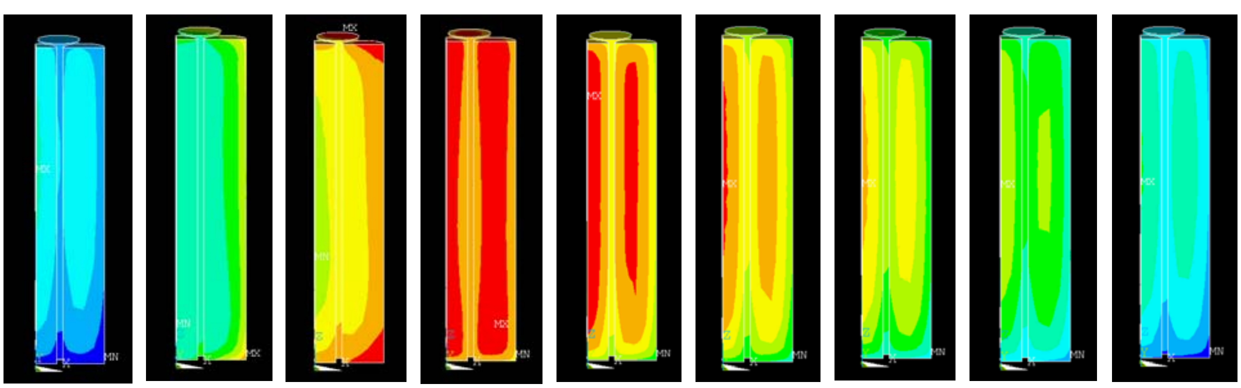
Table 1. Calculated peak temperatures for the CsCl source capsules under NCT.

Heat Load (W)	Fill Gas	Basket Material	PCT (°C/°F)	Temperature Limit*
500	air	SS 304	257/494	<317/603
840	air	SS 304	382/719	>317/603
840	helium	SS 304	224/436	<317/603
1,000	helium	SS 304	257/495	<317/603
840	helium	Al-1100	183/361	<317/603
1,000	helium	Al-1100	207/404	<317/603
1,000	helium	Pb	238/460	<317/603
1,000	helium	DU	245/473	<317/603

*The design temperature limit is that at the salt–metal interface [5].

Hypothetical Accident Conditions (HAC)

Figure 6 shows the evolving temperature profiles for the Model 9602 cask with seven CsCl capsules in a DU basket inside a helium-filled SS CV, with a total decay heat load of 1000 W, during and after a 30-minute, 800°C (1,472°F) HAC fire.



0 min 28 min 50 min 78 min 2 hr. 2.5 hr. 3 hr. 4 hr. 6 hr.

Figure 6. Evolving temperature profiles for the Model 9602 cask with seven CsCl capsules in a DU basket inside a helium-filled SS CV, with a total heat load of 1,000 W during and after an HAC fire.

The calculated peak temperatures for the CsCl capsules is 496°C (924°F). The capsules reached their peak temperatures after the 30-minute, 800°C (1472°F) HAC fire was terminated, or 78 minutes from the start of the HAC fire. Thermal analyses for the Model 9602 cask under HAC fire were also conducted for SS and DU baskets, with air and helium fill gas inside an SS CV, for total decay heat loads of 500, 840, and 1,000 W. Table 2 summarizes the results. The calculated peak temperatures for the CsCl capsules generally occurred after the 30-minute fire was terminated. While lower than the allowable HAC temperature limit of 600°C (1,112°F), they exceed the CsCl phase-transition and melting temperatures of 330°C (626°F) and 430°C (806°F), respectively. However, the personnel shield with wire mesh shown in Figure 1(a) should provide a sufficient thermal barrier for the Model 9602 cask, even after damage accumulated from the HAC drop and puncture.

Table 2. Calculated peak temperatures for the CsCl source capsules under HAC fire

Heat Load (W)	Fill Gas	Basket Material	PCT (°C/°F)	Temperature Limit*
500	air	SS 304	412/774	<600/1,112
500	helium	SS 304	419/787	<600/1,112
840	helium	SS 304	436/817	<600/1,112
1,000	helium	SS 304	466/870	<600/1,112
500	helium	DU	432/810	<600/1,112
840	helium	DU	468/875	<600/1,112
1,000	helium	DU	496/924	<600/1,112

*The design temperature limit is based on data from Table 1-1 in reference [5].

SUMMARY AND DISCUSSION

The thermal performance of the Model 9602 Type B transportation packaging design for disused CsCl radiological sources has been evaluated using the ANSYS/Mechanical code under the normal conditions of transport (NCT) and hypothetical accident conditions (HAC) prescribed in 10 CFR 71. The results indicate that the calculated peak temperatures for the CsCl source capsules meet the design temperature limits for both NCT and HAC, as do the peak temperatures calculated for all other packaging components (e.g., basket, CV, and cask). Thus, as demonstrated, the thermal performance of the Model 9602 packaging design will provide reasonable assurance that the regulatory requirements of 10 CFR 71 have been met. Fill gas inside the SS CV and the basket material have profound effects on the calculated peak temperature of the CsCl capsules; however, the selection of basket must also consider its radiation shielding performance, which is examined in a companion paper [6]. The major conclusions of the ANSYS/Mechanical analyses of the thermal performance of the Model 9602 packaging design may be summarized as follows:

1) For a SS basket inside an SS CV and filled with air, the total decay heat load of the Model 9602 cask can exceed 500 W, but not 840 W, for up to seven CsCl capsules with uniform decay heat load of 71.4 W per capsule. For all other baskets inside an SS CV and filled with helium, up to seven CsCl capsules can be accommodated with a total heat load up to 1,000 W, under both NCT and HAC.

2) The decay heat loads for the population of disused CsCl source capsules are decreasing with time, as are the decay heat loads for the disused SrF_2 source capsules, the thermal analyses results of which have not been included in this paper. Loading fewer than seven disused CsCl capsules in the basket, and/or mixing CsCl capsules with different decay heat loads are additional options that can create extra safety margins for the thermal performance of the Type B Model 9602 packaging design, if desired.

ACKNOWLEDGMENT

This work is supported by the U.S. Department of Energy (DOE), Office of Packaging and Transportation, Office of Environmental Management, under Contract No. DE-AC02-06CH11357. The submitted manuscript has been created by UChicago Argonne, LLC, as operator of Argonne National Laboratory ("Argonne") under contract no. DE-AC02-06CH11357 with the U.S. Department of Energy. The U.S. government retains for itself, and others acting on its behalf, a paid-up, nonexclusive, irrevocable worldwide license in said article to reproduce, prepare derivative works, distribute copies to the public, and perform publicly and display publicly, by or on behalf of the government.

REFERENCES

1. R.H. Pryor, "End of Life Decisions for Sealed Radioactive Sources," *Health Physics*, Feb. 2016, Vol. 110, No. 2, pp. 168–174.
2. L. Price, M. Gross, J. Prouty, M. Rigali, B. Craig, Z.H. Han, J. Lee, Y.Y. Liu, R. Pope, K. Connolly, M. Feldman, J. Jarrell, G. Radulescu, J. Scaglione, and A Wells, "Groundwork for Universal Canister System Development," Sandia report, SAND2015-8332, September 2015.
3. Z.H. Han, Y.Y. Liu, and J.M. Shuler, "Structural Analysis of the Model 9602 Type B Packaging Design for Disused Radiological Sources," *Proc. 19th International Symposium on the Packaging and Transportation of Radioactive Materials*, PATRAM 2019, August 4–9, 2019 New Orleans, LA.
4. M.G. Plys and W.C. Miller, *Summary Report for Capsule Dry Storage Project*, WMP-17265, Fluor Hanford, 2003.
5. F.J. Heard, K.R. Roberson, J.E. Scott, M.G. Plys, S.J. Lee, and B. Malinovic, *Thermal Analysis of a Dry Storage Concept for Capsule Dry Storage Project*, WMP-16940 DE2003816303, Fluor Hanford, 2003.
6. D. Kontogeorgakos, Z.H. Han, Y.Y. Liu, and J.M. Shuler, "Shielding Analysis of the Model 9602 Type B Packaging Design for Disused Radiological Sources," *Proc. 19th International Symposium on the Packaging and Transportation of Radioactive Materials*, PATRAM 2019, August 4–9, 2019 New Orleans, LA.