POTENTIAL CHALLENGES WITH TRANSPORTATION OF FRESH (UNIRRADIATED) ADVANCED REACTOR FUEL TYPES

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ABSTRACT

This report discusses potential challenges and issues associated with transportation of fresh unirradiated advanced reactor fuel (ARF) by presenting information associated with select package designs approved by the U.S. Nuclear Regulatory Commission (NRC), and comparing attributes of approved designs to characteristics of non-light water reactor (LWR) fuel. Certificates of Compliance (CoC) are issued for approved radioactive materials packages that meet applicable safety standards set forth in Title 10, Code of Federal Regulations (10 CFR), Part 71. A CoC certifies that the contents and packaging meet safety requirements outlined in NUREG–1609, Standard Review Plan for Transportation Packages for Radioactive Material. The Standard Review Plan (SRP) addresses topics such as criticality, shielding, structural, containment, and thermal functions of packages. CoCs specify physical limits (e.g., material amounts) and constraints (e.g., type and form of radioactive material) for package contents. We identified fuel type and components, maximum fissile material quantity and enrichment, and internal dimensions to be key design parameters of the packages used to transport unirradiated ARF types. For TRISO fuel, CoC No. 9342 is likely to meet criticality, shielding, structural, thermal, and containment requirements at 10 CFR Part 71. However, additional criticality evaluations may be needed prior to transportation of TRISO fuel, which has combinations of enrichment and U-235 mass outside of current CoCs. Three packages (CoC 5086, 9315, and 9342) were identified as likely to meet requirements at 10 CFR Part 71 for transporting unirradiated metal fuels; however, issues related with structural integrity of metal fuel pins and containment of fuels containing reactive sodium may need to be addressed prior to extending these CoCs to transportation of metal fuels.

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ABBREVIATIONS/ACRONYMS

ARF	advanced reactor fuel
10 CFR	Title 10 of *Code of Federal Regulations*
CNWRA	Center for Nuclear Waste Regulatory Analyses®
CoC	Certificates of Compliance
EBR-II	Experimental Breeder Reactor-II
HTGR	high-temperature gas-cooled reactors
LWR	light water reactor
NRC	U.S. Nuclear Regulatory Commission
SRP	Standard Review Plan
TRISO	tristructural isotropic

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QUALITY OF DATA, ANALYSES, AND CODE DEVELOPMENT

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1 INTRODUCTION

1.1 Background

As the U.S. Nuclear Regulatory Commission (NRC) staff prepares for regulatory interactions and potential applications for non-light water reactor (LWR) technologies, a need to develop an understanding of potential challenges associated with regulating the long-term storage, transportation, and disposal of advanced reactor fuel (ARF) types has been identified. For example, revisions may be needed to guidance documents and rules in Title 10 of the *Code of Federal Regulations* (10 CFR) Part 71 and 10 CFR Part 72. Potential ARF types that may be subject to NRC regulation in the future include metallic fuels, uranium fuels for high-temperature gas-cooled reactors (HTGR), and molten fuel salt.

The Center for Nuclear Waste Regulatory Analyses (CNWRA®) has been tasked with identifying and assessing the significance of potential technical challenges and issues associated with the storage, transportation, and disposal of ARF types. This report evaluates potential issues for transportation of fresh ARF types. ARFs incorporate designs that present the potential for additional and unique NRC licensing review considerations and challenges. Within the context of transportation, special considerations pertain to the availability of NRC certified packages for use with ARF and non-LWR fuel. ARFs incorporate designs that may necessitate new package designs requiring certification. Early identification of the distinctive characteristics of ARFs that could affect future NRC reviews can aid planning and preparing for such reviews.

1.2 Purpose and Scope

The first report in this series (Hall et al., 2019) reviewed available operating experience with transportation of fresh ARF types. This second report identifies potential regulatory challenges for transportation of these fresh fuels by considering the known or expected characteristics of the ARF and the characteristics of currently certified transportation packages in the context of applicable NRC safety review topics for transportation packages. Packages used to ship fresh fuel types must demonstrate compliance with applicable regulations, including 10 CFR Part 71. Additionally, package designs reviewed by NRC using the NUREG–1609 standard review plan (NRC, 1999; SRP) address review topics such as criticality, shielding, structural, containment, and thermal. (Note that NUREG–1609 is expected to be superseded by a new SRP in the near future.) Radioactive materials packaging that meets regulatory requirements receives a Certificate of Compliance (CoC) that specifies physical limits (e.g., material amounts) and constraints (e.g., type and form of radioactive material) for package contents. CoCs issued for transportation packages authorize use of a specific packaging for a specified time period and scope of activity. For this report, characteristics of selected non-LWR fuel types were compared to select CoCs listed in NUREG–0383, Directory of Certificates of Compliance for Radioactive Materials Packages (NRC, 2013). Characteristics of the non-LWR fuel types discussed in the first deliverable of this project (i.e., nuclear metal fuel and TRISO fuel) are compared to similar fuels listed in the CoCs. Based on this comparison, possible technical and regulatory issues associated with the transportation of fresh ARF types are identified.

2 CHARACTERISTICS OF ARF TYPES AND PACKAGING FOR TRANSPORTATION

NRC regulations in 10 CFR Part 71 establish requirements for transportation package approval. For transportation of fresh fuel, the characteristics of the fuel that need to be evaluated in NRC transportation package certification reviews include type, form, and components of the fuel, the maximum allowed quantity of fissile material, the enrichment level, and physical dimensions of the fuel. In Task 1, Subtask 1, of this project (Hall et al., 2019) Certificate No. 9342 for the Versa-Pac Models VP-55 and VP-110 was identified to be a certified packaging that could be used to transport TRISO fuel (NRC, 2013). The key design parameters and CoC conditions affecting transportation of fresh coated particle fuel using this certified package are listed in Table 2-1.

A review of literature for operating reactors using nuclear metal fuel did not identify certified packages that were used for transportation of fresh fuel, nor possible scenarios defining exact package contents. Two likely scenarios for transportation of fresh metal fuel include (i) transportation of individual components (e.g., metal fuel slugs, cladding, and sodium) separately if fuel fabrication or recycling of spent fuel is planned at the same site as the reactor and (ii) transportation of the fabricated fuel pins. In the first scenario, the fuel pins would be fabricated on-site using either fresh fuel slugs or recycled spent fuel. This was the practice at EBR-II, where the fuel cycle facility was adjacent to the reactor containment vessel (Westfall, 2004). If this approach were used in the future, the fuel slugs and the spent fuel would need to be transported between the reactor and fuel cycle facility. In the operating EBR-II, when spent fuel was recycled, fuels were transported using a cask in an underground tunnel. However, a concept similar to the original EBR-II that integrates spent fuel reprocessing and re-fabrication on-site may not be feasible; therefore, fuel pins would likely need to be transported to the site of an operating reactor from an off-site fuel fabrication facility.

In the second scenario fuel pins would be fabricated off-site and transported to the reactor site. This scenario might be considered more feasible for future commercial implementation of non-LWR ARF because it aligns more closely with the existing LWR fuel cycle experience (i.e., separate facilities for fuel fabrication and power production). Under this scenario, considering the components of metal fuel pins, the fuel slugs made from uranium alloys are the only radioactive component. Available information based on past operating experience indicates the mass of a fuel slug would be about 47–83 g [1.7–2.9 oz] (Fast Reactor Working Group, 2018), the outer diameter of the stainless steel cladding would range from 4.4 to 6.9 mm [0.17 to 0.27 in], and the length of the fuel pin would be 460 to 749 mm [18.1 to 29.5 in]. A review of NUREG–0383, Directory of Certificates of Compliance for Radioactive Materials Packages, did not identify a direct match of the fuel characteristics with certified packages that can be used to transport nuclear metal fuel. However, (i) Certificate No. 5086 for UNC-2600 Model lists uranium-zirconium, (ii) Certificate No. 9315 for ES-3100 Model lists uranium alloys including uranium-zirconium and uranium-molybdenum, and (iii) Certificate No. 9342 for the Versa-Pac Models VP-55 and VP-110 lists uranium alloys as approved materials.

The key design parameters affecting transportation of fresh metal fuels containing uranium alloys using these certified packages are listed in Table 2-2.

Table 2-1. Design parameters and conditions of CoC No. 9342 (NRC, 2013) and characteristics of TRISO-coated particle fuel		
Parameter	**CoC No. 9342**	**Coated Particle Fuel**
Fuel Type and Component	TRISO-C/SIS/C coated $ThUC_2$ particles pressed with a carbon matrix to form rods.	TRISO as described in Task 1 Subtask 1 report (Hall et al., 2019)
Fissile Material Quantity (g)	Maximum 350 g [12.3 oz] U-235	1.47 g [0.0518 oz] heavy metal loading for each compact (IAEA, 2012); 0.545 g [0.0192 oz] and 1 g [0.04 oz] U-235 per fuel sphere (INL, 2010)
Enrichment (weight percent U-235)	Maximum 100	High-enrichment U up to 21 percent U-235 and low-enrichment U of 7.8 percent U-235
Physical Dimensions	Containment cavity: 38 cm [15 in] inner diameter and 66 cm [26 in] height or 53 cm [21 in] inner diameter and 76 cm [30 in] height	Prismatic block design: 1.3 cm [0.51 in] in diameter and 5 cm [2 in] long for each fuel compact; Pebble-bed design: 6.0 cm [2.4 in] diameter sphere (INL, 2010)

Table 2-2. Typical design parameters and conditions of select CoCs (NRC, 2013) and characteristics of metal fuel				
Parameter	**CoC No. 5086**	**CoC No. 9315**	**CoC No. 9342**	**Metal Fuel** (Fast Reactor Working Group, 2018)
Fuel Type and Component	Unirradiated U-Zr	U alloys	U alloys	U alloys such as U-Zr or U-Pu-Zr as described in Task 1 Subtask 1 report (Hall et al., 2019)
Fissile Material Quantity (g)	375 g [13.2 oz] U-235	24,324–34,749 g [53.6 to 76.6 lb] U-235	350 g [12.3 oz] U-235	47–83 g [1.7–2.9 oz] for each fuel slug
Enrichment (weight percent U-235)	Maximum 100	Maximum 100	Maximum 100	26–93 (Hall et al., 2019)
Physical Dimensions	Containment cavity: 6.7 cm [2.6 in] high × 18 cm [7.1 in] wide × 244 cm [96 in] long	Containment cavity: 82 cm [32 in] high and 13 cm [5 in] inner diameter (ID)	Containment cavity: 35 cm [14 in] inner diameter and 66 cm [26 in] high or 53 cm [21 in] inner diameter and 76 cm [30 in] high	Fuel pin length ranged from 46 to 75 cm [18 to 30 in] and outer diameter of the cladding ranged from 0.44 to 0.69 cm [0.17 to 0.27 in]

3 ASSESSMENT OF FRESH FUEL TRANSPORTATION

The characteristics of the ARFs and the packages identified in Tables 2-1 and 2-2 were evaluated within the context of regulatory requirements and safety review topics applicable to the transportation of fresh fuel identified in the SRP (NRC, 1999). Because of present uncertainties regarding specific designs of ARFs that might be submitted to NRC in future license applications, this evaluation focuses broadly on both the early identification of potential issues in utilizing existing certified packages, as well as on potential issues for new package certifications. Therefore, this chapter evaluates in more detail the selected ARF and existing package characteristics within the context of the package safety evaluation topics of criticality, shielding, structural, and thermal performance.

3.1 Criticality Evaluation

As described in NUREG–1609 (NRC, 1999), the specifications for the fissile material contents relevant to the criticality safety evaluation include fissile material mass, dimensions, enrichment, physical and chemical composition, density, moisture, and other characteristics dependent on the specific contents. The primary attributes of coated particle fuel and nuclear metal fuel that are important to criticality evaluation are the fissile material mass and enrichment. The assessment of potential issues for each of the ARF types is discussed in this section in the context of the criticality safety requirements of 10 CFR Part 71 and the attributes of the two ARF types.

NRC regulations in 10 CFR Part 71 provide fissile-material exemptions and general licenses for packaging and transportation of radioactive material. The fissile-material exemptions include requirements for up to 2 g [0.07 oz] of fissile material per package and for uranium enriched to less than 1 weight percent U-235 in §§71.15(a) and 71.15(d), respectively. The fissile material general licenses specify the U-235 mass limit of 63 g [2.2 oz] in Table 71-1 of §71.22 for unknown enrichment. The mass limits for general license packaging containing U-235 of known enrichment are listed in Table 71-2 of §71.22. For example, the U-235 mass limits are 63 g [2.2 oz] with an enrichment up to 24 weight percent and 108 g [3.8 oz] with an enrichment of 5 weight percent. These provisions facilitate the safe transport of fissile material in small quantities or low concentrations by relieving shipments of these materials from the fissile material packaging requirements without needing NRC approval.

For packaging certified by NRC for transportation of radioactive material, the package design must meet the criticality safety requirements of § 71.55 for a single package and § 71.59 for an array of packages under normal conditions of transport and hypothetical accident conditions.

The Versa-Pac package CoC lists the approved contents as including uranium compounds and thorium-232 as TRISO fuel (as C/SIS/C coated $ThUC_2$ particles pressed with a carbon matrix to form rods). The fuel kernel in the international consensus TRISO-coated particle design consists of high-density, low enriched UO_2 or UCO with a uranium enrichment less than 20 percent U-235 (INL, 2010).

The maximum quantity of fissile material for the Versa-Pac package is 350 g [12.3 oz] U-235 enriched up to 100 weight percent. The 350 g [12.3 oz] U-235 limit is equivalent to a maximum quantity of TRISO fuel material of approximately 608 rods with each rod containing up to 0.545 g [0.0192 oz] U-235. Alternatively, this limit is equivalent to a maximum quantity of approximately 350 spherical compacts with each sphere containing 1 g [0.035 oz] U-235. This limit bounds the enrichment levels expected for the reference TRISO-coated particle fuel. Both the mass of U-235 in the TRISO-coated particle fuel of 0.545 g [0.019 oz] per rod, and 1 g [0.035 oz] per fuel sphere, as well as the physical dimensions of the fuel (Table 2-1), fall within the limits of the fissile material quantity and the physical dimensions of the Versa-Pac. Additionally, the total mass of U-235 contained in the TRISO-coated particle fuel falls within the limits of 63 g [2.2 oz] U-235 for general license packaging containing U-235 of known enrichment listed in Table 71-2 of § 71.22. For TRISO-coated particle fuel compacts with different combinations of enrichment and mass, additional criticality evaluations may be required to verify the authorized contents.

For nuclear metal fuel, typical enrichment levels ranged from 52 to 78 percent U-235 (Fast Reactor Working Group, 2018). Because the enrichment levels of metal fuel do not meet the fissile-material exemptions and general license requirements in § 71.15 and § 71.22 and the packages identified in Table 2-2 were certified to transport metal fuels, not specifically fuel pins, criticality evaluations for package certification would be needed prior to safe transportation of the metal fuel or fuel pins.

3.2 Shielding Evaluation

For packaging certified by NRC for transportation of radioactive material, the shielding design of the packages must meet the external radiation requirements in § 71.47 and § 71.51 under normal conditions of transport and hypothetical accident conditions. Transportation of both fresh ARF types using existing certified transportation packaging is expected to meet the shielding safety requirements because of the low radiation of the fresh fuel. For example, the Versa-Pac package for transportation of the authorized contents as fresh TRISO fuel does not require extra shielding (NRC, 2010).

3.3 Structural Evaluation

For packaging certified by NRC for transportation of radioactive material, the packages must meet the structural requirements in §71.31, §71.33, §71.35, §71.71, and §71.73 under normal conditions of transport and hypothetical accident conditions. Under normal conditions of transport, the packages need to be tested under heat, cold, reduced external pressure, increased external pressure, vibration, water spray, free drop, corner drop, compression, and penetration conditions to ensure structural integrity. Under hypothetical accident conditions, the packages need to be tested under free drop, crush, puncture, thermal, and immersion conditions to ensure structural integrity. The Versa-Pac package is certified to transport TRISO fuel. As such, it is expected that it meets the structural requirement for transporting this type of fuel.

Although the three types of packages identified in Table 2-2 are certified to transport uranium alloys, they are not certified to transport metal fuel pins that are fabricated from several components including the fuel slugs, sodium, and cladding. The package internal structure will need to be designed to retain the fuel pins and provide impact protection to the fuel pins. Therefore, it is expected that applicable analyses will need to be developed to demonstrate that existing certified packages fulfill structural requirements for transport of metal fuel pins.

Metal fuel pins at EBR-II must satisfy dimensional and leak-tight requirements and welds absent of flaws. During fabrication of the metal fuel pins, a sodium bonding process is applied to remove any voids present in the annulus between the fuel slug and cladding (Burkes et al., 2009). Sodium is a soft metal with a melting point of only 98 °C [208 °F]. During transportation, sodium may soften and shift in location, especially under the influence of vibration and gravity, potentially compromising the bonding achieved during fabrication. As such, one of the challenges associated with transportation of metal fuels is maintaining intact bonding between sodium and fuel slugs and sodium and cladding. Structural evaluations for package certification would be needed prior to transportation of the metal fuel pins.

3.4 Thermal Evaluation

For packaging certified by NRC for transportation of radioactive material, the design must meet the regulatory requirements applicable to the thermal evaluation in §71.31, §71.33, §71.35, §71.43, §71.51, §71.71, and §71.73 under normal conditions of transport and hypothetical accident conditions. Transportation of both fresh ARF types using existing certified transportation packaging is expected to meet the thermal performance requirements because of the low thermal activity of the fresh fuel.

3.5 Containment Evaluation

For packaging certified by NRC for transportation of radioactive material, the design must meet the regulatory requirements applicable to the containment evaluation in §71.31, §71.33, §71.35, §71.43, §71.51, §71.71, and §71.73 under normal conditions of transport and hypothetical accident conditions. Transportation of coated particle fuel using the certified Versa-Pac package is expected to meet the containment requirements. Although the three types of packages identified in Table 2-2 are certified to transport uranium alloy, they are not certified to transport metal fuel pins in which uranium alloy is only one of several components. One possible issue associated with transportation of the metal fuels is limiting the hazard associated with sodium, which is contained in fuel pins. Sodium reacts violently with water and burns quickly in air once it is released. Containment evaluations for package certification would possibly need to consider this scenario prior to transportation of assembled metal fuel pins.

4 SUMMARY AND CONCLUSIONS

Fuel type and component, maximum fissile material quantity and enrichment, and internal dimensions are identified to be key design parameters of the packages used to transport unirradiated ARF types. The current approaches and technologies associated with the Versa-Pac Models VP-55 and VP-110 with Certificate No. 9342 are compatible with the transportation of TRISO fuel. Versa-Pac packages covered by Certificate No. 9342 are likely to meet criticality, shielding, structural, thermal, and containment requirements of 10 CFR Part 71 in transporting unirradiated TRISO fuels. However, additional criticality evaluations may be needed prior to transportation of TRISO fuel with different combinations of enrichment and U-235 mass.

Three packages are identified to be potentially compatible with the transportation of metal fuels, but uncertainty remains regarding the specific fuel design and whether limitations presented in corresponding CoCs consider unique characteristics of the ARF. The 3 packages identified in Table 2-2 are likely to meet the requirements of 10 CFR Part 71 in transporting unirradiated metal fuels, however, two possible issues associated with structural integrity of metal fuel pins and containment of fuels containing reactive sodium were identified and may need to be addressed prior to the transportation of metal fuels.

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