TRANSPORTATION EXPERIENCE AND POTENTIAL CHALLENGES WITH TRANSPORTATION OF SPENT (IRRADIATED) ADVANCED REACTOR FUEL TYPES

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ABSTRACT

This report identifies degradation processes that may challenge transportation package designs used for transportation of spent non-light water reactor (non-LWR) fuel. Non-LWR fuel for which challenges were identified includes solid coated particle fuel, commonly known as tristructural isotropic (TRISO), and nuclear metal fuel characteristic of compact fast reactors. Nuclear metal fuel consists of uranium alloys such as U-Pu, U-Zr, U-Mo, and U- Pu-Zr, often with Na between fuel and cladding. Transportation experience was reviewed for applicable spent TRISO and metal fuels. This report also assesses historical performance of both the spent fuels and transportation packages during transportation, and identifies potential challenges, including degradation processes that may affect transportation package and fuel integrity for these advanced reactor fuels (ARFs), based on characteristics of spent fuel that would require evaluation under Title 10 of the *Code of Federal Regulations* (CFR) 10 CFR Part 71 and NUREG–1617, Standard Review Plan for Transportation Packages for Spent Nuclear Fuel (NRC, 2000). Packages used for transportation of spent TRISO were identified, including Certificate of Compliance (CoC) No. 9253 for the TN-FSV, as well as spent metal fuel and the converted high-level radioactive waste (HLW) forms, including the T-3 cask (expired CoC No. 9132), NLI-1/2 cask (expired CoC No. 9010), NAC-LWT cask (CoC No. 9225), and the RH-TRU 72-B cask (CoC No. 9212). All of these casks use concentric stainless steel shells, shielding between inner and outer shells, and have impact limiters to absorb the impact. TN-FSV was used for transporting graphite block high-temperature gas-cooled reactor (HTGR) fuel elements from Fort St. Vrain (FSV). Design parameters and conditions for this CoC suggest that it would be acceptable for transportation of TRISO solid particle fuel. For the use of the TN-FSV cask during transportation of FSV fuel, there are no known environmental, thermal, mechanical, or irradiation-induced degradation mechanisms that are expected to compromise the fuel or cask performance. However, unique physical and chemical characteristics warrant further investigation, including higher burnup, enrichment, and thermal performance. In similar regard, TRISO fuel design parameters envisioned for modern reactors, in particular burnup—which would affect mostly thermal, criticality, and shielding performance of transportation packages—would warrant additional study. For metal fuel, possible environmental conditions that would affect fuel and cask performance during normal transportation include intergranular corrosion, sensitization, and stress corrosion cracking of stainless steel cladding. Operating experience data suggest that vibration would be negligible during transportation. For transportation packages with metal fuel including sodium, residual moisture and O_2 may react with sodium to produce sodium oxides, hydroxides, and H_2, and possibly uranium oxides and hydrides. The reaction could lead to physical challenges such as cladding rupture, fuel fragmentation, and restructuring-swelling. For these reasons, additional study of cladding performance in transportation packaging is recommended, particularly as it relates to understanding corrosion rates, material chemistry, and the susceptibility of spent fuel to intergranular corrosion, sensitization, stress corrosion cracking, and other degradation mechanisms in abnormal transportation environments.

REFERENCE

NRC. NUREG–1617, "Standard Review Plan for Transportation Packages for Spent Nuclear Fuel, Final Report." Washington, DC: U.S. Nuclear Regulatory Commission. 2000.

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ABBREVIATIONS/ACRONYMS

ARF	advanced reactor fuel
AVR	Arbeitsgemeinschaft Versuchsreaktor
BISO	bistructural isotropic
CFR	*Code of Federal Regulations*
CNWRA®	Center for Nuclear Waste Regulatory Analyses
CoC	Certificate of Compliance
DOE	U.S. Department of Energy
EBR-II	Experimental Breeder Reactor-II
FFTF	Fast Flux Test Facility
FHR	fluoride salt-cooled high-temperature reactor
FSV	Fort St. Vrain
HFEF	Hot Fuel Examination Facility
HLW	high-level radioactive waste
HTGR	high-temperature gas-cooled reactor
INL	Idaho National Laboratory
INTEC	Idaho Nuclear Technology and Engineering Center
LWR	non-light water reactor
MIC	microbiologically influenced corrosion
NAC-LWT	NAC International Legal Weight Truck
NRC	U.S. Nuclear Regulatory Commission
RH-TRU	remote-handled transuranic
RSWF	Radioactive Scrape and Waste Storage Facility
SNF	spent nuclear fuel
SRP	Standard Review Plan
SSC	stress corrosion cracking
THTR	Thorium High Temperature Reactor
TN-FSV	Transnuclear Fort St. Vrain
TRISO	tristructural isotropic
WIPP	Waste Isolation Pilot Plant

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1 INTRODUCTION

1.1 Background

As the U.S. Nuclear Regulatory Commission (NRC) staff prepares for regulatory interactions and potential license applications for non-light water reactor (non-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. Potential ARF types that may be subject to NRC regulation in the future include metal fuels (i.e., uranium alloys such as U-Pu, U-Fs, U-Zr, U-Mo, U- Pu-Zr, often with Na between fuel and cladding), 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 spent ARF types. ARFs incorporate designs that present the potential for additional and unique NRC safety review considerations and challenges. Within the context of transportation, special considerations pertain to the availability of NRC certified packages for use with ARFs. ARFs incorporate features that may necessitate new package designs requiring certification. Early identification of the distinctive characteristics of ARFs, challenges with material performance, and fuel degradation mechanisms that could affect future NRC reviews may aid planning and preparing for such reviews.

1.2 Purpose and Scope

This report presents available operating experience with transportation of spent ARF types and identifies potential technical challenges for transportation of these fuels. Transportation challenges are examined by considering known or expected characteristics of the spent ARF, and potential degradation mechanisms that would apply to ARF and the certified packaging relied upon for transportation. Packages used to ship spent ARF types must demonstrate compliance with applicable regulations, including Title 10 of *Code of Federal Regulations* (CFR) 10 CFR Part 71. Additionally, reviews by NRC of package designs using NUREG–1617, Standard Review Plan for Transportation Packages for Spent Nuclear Fuel (NRC, 2000), address topics such as criticality, shielding, structural, containment, and thermal performance. Identification of challenges related to fuel performance during transportation and to these safety review topics helps to pinpoint important degradation mechanisms that could affect package certification and fuel performance for transportation of ARFs. Because of present uncertainties regarding specific designs of ARFs, this evaluation focuses broadly on the identification of potential issues in utilizing existing certified packages, degradation mechanisms of spent ARF, and potential issues for package certification and transportation of spent ARF.

The report first presents characteristics of the spent ARFs and identified potential transportation packages. Key characteristics of the spent ARF to be evaluated in NRC transportation package certification reviews include the type of spent nuclear fuel (SNF) and maximum initial U-235 mass, associated burnup, specific power, cooling time, heat load, maximum and minimum initial enrichment, and physical dimensions. Additionally, the operating experience with transportation of ARF types was reviewed, including records of observed degradation or damage to spent fuel elements, as well as any safety issues noted for the casks during transportation.

Based on the relevant operating experience, known characteristics of ARF types, and existing certificates of compliance (CoCs), possible technical challenges with relevance to the safety evaluation topics of criticality, shielding, structural, thermal, and containment performance were identified or considered. Additionally, relevant degradation mechanisms that could result in fuel failure and compromise the fuel configuration during transport operations were reviewed and discussed.

2 DESIGN PARAMETERS OF CASKS FOR TRANSPORTING SPENT ARF TYPES

NRC regulations in 10 CFR Part 71 establish requirements for transportation package approval. For transportation of spent fuel, the characteristics of the fuel to be evaluated in NRC transportation package certification reviews include the type of SNF and maximum initial U-235 mass, associated burnup, specific power, cooling time, heat load, maximum and minimum initial enrichment, and physical dimensions.

CoC No. 9253 for the Transnuclear Fort St. Vrain (TN-FSV) cask was identified as a certified package that could be used to transport spent tristructural isotropic (TRISO) fuel (NRC, 2014). The TN-FSV cask utilizes stainless steel and lead shielding (Figure 2-1). The cask geometry is a right circular cylinder (i.e., the cylinder wall is perpendicular to the base) [Figure 2-1(a)] with impact limiters at two ends [Figure 2-1(b)] (Turner and Lynn, 2004). The cask body is made of two concentric Type 304 stainless steel shells that are welded to a bottom plate and a top closure flange. The 2.8-cm [1.1-in] thick inner shell has an inside diameter of 46 cm [18 in] and the interior cavity is 505 cm [199 in] long. The 3.8-cm [1.5-in] thick outer shell has an outside diameter of 79 cm [31 in]. A layer of lead is filled between the inner and outer shells for shielding. The cask has three shipping configurations. Configuration 1 is for shipping irradiated HTGR fuel elements from Fort St. Vrain (FSV). The FSV spent fuel elements are stacked in a fuel storage container to serve as a secondary, leak-tight containment vessel in the TN-FSV cask.

The key design parameters and CoC conditions affecting transportation of spent coated particle fuel using this certified package are listed in Table 2-1. The characteristics of the spent coated particle fuel can be found in Hall et al. (2019a).

As discussed in Hall et al. (2019a), because of the reactive nature of sodium, spent metal fuel, especially the driver fuel (i.e., fuel in the core of a breeder reactor with enrichment level higher than natural U, which is used to drive the fission process), is likely to be chemically treated to deactivate the sodium and converted to other possible high-level radioactive waste (HLW) forms, such as ceramic and metallic. (In this report, the term HLW refers to radioactive products of SNF treatment, not of reprocessing.) Rechard et al. (2017) indicated that salt waste containing transuranic elements and fission products can be another more economical HLW form before it is converted to ceramic HLW. Because blanket fuel (i.e., fuel around the core of a breeder reactor with natural U) experiences more limited irradiation during reactor operation, spent blanket fuel may be treated using different methods to separate the sodium and the fuel; however, fuel properties may not be changed by the treatment (DOE, 2014). As a result, three likely forms of spent metal fuel would require transport: (i) sodium-bonded spent metal fuels, (ii) spent blanket fuel without metallic sodium, and (iii) converted HLW forms without metallic sodium. (Note that if potential future reactors using metal fuels are not breeder reactors, the distinction between driver and blanket fuels will not be applicable.) Based on information in the literature, the following three casks with previously and currently NRC-certified CoCs can be used for transporting sodium-bonded spent metal fuels:

(a) (b)

Figure 2-1. (a) TN-FSV cask body (DOE, 2000) and (b) cask body with impact limiters at two ends (Turner and Lynn, 2004)

Table 2-1. Design parameters and conditions of CoC No. 9253 (NRC, 2014)

Parameter	CoC No. 9253 (Model TN-FSV)
Fuel Type and Component	TRISO-coated thorium/uranium carbide and thorium carbide fuel particles in graphite block fuel elements
Fuel Content	6 FSV spent fuel elements in a fuel storage canister; each fuel element contains a maximum of 1.4 kg [3.1 lb] enriched uranium and 11.3 kg [24.9 lb] thorium
Enrichment (weight percent U-235)	Maximum 93.5 percent
Burnup	Maximum 70 GWd/MTHM
Heat Load	Maximum 360 W total; maximum 60 W per fuel element
Cooling Time	Minimum 1,600 days
Physical Dimensions	Containment cavity: 46 cm [18 in] inner diameter and 505 cm [199 in] height

and non-sodium-bonded spent blanket fuels covering forms i and ii [form iii is discussed later based on Rechard et al. (2017)]:

(1) Certificate No. 9010 for Model NLI-1/2 (NRC, 2009)
(2) Certificate No. 9132 for T-3 Model (NRC, 2006)
(3) Certificate No. 9225 for NAC-LWT (NRC, 2015a)

The NLI-1/2 Cask with an expired CoC (NRC, 2009) is cylindrical with stainless steel walls and shielding consisting of depleted uranium, borated water and ethylene glycol mixture, and lead. The internal cavity is 32.1 cm [12.6 in] in diameter and 452 cm [178 in] length. Similar to the TN-FSV cask shown in Figure 2-1, the cask is protected by upper and lower impact limiters.

There are four cask configurations with different inner cavity arrangements for different contents. This cask can be used to transport irradiated metal fuels of two specifications: (i) Fermi-1 fuel with U-Mo alloy as fuel and Zr as cladding and (ii) Experimental Breeder Reactor-II (EBR-II) blanket fuel with U as fuel in an aluminum container. The containment vessel is closed and sealed before transportation.

The T-3 cask (Figure 2-2) was used to transport spent Fast Flux Test Facility (FFTF) metal fuel from Hanford to Idaho National Laboratory (INL) (Ross et al., 2014). The CoC expired in April 2011 (NRC, 2006). The cask is a right circular cylinder with outer and inner shells made from stainless steel. The outer stainless steel shell is 2.5-cm [1.0 in] thick overlaid with a stainless steel cover. 0.2-cm [0.08-in] diameter wire is wrapped between the outer shell and the cover to provide an air gap for additional thermal insulation. The inner shell, which also is the containment vessel, has an outer diameter of 22 cm [8.6 in] with a nominal wall thickness of 0.81 cm [0.32 in]. The annular space between the inner and outer shells is filled with 0.2-m [8 in] thick lead for shielding. Rigid polyurethane foam is encased in steel as impact limiters at the cask upper and lower ends. The cask without the impact limiters at two ends is 4.50 m [177 in] in length and 0.673 m [26.4 in] in diameter. The overall dimensions with the impact limiters are 5.41 m [213 in] in length and 1.3 m [52 in] in diameter. The containment vessel is closed and sealed before transportation.

The NAC International Legal Weight Truck (NAC-LWT) cask (Figure 2-3) is a steel encased lead shielded shipping cask. In the final environmental impact statement for the treatment and management of sodium-bonded SNF (DOE, 2000), the U.S. Department of Energy (DOE) planned to use this cask and the TN-FSV cask to transfer Experimental Breeder Reactor-II (EBR-II) fuel between facilities at INL. The overall dimensions of the NAC-LWT cask with impact limiters at two ends are 589 cm [232 in] long and 165 cm [65.0 in] in diameter. The cask body is approximately 508 cm [200 in] in length and 112 cm [44.0 in] in diameter. The cask cavity is 34.0 cm [13.4 in] in diameter and 452 cm [178 in] in length. The maximum weight of the package is 23,587 kg [52,000 lb] and the maximum weight of the contents and basket is 1,814 kg [4,000 lb]. The containment vessel is closed, sealed, and tested for leakage before transportation.

Rechard et al. (2017) analyzed the feasibility of direct disposal of salt waste, which is one of the converted HLW forms of the spent nuclear metal fuel. The researchers proposed the following casks to transport the salt waste for disposal at the Waste Isolation Pilot Plant (WIPP) or deep borehole:

(1) Certificate No. 9212 for Model RH-TRU 72-B (NRC, 2015b)
(2) Certificate No. 9218 for Model TRUPACT-II (NRC, 2014)

The remote-handled transuranic (RH-TRU) 72-B cask [Figure 2-4(a)] is designed to transport remote-handled wastes, which emit large amounts of penetrating gamma radiation. The cask is leak tight and constructed with inner and outer containment vessels. A 4.1-cm [1.6-in] thick layer of lead is filled in between the two vessels for shielding. The cask geometry is a cylinder approximately 3.61 m [142 in] in length and 1.1 m [42 in] in diameter. The inner vessel is 330 cm [130 in] in length and 79 cm [31 in] in inner diameter. The cylinder fits into circular impact limiters at two ends. The cask has an outer thermal shield to protect the container against potential fire damage. The containment vessel is closed and sealed before transportation. Because this type of cask has not been used to transport salt waste, an amendment may be needed to certify the package for this use.

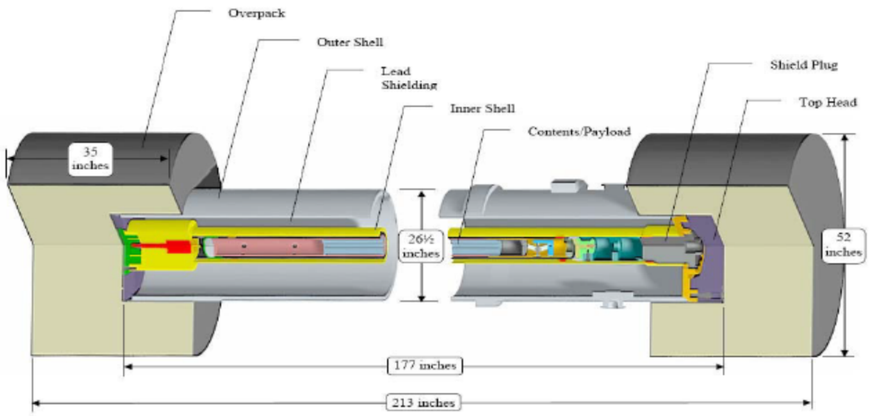
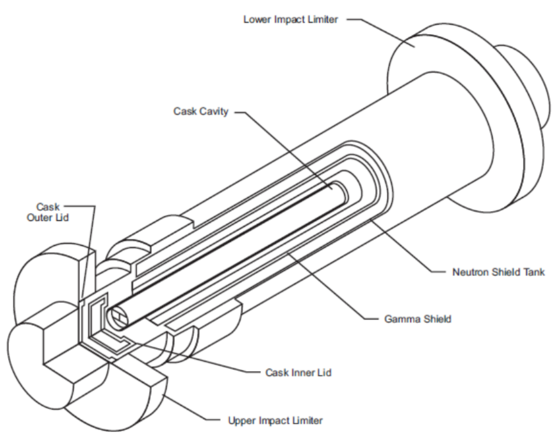


Figure 2-2. **T-3 cask used to transport sodium-bonded spent FFTF metal fuel from Hanford to INL (Ross et al., 2014)**



(a)

(b)

Figure 2-3. **(a) Simplified drawing and (b) a photo of a NAC-LWT (legal weight truck) shipping cask (DOE, 2000)**

The TRUPACT-II [Figure 2-4(b)] is designed to transport contact-handled transuranic wastes without significant gamma or neutron shielding. The cask is an alternative transportation cask to ship waste to WIPP. The cask is constructed with leak-tight inner and outer containment vessels from stainless steel. A 25-cm [10 in] thick layer of polyurethane foam is filled in between the inner and outer vessels. The cask is approximately 2.4 m [8.0 ft] in diameter and 3.0 m [10 ft] high. Additional radiation shielding would be needed if it is used to transport spent metal fuel or the converted HLW forms. If the package weight with additional shielding exceeds the maximum package weight, drop tests may be needed and an amendment will likely be needed to certify the package for this use.

Key design parameters of CoCs and conditions affecting transportation of spent metal fuels using these certified packages are listed in Table 2-2. Because the spent metal fuels are more complex than the TRISO fuel, some relevant characteristics of this ARF type that were described in Hall et al. (2019a) are included in Table 2-2 for comparison with the certified packages. Certificate No. 9218 for Model TRUPACT-II is not included in the table because this model needs additional shielding for radiation to handle HLW.

(a) (b)

Figure 2-4. Photos of cask models (a) RH-TRU 72-B (Rechard et al., 2017) and (b) TRUPACT-II (DOE, 2019)

Table 2-2. Typical design parameters and conditions of select CoCs and characteristics of spent metal fuel					
Parameter	**CoC No. 9010 (Model NLI-1/2) (NRC, 2009)**	**CoC No. 9132 (Model T-3) (NRC, 2006)**	**CoC No. 9225 (Model NAC-LWT) (NRC, 2015a)**	**CoC No. 9212 (Model RH-TRU 72-B) (NRC, 2015b)**	**Spent metal fuel**
Fuel type and component	Irradiated metal fuel: (i) Fermi-1 and (ii) EBR-II blanket	Irradiated sodium (200 g maximum) bonded metal fuel 10% Zr-20% Pu (maximum)-U	Metallic fuel rods	Transuranic waste	Actinides, fission products, and Na distributed in fuel matrix (Hall et al., 2019a)
Fuel content, maximum	Fermi-1: 300 kg U for 16 assemblies in one cask load; EBR-II blanket: 292 kg U per container	Fissile material: 1.9 kg	54.5 kg U/rod	3,629 kg [8,000 lb] including the canister	47–83 g [1.7–2.9 oz] for each fuel slug
Enrichment, maximum (weight percent U-235)	Fermi-1: 26.0; EBR-II blanket: 0.21	40	0.711 (Natural U)	≤0.96 U-235	26–93 (FRWG, 2018)
Cladding/container	Fermi-1: Zr; EBR-II blanket: aluminum container	Fuel pins in tubes, then in pipes	Aluminum 0.080-in thick	No cladding for converted HLW form	Variations of stainless steel cladding: 304L, 316, D9, HT9 (FRWG, 2018)
Burnup, maximum	Fermi-1: 2.84 GWD/MTU; EBR-II blanket: 2.4 GWD/MTU	Not specified, but used to transport FFTF fuel that the peak burnup was up to 143 GWd/MTHM	1.6 GWd/MTU	Not applicable (converted HLW)	0.3–19.8 atomic percent of heavy metal; 38-143 GWd/MTHM (FRWG, 2018)

Table 2-2. Typical design parameters and conditions of select CoCs and characteristics of spent metal fuel					
Parameter	**CoC No. 9010 (Model NLI-1/2) (NRC, 2009)**	**CoC No. 9132 (Model T-3) (NRC, 2006)**	**CoC No. 9225 (Model NAC-LWT) (NRC, 2015a)**	**CoC No. 9212 (Model RH-TRU 72-B) (NRC, 2015b)**	**Spent metal fuel**
Maximum decay heat	Fermi-1: 20 W; EBR-II blanket: 300	1,400 W	Up to 15 intact metallic fuel rods. Decay heat/rod ≤0.036 kW	50 W	The thermal power for each driver and blanket subassembly is 150 W and 30 W, respectively (Clarksean and Zahn, 1995).
Cooling time	Fermi-1: 5,000 days; EBR-II blanket: 365 days	90 days	1 year	Not available (converted HLW)	Years now at INL
Physical dimensions	Containment cavity: 32.1 cm [12.6 in] inner diameter and 452 cm [178 in] long	Containment cavity: 20 cm [8.0 in] inner diameter and 450 cm [177 in] long	Containment cavity: 34.0 cm [13.4 in] inner diameter and 452 cm [178 in] long	Containment cavity: 79 cm [31 in] inner diameter and 330 cm [130 in] long	Outer diameter of cladding ranged from 0.44 to 0.69 cm [0.17 to 0.27 in] and fuel pin length ranged from 46 to 75 cm [18 to 30 in]

3 SPENT ARF TYPES TRANSPORTATION EXPERIENCE

3.1 Coated Particle Fuel Transportation Experience

3.1.1 Fort St. Vrain

The FSV reactor, shut down since 1989, generated a total of 2,208 spent fuel elements (i.e., 24 MTHM of the SNF) in the form of TRISO-coated particles in graphite prismatic blocks. The first 726 spent fuel elements discharged prior to December 31, 1988, were shipped to INL and stored in a dry storage facility at the Idaho Chemical Processing Plant. DOE used the TN-FSV cask (Figure 3-1) to transport the FSV spent fuel elements to INL by truck (Clark et al., 1994). There have been 43 shipments since 1980. As the result of an agreement with the State of Idaho, DOE stopped the SNF shipments and the remaining spent fuel elements, approximately 16 MTHM of the SNF, were stored at the FSV Independent Spent Fuel Storage Installation (NWTRB, 2017; IAEA, 2012; Lotts et al., 1992).

Detailed information on transporting the FSV spent fuel is very limited. The limited information does not show records of observed degradation or damage of the FSV spent fuel elements and any safety issues of the casks during transportation.

3.1.2 Arbeitsgemeinschaft Versuchsreaktor (AVR) and Thorium High Temperature Reactor (THTR)

As discussed in the third report in this series (Hall et al., 2019a), nearly 290,000 spent fuel elements with several types of TRISO and bistructural isotropic (BISO)-coated particles in graphite pebbles discharged from the Arbeitsgemeinschaft Versuchsreaktor (AVR) reactor are stored in approximately 153 CASTOR Thorium High Temperature Reactor (THTR)/AVR casks at the AVR interim storage facility. The CASTOR THTR/AVR cask is certified in Germany for both storage and transportation. The transport license for the CASTOR THTR/AVR cask was issued in 1987 and is now authorized under the German Certificate of Approval No. D/4214/B(U)F-96 (NRC, 2017a; Laug et al., 1997). Shipping and transfer of spent AVR fuel occurred at different facilities at the reactor site by means of cranes and AVR shipping cans (Niephaus et al., 1997).

The spent fuel elements discharged from the THTR reactor also are stored in CASTOR THTR/AVR casks at an external interim storage facility in Ahaus, away from the reactor site. Special rail wagons were built for transportation of the CASTOR THTR/AVR casks from the THTR reactor to the interim storage facility. A total of 305 CASTOR THTR/AVR casks were transported in 57 shipments (IAEA, 2012; Laug et al., 1997).

Detailed information of transporting the AVR and THTR spent fuels is very limited. The limited information does not show records of observed degradation or damage of the AVR and THTR spent fuel elements and any safety issues of the casks during transportation.

3.2 Spent Metal Fuel Transportation Experience

The characteristics and the storage experience of spent metal fuels generated from three fast reactors (EBR-II, FFTF, and Fermi-1) were reviewed in Hall et al. (2019a,b). The spent fuels generated from FFTF and Fermi-1 were transported to Idaho and stored at several locations at INL along with the spent fuel from EBR-II. As a result, some transportation occurred between states and some occurred inside the INL storage facilities. Table 3-1 summarizes the spent fuel

Figure 3-1. TN-FSV cask under handling operation (Marschman and Winston, 2015)

<table>
<tr><th colspan="7">Table 3-1. Summary of sodium-bonded spent nuclear metal fuel transportation (DOE, 2000)</th></tr>
<tr><th rowspan="2">Fast reactors</th><th rowspan="2">Metric tons of heavy metal</th><th colspan="3">Inter-state transportation</th><th colspan="2">Inter-facility and intra-facility transfer at INL</th></tr>
<tr><th>Origin state</th><th>Storage state</th><th>Transportation cask</th><th>Site</th><th>Transfer cask</th></tr>
<tr><td rowspan="2">EBR-II</td><td>3.1 (driver fuel)</td><td rowspan="2">Idaho</td><td rowspan="2">Idaho</td><td rowspan="2">Not applicable</td><td rowspan="2">Wet storage at INTEC* dry storage at RSWF*</td><td rowspan="2">Inter-facility transfer: TN-FSV (CoC 9253) and NAC-LWT (CoC 9225); Intra-facility: HFEF-5, HFEF-14</td></tr>
<tr><td>22.4 (blanket fuel)</td></tr>
<tr><td>Fast flux test facility</td><td>0.33 (driver fuel)</td><td>Washington/ Hanford</td><td>Idaho</td><td>T-3 (CoC 9132)</td><td>HFEF*</td><td>Not applicable</td></tr>
<tr><td>Fermi-1</td><td>34.2 (blanket fuel)</td><td>Michigan</td><td>Idaho</td><td>Name not found</td><td>Dry storage at INTEC</td><td>PB-1</td></tr>
<tr><td colspan="7">*INTEC: Idaho Nuclear Technology and Engineering Center
HFEF: Hot Fuel Examination Facility
RSWF: Radioactive Scrape and Waste Storage Facility

DOE. “Final Environmental Impact Statement for Treatment and Management of Sodium-bonded Spent Nuclear Fuel.” DOE/EIS-0306. Washington, D.C. 2000.</td></tr>
</table>

types and the transportation experienced by these fuels (DOE, 2000). Figure 3-2 shows some facility locations at INL (NWTRB, 2017) and the two facilities where the spent metal fuels are currently stored.

3.2.1 Experimental Breeder Reactor-II

As described in Task 2 reports (Hall et al., 2019a,b), EBR-II SNF was stored in wet and dry storage facilities at INL, and some of the spent fuel was treated and converted into metallic and ceramic waste forms. Spent nuclear metal fuel from EBR-II was moved between facilities (i.e., inter-facility transfer) for storage and processing using NRC-certified Type B packages, specifically models TN-FSV (CoC 9232) or NAC-LWT (CoC 9225). Using these certified packages, fuel was transferred from the wet storage facility at the Idaho Nuclear Technology and Engineering Center (INTEC) to the dry storage facility at the Radioactive Scrape and Waste Storage Facility (RSWF). Due to shorter moves on DOE controlled roads, intra-facility transfers at RSWF occurred mostly using a non-certified cask, such as Hot Fuel Examination Facility (HFEF)-5 or HFEF-14.

The HFEF-5 and HFEF-14 casks used at RSWF for storage and retrieval operations for transfer of SNF-containers within RSWF. Figure 3-3 shows the structural design of the HFEF-5 cask, and a loaded cask in operation at RSWF (INL, 2012). The HFEF-5 cask is a vertically oriented cylindrical vessel, which is 2.8 m [110 in] tall and 0.84 m [33 in] outer diameter and weighs 16-ton. The outer and inner shells are made from 9.5-mm thick carbon steels and a 0.22 m thick lead layer is placed between the shells for shielding. The cask interior cavity is 0.36 m [14 in] inner diameter and is configured to hold the fuel container. The cask has lead-shielded doors at the top and bottom for use in loading and unloading the fuel containers and the doors

Figure 3-3. (a) Structural design of HFEF-5 cask and (b) a forklift and HFEF-5 cask in operation at RSWF (INL, 2012)

are secured in the closed position by bolts during transfer. The HFEF-5 cask interior cavity is not sealed airtight and cannot be pressurized. The HFEF-14 cask is similar to HFEF-5, but with slightly different dimensions.

Detailed information of transporting the EBR-II spent fuel is very limited. The limited information does not show records of observed degradation or damage of the EBR-II spent fuel elements and any safety issues of the casks during transportation.

3.2.2 Fast Flux Test Facility

As discussed in Hall et al. (2019b), spent metal fuel from FFTF was transported from the Hanford Site to INL. The transportation was performed using a T-3 cask with NRC CoC 9132 (Ross et al., 2014), which is described in Section 2. Detailed information of transporting the FFTF spent fuel is very limited. The limited information does not show records of observed degradation or damage of the FFTF spent fuel elements and any safety issues of the T-3 cask during transportation.

3.2.3 Fermi-1

The Fermi-1 fast reactor contained only blanket metal fuel, which was subjected to low irradiation. As a result, spent blanket fuel contains only about 0.2 weight percent plutonium, compared to approximately 1 weight percent for the spent EBR-II blanket fuel. The inventory of

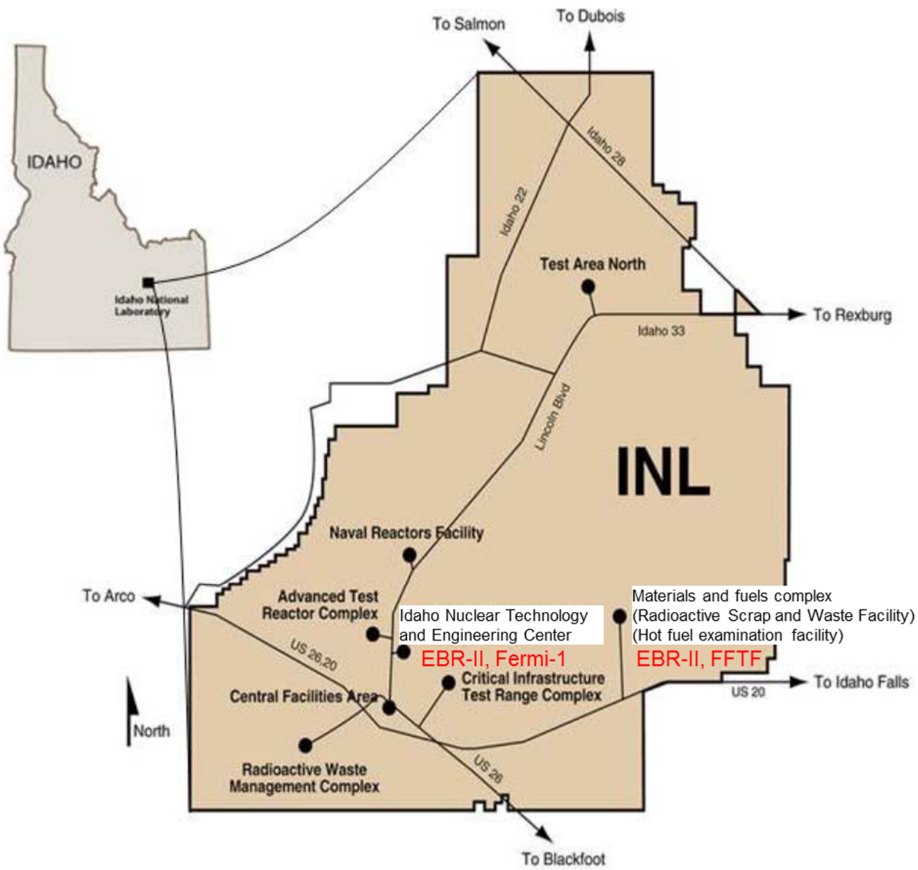


Figure 3-2. Some facility locations at INL (NWTRB, 2017)

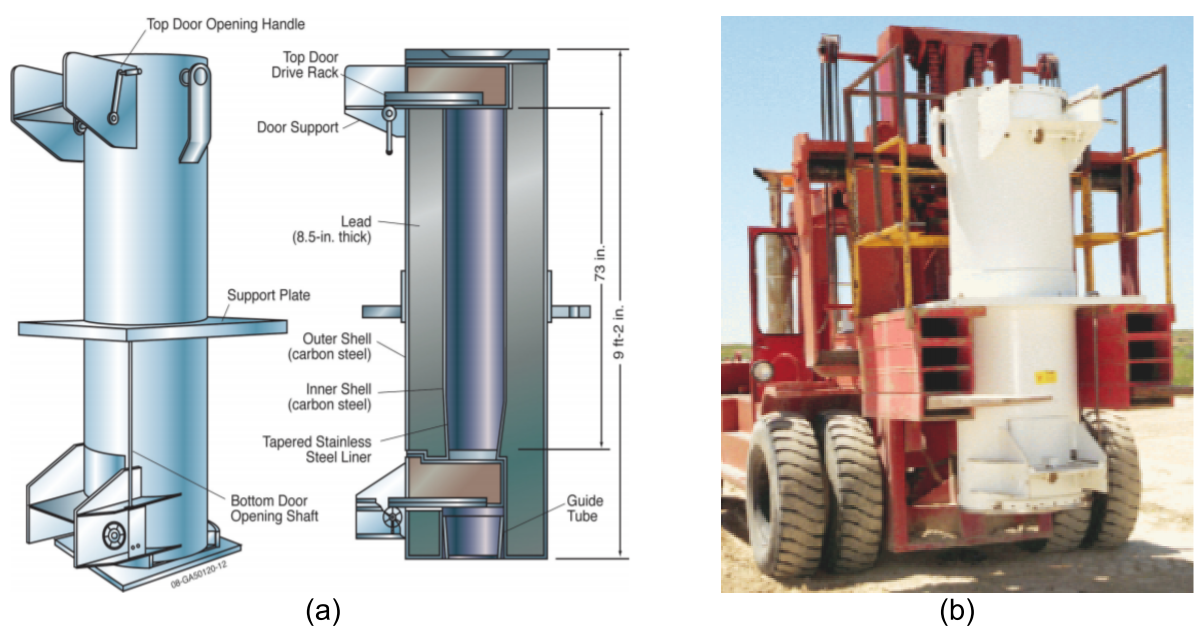


Figure 3-3. (a) Structural design of HFEF-5 cask and (b) a forklift and HFEF-5 cask in operation at RSWF

other fission products, activation products, and transuranics is also low. After the Fermi-1 reactor was permanently shut down, the blanket assemblies were placed into 14 canisters (the name designation of the canister was not found) and transported to INTEC in 1974 and 1975 in 14 shipments (DOE, 2000). The canisters were made of stainless steel with a carbon steel basket inside. The canisters were 3.40-m [134-in] long, 0.648 m [25.5 in] in diameter, and were filled with helium and seal welded after loading. 12 of the canisters contained the radial blanket assemblies and the other 2 contained the shorter axial blanket assemblies. The canisters are in dry storage at INTEC at INL. As discussed in Hall et al. (2019a), DOE is currently evaluating alternative methods in treating these stored fuels. After working out the methods, these spent fuels would be shipped from INTEC to RSWF for treatment. DOE plans to use Type B cask model PB-1 for shipment (DOE, 2000). The PB-1 cask is designed to provide shielding and protection from potential hazards. It has an outer diameter of 1.08 m [42.5 in] and an overall length of 4.85 m [191 in] including impact limiters at two ends. The cask internal cavity is 0.66 m [26 in] in diameter and 4.04 m [159 in] long. The outer shell is made from mild steel with Type 304 stainless steel overlay and the inner shell is made from stainless steel. A 0.159 m [6.25 in] thick layer of lead is filled between the inner and outer shells for shielding.

Detailed information of transporting the Fermi-1 spent fuel is very limited. The limited information does not show records of observed degradation or damage of the Fermi-1 spent fuel elements and any safety issues of the casks during transportation.

4 ASSESSMENT OF SPENT ARF TRANSPORTATION

The characteristics of the spent ARFs and the packages identified in Tables 2-1 and 2-2 were examined within the context of safety review topics applicable to the transportation of SNF identified in the Standard Review Plan (SRP) for Transportation Packages for Spent Nuclear Fuel (NRC, 2000). Because of present uncertainties regarding specific designs of ARFs, this evaluation focused broadly on both the identification of potential issues in utilizing existing NRC-certified packages, as well as on potential issues for new package certifications. This section evaluates spent ARF degradation mechanisms under transportation environments and, in more detail, the selected ARF and existing package characteristics within the context of the package safety evaluation topics of criticality, shielding, structural, thermal, and containment performance.

4.1 Spent Fuel Degradation Mechanisms Evaluation

The mechanisms and extent of degradation depend on the environmental, thermal, mechanical, and radiological conditions in the confinement vessel of the transportation package. For the systems used for transportation of spent ARF types described in Section 2, the containment environment is sealed from air exposure. Because most packages to be used for transporting spent ARF types are not yet approved by NRC, it is not established whether the containment cavity would be backfilled with an inert gas. If it is not, then O_2 and small amounts of moisture that are inducive to corrosion may exist in the system. Assuming the largest cavity volume for these transportation systems of 0.411 m^3 [14.5 ft^3] and 21 volume percent O_2 and 130 g/m^3 [8.1×10^{-3} lb/ft^3] H_2O in ambient air, the maximum amounts of O_2 and H_2O closed in the system would be approximately 3.0 and 3.5 mol, respectively. Under radiolysis, H_2O would decompose into H_2 and oxidizing species, such as H_2O_2.

A number of coated particle fuel failure mechanisms identified under in-reactor or postulated accident conditions were reviewed in Hall et al. (2019b). These coated particle failure mechanisms are not expected to occur during transportation due to the chemical characteristics of the coated particle fuel and lower stressors (e.g., deformation, temperature, radiation rate) in expected conditions of transport.

Table 4-1 summarizes some known environmental, thermal, mechanical, and irradiation-induced degradation mechanisms for stainless steel cladding and spent metal fuel (Guenther et al., 1996; NRC, 2017b). The occurrence and the effects of these degradation mechanisms during transportation are briefly discussed.

a. General corrosion of stainless steel under exposure to moisture and O_2 is likely to occur. Because of the passivity of stainless steel and the extremely low general corrosion rate under normal environmental conditions experienced during transportation, general corrosion of stainless steel cladding is considered to be negligible during normal transportation.

b. Localized corrosion would initiate when the corrosion potential is greater than the repassivation potential. Jung et al. (2013) used the OLI Corrosion Analyzer software to calculate corrosion and repassivation potentials for stainless steel in a 1 and 5 weight percent H_2O_2 aqueous solution saturated with oxygen at 25, 75, and 125 °C [77, 167, and 257 °F], which is more aggressive compared to the transportation environment. These computations suggest that localized corrosion of stainless steel is not likely in a normal transportation environment.

c. As described in Section 2, the inner containment vessel is made from stainless steel. Because of the lack of a galvanic couple, galvanic corrosion between stainless steel cladding and the containment vessel is not likely. If different materials, such as aluminum, are used for internal components within a containment vessel to hold the fuel assembly, galvanic coupling is likely during normal transportation. However, the coupling may not lead to significant corrosion because of the short duration of transportation.

d. Active microbial metabolism requires water and available nutrients to support microbial activity. Although water can be present in the environment, because of the lack of nutrients, microbiologically influenced corrosion (MIC) of stainless steel is not likely during normal transportation.

e. Stainless steel cladding sensitized during reactor operation can be susceptible to continuing sensitization and intergranular attack, especially if the cladding contains welds. The temperature during normal transportation, the duration of transportation, and the initial condition of the cladding would be needed to assess the extent of potential degradation.

f. Stainless steel cladding sensitized during reactor operation also can be susceptible to intergranular stress corrosion cracking (SCC). The residual sodium adhered to the cladding outer surface from reactor operation could react with water and O_2 in the containment vessel, resulting in SCC (“hot cell rot”). SCC can occur quickly, leading to cladding rupture. Similar to sensitization and intergranular attack, the temperature during normal transportation, the duration of transportation, and the initial condition of the cladding would be needed to assess the extent of degradation.

Table 4-1. Environmental, thermal, mechanical, and irradiation-induced degradation mechanisms for cladding and spent metal fuel (Guenther et al., 1996; NRC, 2017b)		
Materials	**Stainless steel cladding**	**Spent metal fuel**
	a. General corrosion b. Pitting and crevice corrosion c. Galvanic corrosion d. Microbiologically influenced corrosion (MIC) e. Sensitization and intergranular attack f. Stress corrosion cracking (intergranular, “hot cell rot”) g. Creep h. Radiation embrittlement i. Fatigue j. Thermal aging	a. Oxidation b. Hydriding c. Fragmentation d. Restructuring-swelling

g. Creep may occur under the influence of stress. During normal transportation, the spent fuel assembly will be secured in its position and the duration of transportation is not expected to be long. As a result, the extent of degradation from creep is considered to be negligible.

h. Embrittlement of metals may occur under exposure to neutron radiation. Depending on the neutron fluence, radiation can cause changes in stainless steel mechanical properties, such as loss of ductility, fracture toughness, and resistance to cracking. Because of the short duration of normal transportation compared to storage, the extent of degradation from radiation embrittlement is considered to be negligible.

i. Fatigue is the progressive structural damage that occurs when a metal is subjected to cyclic loading. Spent fuel transportation is a dynamic process during which the cladding may be subjected to vibration. However, the package is secured to the transportation vehicle during normal transportation and the duration of transportation is not expected to be long. As a result, the extent of degradation from fatigue is considered to be negligible.

j. The microstructures of most stainless steels may change, given sufficient time at elevated temperatures, and these changes from thermal aging may alter the material’s strength and fracture toughness. Because of the short duration of normal transportation compared to storage, the extent of degradation from thermal aging is considered to be negligible.

k. Any residual moisture and O_2 contained in the transportation system is expected to react with sodium, producing sodium oxides, hydroxides, and H_2. Some of the moisture and O_2 may also react with U metal, forming uranium oxides and hydrides. The reactions could lead to fuel fragmentation and restructuring-swelling. The extent of degradation depends on the presence of sodium. Without sodium in the fuel, the reaction of U metal with O_2 and moisture is not expected to lead to extensive damage to the fuel during transportation.

4.2 Structural Evaluation

For packaging certified by NRC for transportation of SNF, the package design must have adequate structural integrity to 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 TN-FSV cask is certified to transport spent FSV fuel. Structural analyses of various TN-FSV cask components demonstrate that the package performance standards are satisfied (Transnuclear, 1993). As such, transportation of spent TRISO fuel using existing certified transportation packaging is expected to provide adequate structural integrity for transportation of spent solid coated particle fuel.

The NLI-1/2, T-3, and NAC-LWT casks were certified by NRC to transport certain types of spent metal fuels with different fuel dimensions and configurations. However, the T-3 and NLI-1/2 certifications have expired and there is a wide range of fuel dimensions and configurations of spent metal fuels. The system design can affect the vibration that the fuel assembly may experience during transportation and affect degradation mechanisms, such as fatigue, induced by mechanical stress (Section 4.1). Furthermore, the dimensions, configurations, and properties of the converted HLW forms are uncertain and there are no transportation packages certified for these converted forms. Therefore, structural evaluations would be needed prior to transporting the spent metal fuel and any converted HLW forms.

4.3 Thermal Evaluation

For packaging certified by NRC for transportation of SNF, the thermal performance of the package design must meet the thermal requirements 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.

The TN-FSV cask is certified to transport spent FSV fuel. Thermal analyses of the TN-FSV package design demonstrate that design performance in the area of thermal loading is satisfied (Transnuclear, 1993). Because efficient cooling of the TRISO fuel in FHRs using salt coolant allows power densities that are four to ten times higher than HTGRs, with its higher heavy metal loading the FHR SNF is expected to have much higher decay heat relative to HTGR SNF (Forsberg and Peterson, 2015; Andreades, et al., 2014). Therefore, thermal evaluations for transport of spent TRISO fuel with higher decay heat would be needed to ensure that the package design satisfies the thermal performance requirements.

The NLI-1/2, T-3, and NAC-LWT casks were certified by NRC to transport certain types of spent metal fuels with different decay heat. However, the T-3 and NLI-1/2 certifications have expired and there is a wide range of decay heat of spent metal fuels. Under accident conditions, degradation mechanisms can change. For example, at elevated temperatures during a fire, high temperature oxidation of stainless steel cladding can cause degradation. Furthermore, the decay heats of the converted HLW forms are uncertain and there are currently no certified transportation packages for these converted forms. Therefore, thermal evaluations would need to consider the specific decay heat of the spent metal fuel or converted waste forms and the corresponding thermal performance of the transportation package based on its constituent materials.

4.4 Containment Evaluation

For packaging certified by NRC for transportation of SNF, the package design must meet the containment requirements 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.

The TN-FSV cask is certified to transport spent FSV fuel. Containment evaluations of the TN-FSV package design demonstrate that the containment criteria are satisfied (Transnuclear, 1993). As such, transportation of spent TRISO fuel using existing certified transportation packaging is expected to meet the design requirements for containment.

The NLI-1/2, T-3, and NAC-LWT casks were certified by NRC to transport certain types of spent metal fuels. However, the T-3 and NLI-1/2 certifications have expired and there is a wide range of spent metal fuels. The sodium contained in the fuel is extremely reactive in contact with moisture. If there is sodium contained in the fuel, it would be critical to ensure the system maintains the confinement function during normal and accident transportation conditions. Therefore, containment evaluations would need to consider the specific spent fuel composition, including the spent fuel and converted forms, in the cask environment.

4.5 Shielding Evaluation

For packaging certified by NRC for transportation of SNF, 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.

The TN-FSV cask is certified to transport spent FSV fuel. Shielding analyses of the TN-FSV cask for shipping FSV spent fuel elements in Configuration 1 show that the calculated dose rates are within the limits (Transnuclear, 1993). As such, transportation of spent TRISO fuel using existing certified transportation packaging is expected to provide adequate shielding for transportation of spent solid coated particle fuel.

The NLI-1/2, T-3, and NAC-LWT casks were certified by NRC to transport certain types of spent metal fuels with different radiation levels. However, the T-3 and NLI-1/2 certifications have expired and there is a wide range of radiation levels from spent metal fuels. Furthermore, the radiation levels of the converted HLW forms are uncertain and there are no transportation packages certified for these converted forms. Therefore, shielding evaluations would be performed as part of transportation package certification and would consider the wide varieties of characteristics attributed to spent metal fuels, including chemical compositions of the HLW forms.

Because of their material, burnup, and enrichment differences with spent LWR fuels, there is expected to be a need for validation of source terms for shielding analyses in safety reviews of transportation of spent ARF types.

4.6 Criticality Evaluation

For packaging certified by NRC for transportation of SNF, 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. NUREG–1617 (NRC, 2000) provides guidance for demonstrating compliance with the criticality safety requirements using burnup credit.

The TN-FSV cask is certified to transport spent FSV fuel enriched to a maximum of 93.5 weight percent U-235, and the maximum burnup of the spent fuel is 70 GWd/MTHM (NRC, 2014). The TRISO fuel design parameters envisioned for modern HTGRs include a maximum fuel burnup of 150–210 GWd/MTHM (NEA, 2014). The average burnup of the TRISO fuel expected to be discharged from the Mark-1 fluoride salt-cooled high-temperature reactor (FHR) design is estimated to be 180 GWd/MTHM (Andreades et al., 2014). As such, transport of high burnup and enriched TRISO fuel poses a potential challenge that may require changes to the current licensed fuel burnup and enrichment limits. Criticality evaluations for transport of spent TRISO fuel with higher burnup and higher enrichment combinations would be needed to ensure subcritical margins are maintained.

As shown in Table 2-2 and the transportation experience described in Section 3.2 for spent metal fuels, the NLI-1/2, T-3, and NAC-LWT casks were certified by NRC to transport certain types of spent metal fuels with different enrichment levels and burnups and these casks have been used to transport different types of spent fuels. However, the transportation of spent metal fuels can be complicated by the wide range of enrichment and burnup levels they represent. Spent metal fuels have much higher U-235 enrichment than LWR fuel and the burnup level also can be higher. These high levels pose a potential challenge that may require changes to the current licensed fuel burnup and enrichment limits. Some spent metal fuels stored at INL have been treated and converted to other HLW forms and DOE continues to work on methods to treat the remaining fuels. There is very limited experience in transporting these converted HLW forms and there are no transportation packages certified for these converted forms. Considering the wide range of enrichment and burnup levels and uncertainty of the characteristics of converted HLW forms, criticality evaluations would be needed for each unique fuel configuration and chemical composition prior to transporting the spent metal fuel or its HLW forms.

Because of their material and enrichment differences with spent LWR fuels, there is expected to be a need for validation of criticality codes used in safety reviews of transportation of spent ARF types. Additional research would be needed were burnup credit to be applied in these safety analyses.

5 SUMMARY AND CONCLUSIONS

This report identified possible technical issues that may need to be addressed during safety reviews of packages used for transportation of spent ARF types. Primary considerations were given to identifying degradation processes of spent ARFs that may challenge current package designs used for transportation of spent non-LWR fuel. Non-LWR fuel for which challenges were identified includes solid coated particle fuel, commonly known as TRISO, and nuclear metal fuel characteristic of compact fast reactors. Nuclear metal fuel consists of uranium alloys such as U-Pu, U-Fs, U-Zr, U-Mo, U- Pu-Zr, often with sodium distributed in the fuel matrix. Although uncertainties remain about proposed ARF specifications, performance histories from existing non-LWR fuel were relied upon to provide evidence about possible future performance of ARF. The objective of this report was to review relevant operating experience, assess historical performance of both the spent non-LWR fuel and transportation packages during transportation, and identify potential challenges, including degradation processes that may affect transportation package and fuel integrity for ARFs, based on characteristics of spent fuel that would require evaluation under 10 CFR Part 71.

Design parameters and characteristics of the two ARF types were evaluated within the context of regulatory requirements in 10 CFR Part 71 and safety review topics applicable to transportation of spent fuel as identified in NUREG–1617 (NRC, 2000). Potential challenges associated with transportation experience were identified that align with safety review topics of structural, thermal, shielding, criticality, and confinement performance.

For spent non-LWR fuel, characteristics important to NRC transportation package certification were reviewed with a focus on the compatibility for ARF, across parameters important to package certification. These parameters, which are also contained in NUREG–1617 (NRC, 2000) include the maximum initial enrichment, burnup, specific power, cooling time, heat load, maximum and minimum initial enrichment, and physical dimensions of the spent fuel requiring transport. This report also focused on existing technology used for transportation of both fuel types. CoC No. 9253 for the TN-FSV cask was identified as a certified package that could be used to transport spent TRISO fuel. This cask has concentric stainless steel shells, lead shielding, and impact limiters. The cask has one shipping configuration used for transporting graphite block HTGR fuel elements from FSV. Design parameters and conditions for this CoC suggest that it would be acceptable for transportation of TRISO solid particle fuel. Spent metal fuel is often chemically treated to deactivate the sodium and to convert to other HLW forms that are more suitable for transportation and disposal. For these reasons, multiple certified transportation packages for spent metal fuel and converted HLW forms were identified including the NLI-1/2 cask (CoC No. 9010), T-3 cask (CoC No. 9132), NAC-LWT cask (CoC No. 9225), and the RH-TRU 72-B cask (CoC No. 9212). These casks commonly consist of concentric stainless steel shells, shielding between inner and outer shells, and impact limiters at two ends. Typical design parameters and conditions of these CoCs, as well as and characteristics of spent metal fuel are discussed in Section 2.

Transportation experience for non-LWR fuel was reviewed to assess whether there were any records of observed degradation, issues adverse to safety, or damage to the spent non-LWR fuel contained in the transportation packages. For solid coated particle fuel, transportation experience includes FSV, AVR, and THTR. FSV shipped approximately 726 spent fuel elements (prismatic blocks) to INL prior to 1988 using the TN-FSV cask. There are no records of observed degradation or damage of the FSV spent fuel elements and any safety issues of the casks during transportation. For AVR, although shipping and transfer of spent fuel occurred at different facilities at the reactor site with the use of AVR shipping cans, spent TRISO and BISO coated particles in graphite pebbles from the AVR reactor were contained in approximately 153 CASTOR THTR/AVR casks (Hall et al., 2019a). The CASTOR THTR/AVR cask is certified for both storage and transportation, authorized under German Certificate of Approval No. D/4214/B (U) F-96. There were no records of observed degradation or damage of the AVR and THTR spent fuel elements, nor were any safety issues recorded for use of these casks for transportation of spent metal fuel. Transportation experience for EBR-II metal fuel involved INL inter-facility moves using NRC-certified Type B packages, specifically models TN-FSV (CoC 9232) or NAC-LWT (CoC 9225), as well as moves on DOE controlled roads, using steel casks such as HFEF-5 or HFEF-14 that contain lead shielding. Spent metal fuel from the FFTF was transported from the Hanford Site to INL using a T-3 cask with NRC CoC 9132. Spent fuel from Fermi Unit 1 was transported to INTEC using stainless steel canisters containing a carbon steel basket, filled with helium and seal welded. From the transportation experience reviewed for EBR-II, Fermi Unit 1, and FFTF, no degradation or damage of the spent metal fuel elements, nor safety issues of the casks during transportation, were identified.

ARFs and existing transportation package characteristics were evaluated within the context of the package safety evaluation topics of criticality, shielding, structural, thermal, and containment performance contained in the SRP. The evaluation focused on potential issues in utilizing existing certified packages, degradation mechanisms, and potential issues for new package certifications.

For solid coated particle fuel, failure mechanisms were identified under in-reactor or postulated accident conditions, as discussed in Hall et al. (2019a). In the transportation environment, there are no known environmental, thermal, mechanical, or irradiation-induced degradation mechanisms that are expected to compromise fuel or cask performance. However, unique physical and chemical characteristics warrant further investigation. The TRISO fuel design parameters envisioned for modern HTGRs include a maximum fuel burnup of 150–210 GWd/MTHM (NEA, 2014), and in the case of the Mark-1 FHR design, burnup is estimated to be 180 GWd/MTHM. As such, higher burnup TRISO fuel potentially challenges current licensed burnup and enrichment limits, requiring additional criticality evaluations in order to ensure subcritical margins are maintained. The TN-FSV cask, which was certified to transport spent TRISO fuel, was shown to meet design limits with respect to shielding and structural integrity under a variety of conditions, including heat, cold, reduced external pressure, increased external pressure, vibration, water spray, free drop, corner drop, compression, and penetration conditions. Additionally, thermal analyses of the TN-FSV package suggest it will satisfy thermal requirements for decay heat loads associated with spent TRISO fuel.

For spent metal fuel, certified transportation casks were identified. Degradation mechanisms are influenced by environmental, thermal, mechanical, and radiological factors and the dominance of a given degradation mechanism is typically material-dependent. Possible degradation mechanisms for stainless steel cladding during transportation include intergranular corrosion, sensitization, and stress corrosion cracking. Operating experience information suggests that vibration would be negligible during transportation. Any residual moisture and O_2 contained in the transportation system are expected to react quickly with metallic sodium to produce sodium oxides, hydroxides, and H_2. Additionally, residual moisture and O_2 may react with uranium metal, forming uranium oxides and hydrides. The reaction could lead to fuel fragmentation and restructuring-swelling. Criticality performance of spent metal fuels can be complicated by variations in enrichment and burnup levels, which could exceed established limits for transportation package designs. Additionally, possible variations in composition of the spent fuel could warrant the need for further criticality evaluations.

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