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Reviewing the Safety Analysis Report in Packaging Revision Developed for Adding Pu-238 Targets as Approved Content in the BRR Cask - 22158

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ABSTRACT

The BEA Research Reactor (BRR) cask was first licensed in 2009 to transport irradiated research reactor fuel. The leaktight containment and heavy shielding, as well as its design supporting hot cell operation use, makes it adaptable to other types of radioactive payloads. In order to establish a reliable domestic supply of Pu-238 to produce radioisotope thermal generators, neptunium-aluminum cermet pellet-based targets will be irradiated transmuting the Np-237 feedstock into usable Pu-238. After irradiation, the targets will then be shipped in the BRR casks for chemical processing. As such a revision to the Safety Analysis Report in Packaging (SARP) was required to add the targets as new content.

The targets for irradiation at Oak Ridge National Laboratory (ORNL) are termed the High Flux Isotope Reactor Generation II (HFIR GEN II) targets, while the targets for irradiation at Idaho National Laboratory (INL) are termed the Advanced Test Reactor (ATR) Pu-238 targets. The design of the HFIR GEN II targets is considered complete, but the ATR targets are still under development. Additionally, reaching the desired sustainable yearly output of Pu-238 will require further optimization of the targets. Without completion of the ATR Pu-238 target design, Chapter 2 of the SARP for shipping the targets in the BRR package conservatively considers a breach of the target) cladding (i.e., tearing)to be plausible, but acceptable.

This paper details the application and results of the general SARP review process for the proposed revision submitted by the applicant. It also uniquely summarizes the independent modeling developed by the review team, validating the results of the conservatism associated with assuming a cladding breach. Based on the results of the review, the review team concluded that the cask with the new Pu-239 Targets would perform in accordance with the Type B Regulatory Requirements specified by the U.S Code of Federal Regulations in 10 CFR 71.

INTRODUCTION

The United States Department of Energy (DOE) is responsible for fabricating radioisotope thermoelectric generators (RTGs) for the U.S. National Aeronautics and Space Administration (NASA) to use in deep space mission activities. Pu-238, with a half-life of 87.7 years, undergoes an alpha decay event to form U-234, a reaction that also produces excess decay heat. When formed into oxide pellets, the Pu-238 provides a heat source for RTGs. Through thermoelectric conversion , the RTGs harness the decay heat to generate electrical power .

The DOE program responsible for the ensuring Pu-239 supply is named the Pu-238 Supply Program (PSP). It fabricates and assembles production targets containing NpO_2–aluminum cermet pellets, that will be irradiated in the High Flux Isotope Reactor (HFIR) or ATR to produce Pu-238. The neutron transmutation path for this process is shown in Fig. 1.

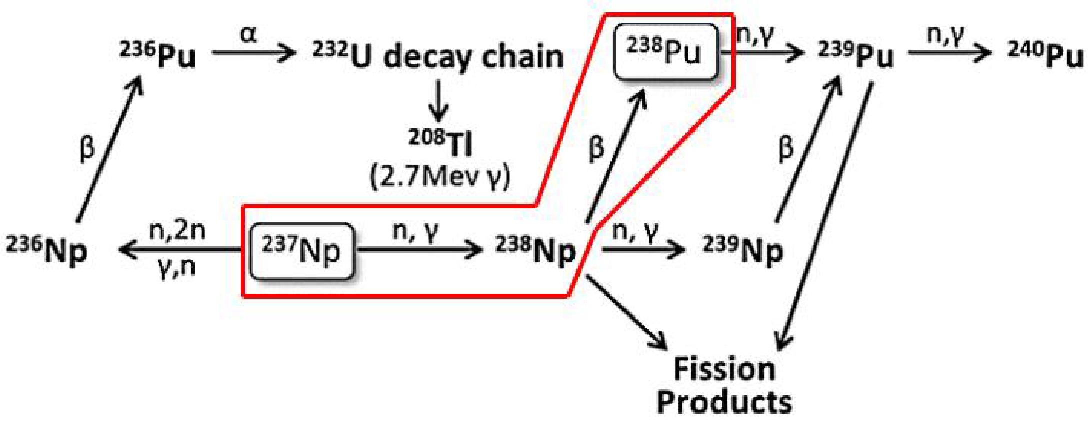

Fig 1. Transmutation Pathway, with Production of Pu-238 from Np-237 Outlined in RFed [1].

After irradiation of the targets, the Pu-238 will be chemically extracted. As part of supporting this effort, shipment of both fresh and spent targets will be required using the INL's BEA Research Reactor (BRR) cask.

The BRR cask was first licensed in 2009 to transport irradiated research reactor fuel. The leak tight containment and heavy shielding, as well as its design supporting use for hot cell operations, makes it very adaptable to supporting shipment other types of radioactive payloads. In fact, each year DOE ships various Type BF shipments using the BRR. Before the BRR cask can be used for the Pu-238 targets, the contents must be authorized by DOE Packaging Certification Program (PCP) for use in the cask. Obtaining this approved content revision from was initiated through a SARP revision request, with proposed revised SARP developed by INL

A DOE PCP SARP follows a nine-chapter format, with the content of the first eight chapters specified by the NRC Reg Guide 7.9 [2], with the addition of Chapter 9, *Quality Assurance,* specific to DOE.

Chapter 1 of a SARP is considered the keystone chapter because it contains both a general description of the packaging and details the authorized packaging contents. Since the content plays such a dominant role throughout the entire SARP development process, the unofficial "modus operandi" is to begin the SARP development only after the content is well-defined. Over multiple decades this approach, has proven its effectiveness. What makes this specific review SARP so unique is that because of the significant need for Pu-238 to support future NASA missions, the revision to add the content was submitted to the DOE PCP for review prior the ATR Pu-238 target design being complete.

This paper details application and key results of the SRNL review conducted for the DOE PCP. In this unique case, where the ATR target (i.e., content) design has not been completed, this paper highlights key review team compensatory activities used to address this ambiguity.

DESCRIPTION

The general actions performed when SRNL performs a SARP review can be considered to occur in two stages. The first stage is termed the "preliminary appraisal." Its purpose is to understand the general organization of the proposed SARP, including how and where additional information was added, as well as to note any inconsistencies. It includes:

- An initial read of the entire proposed SARP, usually performed by the review lead.
- A comparison of the proposed SARP against the current revision.

The second technical stage of the review, is considered the actual "expert review." It includes a review of each chapter by a chapter recognized subject expert along with:

- Additional research and modeling, as required, to validate acceptability.
- Consultation of the DOE SARP Completeness Checklist [3], as well as the DOE Package Review Guide [4], as well as other guidance documents to ensure all required information is contained within the appropriate sections of the SARP.

All questions and comments generated throughout the review are captured on a comment resolution sheet, which must be resolved by the applicant concurred by the SRNL review team.

DISCUSSSION

Preliminary Appraisal

The proposed SARP submittal's addition of the Pu-238 targets closely followed that of the previous revision developed to add Co-60 targets as new content. Chapter 9, however, was being added by the proposed SARP. as the previous DOE revision of the SARP was issued based on an NRC approved Safety Analyses Report (SAR) for the BRR cask, with NRC SARs not containing a Chapter 9.

For Chapter 1, *General Description*, Chapter 2, *Structural*, and Chapter 4, *Containment*, the required information to support the addition of the Pu-238 targets as content was added directly to the existing chapters, while for Chapters 3, *Thermal Analyses*, and Chapter 5, *Shielding*, the additional information was inserted as new sections at the end of their current appendices. For Chapter 6, *Criticality*, there was no impact as the Pu-238 targets contain only exempt concentrations of fissile materials. Chapter 7, *Package Operations*, contained only a few changes that were addressed by revising the chapter text to reflect dry and wet loading of the targets. Chapter 8, *Acceptance Tests and Maintenance Program* contained no substantial changes. As previously stated, since the previous DOE approved SARP was based on an NRC approved SARs, Chapter 9, *Quality Assurance,* was newly developed to support the proposed revision.

For Chapter 1, *General Description*, a detailed comparison was performed by the review team of the proposed SARP to the previous revision (i.e., Rev. 0) with the intent to understand the scope of the changes. The review team noted that Chapter 1 text added design details on the Pu-238 targets and the production rack, while also adding design drawings for the production rack to Appendix A. As Tables 1.2-1 through 1.2-5 were only for reactor fuels, the isotopic content for the Pu-238 targets was provided in Section 1.2.2.7, with the associated reference added to the Chapter 1 list of references.

It was noted by the review team that although Chapter 2, *Structural*, contained a Figure 2.12.8-9 - *Isotope Production Target Basket and Target Holder* for the Co-60 targets, the proposed SARP strangely did not contain a similar figure for the Pu-238 production targets. It was reasoned by the review team that this omission could likely have been caused by ATR target design not being finalized when the proposed SARP was being developed. Based on comments by the review team, the applicant agreed to add figures for the Pu-238 targets.

As part of the preliminary appraisal by the review team, it was noted that Appendix 3.7 was added to address the results of the thermal analyses for the Pu-238 targets. Tables added for transporting Pu-238 production targets under Normal Conditions of Transport (NCT) and Hypothetical Accident Conditions (HAC) included the following:

- Table 3.7-1. *Maximum Temperatures for NCT and HAC when Transporting Pu-238 Production Targets*

- Table 3.7-2. *Summary of Maximum Pressures when Transporting Pu-238 Production Targets*
- Table 3.7-3. *Fission Gas Calculations at 180 Days Decay*
- Table 3.7-4. *NCT Temperatures for BRR Packaging with Pu-238 Production Target Payload*

Table 3.7-5. *HAC Temperatures for BRR Packaging with Pu-238 Production Target Payload* Chapter 4, Containment, contained no significant changes.

As part of the preliminary appraisal of Chapter 5, *Shielding,* it was identified by the review team that Section 5.7 was added to provide a detailed shielding evaluation of the Pu-238 production targets. Tables added for transporting the Pu-238 production targets included the following:

- Table 5.7-1. *Summary of Maximum Total Dose Rates (Exclusive Use) for Pu-238 Production Target Payload*
- Table 5.7-2. *Pu-238 Production Target Gamma Source*
- Table 5.7-3. *Pu-238 Production Target Neutron Source*
- Table 5.7-4. *Key Cask Model Dimensions*
- Table 5.7-5. *Key Square Fuel Basket Model Dimensions*
- Table 5.7-6. *Key Pu-238 Production Target and Target Rack Model Dimensions*
- Table 5.7-7. *Stainless Steel 304 Composition (Density = 8.00 g/cm^3)*
- Table 5.7-8. *Lead Composition (Density = 11.35 g/cm^3)*
- Table 5.7-9. *Dry Air Composition (Density = 0.001205 g/cm^3)*
- Table 5.7-10. *Tally Maximum Dose Rates*
- Table 5.7-11. *Tally Maximum Dose Rates with Failed Targets*

Section 5.7.4.5 was also added by the applicant to address dose rates with failed targets. This section modeled the Pu-238 production target source term in unit quantities of target material and maximum target flux. As the dose rates resulting from transportation of irradiated Pu-238 production targets will bound those from transportation of fresh Pu-238 production target, the fresh production targets source term was not analyzed.

As part of the preliminary appraisal of Chapter 6, *Criticality*, SRNL agreed with the applicant that the production targets were exempt from classification as fissile material per Section 6.10, *Fissile Material Assessment of Pu-238 Production Targets*, and thus were not required to be analyzed as part of a criticality evaluation. In Chapter 7, *Operations*, text was added by the applicant to address the dry and wet shipping Pu-238 production targets, while as part of Chapter 8, *Acceptance Testing and Maintenance*, there were no significant changes

During The preliminary appraisal by SRNL of Chapter 9, *Quality Assurance*, it was noted that new information was added by the applicant that included the Pu-238 target rack in Table 9.1-1 entitled *Quality Categories for BRR Packaging Components.*

Expert Review

With the design of the ATR targets "incomplete" at the time of SARP submittal, the position of the applicant on the ability of the targets to survive NCT and HAC drops changed over time, starting from assuming non-failure to ultimately conservatively considering failure. As stated by the applicant and agreed to by the reviewer, even if failure was assumed, there would be no reconfiguration or concentration of the NpO_2 pellet stacks due to structural failure of the Pu-238 target.

This change in the strategy by the applicant caused some required re-submittals to the proposed for Section 3.7 *Thermal Evaluation for Pu-238 Production Target Payload*, and Section 5.7 *Shielding Evaluation of Pu-238 Production Target Payload.* Despite the changes, the impact from the now modeled target failure resulted in only a slight increase in the maximum cavity pressures when transporting Pu-238 production targets. This is shown in TABLE I and bounded by the maximum pressure identified in Section 3.6.3.2, *Maximum Normal Operating Pressure* of the current SARP as 103,421 Pascal (15 psig).

TABLE I. Summary of Maximum Pressures when Transporting Pu-238 Targets

Condition	Cavity Pressure- w/o Target Failure Pascal (psig)	Cavity Pressure- with Target Failure Pascal (psig)
NCT Hot	22,063 (3.2)	28,269 (4.1)
HAC Hot	49,642 (7.2)	57,227 (8.3)

Gas generation in the target comes from two sources, fission gases (Xe and Kr) and He from alpha decay of the Pu-238. Conservatively, when assuming target failure all the gases generated are assumed to be released from the targets, and none is assumed trapped in the pellet matrix. Krypton and xenon quantities were calculated at the minimum decay time of 180 days and assumed to remain constant thereafter. Helium was calculated by extrapolation to a decay time of 10 years to bound any possible target age. The basic quantities of gas were calculated from the source term for the design of the holder for the BRR cask [6] in terms of mass per length of pellet stack. Within a single rod the maximum pellet stack is 58.42 cm (23 inches) long, with a maximum 96 targets allowed per cask. TABLE II shows the estimated fission gas from the failed target calculated at 180 days of decay.

Table II. Fission Gas Quantities After180 Days

Totals	Krypton, g/cm (g/in)		Xenon, g/cm (g/in)	
	Kr-82	6.50E-07 (2.56E-7)	Xe-128	1.01E-06 (3.98E-7)
	Kr-83	4.17E-05 (1.64E-5)	Xe-129	1.40E-08 (5.5E-9)
	Kr-84	7.39E-05 (2.91E-5)	Xe-130	3.90E-06 (1.54E-6)
	Kr-85	1.83E-05 (7.20E-6)	Xe-131	8.23E-04 (3.24E-4)
	Kr-86	1.17E-04 (4.61E-5)	Xe-131m	2.73E-10 (1.07E-10)
			Xe-132	1.26E-03 (4.96E-4)
			Xe-133	1.40E-14 (5.51E-15)
			Xe-134	1.75E-03 (6.89E-4)
			Xe-136	3.23E-03 (1.27E-3)
Sum	9.92E-05 (2.52E-4)		2.78E-03 (7.07E-3)	
Total g in 58.42 cm	5.80E-03		1.63E-01	
g-mol/target	6.82E-05		1.21E-03	
g-mol/96 targets	6.55E-03		1.16E-01	

Based on the concentration of fission product gases at 180 days, the maximum normal operating pressure (MNOP) within the cask cavity was calculated by the applicant to be 28,269 Pa (4.1 psig), which is less than the bounding level of 103,421 Pa (15 psig) set in Section 3.6.3.2, *Maximum Normal Operating Pressure* of the current SARP.

Section 3.7.4.3.3 *HAC Temperatures with Failed Target* was added by the applicant to the SARP summarizing the resultant HAC temperatures for failed targets increased only slightly, remaining far from the maximum allowable temperature. This is shown as TABLE III.

TABLE III. Peak HAC Temperatures

Component	Peak, w/o Target Failure	Peak, with Target Failure	Allowable
Target	169°C (336°F)	178°C (353°F)	593°C (1100°F)
Square Fuel Basket	166°C (331°F)	175°C (347°F)	427°C (800°F)

The applicant was also required to perform a few changes to Section 5.7 of the proposed SARP, based on assuming target failure. Section 5.7.4.5 was written to address dose rates with failed targets. The calculated maximum dose rates with and without target failure are summarized in TABLE IV.

TABLE IV. Maximum Dose Rates

Location	Total Dose Rate mSv/hr (mrem/hr)		Difference
	w/o Target Failure	with Target Failure	
NCT, Package Surface, Side	0.0844 (8.44)	0.0869 (8.69)	2.9%
NCT, Package Surface, Top	0.0138 (1.38)	0.0131(1.31)	-4.7%
NCT Package Surface, Bottom	0.0203 (2.03)	0.0202 (2.02)	-0.4%
NCT, Trailer Surface, Side	0.0145 (1.45)	0.0147 (1.47)	1.2%
NCT Trailer Side 2m	0.002 (0.20)	0.002 (0.20)	0.2%
HAC Package Side 1m	0.0099 (0.99)	0.0102 (1.02)	2.6%
HAC Package Top 1m	0.009 (0.90)	0.0082 (0.82)	-8.2%
HAC Package Bottom 1m	0.0107 (1.07)	0.0101 (1.01)	-5.9%

As can be seen in TABLE IV, the limits of 10 CFR 71.47 of 2 mSv/hr (2 mrem/hr) on contact with the outside surface of the CASK and 0.1 mSv/hr (10 mrem/hr) at 2 meters will not be approached, with or without target failure. The 10 CFR 71.51 limit of 10 mSv/hr (1 mrem/hr) at 1 meter will also not be approached.

In the applicant's reconfiguration of the targets, all sixteen targets in each basket position are assumed to completely fracture and both the upper and lower portions of the rods fall to the bottom of each square fuel basket tube. However, the applicant provided a bases for the individual pellets not coming loose from the target cladding envelope, such that the pellets of each target remain distributed axially in the fuel tube debris. This is the same as for non-failed target. The applicant justified the retention of the pellets based on the hydrostatic compression of the cladding during fabrication, as well as experience with removal of pellets from irradiated targets. While the review team accepted the applicant's justification, the team also explored the likelihood of actual fracture of the target using dynamic explicit finite element. Because confirmed material properties were not part of the submittal, no firm conclusion of target fracture could be made, but the additional SRNL review team created model suggested that that the applicant's assumption of failure is conservative.

To explore the likelihood of target fracture in a side drop, the target response to the HAC 9-meter (30 ft) drop test was simulated by SRNL using a finite element (FE) model. The target rod geometry of a single target is shown in Fig. 2. Although the cladding has ribs which run lengthwise along the target rod these are conservatively not included in the model. This reduces the cross-sectional area of the rod increasing the conservatism of the results. In the holder, the rod is secured at its base and a little less than halfway along its length, providing the boundary conditions for analysis.

As part of the SRNL review, an FE model was created that assumed that the target cladding was made of 6061-T4 aluminum, filled with target pellets, along the entire length, a bounding assumption. According to the submitting party the cladding aluminum experienced embrittlement due to the radiation from the neptunium. In the modeling, this resulted in a reduction of the fracture strain from 19% to 12%. Because the irradiation embrittled material properties of 6061-T4 aluminum were not documented, two cases, corresponding to different material models, were simulated. The first case was unembrittled 6061-T4 aluminum. The second simulated the embrittled material by including the 12% fracture strain of embrittled aluminum and arbitrarily increased the yield strength to 221 MPa. This was in an effort to increase the elastic region of the stress-strain curve and decrease the plastic region, as is typical in brittle materials. The material properties for these cases are given in TABLE V. The cladding was modeled as a bilinear material to capture plastic deformation during impact. Damage to the material if strained past its ultimate tensile strength, was also included.

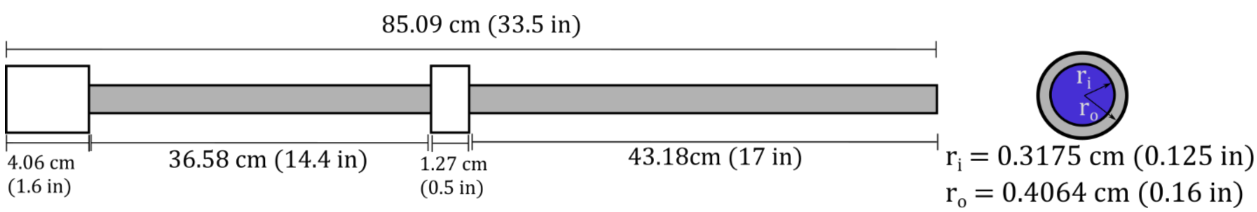

Fig 2. Geometry of a Single Target Rod and Holder used for FE Modeling.

Table V. Mechanical Properties for 6061-T4 Aluminum

Case	Density (kg/m^3)	Young's Modulus (GPa)	Poisson's Ratio	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Fracture Strain
1	2700	68.9	0.33	145	241	19%
2	2700	68.9	0.33	221	241	12%

The NpO_2-aluminum cermet pellets were assumed to run the length of the target rod. The pellets do not lend strength to the rod in tension. This can be reasonably approximated in FE simulations using a foam material plasticity model, which is much weaker in tension than compression. The exact mechanical properties of the cermet were not known, so the pellet material properties were assumed to be the same as the aluminum cladding. Due to the weakness of the cermet in tension, its specific mechanical properties were expected to be irrelevant. A simple check varying the Young's modulus from 50 to 150% of the 6061-T4 aluminum for the cermet foam material showed it had a negligible effect on the stress in the cladding, therefore these assumed material properties were deemed adequate for the modeling. The density of the pellets within the rod, as provided by the applicant, was 16,608 kg/m^3.

Acceleration predictions provided by the applicant showed that the targets would be subject to less than a 120 g acceleration at the time of impact. The von Mises stress in the FE model was predicted based on a 120 g acceleration applied over 0.0114 s, the time duration required at this acceleration to return the falling targets to a velocity of zero. Results of this simulation, at the time frame of maximum deflection, are shown in Fig. 3. The FE embrittled model predicted a maximum stress in the cladding of 234 MPa. This value is above the assumed 221 MPa yield strength, but below the typical 6061-T4 ultimate tensile strength of 241 MPa where damage and crack initiation will occur, with this case bounding the ductile case. Thus, the FE analysis indicates that for a bounding HAC side drop permanent deformation of the rods will occur, but the cladding would likely not fail.

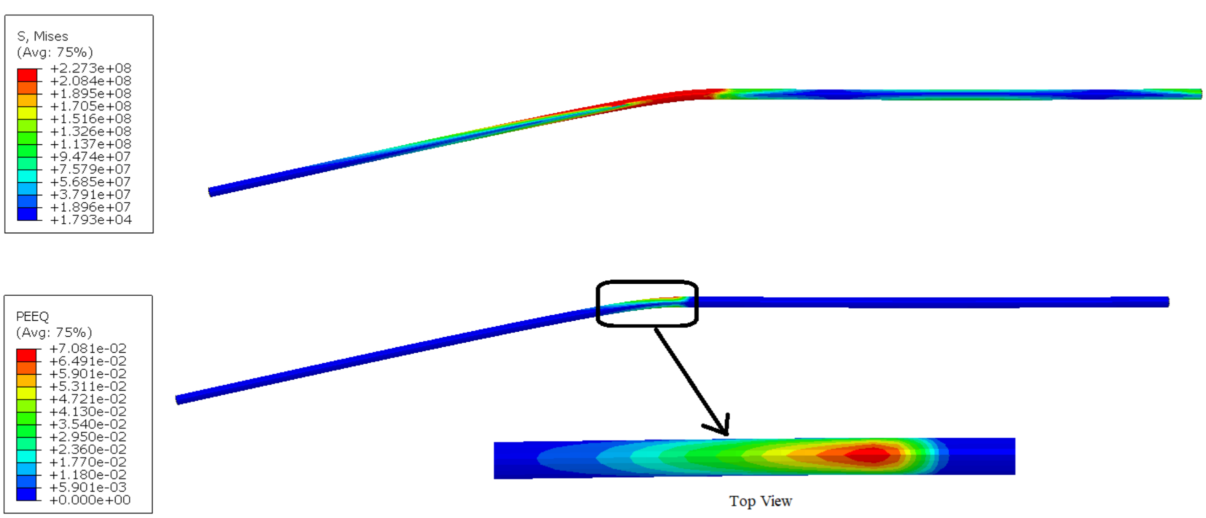

Fig. 3. Deformed Target Von Mises Stress and Plastic Equivalent Strain (PEEQ) Maps, for Top and Bottom Respectively, at the Time of Maximum Deflection (0.25 Scale Factor)

CONCLUSIONS

The SRNL review of the SARP determined that addition of the information to support adding the Pu-238 targets as content in the proposed SARP revision largely follows the layout of the addition of the information previously used to support the Co-60 targets that were added to the SARP as certified content as part of a previous revision.

For Chapter 1, *General Description*, Chapter 2, *Structural*, and Chapter 4, *Containment* the required information to support the addition of the Pu-238 targets as content was added directly to the existing chapters, while for Chapters 3, *Thermal Analyses*, and Chapter 5, *Shielding*, the additional information was inserted as new sections at the end of their current appendices. For Chapter 6, *Criticality* there was no impact as the Pu-238 targets are classified as exempt. Chapter 7, *Package Operations* contained only a few changes that were addressed by revising the chapter text to reflect dry and wet loading of the targets. Chapter 8, *Acceptance Tests and Maintenance Program* contained no substantial changes. As previously stated, since the previous DOE SARP was based on an NRC approved SARP, this Chapter 9, *Quality Assurance* represents a completely new addition to the SARP.

Regardless of if the targets fail (assuming there is no reconfiguration or concentration of the NpO_2 pellet stacks due the structured failure of the production target), the pressure will rise only slightly to account for the release of fission product gases, staying well below the maximum allowable 103,421 Pascals (15 psig). Overall, the impact assuming target failure will have minor impacts on the pressures and temperatures specified in Chapter 3, and only a minor impact on dose rate, as determined in Chapter 5.

However, the acceptability of the results from the target failure is predicated on the fact that failure, as analyzed in the proposed SARP, precludes reconfiguration of the target contents, and hence is not addressed be fully addressed. To provide further justification that reconfiguration does not occur, the review team analyzed the targets in a HAC side drop assuming the bounding acceleration in the SARP and using reasonable although unconfirmed material properties. A finite element model using these parameters showed that for an HAC side drop, failure of the target rods would not be expected. Therefore, ultimately the modeling further supported the applicant's position that the pellets of each target would be expected to remain distributed axially in the fuel tube debris.

REFERENCES

1. E. Collins and R. Wham, "Development of Improved Targets, Separation Processes, and Waste Management for Pu-238 Production," in International Congress on Advances in Nuclear Power, San Francisco, CA (2016).
2. United States Nuclear Regulatory Commission, Regulatory Guide 7.9, Rev. 1, March 2005.
3. DOE 2007 SARP-Completeness Checklist, DOE Packaging Certification Program, Revision 1, March 14, 2007.
4. DOE Packaging Review Guide for Reviewing Safety Analysis Reports for Packagings, UCID-21218 Rev. 3, Lawrence Livermore National Laboratory, February 2008.
5. Standard Review Plan for Transportation Packages for Radioactive Material, NUREG-1609, United States Nuclear Regulatory Commission, March 31, 1999.
6. Idaho National Laboratory Engineering Calculations and Analysis Report (ECAR), No. 4674, *Source Term for Design of PFS Transportation Holder for BRR Shipping Cask*, Revision 0.