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Abstract

The Department of Energy (DOE), in partnership with its national laboratories and the National Aeronautics and Space Administration (NASA), is responsible to produce Pu-238 isotope in the United States for use in space exploration. Major activities in the DOE complex are focused at the Idaho National Laboratory (INL) and Oak Ridge National Laboratory (ORNL). INL is responsible for storing Np-237 feedstock, irradiation qualification in the Advanced Test Reactor (ATR), and irradiating targets containing Np-237 to produce Pu-238. ORNL is responsible for target design, target fabrication, irradiation qualification in the High Flux Isotope Reactor (HFIR), and processing of targets to extract Pu-238 heat source material.

A key part of the program lifecycle is moving irradiated targets from INL to ORNL. The BEA Research Reactor (BRR) cask was identified as a potential shipping cask for the transport of both unirradiated and irradiated targets between the project sites. This paper will discuss the production at INL and shipment of Pu-238 to ORNL using the BRR cask.

PROGRAM OVERVIEW

The Plutonium Fuel Supply (PFS) program's goal is to restart Pu-238 production in the United States. Major activities in the PFS program are focused at Idaho National Laboratory (INL) and Oak Ridge National Laboratory (ORNL). INL is responsible for storing Np-237 feedstock, irradiation qualification in the Advanced Test Reactor (ATR), and irradiating targets containing Np-237 to produce Pu-238; and ORNL is responsible for target design, target fabrication, irradiation qualification in the High Flux Isotope Reactor (HFIR), and processing of targets to extract Pu-238 heat source material.

A key part of the program lifecycle is moving irradiated targets from INL to ORNL. The BEA Research Reactor (BRR) cask was identified as the shipping cask that would be applicable for moving these targets from INL to ORNL. This paper will discuss the production at INL and shipment of Pu-238 to ORNL using the BRR cask.

TARGET DESIGN

Two Pu-238 production target designs, the HFIR Gen II target and the ATR Gen I/HFIR Gen III target, are viable for shipping in the BRR cask. Both target styles consist of Al-6061 clad and have a maximum outer diameter of 10.3 mm (0.404 inches). However, the HFIR Gen II target is roughly 854 mm (33.6 inches) in length whereas the ATR Gen I/HFIR Gen III target is 730 mm (28.7 inches) in length. The feedstock payload is equivalent for both target designs. The insert for shipping these targets is compatible with the BRR cask basket and can accommodate up to

16 targets, and is compatible for loading and unloading at both INL and ORNL shipping facilities. The maximum payload for the BRR cask is 96 targets.

IRRADIATION

INL has qualified the I-7 and South Flux Trap (SFT) for Pu-238 production in the ATR. More recent qualification has been completed for the inner A, H, and Northeast Flux Trap (NEFT). Irradiation in the inner A, H, and flux traps are for one 60-day cycle, while irradiation in the I positions is typically six cycles due to the lower flux. These positions are depicted in Figure 1.

After irradiation, the targets will be allowed to cool for six months. This will allow short-lived radioisotopes to decay, which reduces decay heat and simplifies handling and transportation by reducing the source term of the targets.

INL SAFETY CONSIDERATIONS

The BRR cask is designed, fabricated, and tested to regulations for safe transportation of radioactive material, as documented in the various safety analyses supporting BRR shipments. The safety analyses include the safety requirements for shipping the BRR with these types of targets from the ATR canal area at INL. Examples of these safety requirements include decay/cooling times prior to loading the cask, strict adherence to operating procedures during handling and loading of the targets, and adherence to transport plans once the cask has left the INL.

Specific to the operating procedures during handling and loading of the targets, examples of existing safety requirements include lifting height restrictions and specific hardware associated with the closure lid, shield plug, and retaining bar. For example, targets are loaded into the BRR with the cask submerged in the ATR canal, and a shield plug and retaining bar are required to remove the cask from the canal. Once out of the canal and on the reactor floor, the retaining bar is removed, and the closure lid installed. These portions of the cask, including the specific hardware used, have been analyzed in various drop analyses, therefore strict adherence to previously analyzed conditions is required.

TRANSPORTATION CASK

The BRR cask is a Type B(U)F-96 package designed for transport of used research reactor or Materials Test Reactor (MTR) fuels. Among the approved payloads are fuel elements from many university and government research laboratories, including Testing, Research, Isotopes, General Atomics (TRIGA) elements. It has also been approved to ship up to 3,034 TBq [82,000 Ci] of cobalt-60 targets and has been in use since 2010. The inner cavity has nominal dimensions of 406 mm [16 inches] in diameter and 1,372 mm [54 inches] in length. The nominal side thickness of lead is 203 mm [8 inches]. The lid is fastened using 12, 25 mm [one-inch] diameter alloy steel bolts and sealed with an elastomer containment seal. A drain port is located near the bottom of the cask body. The gross weight of the package is 14,512 kg [32,000 lb]. The cask is NRC-certified for leak-tight containment. A cross section of the package is shown in Figure 2, including upper and lower, closed-cell, polyurethane foam impact limiters.

Because the BRR cask has a very heavy lead shield and may be immersed in water, it is well adapted for use in the transport of high-intensity gamma-emitting payloads, such as isotope production targets, including the Pu-238 targets described above. The principal hazards associated with Pu-238 with regard to a transportation cask are containment of plutonium, heat from the Pu-238, and radiation.

TARGET RACKS

Pu-238 targets are positioned in aluminum target racks that hold up to 16 targets each, as shown in Figure 3. The base of the target holder supports the bottom end and arranges the array of target rods, and the grid plate in the middle provides further support and alignment. The position of the grid plate is fixed by the need to remove the targets from the holder in a hot cell with limited head room. If the grid plate were any higher, it would not be possible to lift the target high enough to clear the plate and remove the target. The targets are captured axially by a closure plate at the top and retained by a stainless steel nut. The top end of the target rack is configured as a pintle for use with a remote lifting fixture. Up to six target racks may be placed into the internal basket structure for a total payload of up to 96 targets in the BRR cask. The configuration of the targets, target racks, and spacers are shown in Figure 4.

The cross-sectional dimension of the target rack is sized to allow the rack to enter the ingress port of the ORNL hot cell. Since an existing, square-opening basket is used with the target racks, an aluminum spacer angle shape is inserted into each opening in the basket to reduce rattle space for the target rack. Of note, while there are a total of eight openings in the basket, only the outer six are utilized for targets. This is because the center two openings are somewhat thermally isolated and “hidden” in terms of heat rejection to the cask side walls, and accordingly, these openings are not used for the heat source targets.

THERMAL – UNDAMAGED TARGETS

Prior to loading and shipment of the irradiated targets, the corresponding thermal load must fall within the safety limits outlined in the BRR Package Safety Analysis Report (SAR). An analytical thermal model of the BRR cask was developed to assess compliance with the SAR under normal conditions for transport (NCT) as well as hypothetical accident conditions (HAC). The base model for the thermal analyses assumed a full payload of targets (96 total) at the maximum decay heat limit defined in the SAR (5.32 W per target, 511 W total). The resulting temperature distribution within the fully loaded cask during NCT is shown in Figure 5(a). The resulting component temperatures were well within the maximum allowable limits for NCT, with the majority having margin greater than 200 ^{o}F.

In addition to the expected NCT scenario, the performance of the fully loaded BRR cask was assessed under several HACs. These conditions include exposure to fire conditions, as well as failed target rods due to an accidental drop of the loaded cask. The fire conditions assume the loaded BRR cask is engulfed in flames for 30 minutes, and the results are shown in Figure 5(b). The transient thermal response of the cask and its contents were monitored for a total of 8.83 hours following the fire conditions. The thermal shield and impact limiters sustain the bulk of the thermal load while the rest of the cask components, including the Pu-238 targets, remain significantly below their maximum allowable temperature limits. The results of the analytical model under NCT and HAC scenarios show that the BRR cask provides sufficient thermal protection to ensure safe transport and storage of a full payload of Pu-238 targets.

THERMAL – DAMAGED TARGETS

The three fundamental safety functions of a transport cask are containment (which typically depends on structural and thermal performance), shielding, and criticality. Since the BRR cask is leak tight per the definition of ANSI N14.5 [1], the containment criterion is met. The thermal and shielding performance of the Pu-238 target payload depends on the structural performance of the target itself, since as noted previously, the upper end of the target is cantilevered in the rack for handling purposes. In an accidental side drop impact event, the targets are placed in a bending mode. If they were to fail in this mode and become concentrated, they could create a greater concentration of heat and radiation source than if the targets were to remain intact and separated in the racks.

Consideration was given to an analysis that would demonstrate the targets did not fail under the worst-case side impact acceleration. However, uncertainties regarding the effect of the hydrostatic compression of the cladding on the pellet stack inside the cladding, the swelling or shrinkage of the irradiated pellets, the location of the bending plane (on a pellet or on a pellet joint), among others, made a positive demonstration unlikely to be successful. Instead, it was chosen to demonstrate that a failure and consolidation of the targets would meet all of the necessary safety criteria.

While prototyping the target rods, it was shown that pellets could not fall out of a sectioned target cladding (the cladding had to be slit and pried open to remove the irradiated pellets), which ensured that pellets from broken targets could not accumulate in a pile in the cask cavity. Furthermore, the broken targets could not escape the individual basket openings into which they had been placed. The basket, the target rack, and the spacer bar ensure that the hypothetically broken targets remain within their individual basket cavities. Consequently, the worst-case accident configuration was to consider the targets consolidated into compact bundles on one side of each of the six basket openings that are used. This conservatively concentrated the heat to maximize the target temperature and concentrated the source term to maximize dose rate consequences. To simplify the analysis and increase conservatism, the entire target, not just the cantilevered portion, was assumed to consolidate into a compact bundle.

An end view of the thermal model with failed targets is shown in Figure 6. The bundle of targets is modeled as a rectangular region within each basket opening, located atop the angle spacer, which conservatively adds the contact resistance of the angle spacer to the thermal resistance between the targets and the outside. The result shows that the failed target temperature under hypothetical fire conditions is only 9 °C [17 °F] hotter than un-failed targets suspended and separated by a target rack, and well below the thermal limit for the aluminum cladding. Since the pellets could not individually escape the cladding and accumulate, there was essentially no thermal effect on sensitive cask components such as the drain port containment seal.

SHIELDING AND CRITICALITY

The shielding evaluation is relatively straightforward. Since the BRR cask has no neutron shielding but heavy gamma shielding, and due to the specific source term, the dose rate is dominated by neutrons, but the total dose rate is far below the regulatory limits, even when concentrated in the hypothetical post-accident configuration. For criticality, no evaluation of unirradiated targets is necessary because the neptunium contained in the targets is not fissile. For the plutonium-bearing irradiated targets, 10 CFR 71.15 [2] states that if the total plutonium mass is not more than 1000 grams, of which no more than 20% by mass is fissile plutonium isotopes, the material may be considered non-fissile. The irradiated targets meet this criterion, thus all of the safety functions of the BRR cask are met when transporting Pu-238 unirradiated or irradiated targets.

SUMMARY

The BRR cask provides key support for Pu-238 production at INL and transport to ORNL for processing. Qualification of irradiation targets for Pu-238 production was used as a basis to determine thermal and shielding compliance with the BRR license.

ACKNOWLEDGEMENTS:

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REFERENCES

1. ANSI N14.5–2014, American National Standard for Radioactive Materials – *Leakage Tests on Packages for Shipment*, American National Standards Institute (ANSI), Inc.
2. Title 10, Code of Federal Regulations, Part 71 (10 CFR 71), *Packaging and Transportation of Radioactive Material*.

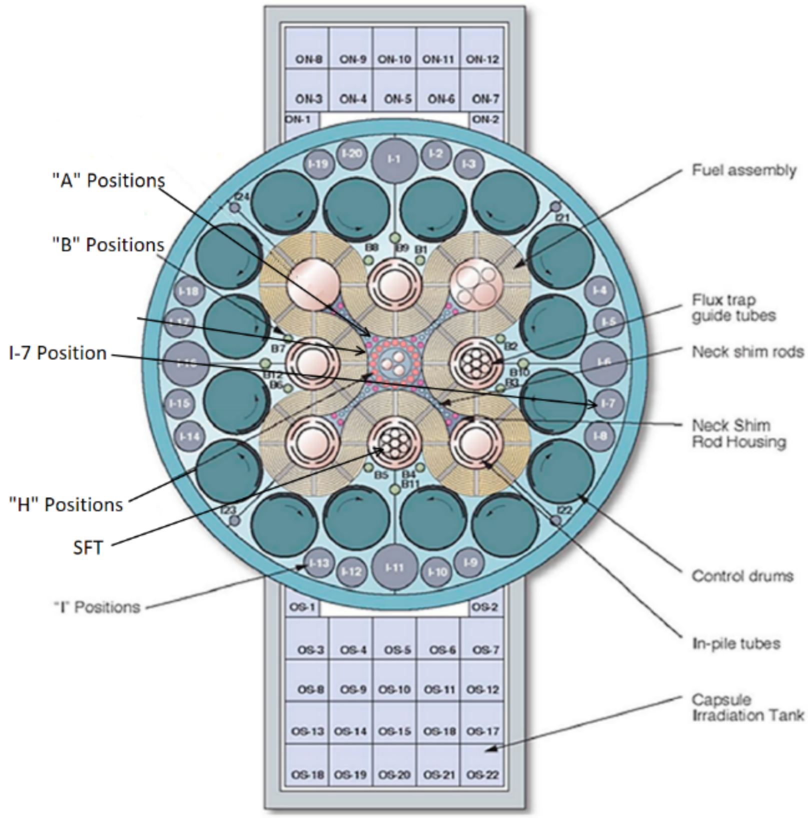


Figure 1. Sectional view of the ATR.

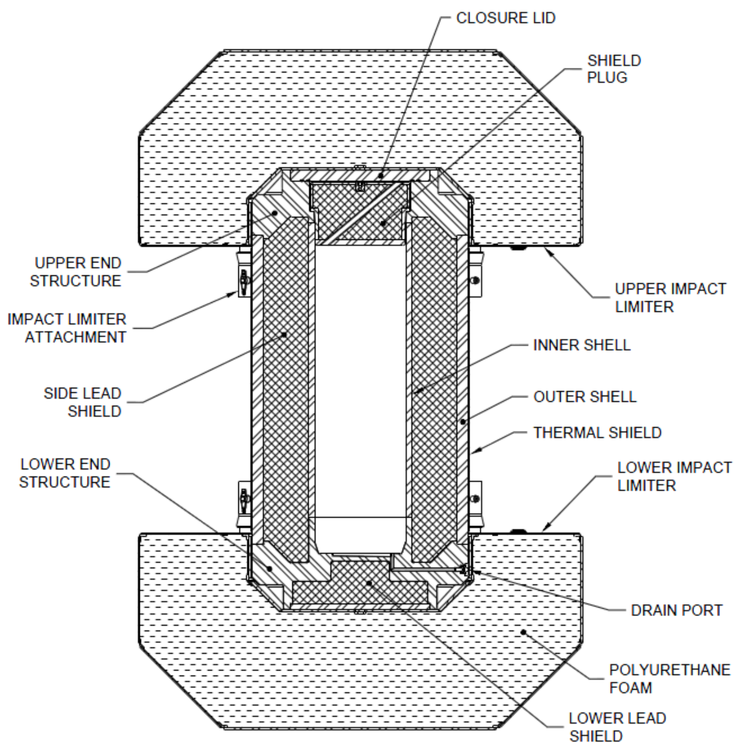


Figure 2. BRR package cross section.

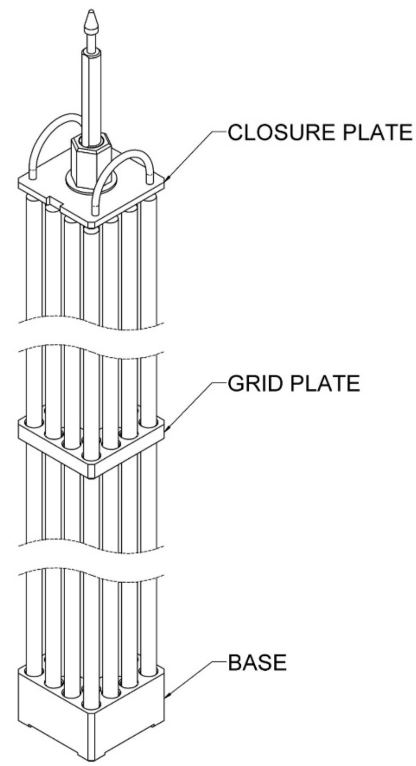


Figure 3. Pu-238 target rack.

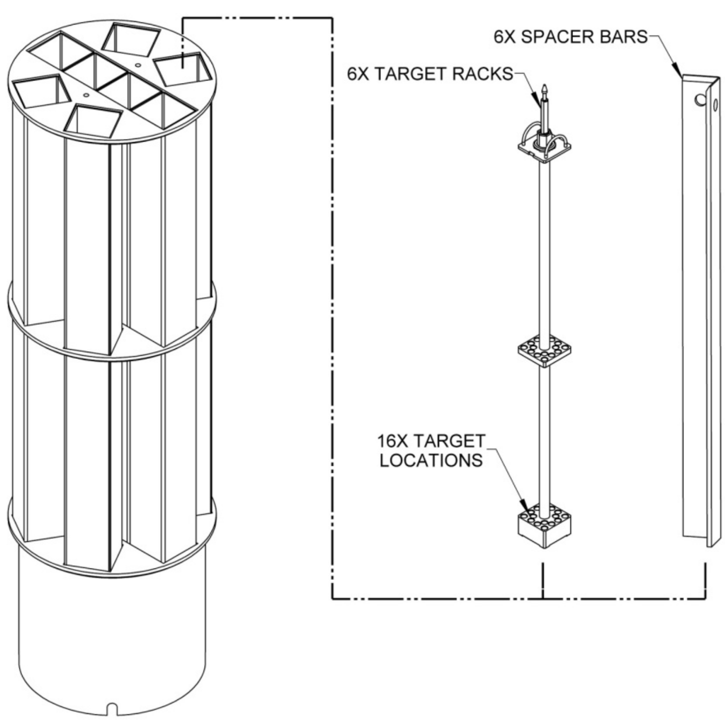
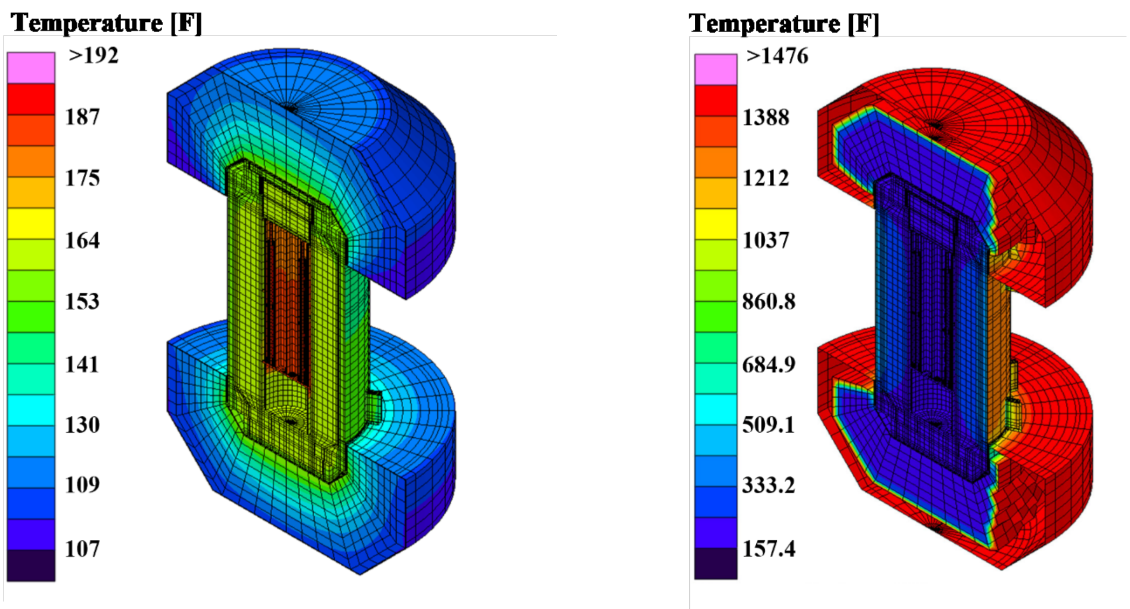


Figure 4. BRR Pu-238 payload structure and rack loading.



(a) (b)

Figure 5. Resulting temperature for a BRR cask fully loaded with Pu-238 targets under (a) steady-state NCT and (b) 30 minutes after a fire HAC.

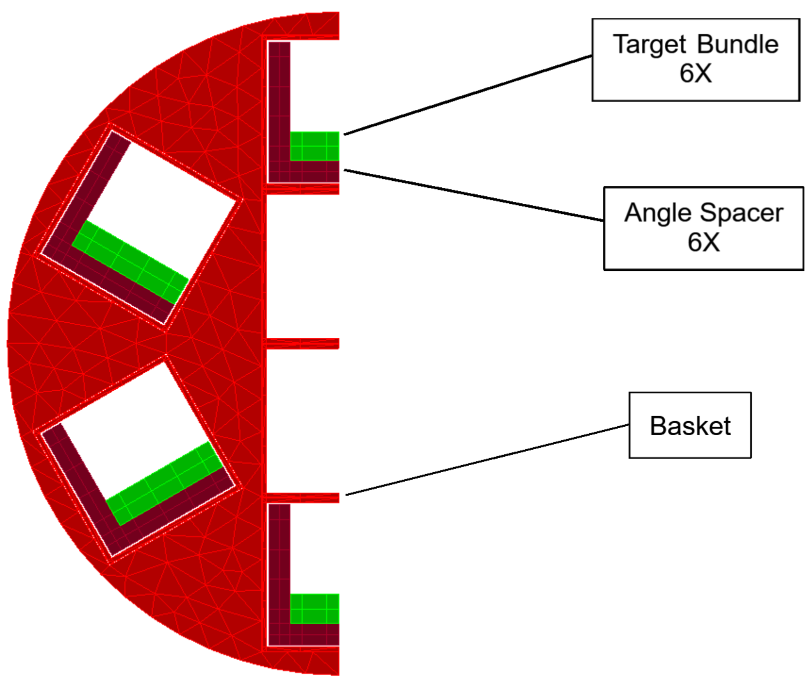


Figure 6. Thermal Model of Failed Targets.