REVIEW OF OPERATING EXPERIENCE FOR TRANSPORTATION OF FRESH (UNIRRADIATED) ADVANCED REACTOR FUEL TYPES

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ABSTRACT

This report presents information associated with transportation of fresh (unirradiated) non-light water reactor (LWR) fuel types based on a review of relevant operating experience. Non-LWR fuel considered in this review includes solid coated particle fuel, commonly referred to as tristructural isotropic (TRISO), and nuclear metal fuel characteristic of compact fast reactors. The transportation operating experience of several reactors that utilize these fuel technologies in the United States (U.S.) and abroad was reviewed. Available operating experience with solid coated particle fuel was associated primarily with high temperature gas reactors (HTGRs) that generally contained one of two types of fuel assemblies. In the case of Fort St. Vrain (FSV) and Peach Bottom Unit-1 (PB-1), fuel compacts were formed into prismatic block style fuel assemblies. The Arbeitsgemeinschaft Versuchsreaktor (AVR) thorium high temperature reactor (THTR) and high temperature gas-cooled reactor-10 (HTR-10) utilized pebble-style fuel compacts comprised of the same or similar basic solid coated particle fuel, or fuel kernel. Available transportation operating experience for nuclear metal fuel was associated with the Experimental Breeder Reactor II (EBR-II), Fast Flux Test Facility (FFTF), and Enrico Fermi Nuclear Generating Station Unit 1 (Fermi 1). Metal fuel consists of metal fuel slugs, cladding, a thermal bond material between the fuel and the cladding, a gas plenum, and end plugs. Typically this fuel is fabricated using injection casting and other techniques. For fresh (unirradiated) fuels, very few documents are available describing the specific methods used for transporting fresh fuel to the reactors and documenting the operating experience. In the available documents, there are no records of observed or postulated degradation mechanisms during transportation of fresh fuel. However, non-LWR fuels incorporate distinctive designs with the potential for additional considerations for future U.S. Nuclear Regulatory Commission (NRC) licensing reviews. Within the context of transportation, these considerations include the availability of NRC certified packages and potential considerations and challenges for NRC package certification and reactor licensing environmental reviews. The details of packaging used to ship fresh non-LWR fuels were not described in the documentation of the operational experience evaluated in this report. Further cursory review of information about NRC packages certified for transportation identified certificates that list approved contents as including uranium compounds and thorium-232 as TRISO fuel. NRC-certified packaging applicable to metal fuel was not readily identified from an initial review. If certified packaging is not available, then additional package certification would be needed prior to transportation of the fuel. Additionally, the generic fuel cycle environmental data and transportation environmental impacts listed in Tables S-3, and S-4, of the Title 10 of the *Code of Federal Regulations* (10 CFR) 10 CFR 50.51, and 10 CFR 50.52, respectively, apply to LWRs. Therefore, in future advanced reactor licensing actions, the environmental reports submitted by applicants and the Environmental Impact Statements (EIS) prepared by NRC staff may need to address site specific (i.e., non-LWR-specific) fuel cycle and transportation environmental impacts.

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ABBREVIATIONS/ACRONYMS

ANL	Argonne National Laboratory
ARF	advanced reactor fuel
AVR	Arbeitsgemeinschaft Versuchsreaktor
BISO	bistructural isotropic
CFR	Title 10 of *Code of Federal Regulations*
CNWRA	Center for Nuclear Waste Regulatory Analyses®
DFR	Dounreay Fast Reactor
DOE	U.S. Department of Energy's
EBR-II	Experimental Breeder Reactor-II
EIS	Environmental Impact Statement
FSV	Fort St. Vrain
FFTF	Fast Flux Test Facility (FFTF)
HEU	high-enrichment uranium
HTGR	high-temperature gas-cooled reactors
HTR-10	high temperature gas-cooled reactor-10
HTTR	high temperature test reactor
INEEL	Idaho National Engineering and Environmental Laboratory
INL	Idaho National Laboratory
LEU	low-enrichment uranium
LWR	light water reactor
MSR	molten salt reactor
Mo	molybdenum
Nb	niobium
NRC	U.S. Nuclear Regulatory Commission
PBRs	Pebble-Bed Reactors
PB1	Peach Bottom Unit 1
Pd	palladium
PSC	Public Service Company
Pu	plutonium
PyC	pyrolytic carbon
Ru	ruthenium
SiC	silicon carbide
SFR	sodium fast reactor
SRP	Standard Review Plan

THTR	thorium high temperature reactor
TRISO	tristructural isotropic
U	uranium
UCO	uranium oxycarbide
U.S.	United States
USDOT	United States Department of Transportation
Zr	zirconium

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QUALITY OF DATA, ANALYSES, AND CODE DEVELOPMENT

DATA: There are no original CNWRA-generated data in this report. Sources of other data should be consulted for determining the level of quality of those data.

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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, there is a need to develop an understanding of the potential challenges associated with regulating the long-term storage, transportation, and disposal of advanced reactor fuel (ARF) types. For example, revisions may be needed to guidance documents and rules promulgated 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 associated with the storage, transportation, and disposal of nuclear fuel types that have not been previously considered, such as ARF types. As the first product of that effort, this report examines the availability of information to identify possible technical challenges that would be addressed as part of an environmental assessment and safety review supporting the future licensing of facilities and activities associated with transportation of fresh ARF types.

Molten salt, compact fast, and HTGRs are non-LWR types associated with notices of intent to engage in regulatory actions with the NRC, each of which incorporate fuel designs with distinctive characteristics (NRC, 2018; Hastings, 2018). This report primarily focuses on non-LWR fuel types for compact fast reactors and HTGRs. The fuel characteristics attributable to each of these non-LWR fuel types is discussed in this report in the context of transportation operating experience for each fuel type in its fresh, or unirradiated, form.

1.2 Purpose and Scope

This report examines the availability of information regarding operating experience of fresh fuel transportation that may be helpful in preparing to review applicants' plans for transportation of ARF types. Due to the unavailability of proprietary ARF design information, and inherent differences between proposed ARF types, domestic and international operating experience for similar technology was sought as an information basis for identifying potential challenges with transportation. Literature describing formerly operating reactors with fuel types similar to the proposed advanced reactors was reviewed to help identify potential topics that would necessitate a more focused review. Most of these reactors have a long continuous operating experience from which practical conclusions may be drawn about the different fuel types during transportation. For this report, non-LWR transportation packages are assumed to contain fuel in its post-fabrication form, characteristic of fuel ready to be delivered to a facility for its initial use in the reactor. Additionally, this report summarizes characteristics of each non-LWR fuel type, as well as information associated with the corresponding fuel assemblies utilized in the reactors.

The advanced reactor technologies associated with formal notices of intent to engage in regulatory interactions with NRC include HTGR, compact fast reactor, and a fluoride salt-cooled high temperature reactor. Advanced reactors utilize fuel which, for purposes of this literature review, was grouped into two general categories based on the nature of the ARF type—metallic fuel or coated particle fuel—as shown in Table 1-1. Operating experience for both ARF types was reviewed, with emphasis on the transportation of fresh (unirradiated) fuel. Table 1-1 also indicates the reactors from which operating experience was reviewed for each ARF type.

Table 1-1. Literature review information sources for ARF categories			
Prospective Applicant	**Non-LWR Technology Type**	**ARF Type**	**Applicable Operating Experience**
X-Energy LLC	HTGR	Tristructural isotropic (TRISO) coated particles in pebble style fuel	Fort St. Vrain and Peach Bottom Unit 1 in the U.S.; Thorium High Temperature Reactor (THTR-300) and Arbeitsgemeinschaft Versuchsreaktor (AVR) in Germany; and HTR-10 in China (IAEA, 2001)
Kairos Power LLC	Fluoride salt-cooled high-temperature reactor	TRISO coated particles in pebble style fuel	Coated particle fuel operating experience (THTR-300, AVR, Peach Bottom Unit 1, and Fort St. Vrain)
Oklo Inc.	Sodium-cooled, compact fast reactor	Nuclear metal fuel (uranium-zirconium U-10Zr fuel alloy with 20% cold worked-316 stainless steel cladding)	Experimental Breeder Reactor-II (EBR-II)* and Fast Flux Test Facility (FFTF) (Devaser, 2017)

*EBR-II is an integral fast reactor prototype that operated at Argonne National Laboratory-West for more than 30 years.
HTR-10—high temperature gas-cooled reactor-10
IAEA—International Atomic Energy Agency
IAEA. “Current Status and Future Development of Modular High Temperature Gas Cooled Reactor Technology.” TECDOC-1198. Vienna, Austria: International Atomic Energy Agency. 2001.
Devaser, N.J. Memorandum (February 2) to J.P. Segala, Division of Engineering, Infrastructure, and Advanced Reactors Office of New Reactors. Washington, DC: U.S. Nuclear Regulatory Commission. 2017. <https://www.Nrc.Gov/Docs/Ml1703/Ml17031a321.Pdf> (8 January 2019).

2 CHARACTERISTICS OF NON-LWRS AND ARF TYPES

2.1 Coated Particle Fuel

The coated particle fuel is a unique all-ceramic fuel form developed for high-temperature gas-cooled reactors (HTGRs) in the pebble-bed and the prismatic core configurations (Demkowicz et al., 2018; IAEA, 2010, 2012; Richards, 2002). Two types of coated particle fuel have been developed: bistructural isotropic (BISO)-coated particles and tristructural isotropic (TRISO)-coated particles. The TRISO-coated particle consists of a spherical fuel kernel of oxide, carbide, or oxycarbide of uranium (U), thorium (Th), or plutonium (Pu) coated with multiple layers of chemical vapor-deposited pyrolytic carbon (PyC) and silicon carbide (SiC). The BISO-coated particle has only two layers of PyC surrounding the fuel kernel. From the 1980s forward, the TRISO-coated particle fuel is accepted as the reference fuel for HTGRs. TRISO-coated particles are dispersed into 60 mm-diameter graphite pebbles to form the fuel elements for the pebble-bed HTGR design [such as the Arbeitsgemeinschaft Versuchsreaktor (AVR) in Germany and the high temperature gas-cooled reactor-10 (HTR-10) in China] or are fabricated into compacts and inserted into hexagonal graphite block fuel elements for the prismatic HTGR design [such as the Fort St. Vrain (FSV) reactor in the United States (U.S.) and the HTTR in Japan] (IAEA, 2010). The fluoride salt-cooled high-temperature reactor employs a 30 mm-diameter pebble to increase surface area per unit volume of the core to allow higher power densities (Forsberg and Peterson, 2016).

The reference TRISO coating consists of four successive layers, including a porous carbon buffer layer, a dense inner PyC layer, a SiC layer, and a dense outer PyC layer (Demkowicz et al., 2018; IAEA, 2010; Richards, 2002). The individual coating layers are designed for particular functions related to fission product retention, creep strength, shrinkage under irradiation, and irradiation performance. The porous buffer layer provides void volume for fission gases while accommodating fuel kernel swelling and protecting the PyC and SiC layers from recoil damage and excessive internal pressure. The two dense PyC layers on either side of the SiC retain gaseous fission products and maintain the SiC layer in a compressive state as the pyrocarbons shrink during irradiation. The SiC layer serves as the primary load-bearing component to contain internal pressure of the coated particle as well as the main fission product barrier to retain all gaseous and metallic fission products (Del Cul et al., 2002).

The primary emphasis in the development of the TRISO-coated particle fuel is on its performance at high temperature, power density, and optimal burnup. The TRISO fuel service conditions and performance requirements envisioned for modern HTGRs are summarized below (NEA, 2014; IAEA, 2012; INL, 2010).

- maximum core temperatures of 1,400 °C [2,552 °F] during normal operation and 1,600 °C [2,912 °F] under accident conditions
- maximum fuel burnup of 150–200 GWd/tHM
- maximum power densities of 12 MW/m^3
- low heavy metal contamination and low as-manufactured particle defect fractions ($\sim 10^{-5}$)
- minimal radionuclide release from in-service particle failure fractions during normal operation and accident conditions ($<10^{-4}$)

Development efforts to achieve high operating temperatures and increased burnup involve a wide variety of fuel kernel types, uranium enrichments, and coating designs (Demkowicz et al., 2018; IAEA, 2012; INL, 2010). A range of fuel kernel compositions has been investigated, including replacement of the UO_2 fuel kernel with uranium oxycarbide (UCO), a two-phase mixture of UO_2 and UC_2. The fuel kernels used high-enrichment uranium (HEU) up to 21 percent U-235 before 1980; low-enrichment uranium (LEU) was used afterwards in the interest of nuclear nonproliferation. The LEU TRISO-coated particle fuel for modern HTGRs is specified with a uranium enrichment of 7.8 percent U-235. In addition to the reference TRISO coating, a modified design with a zirconium carbide layer as a replacement for the SiC layer or as an addition to the TRISO coating has been considered to enhance the retention of fission products.

2.2 Nuclear Metal Fuel

In order to create compatibility with the sodium coolant used in a sodium fast reactor (SFR), metal fuel was utilized in fast reactors such as the Experimental Breeder Reactor (EBR)-I, EBR-II, Fermi-1, and Dounreay Fast Reactor (Carmack, 2009). Figure 2-1 is a schematic of the improved and most common configuration of metal fuel design in a cylindrical pin. The metal fuel components include metal fuel slugs, cladding, a thermal bond material between fuel and cladding, a gas plenum, and end plugs. The fuel slug is either one full-length slug or a stack of fuel segments, which is loaded inside the cladding. The gap between the slug and cladding is filled with sodium which acts as a thermal bond until fuel swells out to contact the cladding. The gas plenum collects the fission gas to buffer the pressure on the cladding. The end plugs are welded to seal the cylindrical pin to prevent gas or sodium release. Two important terms commonly used in characterizing metal fuel design are smear density and plenum to fuel volume ratio. Smear density is the cross-sectional area fraction occupied by fuel. The plenum to fuel volume ratio refers to the relative volume of the gas plenum to that of the fuel.

Metal fuel typically consists of uranium alloyed with various other metals to improve irradiation performance. For example, EBR-II used metal fuel composed of 95 weight percent U and 5 weight percent Fs. [Fs is an abbreviation for the portion containing 2.4 weight percent Mo, 1.9 weight percent Ru, 0.3 weight percent Rh, 0.2 weight percent palladium (Pd), 0.1 weight percent zirconium (Zr), and 0.1 weight percent niobium (Nb) (Fast Reactor Working Group, 2018).] Later on, binary fuels (U-Zr) and ternary fuels (U-Pu-Zr) were used because zirconium was more compatible with cladding, thereby adjusting fuel alloy solidus and fuel cladding eutectic temperatures. Cladding materials include Type 316 stainless steel, D9 (a titanium modified variant of Type 316 stainless steel), and HT9 (a high strength martensitic stainless steel). Typical enrichment for nuclear metal fuels range from 52 percent U-235 to approximately 78 percent U-235 (Fast Reactor Working Group, 2018). Metal fuels have some notable performance characteristics. Because the fuel is metallic, it has high thermal conductivity, which reduces peak cladding temperatures and local fuel hot spots. As a result, operating power margins can be greater compared to oxide fuel used in conventional light water reactors. Furthermore, because the fuel is compatible with sodium coolant, the fuel can maintain off-normal performance characteristics, in particular for the run-beyond-cladding-breach conditions (Crawford et al., 2007). Metal fuel can be fabricated using injection casting and other techniques. Pyroprocessing based on electrorefining is a technique that can be used to reprocess used metal fuel (Li et al., 2005).

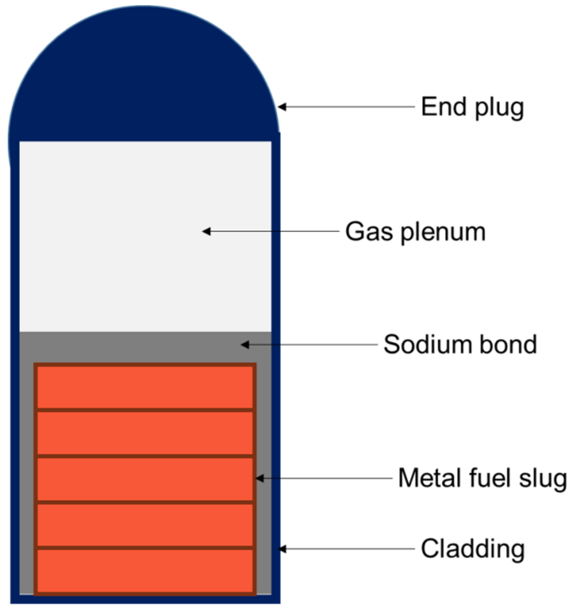

Figure 2-1. Schematic of cylindrical metal fuel pin as one example of the metal fuel design

3 TRANSPORTATION EXPERIENCE

3.1 Coated Particle Fuel Operating Experience

Transportation operating experience with coated particle fuel is available in high-temperature gas-cooled reactors (HTGRs), which generally contain two fuel assembly types composed of fuel compacts as discussed in Chapter 2. In the case of the prismatic block style fuel assembly, fuel compacts are loaded into predrilled holes in a machined graphite block to make the fuel element. The prismatic block HTGR core is based on columns of hexagonal prismatic fuel elements that contain additional holes to accept control rods and provide a path for flowing coolant. The block style fuel elements are shipped and stored together (Kasten and Bartine, 1981). Pebble-bed style reactors (PBRs) contain fuel elements that take the form of spherical compacts (i.e., pebbles) of approximately 6-cm diameter. Fuel pebbles are passed continuously through the core during reactor operation.

Both PBRs and Prismatic Block type reactor cores generally used tristructural isotropic (TRISO) or the similar bistructural isotropic (BISO) fuel. Fuel grains used in both of these fuels have a density of a few hundred grains per cubic centimeter (DeHart and Ulses, 2009).

HTGRs for which operating experience was reviewed are shown in Table 3-1.

Table 3-1. Coated particle fuel experience in HTGRs

Reactor	PB-1	FSV	AVR	THTR	HTR-10
Fuel Type	Carbide BISO	Carbide TRISO	Carbide/Oxide BISO/TRISO	Oxide BISO	Oxide TRISO
Fuel Element Type	Prismatic Block	Prismatic Block	Pebble Bed	Pebble Bed	Pebble Bed
Enrichment Type	HEU	HEU	HEU/LEU	LEU	LEU
Years of Operation	1966-1974	1976-1989	1967-1988	1986-1989	2000-present
Rated Power (MWth)	115	842	46	750	10

AVR—Arbeitsgemeinschaft Versuchsreaktor
BISO—bistructural isotropic
FSV—Fort St. Vrain
HEU—high-enrichment uranium
HTGRs—high-temperature gas-cooled reactors
HTR—High Temperature Reactor
LEU—low-enrichment uranium
PB-1—Peach Bottom Unit-1
THTR—thorium high temperature reactor
TRISO—Tristructural isotropic

3.1.1 PB-1 Operating Experience

Peach Bottom Unit-1 (PB-1) was an HTGR with an initial rated capacity of 115 MW (thermal) and was operated from 1966 to 1974 by Philadelphia Electric Company. PB-1 utilized a hexagonal prismatic block reactor core design. Each fuel compact was cylindrical in shape and approximately 8.9 cm [3.5 in] diameter and 3.7-m [12-ft]-long. Each standard fuel element contained 30 fuel compacts, composed of fuel particles in a graphite matrix. The core was designed to contain approximately 805 fuel elements (Kingrey, 2003).

No documentation of operating experience for transportation of fresh nuclear fuel for PB-1 was found, nor records indicating degradation or damage of fresh fuel at PB-1 during transport.

3.1.2 Fort St Vrain (FSV) Operating Experience

FSV commercially operated from approximately 1976 to 1989 (IAEA, 2001). FSV utilized a core of hexagonal, graphite block fuel elements (TRISO-coated particles) and reflectors (AEC, 1972). For FSV, the particles are compacted together fuel rods 1.3 cm [0.5 in] in diameter and 5.1 cm [2 in] long. The rods are aggregated into fuel elements of 33 cm [13 in] in length and 36 cm [14 in] wide.

Transportation of fresh fuel for FSV occurred via truck, from Gulf General Atomic in San Diego, California, to the plant site, a shipping distance of approximately 1,200 miles (AEC, 1972). The fuel was packaged in double-drum type containers with vermiculite packing, and each contained one fuel element per drum. These packages were approved by AEC and the U.S. Department of Transportation (USDOT) (AEC, 1972). In order to support regular refueling intervals, FSV estimated approximately 80 drums could be carried per truckload. The initial core load required 20 truckloads, and approximately one-sixth of the fuel was estimated to be replaced each year, which required 3 or 4 regular truckloads of fresh replacement fuel (AEC, 1972).

There are no records of observed degradation or damage of fresh fuel at FSV during transport.

3.1.3 Arbeitsgemeinschaft Versuchsreaktor (AVR) and Thorium High Temperature Reactor (THTR) Operating Experience

AVR was a 15 MWe PBR, constructed as an experimental power station for testing nuclear fuels (Beck and Pincock, 2011). The AVR was shut down in 1988 after 21 years of operation as a power reactor and large scale test facility (NRC, 2001). The 300 MWe THTR operated in Germany for less than 4 years as a HTGR demonstration plant (NRC, 2001). Both the THTR and AVR operated with pebble style fuel with a 60 mm [2.4 in] diameter (IAEA, 2010). Spherical fuel elements (i.e., pebbles) form an unrestricted configuration in the core and are surrounded by a graphite reflector (Kugeler and Zhan, 2018; NRC, 2001).

No documentation of operating experience for transportation of fresh nuclear pebble-style fuel was found for the THTR and AVR; nor records of issues of transportation of fresh pebble-style fuel at THTR and AVR.

3.1.4 High Temperature Gas-Cooled Reactor-10 (HTR-10) Operating Experience

The HTR-10 was designed and constructed by the Institute of Nuclear and New Energy Technology in China as a test reactor to further test HTGRs. The reactor produced full power in 2003 and is currently operating at 10 MWth (Beck and Pincock 2011). The HTR-10 utilizes pebble style fuel composed of TRISO-coated particles, which are embedded in a graphite matrix (INL, 2005). Each of the spherical fuel elements (pebbles) is approximately 6 cm [2.4 in] in diameter with an enrichment of 17 percent (IAEA, 2013).

No documentation of operating experience for transportation of fresh nuclear pebble style fuel was found for HTR-10, nor records of issues associated with transportation of this fuel.

3.2 Nuclear Metal Fuel Operating Experience

Fast reactors using nuclear metal fuel for which operating experience was reviewed are shown in Table 3-2.

Table 3-2. Nuclear metal fuel experience in reactors

Reactor	EBR-I	EBR-II	Fermi-1	FFTF	Dounreay Fast Reactor
Fuel Type	U, U-Pu	U-5Fs initially, then U-10Zr	U	U-10Zr	U-Mo
Cladding	Stainless steel	304L, 316, cold worked D9, cold worked 316, HT9	Stainless steel	HT9	Stainless steel
Enrichment, weight percent ^{235}U	93	52, 67, 66.9, 69.6, 78	26	Not found	Natural
Primary Coolant	Sodium-potassium	Sodium	Sodium	Sodium	Sodium-potassium
Rated Power (MWth)	1.4	62.5	200	400	60
Years of Operation	12 (1951–1963)	30 (1964–1994)	9 (1963–1972)	10 (1982–1992)	18 (1959–1977)

EBRI-I—Experimental Breeder Reactor-I
EBR-II—Experimental Breeder Reactor-II
Fermi-1— Enrico Fermi Atomic Power Plant Unit 1
FFTF—Fast Flux Test Facility
U—Uranium
Pu—Plutonium
Mo—Molybdenum
HT9—High Chromium Martensitic Steel

3.2.1 Experimental Breeder Reactor-1 (EBR-I) Operating Experience

EBR-I used metal fuels composed of uranium, plutonium, or their alloys and cooled by a sodium-potassium mixture (DOE, 1970). The fuel elements for EBR-I were stainless steel tubes filled with fully enriched metallic uranium slugs. The tubes were filled with a sodium-potassium alloy (NaK) (DOE, 1970).

No documentation of operating experience for transportation of fresh metal fuel for EBR-1 was found. The EBR-1 reactor was designed and constructed by a team at the Argonne National Laboratory (ANL) and U.S. Department of Energy (DOE) and, as such, the metal fuel pins were also fabricated there (DOE, 1970).

3.2.2 Experimental Breeder Reactor-II (EBR-II) Operating Experience

EBR-II is a sodium-cooled fast reactor, which was designed, built, and operated by ANL at the National Reactor Testing Station in Idaho. Initial operations began in July 1964 and the reactor achieved criticality in 1965. EBR-II was the reactor with the longest continuous operating experience using metal fuel in the United States (U.S.) (Fast Reactor Working Group, 2018). Although many fuel forms were tested over the 30-year operating history of EBR-II, the driver fuel was consistently metal. More than 130,000 metal fuel elements were irradiated during the 30-year lifetime of EBR-II (Fast Reactor Working Group, 2018). Over the operation of EBR-II, greater than 130,000 metal fuel pins were irradiated (Fast Reactor Working Group, 2018).

In addition to demonstrating the feasibility of metal-fueled, sodium-cooled, fast breeder reactors as power plants, another objective of the EBR-II was to demonstrate the applicability of pyrometallurgical techniques for onsite reprocessing of spent fuel (ANL, 1980). To meet this objective of on-site reprocessing, a complex of facilities was built, including a fuel manufacturing facility, and other companion facilities. The spent fuel was reprocessed onsite at the fuel reprocessing facility. Then the metal fuel slugs and fuel pins were refabricated at the onsite fuel manufacturing facility.

No records of operating experience for transportation of fresh metal fuel for EBR-II were found in any of the documents reviewed.

3.2.3 Fermi 1 Operating Experience

Fermi 1 was a sodium-cooled prototype fast breeder reactor fueled by metallic uranium. The reactor plant was designed for a maximum capacity of 430 MWth; however, the maximum reactor power with the first core loading was 200 MWth. The primary system was filled with sodium in 1960 and criticality was achieved in 1963. In 1972, the reactor was decommissioned. Fuel element configurations included both radial and axial blanket fuel types, consisting of 97 percent depleted uranium and 3 percent molybdenum alloy (Toews et al., 2002). Radial fuel element assemblies were approximately 180 cm [72 in], and axial assemblies were 36 cm [14 in] (Toews et al., 2002).

No documentation of operating experience for transportation of fresh metal fuel for Fermi-1 was found; however, it is very likely the fuel pins were fabricated onsite.

3.2.4 Fast Flux Test Facility (FFTF) operating experience

FFTF is a 400 MW experimental fast neutron reactor located on the Hanford Site (Nielsen et al., 2002). FFTF is cooled with liquid metal. The standard driver fuel assembly for the FFTF is held in pin containers approximately 3.6 m [12 ft] high with fuel pins approximately 2.3 m [7.5 ft] long. Each container contains 217 fuel pins (Montierth et al., 1999). Uranium and plutonium content for fresh driver fuel varied depending on the particular assembly, but was approximately 70 to 77 percent (Montierth et al., 1999).

No documentation of operating experience for transportation of fresh metal fuel for FFTF was found. It is very likely that the metal fuel pins were fabricated onsite.

3.2.5 Dounreay Fast Reactor (DFR)

DFR was operated by United Kingdom Atomic Energy Authority and first achieved criticality in November 1959 (Cochran et al., 2010). DFR utilized hexagonal fuel assemblies containing 325 fuel rods, each 2.25 m [7.38 ft] in length and 5.84 mm [0.230 in] in diameter (Jensen and Olgaard, 1995). Average fuel enrichment for DFR was approximately 25 percent (Jensen and Olgaard, 1995).

No documentation of operating experience for transportation of fresh metal fuel for DFR was found. It is very likely that the metal fuel pins were fabricated onsite, and transport of fuel was not needed.

3.3 Considerations for Future Licensing

ARFs incorporate designs that present the potential for additional and special U.S. Nuclear Regulatory Commission (NRC) licensing review considerations and challenges. Within the context of transportation, these considerations include the availability of NRC certified packages and potential considerations and challenges for NRC package certification and reactor licensing environmental reviews. Early identification of those distinctive characteristics of ARFs that could potentially affect future NRC reviews can aid planning and preparation for such reviews.

The details of packaging used to ship fresh fuel for the reviewed non-light water reactor (LWR) fuel types were not described in the documentation of the operational experience evaluated in previous sections. Further cursory review of information about NRC packages certified for transportation in the NRC directory of certificates of compliance (NRC, 2013) identified Certificate No. 9342 for the Versa-Pac Models VP-55 and VP-110. That certificate 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). Certified packaging applicable to metal fuel was not readily identified from an initial review of the directory. If certified packaging is not available, then additional package certification would be needed prior to transportation of the fuel.

In addition to safety reviews, NRC conducts environmental reviews of reactor licensing actions. These reviews include the NRC evaluation of an applicant's environmental report and preparation of an Environmental Impact Statement (EIS). An applicant's environmental report and the NRC EIS include assessments of the environmental impacts of transportation of the fuel to and from the reactor site, as well as of the potential nuclear fuel cycle impacts of licensing a new reactor. NRC regulations in Title 10 of the *Code of Federal Regulations* (10 CFR) Part 51 provide generic information and analyses that are applicable to conducting these impact assessments. Within this context, the generic fuel cycle environmental data and transportation environmental impacts listed in Tables S-3 and S-4 of 10 CFR 50.51 and 10 CFR 50.52, respectively, apply to LWRs. Therefore, in future advanced reactor licensing actions, the environmental reports submitted by applicants and the EISs prepared by NRC staff may need to address site-specific (i.e., non-LWR-specific) fuel cycle and transportation environmental impacts.

4 SUMMARY

The transportation of fresh (unirradiated) non-light water reactor (LWR) fuel presents possible technical challenges that would need to be addressed as part of future licensing activities for facilities utilizing advanced reactor fuel (ARFs). This report described selected non-LWR fuel types and the limited transportation operating experience available for them. A subsequent report will elaborate on the safety and regulatory challenges potentially posed by these non-LWR fuel types. Non-LWR fuel from which operating experience was reviewed includes solid coated particle fuel, commonly referred to as tristructural isotropic (TRISO), and nuclear metal fuel characteristic of compact fast reactors. Operating experience with solid coated particle fuel was available primarily from high-temperature gas-cooled reactors (HTGRs) that generally contained two types of fuel assemblies. In the case of Fort St. Vrain (FSV) and Peach Bottom Unit-1 (PB-1), fuel compacts were formed into prismatic block style fuel assemblies. The Arbeitsgemeinschaft Versuchsreaktor (AVR), thorium high temperature reactor (THTR), and high temperature gas-cooled reactor-10 (HTR-10) utilized pebble-style fuel compacts comprised of the same or similar basic solid coated particle fuel, or fuel kernel. The fuel kernels used high-enrichment uranium (HEU) up to 21 percent U-235 before 1980; low-enrichment uranium (LEU) was used afterwards in the interest of nuclear nonproliferation. The LEU TRISO-coated particle fuel for modern HTGRs is specified with a uranium enrichment of 7.8 percent U-235. Operating experience for nuclear metal fuel was available from the Experimental Breeder Reactor-II (EBR-II), Fast Flux Test Facility (FFTF), and Fermi 1. Metal fuel consists of metal fuel slugs, cladding, a thermal bond material between the fuel and the cladding, a gas plenum, and end plugs. Typical enrichment for nuclear metal fuels range from 52 percent U-235 to approximately 78 percent U-235.

For transportation of fresh (unirradiated) non-LWR fuel, very few documents are available that describe specific methods used for transporting fresh fuel to the reactors used for this operating experience review. Some of the reactors utilized fuel that was fabricated onsite and therefore did not involve the transportation of fresh fuel. There are no records of observed or postulated degradation mechanisms during transportation of fresh fuel. Non-LWR fuels incorporate distinctive designs, including high enrichment and atypical physical dimensions that present the potential for additional and unique considerations for future U.S. Nuclear Regulatory Commission (NRC) licensing reviews. Within the context of transportation, this also includes potential considerations for NRC package certification and environmental reviews. For this report, an initial review identified a certified transportation package for TRISO fuel. A certified package was not identified for nuclear metal fuel although this will continue to be evaluated.

Environmental reports and NRC Environmental Impact Statements (EISs) prepared for early site permits or the combined license stage of an advanced reactor evaluate the environmental impacts of the nuclear fuel cycle and of transportation of fuel to and from the proposed reactor. The generic fuel cycle environmental data and transportation environmental impacts listed in Tables S-3 and S-4 of Title 10 of the *Code of Federal Regulations* (CFR) 10 CFR 50.51 and 10 CFR 50.52, respectively, apply to LWRs. Therefore, in future advanced reactor licensing actions, the environmental reports submitted by applicants and the EISs prepared by NRC staff may need to address site-specific (i.e., non-LWR-specific) fuel cycle and transportation environmental impacts.

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