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

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## ABSTRACT

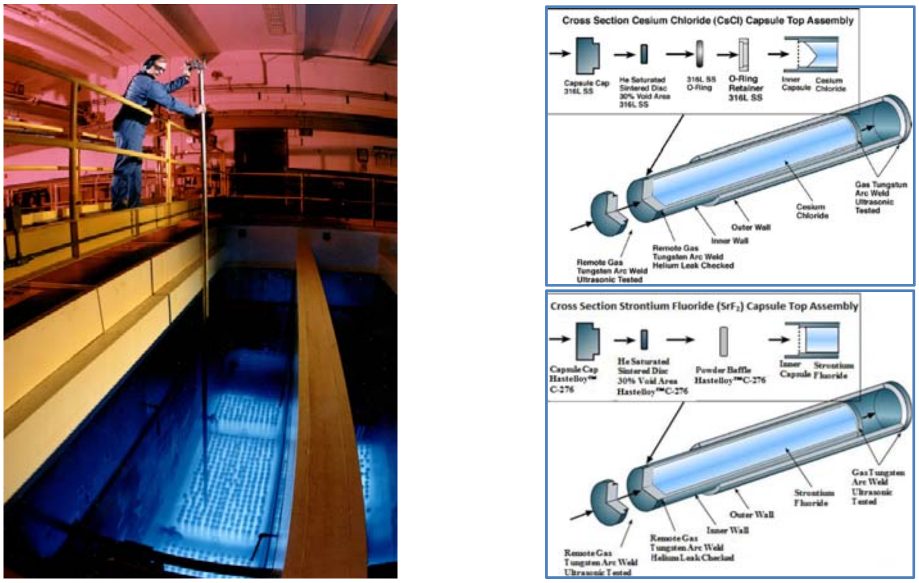
A new compact Type B transportation packaging, designated as Model 9602, is being designed by Argonne National Laboratory researchers for storage, transport and disposal of disused radiological sources. This paper describes the mechanical design of Model 9602 packaging, along with the structural analysis performed as part of the preparation of a Safety Analysis Report for Packaging, which is to be submitted to the regulatory authority for an application of a Certificate of Compliance for the packaging design. The structural performance of Model 9602 under normal conditions of transport and hypothetical accidents (HACs) prescribed in Title 10 of the U.S. Code of Federal Regulations (10 CFR 71), *Packaging and Transportation of Radioactive Material,* was evaluated by using the finite element code ABAQUS. The results showed that the packaging design with a full payload endured the most cumulative damage during a 30-ft bottom-down drop, followed by a top-down drop onto a puncture bar, and yet the containment boundary of the cask remained intact, without any damage to the containment vessel (CV) inside, or the internal basket holding the disused radiological sources. These results are significant in that the undamaged configurations of the basket, CV, and cask following the 30-ft drop and puncture will continue to provide thermal protection during the 800°C HAC fire, as well as radiological containment and radiation shielding after the HAC. Thus, the dynamic structural analysis has demonstrated that the structural performance of the Model 9602 packaging design will provide reasonable assurance that the regulatory requirements of 10 CFR 71 have been met. Moreover, the all-stainless-steel packaging design of Model 9602 should provide excellent protection against general corrosion during long-term storage, thus enabling subsequent transportation, without repackaging of the disused radiological sources, to a repository or deep borehole for final disposal.

## INTRODUCTION

Radiological sources are found in many countries because of their beneficial uses in medical and industrial applications. Some of the radioisotopes used in the sources have relatively short half-lives, e.g., 73.8 days for Ir-192 and 5.27 years for Co-60, while others have much longer half-lives, e.g., 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 a significant risk in terms of inadvertent or deliberate misuse of the material and other problems. [1]

The U.S. Department of Energy (DOE) has planned since the mid-1980s 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, as well as an option for deep borehole disposal of "small" waste forms, such as the Cs/Sr capsules currently stored in the pool cells at Hanford's Waste Encapsulation Storage Facility (WESF). However, space restrictions and other limits (e.g., heat load, radioactivity, floor loading) imposed on the hot cells would permit only a limited number of Cs/Sr capsules to be brought from the pool cells into the hot cells for packaging and transfer to an on-site facility for dry storage. This paper describes a new compact Type B packaging design and structural 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 of 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]

Figure 1 shows Cs/Sr capsules stored under water in the pool cells in the WESF. There are 12 concrete pool cells in the WESF, storing a total of 1,936 Cs and Sr capsules. These Cs/Sr capsules are constructed of 316L stainless steel (SS) or Hastelloy C-276, and the outer diameter and full length of the capsules are approximately 6.86 and 53.34 cm (2.7 and 21 inches), respectively. The water in the pools is ~3.96 m (13 ft) deep and provides cooling and shielding for the radiation from the capsules. These capsules can be transferred from the individual pool cell, by using the existing equipment in the WESF, to the adjacent hot cell G [2.44 m (8 ft) W × 4.88 m (16 ft) L × 3.66 m (12 ft) H] for packaging and transfer operations. Other operational limits of hot cell G include heat load (1,800 W), radioactivity ($1.50 \times 10^5$ Ci), and floor weight (928 $kg/m^2$ or 180 $lb/ft^2$). These requirements and other considerations for long-term dry storage, subsequent transportation, and disposal in a repository or deep borehole are all taken into account in the compact Type B packaging design described below.

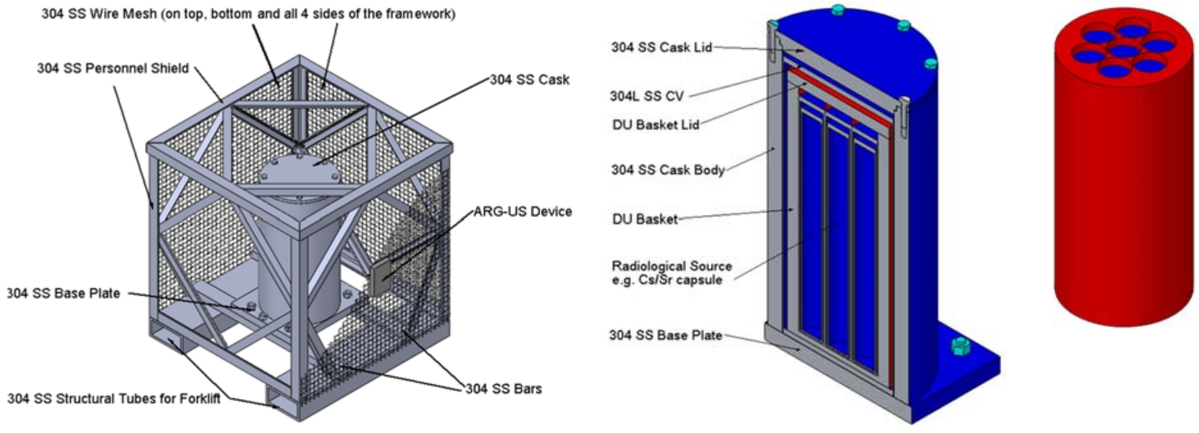


(a) (b)

Figure 1. (a) Cs/Sr capsules stored under water in the pool cells in the WESF; (b) Typical Cs and Sr capsules. [3]

## COMPACT TYPE B PACKAGING DESIGN

Figure 2 shows the compact Type B packaging design (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 holding up to seven (7) Cs/Sr capsules, with a total heat load limit of 1,000 W. The overall dimensions of the packaging are ~0.91 m (3 ft) L × 0.91 m (3 ft) W × 1.07 m (3.5 ft) H. All packaging components, except for the basket, are made of 304 SS or 304L SS (CV only). The basket can be made of DU, SS, or aluminum, depending on the radioactivity of the contents. 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, whereas the space in 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), e.g., a 9-m (30-ft) drop followed by impact on a puncture bar, as prescribed in 10 CFR 71.73. The 304 SS cask is designed to provide confinement of a welded 304L SS CV; 304L SS is used for the CV because of its known improved resistance to chloride-induced stress corrosion cracking. The cask lid is closed with eight bolts, and the base plate of the cask is attached to two 304 SS bars, which are mounted on the structural tubes for a forklift. All the bolts are fabricated from ASTM A-193 Grade B6 SS. The design and the structural performance of the packaging shall meet the requirements specified in Title 10 of the U.S. Code of Federal Regulations (CFR) Part 71, *Packaging and Transportation of Radioactive Material*. The DU is used for the basket because of its excellent performance as a shielding material for high-energy gammas.



(a) (b) (c)

Figure 2. (a) Schematic of the compact Type B packaging design; (b) cask and CV; and (c) DU basket accommodating up to 7 Cs/Sr capsules for a total heat load of 1,000 W.

It should be noted that after loading the Cs/Sr capsules into the basket inside the CV in hot cell G, the CV will be filled with helium and the lid will be sealed with a full-penetration weld in a remote operation. The design of the CV and the remote welding procedure will be developed such that the weld shall meet or exceed the requirements of the ASME Boiler & Pressure Vessel Code (BPVC), Section III, Division 3, Subsection WB, *Containments for Transportation and Storage of Spent Nuclear Fuel and High Level Radioactive Material and Waste,* or its equivalent, Division 1, Subsection NB.

## SAFETY STANDARDS FOR STRUCTURAL PERFORMANCE EVALUATION

The design and performance of the compact Type B packaging shall meet all the safety standards and requirements specified in 10 CFR 71 under normal conditions of transport (NCT) and HACs. The structural performance of the packaging design was evaluated by finite element analysis using the ABAQUS code. The allowables for the CV are based on ASME BPVC, Section III, Division 1, Subsection NB. Permanent deformation of the personnel shield occurs when the effective stress (von Mises stress) exceeds the yield strength of the material. Rupture of a structural member is assumed to occur conservatively, when the effective stress exceeds the tensile strength of the material.

Two separate analysis models were used to determine the maximum damage to the Model 9602 package. The first analysis model was used to determine which drop orientation would result in the maximum loads to the cask and the CV, as shown in Figure 3. For this analysis model, relatively coarser mesh was used, and eleven possible drop orientations were considered to determine the worst-case-scenario drop orientation. Because there is no symmetry for the edge and corner drops, a full model has to be used. These 11 cases are summarized in Figure 4. By using this model, it was determined that the bottom-down drop, which produced the maximum acceleration, followed by a puncture test with the puncture bar targeting the cask lid, would cause maximum cumulative damage to the cask and the CV. The weight of the Model 9602 package exceeds 500 kg, and therefore a crush test is not required.

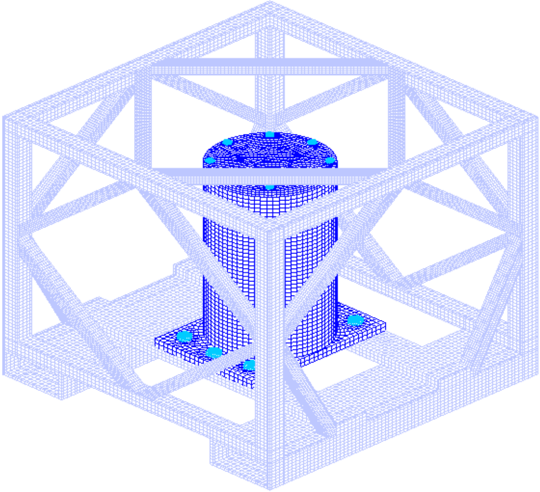
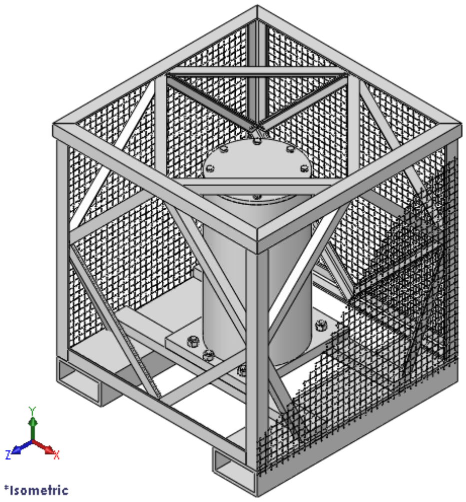


Figure 3. ABAQUS model used for the NCT and HAC analyses (Model 1).



**No Drop Orientation**

1. Bottom Drop (X-Z Plane)
2. Top Drop (X-Y Plane)
3. Side Drop 1 (X-Y Plane)
4. Side Drop 2 (Y-Z Plane)
5. Top Edge Drop 1 (Along X Axis)
6. Top Edge Drop 2 (Along Z Axis)
7. Bottom Edge Drop 1 (Along X Axis)
8. Bottom Edge Drop 2 (Along Z Axis)
9. Vertical Edge Drop (Along Y Axis)
10. Top Corner Drop
11. Bottom Corner Drop

Figure 4. Drop orientations for NCT 4-ft and HAC 30-ft free drops.

The second analysis model was used to determine the maximum loads on the cask and the CV, as shown in Figure 5. The analysis scenario assumed that the packaging is subjected to a 9-m (30-ft) bottom-down drop, followed by a 1.02-m (40-inch) top-down puncture, a sequence that was determined to cause maximum cumulative damage to the CV and represent the greatest challenge to the closure bolts of the cask. Figure 5(a) shows the ABAQUS finite element model of the Type B packaging design for the 9-m (30-ft) drop. Following the 9-m (30-ft) drop, the deformation of the package was imported into the finite element model for the 1.02-m (40-in.) puncture test, as shown in Figure 5(b). Only a quarter of the package was modeled in the drop and puncture analyses, owing to symmetry. For simplicity and without affecting the main objective of the structural analysis, the contents inside the CV, i.e., the basket, including its lid and the Cs/Sr capsules, were modeled as one solid piece having the same weight. For conservatism, the plastic deformation of the contents was not modeled.

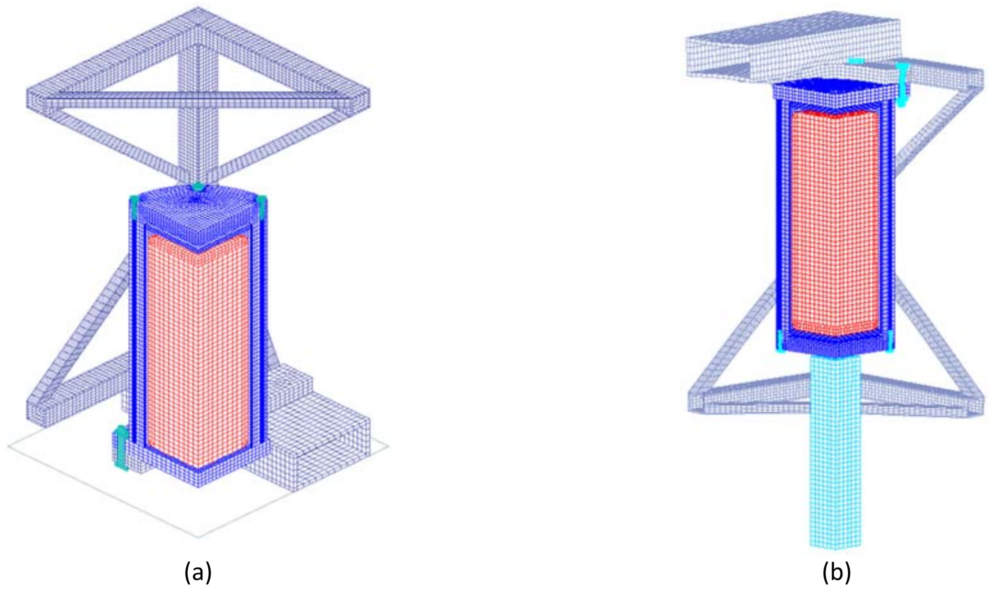


Figure 5. (a) ABAQUS finite element model of the Type B packaging for a 9-m (30-ft) bottom-down drop; (b) deformed packaging model following 9-m (30-ft) drop for puncture test.

Figure 6(a) shows the deformation (in terms of plastic equivalent strain, PEEQ) of the cask closure bolts. The cumulative plastic strain following the 9-m (30-ft) drop and the 1.02-m (40-inch) puncture is less than 5%, which is well below the failure strain of the bolting material—indicating that the cask can maintain its confinement function for the CV and its radioactive contents. Figure 6(b) shows the cumulative deformation of the CV after the 9-m (30-ft) drop; the maximum plastic strain in the CV is ~ 0.13%. The maximum plastic strain is ~2% after the subsequent 1.02-m (40-inch) puncture (Figure 6(c)), which means that the CV maintains its integrity during the drop and puncture.

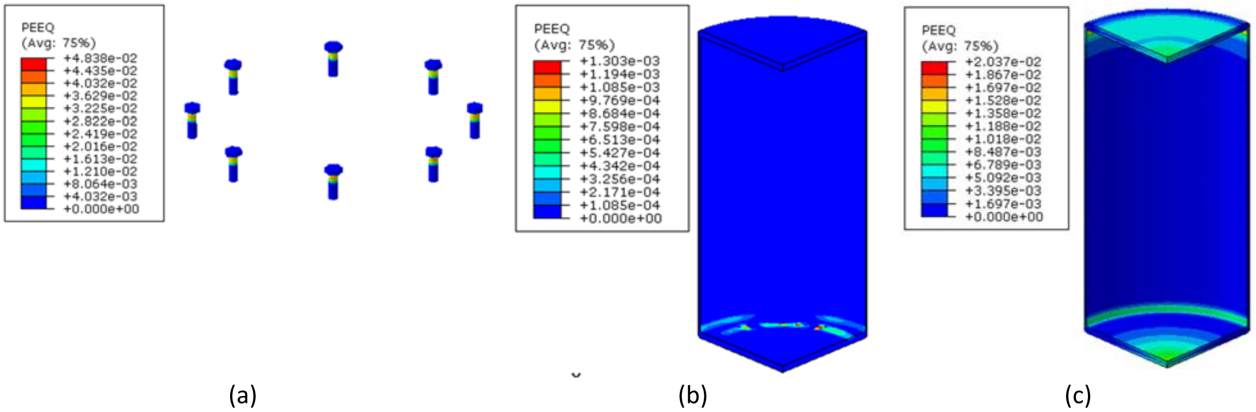


Figure 6. (a) Cask closure bolts following the 9-m (30-ft) drop and 1.02 m (40-in.) puncture; (b) CV following the 9-m (30-ft) drop; and (c) CV following the 9-m (30-ft) drop and 1.02-m (40-in.) puncture.

## DISCUSSION AND FUTURE WORK

As stated by Barlow in a recent paper, *End-of-life Management for Disused Sealed Sources*, the management of disused sealed radioactive sources is an intrinsic part of radiological security. [4] Responsible security of radioactive sealed sources should be understood to include responsibilities on the part of user communities and governments to ensure end-of-life management of sealed sources. Among the many challenges of end-of-life management, source recovery, packaging, and transportation require resources and expertise, as well as certified shipping containers, which many nations lack. [5] The new Type-B packaging design for disused radiological sources can be made available to interested parties after it is certified by the regulatory authorities and used not only for transportation, but also for storage and disposal.

The 2016 Nuclear Security Summit Communiqué stated that "The threat of nuclear and radiological terrorism remains one of the greatest challenges to international security, and the threat is constantly evolving." Numerous incidents reported to the Incident and Trafficking Data Base (ITDB) in 2015 demonstrated that illicit trafficking, thefts, losses, and other unauthorized activities and events involving nuclear and other radioactive material continue to occur. As of December 31, 2015, the ITDB listed a total of 2,889 confirmed incidents, including 454 incidents involving unauthorized possession and related criminal activities, 762 incidents involving theft or loss, and 1,622 incidents involving other unauthorized activities and events. At one time, all the radiological sources have been stored at manufacturing sites or user sites, and they must be transported between the manufacturing sites or import locations, user sites, and disposal sites or export locations. Management of the security of radiological sources is important for each phase during the life cycle of transportation, use, storage, and disposal.

Over the past 10 years, researchers at Argonne National Laboratory have developed the ARG-US (meaning the "Watchful Guardian") remote monitoring and tracking systems technology, [6] which can be used to enhance safety, security and safeguards of disused radiological sources during storage, transportation and disposal. An ARG-US device, shown schematically in Fig. 2(a), is attached to the wire mesh framework of the Type B packaging design. The device contains a suite of sensors, batteries, and communication media for wireless data transmission and automatic alert/alarm when any of the preset sensor thresholds is violated. The reliability and performance of the ARG-US remote monitoring and tracking systems have been demonstrated in various field tests and applications in a real-world environment since 2010. The patented technology has also been licensed and is commercially available, and meets the United States' export control requirements.

Preparation of the Safety Analysis Report for Packaging (SARP) for the new Type B packaging design for disused Cs/Sr sealed sources has begun. The SARP has nine chapters: General information and drawings (chapter 1), structural evaluation (chapter 2), thermal evaluation (chapter 3), containment evaluation (chapter 4), shielding evaluation (chapter 5), criticality evaluation (chapter 6), operating procedures (chapter 7), acceptance testing and maintenance (chapter 8), and quality assurance (chapter 9). We plan to construct two prototypes of the packaging design for regulatory testing and will perform any additional engineering analysis deemed necessary to support the final design of the packaging. The thermal and radiation shielding analyses of Model 9602 packaging design can be found in the companion papers in references [7] and [8], respectively.

## SUMMARY

A new compact Type B packaging design, designated as Model 9602, is being designed for transfer, long-term dry storage, transportation, and disposal of disused radiological sources, such as the Cs/Sr sealed sources at Hanford's Waste Encapsulation Storage Facility. The compact packaging design is suitable for loading, unloading and transfer operations in hot cells with restricted space and thermal, radiological and floor loading limits. Engineering analysis conducted to date showed that the packaging design can accommodate up to seven disused Cs/Sr sealed sources, with heat dissipation capability up to 1000 W. The packaging design has excellent structural performance under both NCT and HACs. The all-SS structure of the packaging design provides excellent resistance to general corrosion and stress corrosion cracking during extended dry storage for at least 50 years. The packaging design is suitable for transportation after long-term dry storage, without repackaging of the Cs/Sr sealed sources, directly into a repository, or into a deep borehole for final disposal. The packaging design includes options to use the ARG-US remote monitoring systems to enhance safety and security during storage, transportation and disposal.

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