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Initial Evaluation of Microreactor Disposition Options

Evans D. Kitcher

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Evans D. Kitcher

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Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

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ABSTRACT

The U.S. Department of Energy (DOE) is supporting the U.S. advanced reactor industry through funding, legislation, and regulatory development in order to actively pursue several microreactor design concepts. Idaho National Laboratory (INL) is strategically positioned due to its world-class nuclear R&D experimental facilities and well-established track record of nuclear facility operations to support demonstrations of microreactor technology. This report provides an initial evaluation of disposition options for microreactor spent nuclear fuel (SNF) generated in the microreactor technology demonstration program. In the absence of detailed microreactor design information, assumptions were made to facilitate the identification of disposition options. The details of any component of an identified disposition pathway are highly microreactor design specific, and such details have not been provided at this time. The variety of potential microreactor SNF is reflected in the diverse nature of DOE-owned SNF stored at INL. Therefore, it is highly probable that DOE currently stores and manages fuels that are analogous to most microreactor fuel concepts. Therefore, disposition options for microreactor SNF are expected to be much the same as existing INL fuels. Two generic microreactor concepts were selected for the purposes of this options assessment. The selected reactor concepts are a tristructural isotropic (TRISO) fueled high temperature gas reactor (HTGR) and a sodium/potassium-bonded heat pipe reactor. Both concepts are assumed to use high-assay low enriched uranium (HALEU) as the initial fuel composition. Interim storage, treatment, material recovery, packaging, and extended dry storage options are identified for these reactors. The disposition options discussed include existing INL facilities and capabilities as well as new facilities developed as part of the microreactor program, or as part of DOE's overall strategy for packaging and consolidation of INL SNFs in preparation for shipment to a future repository or another storage facility, i.e. centralized interim storage. The details of any disposition option are highly microreactor design specific and further investigation, evaluation and analyses must be performed once this information is available.

CONTENTS

FIGURES

TABLES

ACRONYMS

BWR – Boiling water reactor

CFR – Code of federal regulations

DOE – U.S. Department of Energy

DOE-NE – DOE Office of Nuclear Engineering

DOD – U.S. Department of Defense

DSC – Dry Shielded Canisters

EBR – Experimental Breeder Reactor

FDPA – Fluorinel Dissolution Process Area

FSA – Fuel Storage Area

FSV – Fort St. Vrain Nuclear Reactor

HALEU – High-assay, low-enriched uranium

HFEF – Hot Fuel Examination Facility

HLW – High-level radioactive waste

HSM – Horizontal Storage Modules

HTGR – High Temperature Gas Reactor

IFSF – Irradiated Fuel Storage Facility

INL – Idaho National Laboratory

INTEC – Idaho Nuclear Technology and Engineering Center

ISFF – Idaho Spent Fuel Facility

ISFSI – Independent Spent Fuel Storage Installation

LLW – Low-level radioactive waste

MCO – Multi-canister overpack

MFC – Materials and Fuels Complex

MTHM – Metric tons of heavy metal

NRC – U.S. Nuclear Regulatory Commission

OFSF – Outdoor Fuel Storage Facility

PWR – Pressurized water reactor

RSWF – Radioactive Scrap and Waste Facility

SNF – Spent nuclear fuel

TMI – Three Mile Island Nuclear Reactor

TRIGA® – Training, Research, Isotopes, General Atomics

TRISO – Tristructural isotropic

TRU – Transuranic

Initial Evaluation of Microreactor Disposition Options

1. INTRODUCTION

Microreactors are very small nuclear reactors with a power output of 20MW thermal or less. These reactors are typically intended for independent operation in off-grid remote locations but can also be operated as part of a local microgrid. Microreactors are designed to be factory-built, modular in nature, and portable – whether by road, rail and/or barge. The reactor can then be assembled on site to provide electric, process heat, or high-quality steam for industrial applications. Microreactor applications include power for remote locations, mobile backup power, mining operations, military installations, space missions, desalination and emergency power supplies in support of disaster relief operations.

The U.S. Department of Energy (DOE) is supporting the U.S. advanced reactor industry through funding, legislation and regulatory development in order to actively pursue several microreactor design concepts. The U.S. Department of Defense (DOD) is also increasingly pursuing a microreactor design concept as its military operations become more energy intensive and require portable, dense power sources. Remote rural communities that rely on diesel generators for electricity are also considering microreactors as a source of reliable, zero-carbon energy capable of operation for several years without refueling.

For a variety of reasons, Idaho National Laboratory (INL) is strategically positioned to support demonstration of microreactor technology due to its well-established track record of nuclear facility operations. INL has world-class nuclear R&D experimental facilities and capabilities to support demonstration needs, a well-characterized site with a controlled emergency planning zone and mechanisms for the necessary U.S. Nuclear Regulatory Commission (NRC) licensing and DOE-authorization of its facilities as appropriate. As a result, reactor design entities are collaborating with INL to develop and test microreactors with the intent of near-term demonstrations.

1.1 Purpose/Objective

In support of such demonstrations, the DOE office of Nuclear Engineering (DOE-NE) must address the safe and secure storage, transportation and disposition of spent nuclear fuel (SNF) generated in microreactor technology demonstrations. The purpose of this report is to identify options for the interim storage of microreactor SNF generated in demonstrations of microreactor technology. As an initial evaluation, disposition options/pathways are identified at a more strategic level. Due to a lack of specific information on microreactor fuel, only general assumptions can be made about the requirements for storage. This report, in conjunction with future detailed analyses, will allow INL and DOE-NE to perform cost benefit analyses of the identified disposition options.

1.2 General Assumptions

The information currently available constitutes the basis for the options identified and discussed in this document. Where gaps in the available information were encountered – such as absence of detailed microreactor design information, assumptions were developed to facilitate the identification of disposition options. As improved characterization of the reactor designs, operational modes and other information becomes available, some of these assumptions may become invalid, resulting in a need to reevaluate the identified options or identify new options. Furthermore, facility operations, changing inventories and storage space availability can also affect the identification of disposition options. Many issues can affect disposition pathways including regulatory and policy changes. The following set of governing general assumptions have been made to facilitate the identification and assessment of disposition options for microreactors at INL:

- Only DOE-owned SNF generated in demonstration reactors would be eligible for storage at INL unless otherwise negotiated. This limits the scope of this report to DOE-owned high-assay, low enriched uranium (HALEU) fuel used for demonstration reactors. This material will only be considered for disposition once it has been declared spent.
- The reactor fuel is assumed to be on-site at INL when declared spent. This limits the scope of disposition options to technologies that can be deployed on-site.
- Disposition options includes packaging of the SNF for eventual transport to a permanent repository. This may include treatment where necessary to meet repository requirements.
- Activated reactor components, structural materials and low-level radioactive waste (LLW) generated during reactor and decommissioning are not considered in this report.
- If regulated by DOE, identified disposition options must meet the requirements of 10 CFR 830, Nuclear Safety Management. Packaging of the SNF for transportation must meet 10 CFR 71 requirements. If licensed by NRC, the interim storage system design and operation must meet 10 CFR 72 requirements.
- Due to the concept of operations characteristic of microreactors (i.e. factory-built/shipped, mobile power supply, etc.), reactor and nuclear material-bearing components will be designed with integral shielding and criticality control. The transportation envelope of the microreactor will meet all requirements in 10 CFR 71. Interim storage options will look to leverage any such design features.

1.3 Identification of Disposition Options

For the purposes of this report, disposition options include all processes necessary to support safe and secure storage of the spent microreactor fuel in a ‘road-ready’ configuration (i.e. a configuration that is ready for shipping to an ISFSI or permanent repository). These may include; (1) interim storage for the dissipation of heat and reduction of radiation dose immediately after discharge, (2) treatment of reactive materials and damaged fuel, (3) potential recovery of transuranic (TRU) material (if desirable or as a result of treatment processes), (4) packaging for extended dry storage or transport to a repository, (5) extended dry storage while awaiting packaging or transport to a repository, and (6) transport to a repository. Figure 1 shows how these processes are related.

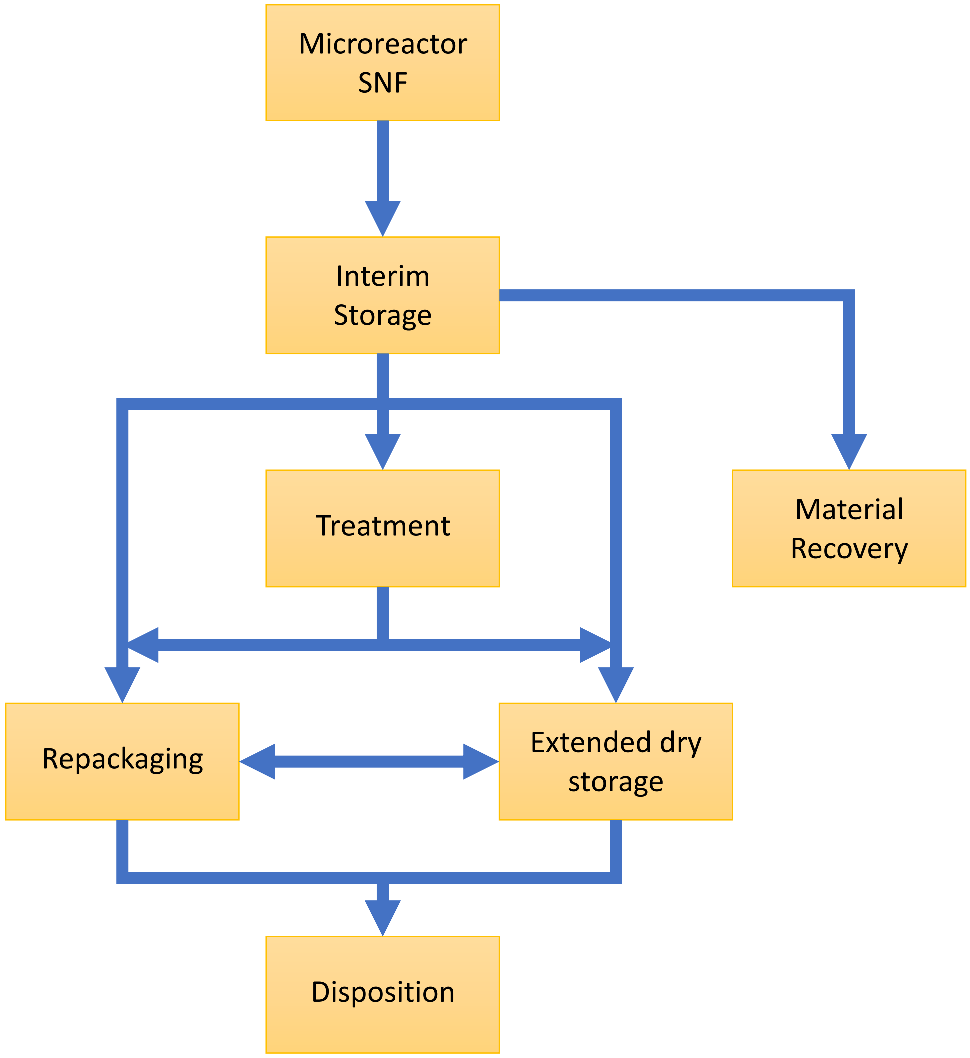

Figure 1: Disposition pathway for spent microreactor fuel

1.4 Spent Nuclear Fuel Currently Stored at INL

The characteristics of DOE SNF vary greatly and have been grouped into 34 groups (DOE SNF Groups) for DOE's Yucca Mountain Repository License Application Safety Analysis Report based on fuel characteristics that have a major impact on the release of radionuclides from DOE SNF and are important to nuclear criticality (DOE 2009). The group name (e.g., "Uranium Oxide, Zirc Clad, Intact, High-Enriched Uranium" for Group 5) identifies the fuel compound and any other characteristics needed to describe the group, such as matrix, type of cladding, cladding condition, and enrichment, respectively. The DOE SNF Groups are then used to aggregated DOE SNF into different "groups"—for example, "degradation groups" and "criticality groups". For each group, the number and type of packages that could be used for off-site transportation were also identified. Additional information on these fuel groups may be found in the Yucca Mountain Repository License Application Safety Analysis Report (DOE 2009). This group structure constitutes the analytical envelop for evaluation of DOE SNF and as such would serve to bound any new microreactor SNF.

The SNF inventory at INL includes over 250 different types of SNF (Hill and Fillmore 2005). Figure 2 shows some of the different fuel types stored at INL. Table 1 lists INL's storage facilities and summarizes the distinguishing characteristics of most of the stored SNF (NWTRB 2017b). Only the most prevalent types (by mass) are described in Table 1.

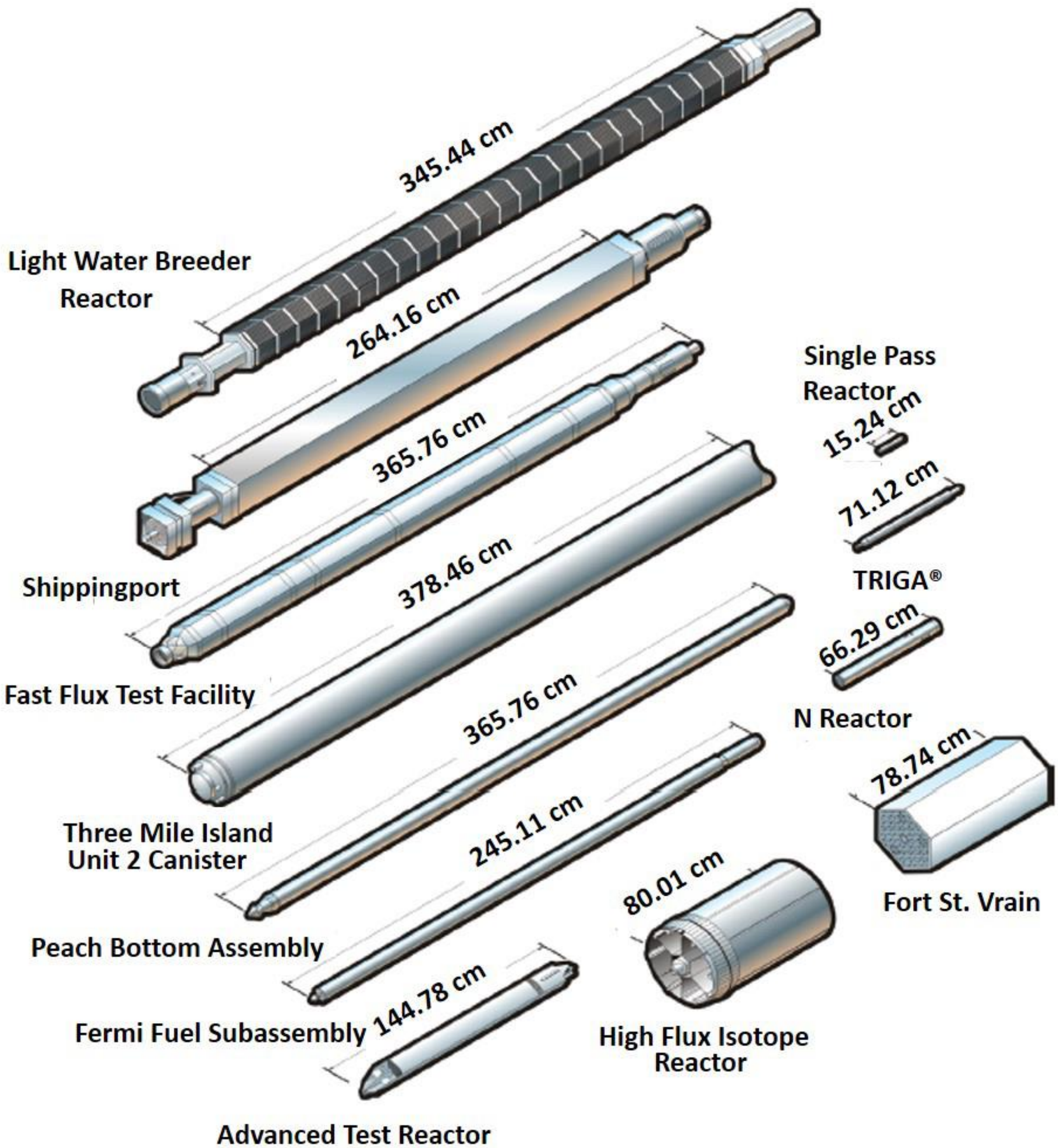

Figure 2: Some of the SNF types stored at INL

Table 1: SNF and Storage Facilities at INL

Storage Facility	Storage Type	Main Source of SNF	SNF Characteristics (fuel and cladding type)
INTEC CPP-749	Dry	Shippingport Atomic Power Station; light water breeder reactor core	Thorium-uranium dioxide fuel with zirconium alloy or stainless-steel cladding
	Dry	Fermi-1 fast breeder reactor blanket assemblies	Uranium-molybdenum alloy fuel with sodium bonding between the fuel and the stainless-steel cladding
	Dry	Peach Bottom Unit 1, Core 1	Thorium-uranium carbide fuel in a graphite matrix
INTEC CPP-2707	Dry Cask	Commercial nuclear power reactors	Uranium dioxide fuel with zirconium alloy or stainless-steel cladding
	Dry Cask	14 fuel types from Post Irradiation Examination and Loss of Fluid Test Fuel	Various
INTEC CPP-666	Wet	Advanced Test Reactor fuel discharged after fiscal year 2005	Uranium aluminide fuel with aluminum cladding
	Dry Cask	21 fuel types transferred from the CPP-666 pool, including all Advanced Test Reactor fuel discharged prior to fy. 2006	Various
MFC RSWF	Dry	Experimental Breeder Reactor-II blanket assemblies	Low-enrichment uranium metal fuel with sodium bonding between the fuel and the stainless-steel cladding
	Dry	Experimental Breeder Reactor-II driver assemblies	High-enrichment uranium-molybdenum alloy fuel with sodium bonding between the fuel and the stainless-steel cladding
INTEC CPP-603	Dry	Fort St. Vrain commercial nuclear power reactor	Thorium-uranium carbide fuel in a graphite matrix
	Dry	20 fuel types from domestic and foreign research reactors	Various

1.5 Legal and Regulatory Constraints on the Management of Spent Nuclear Fuel

There are several legal and regulatory constraints on the management and disposal of DOE-owned SNF. A significant legal agreement affecting SNF is management at INL is the 1995 Settlement Agreement between the state of Idaho, DOE, and the U.S. Navy (Idaho, DOE, Navy 1995). The agreement places certain constraints on the transfer of SNF into and out of the state of Idaho. Part of the 1995 Settlement Agreement mandated the move of fuel from wet storage to dry.

In accordance with the National Environmental Policy Act of 1969 (NEPA 1969), DOE issued two decisions that influence how DOE-owned SNF is managed. The first, a programmatic environmental impact statement, directed that SNF be consolidated by type at Hanford, INL, and SRS pending future decisions on ultimate disposition (DOE 1995a, 1995b). This was amended in light of the 1995 Settlement Agreement, leaving similar types of SNF at all three sites (DOE 1996a, 1996b). The second decision pertained to accepting foreign research reactor SNF in accordance with a proposed nuclear weapons nonproliferation policy regarding uranium enriched in the US in aluminum based SNF and Training, Research, Isotopes, General Atomics (TRIGA®) SNF (DOE 1996).

Regulations on storing, transporting, and disposing of DOE SNF cover a broad spectrum of safety management issues and affect the activities that DOE undertakes to manage and dispose of its SNF. DOE self-regulates the management of DOE-owned SNF at its storage locations. Table 2 provides a list of regulations from the NRC (Title 10) and U.S. Environmental Protection Agency (Title 40) relevant to how DOE manages and disposes of SNF. At present, it is unclear how demonstrations of microreactor technology fits into the existing legal and regulatory framework. This is true both in general and particularly with respect to the disposition of microreactor SNF.

Table 2: NRC and EPA regulations that relevant to DOE management and disposal of SNF

Regulated Activity	Regulation	Title of Regulation
Facility Management	10 CFR 830	Nuclear Safety Management of Facilities
Occupational Safety	10 CFR 835,	Occupational Radiation Protection Program.
Storage	10 CFR 72	Licensing Requirements for the Independent Storage of Spent Nuclear Fuel, High-Level Radioactive Waste, and Reactor-Related Greater-Than-Class-C Waste
Transportation	10 CFR 71, 49 CFR 173	Packaging and Transportation of Radioactive Material
Disposal	40 CFR 197	Public Health and Environmental Radiation Protection Standards for Yucca Mountain, Nevada
Disposal	10 CFR 63	Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada
Disposal	40 CFR 191	Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes (applicable to disposal at sites other than Yucca Mountain)
Disposal	10 CFR 60	Disposal of High-Level Radioactive Wastes in Geologic Repositories (applicable to disposal at sites other than Yucca Mountain)
Hazardous Chemical Waste Management	40 CFR 261 (Subpart C)	Characteristics of Hazardous Waste

2. CHARACTERISTICS OF SPENT FUEL AND ITS MANAGEMENT AND DISPOSAL

2.1 Criticality

For purposes of storage, transportation and disposition of SNF, measures must be taken to maintain subcriticality of the SNF package. Criticality safety evaluations define the design of the SNF canister to prevent inadvertent criticality. Some components are used to maintain a specific geometry of the SNF. Neutron-absorbing materials may be added to the disposal canister to mitigate the potential for criticality. Comprehensive criticality analyses have been done for the disposal of a broad range of fuels currently in the INL inventory that can reasonably be expected to bound the range of potential microreactor SNF. In the unlikely event that the microreactor SNF falls outside the bounds of these fuels, the same processes can be exercised to extend the space of the analyses.

The criticality potential during storage, handling and disposal of HALEU-fueled microreactors could be higher than that of typical commercial SNF but it is considerably less than highly enriched uranium which is routinely stored at INL. For the purpose of analyzing criticality, DOE classified its SNF into nine separate criticality groups (DOE 2009) and individually analyzed the potential for naval SNF criticality. Within each of the nine criticality groups, DOE selected a single fuel design as representative of the remaining fuel within each group (see Table 3 NWTRB 2017a). DOE defined the term "representative" to mean "… that all fuels would perform similarly regarding chemical interactions within the waste package and basket, and that canister loading limits from the representative fuel (ranges of key parameters important to criticality such as linear fissile loading and total fissile mass) are established, for which other fuels within the group can be shown to not exceed" (DOE 2009). The parameters of a representative fuel are used during criticality calculations for each criticality group (e.g., N Reactor for criticality group 1). Several criticality groups require the addition of neutron absorbers during packaging for criticality control.

For each representative fuel, comprehensive evaluations have been performed including various degradation states (from fully intact to fully degraded) and criticality control limits established to maintain subcriticality under the most conservative scenarios for each criticality group (DOE 2009). This approach can be used for microreactor designs that can be demonstrated to fall within these same SNF groups currently under DOE control. Should a microreactor fuel design fall outside these envelopes, a new group of fuel type will be created, and at the corresponding analysis performed to facilitate safe disposal.

Table 3: Criticality groups with their fuel type and representative fuel

Criticality Group Number	Fuel Type	Representative Fuel
1	Uranium metal	N Reactor
2*	Mixed oxide	Fast Flux Test Facility
3*	Uranium-molybdenum/ uranium-zirconium alloy	Enrico Fermi
4	High-enriched uranium oxide	Shippingport pressurized water reactor Core 2 seed
5*	Uranium-233/thorium oxide	Shippingport Light Water Breeder Reactor
6	Thorium-uranium carbide	Fort St. Vrain
7*	Uranium-zirconium hydride	Training, Research, Isotopes, General Atomics (TRIGA®)
8*	Highly enriched aluminum clad uranium aluminide	Advanced Test Reactor
9	Low-enriched uranium oxide	Three Mile Island Unit 2 debris

*These criticality groups may require the addition of neutron absorbers for criticality control during packaging into DOE Standardized Canisters.

2.2 Confinement

Nuclear material must be confined to assure that it is not released to the environment. This is initially a function of the fuel design, whether the function is achieved by use of metal cladding or by graphite and ceramic coatings. In a molten salt reactor, the primary confinement is the reactor vessel. In spent fuel management the barrier that assures confinement may be the canister, since some fuel may have breached cladding. Maintenance of the barrier is done by controlling internal and external corrosion and assuring that the barrier will not be compromised by any of several effects.

2.3 Heat Generation

After removal from the reactor, SNF will continue to generate residual heat. The intensity of the heat generation rate is largely determined by the burnup and the cooling time of the SNF. Typically, fuels with higher enrichment can achieve higher burnups and therefore may have higher heat generation rates per unit mass of SNF. DOE currently manages SNF with enrichments from 0.72 percent to 93 percent uranium-235 over a wide range of burnups from slightly irradiated to over 500 gigawatt-days per metric ton of uranium (GWd/MTU). If the storage package cannot dissipate heat effectively, the package could become pressurized, leading to a compromised confinement barrier. It is expected that the heat generation rates observed in microreactor SNF will be well within the range of current operational experience and would not present a significant hurdle with respect to safe and secure disposition.

2.4 Storing Spent Nuclear Fuel

Two options exist for SNF storage; wet storage and dry storage. Wet storage is typically used immediately after the fuel is discharged from the reactor, when the radiation dose and heat generation rates are very high. Reactor and spent fuel pools are typically co-located with the reactor and used in normal reactor operations such as refueling. With most microreactors proposing modular operation in which fuel is loaded and unloaded only in the manufacturing facility, it is unlikely that out-of-core wet storage capacity will be provided in commercial microreactor designs. Wet facilities may be necessary for disassembly and handling of prototype and/or demonstration microreactors operated at INL. After a period of cooling, the SNF can be transferred to dry storage. Dry storage facilities may include, hot cells, in-building or underground dry storage vaults, or multipurpose dry storage and transportation casks. Modular microreactor design may include an integral shielding package that meet the functional criteria for dry storage and transportation. If the microreactor design is not compatible with interim storage and transportation, INL has the facilities and capabilities to provide adequate dry storage for various types of discrete SNF.

Dry storage design requirements depend on factors including radiation dose and heat generation rates, the physical condition of the fuel, criticality potential (enrichment, burnup, and geometry), and chemical reactivity. These factors also influence preconditioning and monitoring that may be required before or during dry storage. Some microreactor fuel types may require processing to remove reactive materials (as in the case of sodium/potassium bonded fuels), decrease the final repository load (graphite matrix fuels) and/or foster material recovery. Such processing will produce various waste streams that will be dealt with separately from the SNF.

The SNF is required to be stored using a design that 1) assures subcriticality, 2) maintains the fuel as integral units that can be individually be handled for repackaging, 3) provides structure is able to confine the radioactive material to prevent release to the environment in operational and accident conditions, 4) provides thermal control to dissipate heat that could adversely affect the system’s containment function, and 5) provides radiation shielding to minimize personnel dose to levels acceptable in storage and transportation. (Ref. NUREG-1563)

2.5 Packaging Spent Nuclear Fuel for Transportation and Disposition

In order to transport microreactor SNF to a final repository following a demonstration at INL, the SNF must be packaged, transported and received at the repository where they are transferred into a waste package prior to emplacement. The DOE strategy for packaging and transporting its

SNF is to use commercial transportation casks containing either bare SNF, multi-canister overpacks (MCOs), or DOE Standardized Canisters and three types of multi-purpose canisters. Microreactor SNF storage and transportation packaging will ideally be compatible with this strategy. It is assumed that most microreactor SNF types can be adapted to be consistent with this approach. Depending on the characteristics of the microreactor SNF, changes in canister internals and materials may be required. Any treatment or conditioning of microreactor SNF will depend on the characteristics and condition of the microreactor SNF

Three canister types have been identified for use in packaging, transportation and disposition of DOE-owned SNF; the multi-canister overpack, the naval SNF canister and the DOE Standardized Canister. Of the three, only the DOE Standardized Canister has not been deployed in the field for storage of SNF to date. The MCO has been used to package low-enriched Hanford SNF from 2002 to 2012 (Bader 2013). DOE, through its National Spent Nuclear Fuel Program, developed the DOE Standardized Canister design as a component of a system for SNF disposal. The DOE Standardized Canister provides a leak tight barrier that contains radionuclides and prevents moderator intrusion during normal and hypothetical accident conditions during storage, transport, and repository operations.

There are four sizes of the DOE Standardized Canister, varying in diameter (18-inch and 24-inch) and height (10-foot and 15-foot). The four sizes of canisters are needed to accommodate the varied sizes and shapes of DOE SNF and to maximize packaging efficiency. Figure 3 shows a schematic of the DOE Standardized Canister. It is expected that various microreactor designs will be accommodated in DOE Standardized Canister configurations. Several internal basket assemblies are used to fit various fuels; five examples are shown in Figure 4. Figure 4A shows the basket used for loading aluminum clad fuels (Advanced Test Reactor (ATR), Massachusetts Institute of Technology Reactor (MIT), University of Missouri Research Reactor (MURR), and the Oak Ridge Research Reactor (ORR)). This same basket can be used to hold graphite structure thorium-uranium carbide Peach Bottom SNF. Figures 4B through 4E show the TRIGA® fuel, FSV fuel. Three Mile Island (TMI) Unit 2 and Shippingport PWR Core 2 fuel baskets respectively. The internal basket assemblies facilitate loading of the SNF into the canister during packaging and provide structural support for the DOE SNF during packaging and transportation. Depending on the microreactor SNF characteristics, an existing canister basket may be used, or a new basket developed. Supplemental criticality control in the form of neutron absorber materials may be required as part of the canister internals. The same strategies can be applied to microreactor SNF. The dimensions of the SNF will serve to establish the customized requirements for the canister internals to accommodate the physical dimensions, type, and number of fuel assemblies to be packaged inside the DOE Standardized Canister.

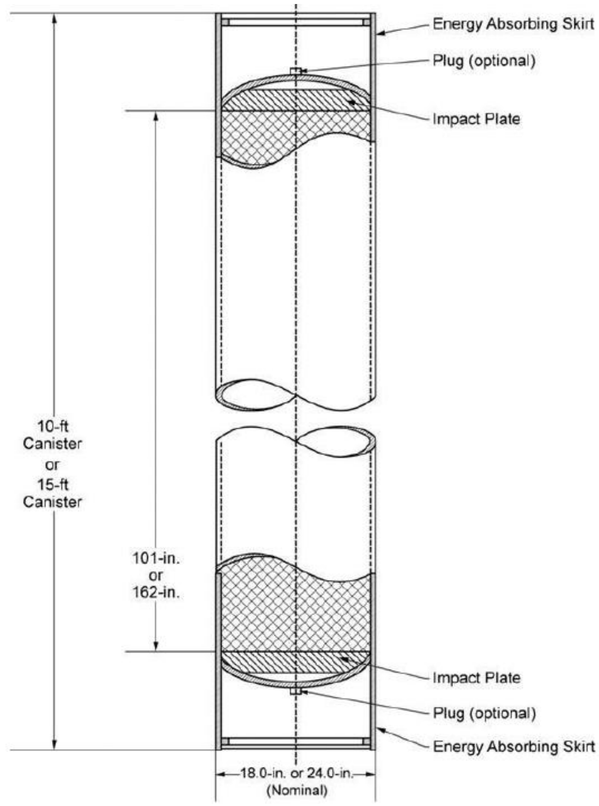

Figure 3: DOE Standardized Canister for the disposition of SNF

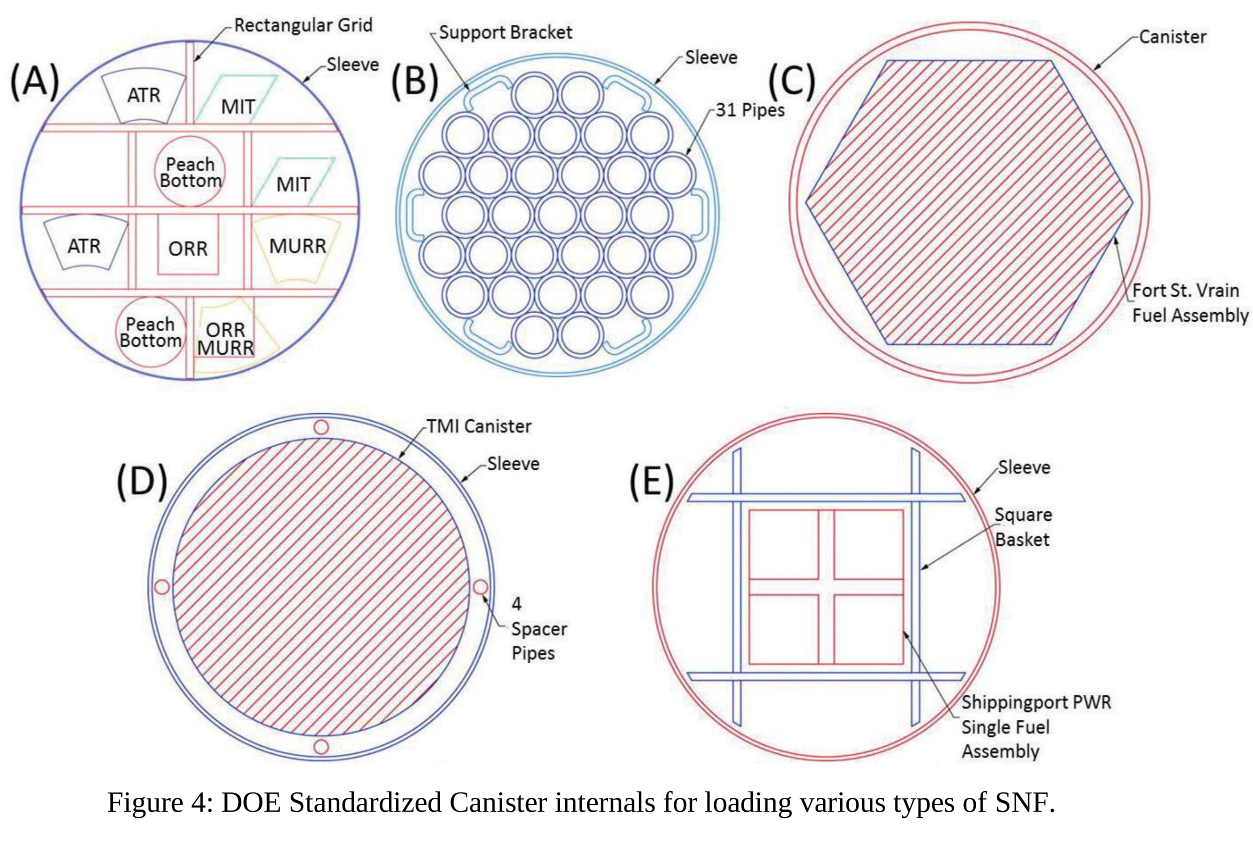

Figure 4: DOE Standardized Canister internals for loading various types of SNF.

2.6 Transporting Spent Nuclear Fuel

For the Yucca Mountain Repository project, DOE intended to transport all DOE-owned SNF from INL to a final repository via railroad. These shipments will utilize commercially available transportation cask systems. Intact commercial BWR and PWR fuel will be handled using standard commercial practices (NWTRB 2017a). All other DOE SNFs will be transported in a commercial cask containing an array of DOE Standard Canisters or MCOs. As identified earlier, unless the microreactor design has integral or custom-designed storage and transportation functionality, it is expected that microreactor SNF storage, transportation and disposition will use the DOE Standardized Canister. For any microreactor design, it will be necessary to have a licensed transportation solution using either the DOE Standardized Canister system or a commercial transportation package. It should be noted that many microreactor designs propose modular operation with all fuel handling operations performed in the manufacturing facility. Thus, it is likely that the certified reactor system will include an NRC-certified means for transporting the reactor and fuel.

2.7 Disposal of Spent Nuclear Fuel

The most mature permanent repository disposal concepts have been developed for repository systems constructed in salt, crystalline rock, clay/shale, or volcanic tuff formations. Depending on the disposal concept, waste isolation may depend more on the engineered components (the waste form, waste package etc.) than the natural components (the host rock) of the repository. The microreactor SNF radiation dose and heat generation rates, physical condition (intact or damaged), criticality potential (enrichment, burnup, and geometry), and chemical reactivity (material selection) will affect the waste form performance in a permanent repository. The diverse nature of proposed microreactor SNF is consistent with DOE's current SNF inventory and therefore the permanent disposition options of microreactor SNF are much the same as that for other DOE-owned SNF. Treatment and conditioning of the SNF may be necessary to ensure safe interim storage, safe transport, and disposal. The diversity of proposed microreactor SNF types, along with the intent to use HALEU, may require use of supplemental neutron absorbers for criticality control.

3. DESCRIPTION OF MICROREACTOR FUELS

Identification and evaluation of disposition options requires a detailed characterization of the SNF and is dependent on several factors. These factors include the design and operational conditions of the reactor, the physical and chemical characteristics of the fuel, the duration of post irradiation cooling and the current condition of the fuel (intact or damaged). In the absence of a sufficiently detailed microreactor description, two generic microreactor concepts were selected for this options assessment in support of near-term demonstrations of microreactor technology at INL using DOE-owned HALEU. The selected reactor concepts are examples of the two general microreactor types under consideration in the U.S: a tristructural isotropic (TRISO)-fueled high temperature gas reactor (HTGR) and a sodium/potassium-bonded heat pipe reactor with uranium oxide fuel. Both concepts use nearly the same amount of HALEU, although in different forms. Other reactor concepts such as liquid-metal cooled, fast-spectrum reactors that use either sodium or lead coolant have historically been considered highly suited for small reactor applications. Presently there is no evidence of U.S. developer interest in this technology and as such a generic concept is not considered here. (Kennedy et al. 2018)

3.1 TRISO Fueled Microreactor

HTGRs using TRISO fuel are thermal neutron spectrum reactors typically with helium as the coolant. The use of graphite blocks and TRISO particle fuel with the ability to retain fission products within the multi-layer spherical particles also reduces the risk of radioactivity release to the environment (DSB 2016.). The modern TRISO fuel particle consists of a nominally 350 micron diameter uranium oxycarbide fuel kernel encapsulated in alternating layers of impermeable carbon and ceramic that yield an 800 micron outer diameter sphere designed to prevent the release of radioactive fission products produced within the fuel kernel. Figure 5 shows a schematic of a TRISO fuel particle. These fuel particles may be dispersed into a graphite matrix and pressed into fuel compacts for use in a prismatic block for a monolithic core design or formed into a spherical fuel spherical fuel pebble for the flowing pebble bed variation of the HTGR. Figure 6 shows an FSV-type prismatic block fuel element and a pebble bed-type pebble (Fortescue et al. 1965). All variations of TRISO particle-containing fuel benefit from high retention of fission products. There is extensive operational experience with TRISO fuel with the Fort St Vrain in Colorado (DSB 2016.).

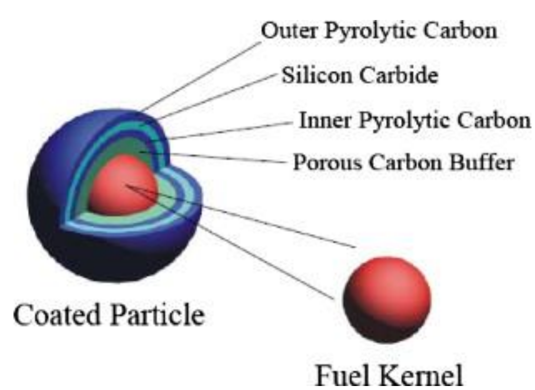

Figure 5: Schematic of a TRISO particle

Figure 6: Typical US prismatic graphite fuel blocks

3.2 Heat Pipe Microreactor

The heat pipe reactor concept is predicated on taking advantage of the high heat removal capacity of modern heat pipe technology to quickly dissipate heat generated within the reactor core. The heat pipe transfers heat between two bodies by utilizing the phase change of the fluid as it moves from evaporation at one end to condensation at the other. This ability makes heat pipes ideal for extracting thermal power from a nuclear reactor. Figure 7 shows a schematic of a generic heat pipe with the heated region to the left and the cooled region to the right. at the bottom (Bragg-Sitton 2004). Researchers at LANL and the U.S. National Aeronautics and Space Administration (NASA) have a long history of investigating the use of small highly reflected fast reactor concepts with liquid-metal heat pipes as the means of heat removal from the reactor core for tens to hundreds of kilowatt scale (Gibson et al.). The Special Purpose Reactor, also known as the “MegaPower” reactor, is a 5 MW thermal, fast reactor design concept producing approximately 2 MW of electric energy. The fuel is uranium dioxide pellets (19.75% enriched) contained in a stainless-steel monolith of fuel channels and heat pipes. The heat pipe uses potassium as the working fluid (McClure et al. 2015). Heat pipe reactors, that use alkali metals such as sodium or potassium can be designed to use metallic, oxide, or nitride fuel. Figure 8 shows a design concept of the MegaPower power reactor. Based on this core design, it is assumed that the core would require disassembly and potentially treatment prior to disposition of the SNF.

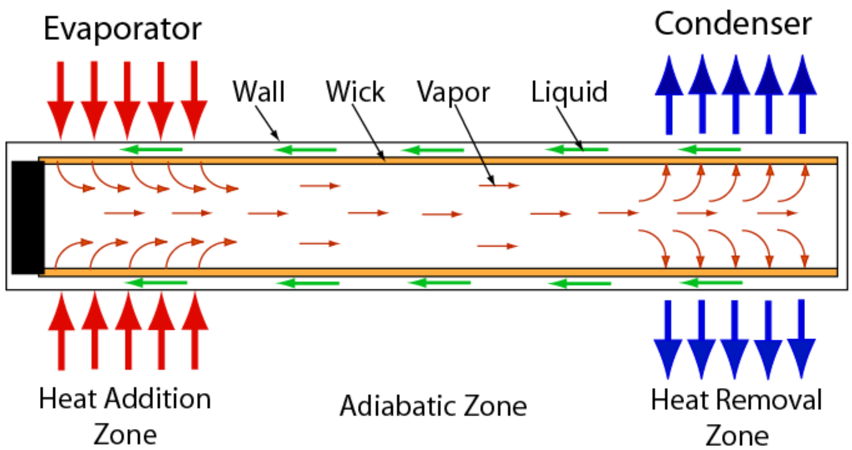

Figure 7: Generic heat pipe showing heated region to the left and the cooled region to the right

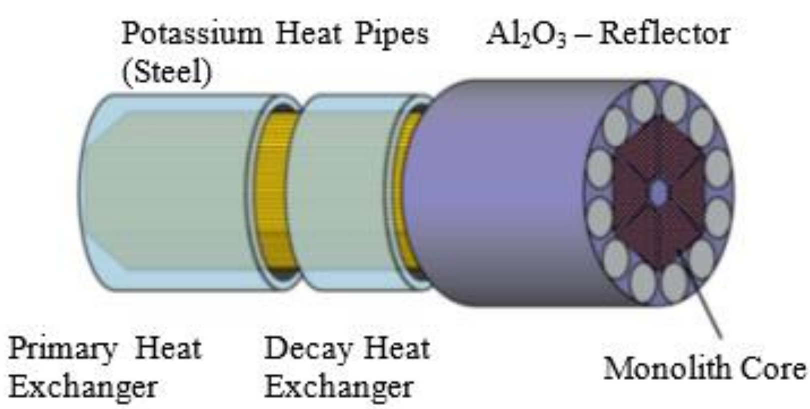

Figure 8: A heat-pipe reactor showing key components of the design.

4. INL FACILITIES FOR MANAGEMENT OF SPENT NUCLEAR FUEL

As stated, INL currently stores and manages over 250 types of SNF. Its SNF inventory totals approximately 315 MTHM (INL 2019) stored in both wet and dry storage facilities at the Idaho Nuclear Technology and Engineering Center (INTEC), Materials and Fuels Complex (MFC), Naval Reactors Facility (NRF). The individual facilities considered suitable and potentially available for microreactor SNF storage are: (1) CPP-603 - Irradiated Fuel Storage Facility, (2) CPP-749 - Underground Fuel Storage Facility, (3) CPP-2707 - Cask Pad Facility, and (4) The Radioactive Scrap and Waste Facility (RSWF). The Hot Fuel Examination Facility has capacity to store some SNF; however, its primary purpose is the post irradiation examination of irradiated specimens and additional storage interferes with its primary mission. The CPP-666 - Fuel and Storage Facility has both wet and dry storage capabilities that could be used for microreactor SNF; however, under the 1995 Settlement Agreement, all SNF is scheduled to be out of wet storage by the end of 2023. Figure 9 shows an aerial view of the storage facilities at INTEC showing the CPP-603, CPP-749, CPP-2707 and CPP-666 facilities. Table 4 summarizes information about SNF currently stored in these facilities. It includes only those fuel types, that by total mass, account for most of the inventory.

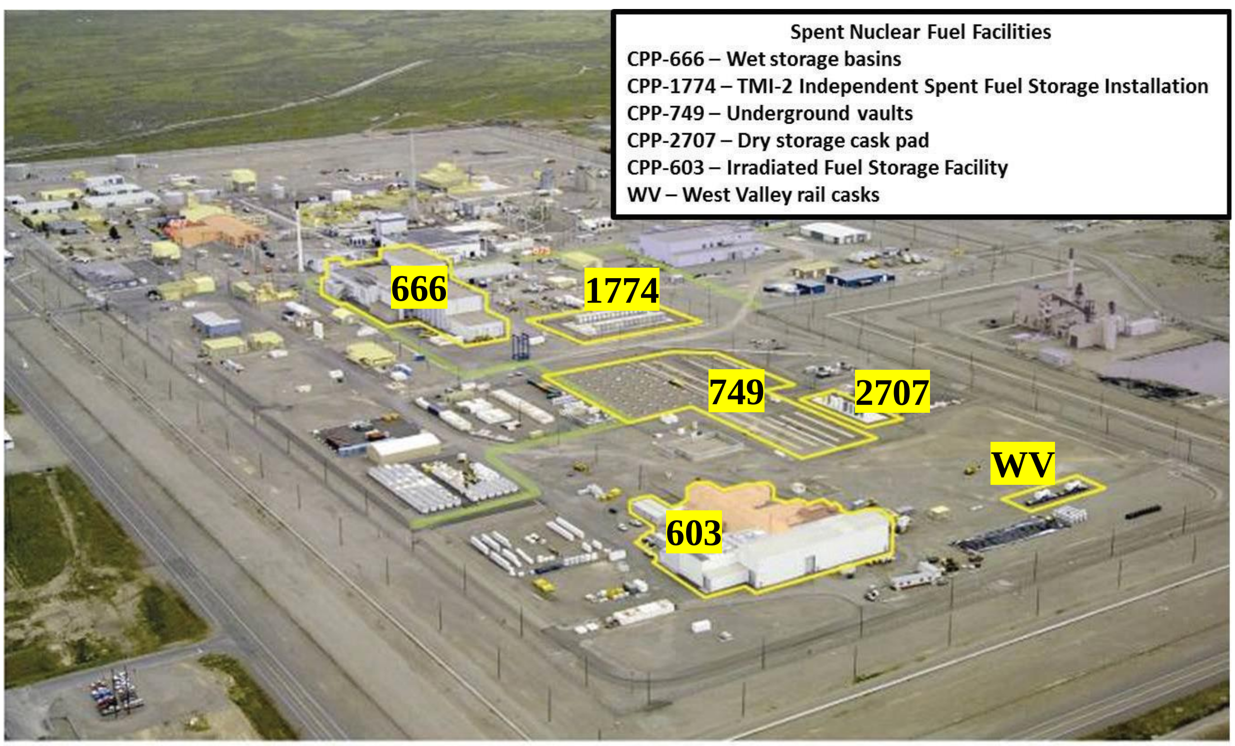

Figure 9: Aerial view of storage facilities at the Idaho Nuclear Technology and Engineering Center.

Table 4: Characteristics of INL SNF storage facilities

Storage Facility	Type of Storage	Storage Containers and Arrangement	Storage Capacity	Currently in Storage or in Use	Design Life of Facility or Year of Construction or First Use	Authorized Storage Ends in Calendar Year
CPP-603	Dry vault in building	Vertical storage tubes inside shielded vault	636 storage tubes	~580 in use	First use in 1974	2035
CPP-749	Dry vaults outside	Carbon steel pipes with shield plugs, installed below-grade as individual vaults; three types built between 1971 and 1985	218 vaults	128 in use	First use in 1971	2035
CPP-2707	Dry cask outside on pad	Commercial casks (REA 2023, VSC-17, TN-24P, CASTOR® V/21, Nu-Pac 125B, MC-10) on concrete pad	20 casks	6 casks	Pad constructed in 2003, 40 years	2035
CPP-666	Pool system inside building	Six stainless steel–lined pools with lidded racks	2,911 storage positions	~870 in use	Operational in 1984, 40 years	2035
	Dry cask	Cans in Nu-Pac 125B casks	–	208 cans in 2 casks	-	2035
RSWF	Dry, silos outside below-grade	Inner and outer container within carbon steel liners	~1,350 silos	–	Built in 1965	2035

4.1 CPP-603 – Irradiated Fuel Storage Facility

The CPP-603 Irradiated Fuel Storage Facility (IFSF) was built in 1974 as an addition to the CPP-603 basin storage facility. The facility was designed to store the irradiated fuel from the FSV HTGR in Colorado. However, due to legal challenges, only one-third of the FSV SNF were shipped to Idaho. The remaining capacity of CPP-603 is now used to store fuels from domestic and foreign research reactors.

IFSF includes the fuel handling cave and the fuel storage area. The storage area is a vault with 4-ft thick concrete shield walls that is fitted with an open steel substructure that supports 636 18 in OD x 11 ft long canisters. Storage positions are arranged in a triangular lattice, with a nominal center-to-center lattice pitch of 24.0-in. Canisters are placed in the storage positions (holes in the steel deck plate) and hang from supported by the canister upper flange. The storage area is serviced by a 10-ton bridge crane that rides on rails that traverse the length of the storage area at approximately 15 feet height. Figure 10 shows a plan view of the IFSF and Figure 11 shows remote handling of a canister in the fuel storage area (Davis 2009).

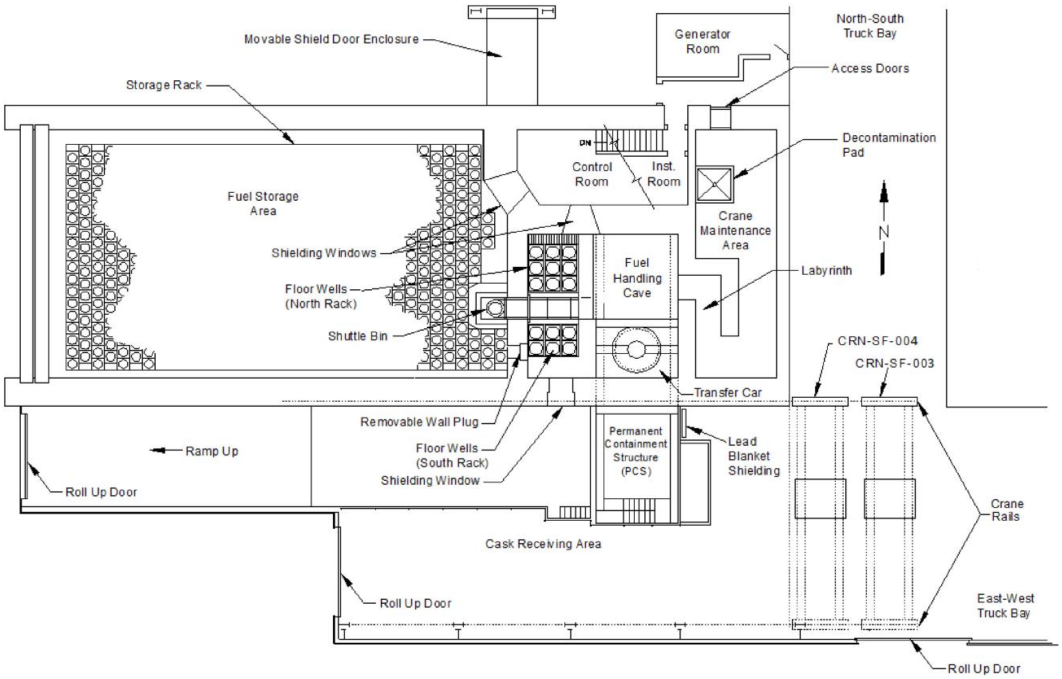

Figure 10: Plan view of the Irradiated Fuel Storage Facility.

The fuel handling cave was designed for receipt of casks and preparation of fuel for storage. It includes the north and south floor wells that are used for storage during fuel handling, conditioning, and packaging. Wells 1 through 9 are in a 3 × 3 square pitch array north of the shuttle bin, while wells 10 through 15 are in a 2 × 3 square pitch array south of the shuttle bin station. The facility has the capability for both forced and natural ventilation to ensure decay heat removal. Prior to placing SNF in the fuel storage area, DOE uses a heated vacuum system to remove water from previously wet-stored fuels by heated vacuum drying their storage container at 100°C (Beller 2014a). DOE has used this method to dry Training, Research, Isotopes, General Atomics (TRIGA®) fuel, uranium alloy fuels, ATR fuel, and other aluminum test reactor fuels (Beller 2014a) stored at this facility (DOE 2005). SNF is remotely handled (RH) and stored in 18-inch-diameter cylindrical stainless-steel canisters. The facility can handle Advanced Test Reactor, FSV, and Peach Bottom cask types (Bohachek et al. 2013).

Figure 11: Remote handling of a storage canister in the CPP-603 vault.

The IFSF was designed to provide safe interim fuel storage. To meet this goal, the main operations performed in the IFSF include receiving nuclear fuels from other facilities, packaging and conditioning fuels for interim storage, safely storing fuels, storing fuel-loaded storage casks on an interim basis, and packaging fuels for removal from the facility. This makes it suited to support microreactor SNF management needs.

4.2 CPP-749 – Underground Fuel Storage Facility

The CPP-749 storage facility is an outdoor storage facility designed to safely store fuel and retrieval capabilities for eventually transferring the fuel out of the facility. The facility consists of a fenced enclosure containing 218 vertically oriented fuel storage vaults (Birk 2013). Figure 12 shows a plan view of Outdoor Fuel Storage Facility (OFSF) which comprises of both CPP-749 and CPP-2707. The CPP-749 vaults are installed below grade, with the tops slightly above grade. The vaults are principally 30-in.-diameter carbon-steel pipes, closed on the bottom, and placed in holes drilled in the existing soil in the area. CPP-749 is used to store approximately 78.4 MTHM of SNF including SNF from Peach Bottom Unit 1 Core 1, SNF from the Shippingport Light Water Breeder Reactor, and Fermi-1 blanket SNF (DOE 2005).

The first-generation storage vaults were built to store Peach Bottom Unit 1 SNF and loaded in September 1971. However, corrosion issues from moisture intrusion resulted in transition to a second generation of vaults (Kingrey 2003; Beller 2014b). Some of the first-generation vaults remain unusable. Two types of second-generation vaults were built in 1984 and 1985 – one to store un-irradiated Shippingport Light Water Breeder Reactor fuel and another to store Shippingport SNF. The CPP-749 vaults are subject to routine surveillance, gas (hydrogen) monitoring, and corrosion monitoring (Hain 2010; Beller 2014b). Figure 13 shows rows of second-generation vaults at CPP-749 (Davis 2009).

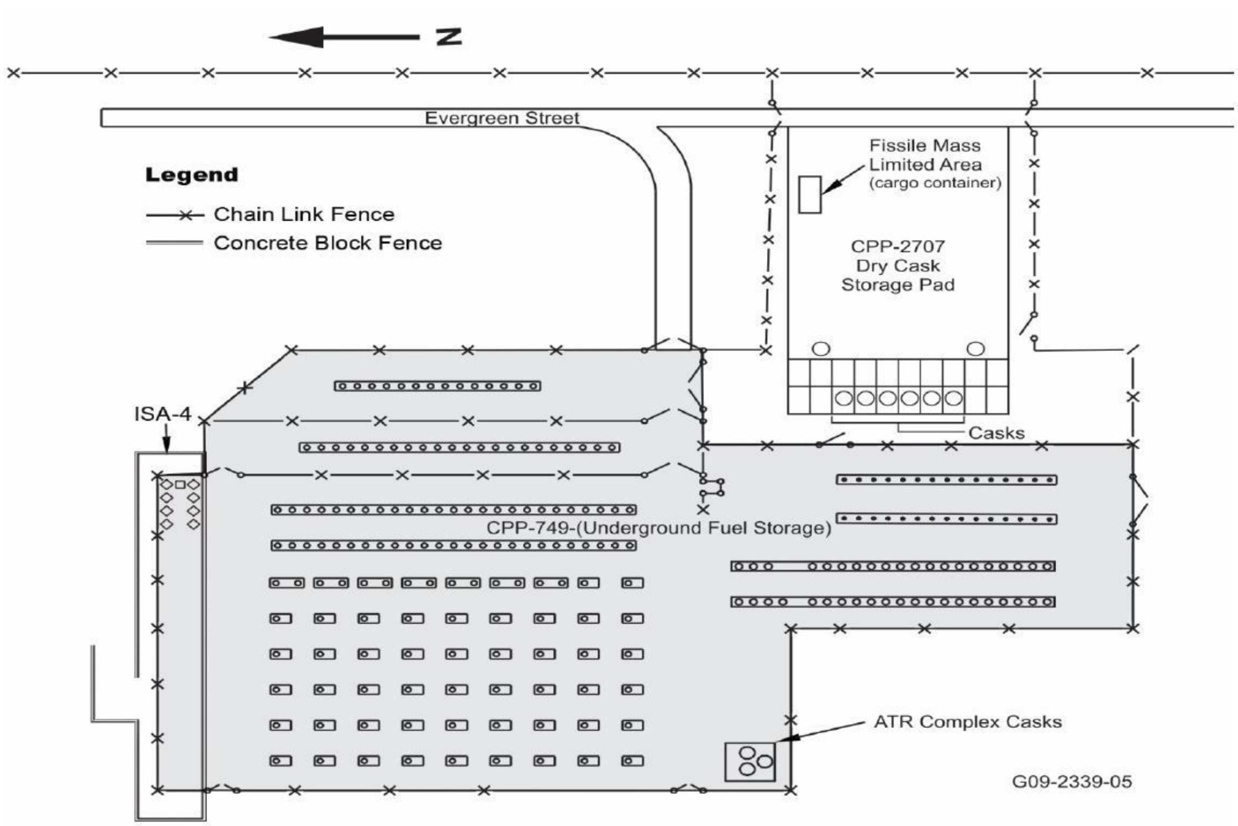

Figure 12: Plan View of the Underground Fuel Storage Facility and the Cask Pad Facility.

Figure 13: Second-generation underground vaults at the Underground Fuel Storage Facility

4.3 CPP-2707 – Cask Pad Facility

The CPP-2707 Cask Pad Facility is part of the Outside Fuel Storage Facility (OFSF), which includes CPP-749. The OFSF is designed to provide safe storage of fuel and to provide retrieval capabilities for eventual transfer of the fuel out of the facility. Figure 12 shows a plan view of the OFSF, including CPP-2707 Cask Pad. The concrete pad area could accommodate 20 cask systems of the type currently in service. Currently, eight fuel loaded casks are located on the concrete pad; The Gesellschaft fur Nuclear-Service (GNS) Castor V/21, Westinghouse MC-10, Ridihalgh, Eggers, and Associates, Inc. (REA)-2023, (5) Transnuclear, Inc. (TN)-24P (6) Pacific Sierra Nuclear Associates Ventilated Storage Cask (VSC)-17; were brought to INL in the mid- to late 1980s to validate the effectiveness of these systems as part of the Dry Cask Demonstration Project. They were moved to INTEC in 2003. They are loaded with a combination of commercial PWR fuel from Virginia Power’s Surry Nuclear Power Plant and Florida Power and Light’s Turkey Point Generating Station under a DOE cooperative agreement. Figure 14 shows the casks currently on the cask pad facility.

Two rail casks—the TN-REG (nominally a TN-40 PWR) and TN-BRP (a TN-68 BWR design)—are also stored at the CP-2707 facility. DOE moved the West Valley rail casks to Idaho in 2003, The casks were used to transport 125 assemblies of intact and damaged PWR and BWR commercial SNF from the West Valley Demonstration Project in New York reprocessing facility to INL. Before the SNF was transported to INL, it had been stored at West Valley since the reprocessing facility was shut down in 1972 (Williams 2004; Hain 2010). Figure 15 shows one of the two rail casks at CPP2707 (Beller 2013).

Figure 14: Dry storage casks on the Cask Pad Facility

Figure 15: One of two West Valley rail casks stored at CPP-2707.

4.4 MFC-771 – Radioactive Scrap and Waste Facility

The MCF-771 RSWF is an outdoor, fenced-in facility designed to provide interim storage for radioactive material that requires shielding to protect workers from the significant gamma radiation fields associated with the material. RSWF currently provides interim storage for SNF, accountable material, RH mixed waste, and various radioactive wastes (e.g., TRU, RH LLW, mixed RH-TRU). The SNF includes Experimental Breeder Reactor-II (EBR-II) blanket and driver fuels and other experimental nuclear fuels, in the form of metal, oxides, nitrides, and carbides of uranium, plutonium, or mixed uranium-plutonium. There are no permanent buildings associated with RSWF. This facility contains about 1,350 below-ground, silo-type storage locations, provides the bulk of interim SNF storage at the MFC. The carbon steel–lined silos are 2ft in diameter and 12ft long (Smith et al. 2001; Gonzales- Stoller Surveillance 2012). Figure 16 shows four of the eight different steel liner configurations in the RSWF.

In 2011, DOE started moving the sodium-bonded EBR-II driver fuel from the CPP-666 basins to the RSWF and plans to complete shipments by 2023. At present, it is assumed that RSWF will function as lag storage prior to molten salt electro-metallurgical “pyroprocessing” through the MFC-765 Fuel Conditioning Facility DOE plans to continue treatment of the driver SNF at FCF. (Lacroix 2014a, 2014b). Non-EBR-II sodium-bonded SNF stored at the RSWF includes sodium debris bed material from Sandia National Laboratories (Kula 2010).

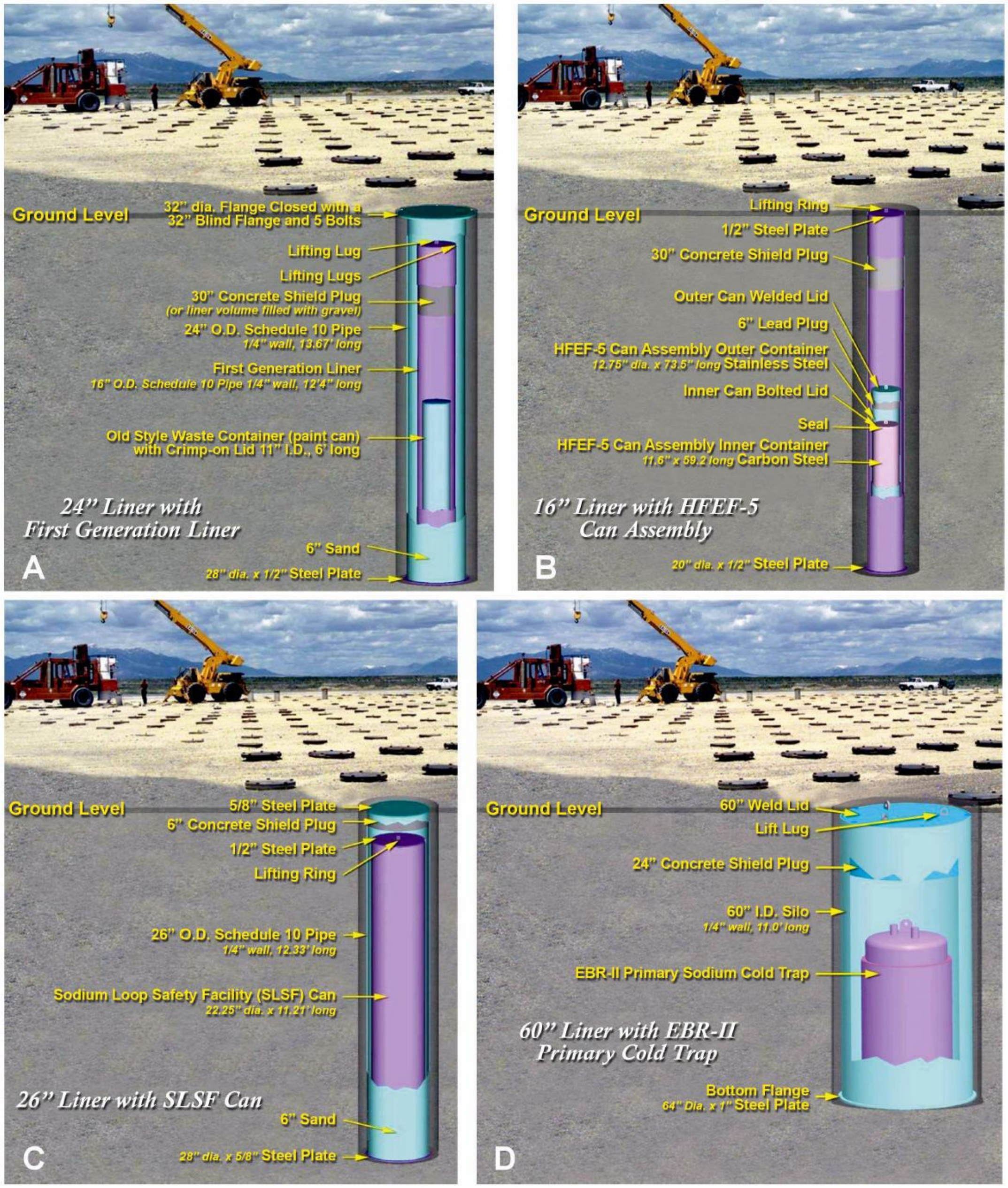

Figure 16: Four of the eight different steel liner configurations in the RSWF.

4.5 MFC Hot Fuel Examination Facility

DOE designed HFEF to be the front end of INL's post-irradiation examination capability (DOE 2012). Commissioned in 1975, the facility consists of a multi-program hot cell system with two adjacent shielded hot cells – one with an air environment and the other in an argon environment (BRC 2010). The facility "can receive and handle kilograms to hundreds of kilograms of nuclear fuel and material in almost any type of cask" (DOE 2012). The missions of the Hot Fuel Examination Facility include bench-scale electrochemical separations testing and engineering-scale, waste-form development to support operations in the Fuel Conditioning Facility at the MFC (DOE 2012).

The DOE designed the Hot Fuel Examination Facility to be the front end of INL's post-irradiation examination capability (DOE 2012). Commissioned in 1975, the facility consists of a multi-program hot cell system with two adjacent shielded hot cells (one with an air environment and the other in an argon environment; BRC 2010). The facility "can receive and handle kilograms to hundreds of kilograms of nuclear fuel and material in almost any type of legal weight truck cask that weighs less than 30,000 lbs." (DOE 2012). The missions of the Hot Fuel Examination Facility include bench-scale electrochemical separations testing and engineering-scale, and post-irradiation examination testing of fuel experiments from the ATR and TREAT reactors. The mission of HFEF is not for fuel storage, but, out of necessity, the facility has the capability of storing small amounts of fuels for research purposes. HFEF may be a component of microreactor demonstration as a facility in which to perform post-irradiation disassembly of fuel that may contain reactive material such as sodium but is not suitable as a storage option for microreactor SNF

4.6 CPP-666 – Fuel and Storage Facility

The CPP-666 FAST (Fuel And STorage) facility has two separate areas, the Fuel Storage Area (FSA), and the Fluorinel Dissolution Process Area (FDPA). The original mission of the FSA was to provide short-term underwater storage of fuels destined to be reprocessed in the FDPA. The FDPA is being used for characterization, packaging, and loading of remote-handled transuranic (TRU) waste to meet off-site disposal criteria. Figure 17 shows the general layout of the areas within the FSA.

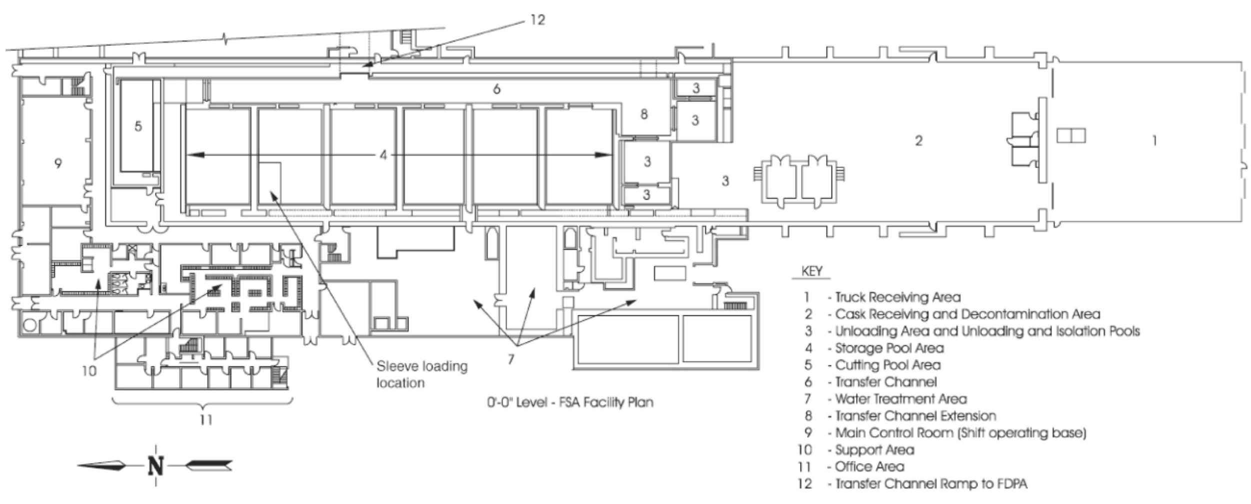

Figure 17: Plan View of the Fuel and Storage Facility

The fuel storage pool area is shown in Figure 18 (Beller 2013). The six interconnected fuel storage pools, divided by concrete walls, contain the underwater fuel storage racks. Each pool has a gate opening on the east wall to provide access to the transfer channel. The entire fuel storage pool area is constructed of reinforced concrete, and each pool is lined with stainless steel. Fuel storage racks are placed in each of the six fuel storage pools. The storage racks can be replaced with any configuration that can be accommodated by the pool dimensions. Storage pools 2 through

6 are 30 ft deep while Pool 1 and the cask unloading pools are 40 ft deep. These pools may provide "the capability for cask unloading and transfer of commercial-length fuels" (DOE 2010b). CPP-666 is being emptied of fuel as a part of the 1995 Settlement Agreement

Figure 18: Five of the six interconnected CPP-666 storage basins.

In addition to the pool storage, two Nu-Pac 125B dry casks that are loaded with miscellaneous small quantity and partially damaged fuels such as those from the Systems Nuclear Auxiliary Power Program and the Aircraft Nuclear Propulsion program are stored in the truck bay at CPP-666 (Beller 2010). DOE monitors the Nu-Pac 125B casks for hydrogen due to the use of fuel baskets that contain a concrete-based neutron poison void filler (Beller 2014b). All Navy fuels were transferred to ECF by 2018 for dry storage. The remaining ATR and EBR-II fuels are being transferred to CPP-603 IFSF for dry storage and MFC Fuel Conditioning Facility for material recovery or to RSWF for interim subterranean storage.

4.7 New Facilities

In addition to existing facilities for the management of SNF, there is also the potential for new facilities and additional commercial options for storing DOE-owned SNF. DOE recognized the need for an INL facility to prepare all its SNF (except for naval SNF), for transportation out of Idaho in accordance with the 1995 Settlement Agreement. In 2001, Foster Wheeler Environmental Corporation, a DOE contractor, applied to NRC for a 10 CFR 72 license to operate the proposed Idaho Spent Fuel Facility (ISFF) as an ISFSI (Rodgers 2001). The application described a vault storage facility. However, following the closure of the Yucca Mountain repository program in 2010 (DOE 2010a), DOE's plans—as embodied in the Idaho Spent Fuel Facility Project—focused on using the new ISFF, or reusing an existing facility, to condition, characterize, and package SNF for off-site transport, and then provide storage for packaged SNF.

The ISFF consists of three principal areas: (1) the Cask Receipt Area, (2) the Transfer Area, and (3) the Storage Area, as shown in Figure 19. For this study, the Storage Area is of greatest interest. This storage area consists of a passively cooled concrete vault housing 246 metal storage tubes. Figure 19 shows a cutaway view of the storage area and shows the handling crane with a transfer cask. Storage tubes are filled with an inert atmosphere to reduce potential corrosion of the ISF canisters during storage. Figure 20 shows a cutaway view of several storage tube assembly loaded with ISF canisters. The design has 216 storage tubes set up for 18in. diameter canisters and 30 set up for 24in. diameter canisters. Once constructed, the ISFF is expected to meet the needs for the disposition of microreactor technology demonstrations at INL.

In addition, several new commercial modular storage systems have the potential to be storage solutions for the DOE Standardized Canister, and as such, would be applicable to disposition of microreactor SNF. Furthermore, there exists the potential for customized offerings for storage of microreactor SNF as part of the microreactor design, INL demonstrations or from commercial vendors.

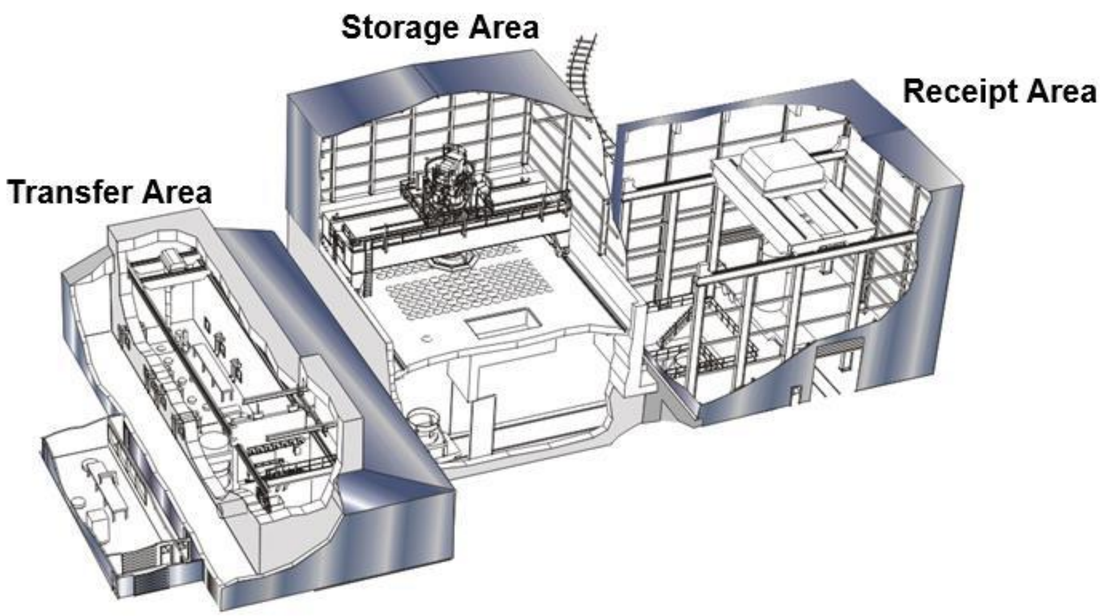

Figure 19: Cutaway view of ISFF storage vault configuration.

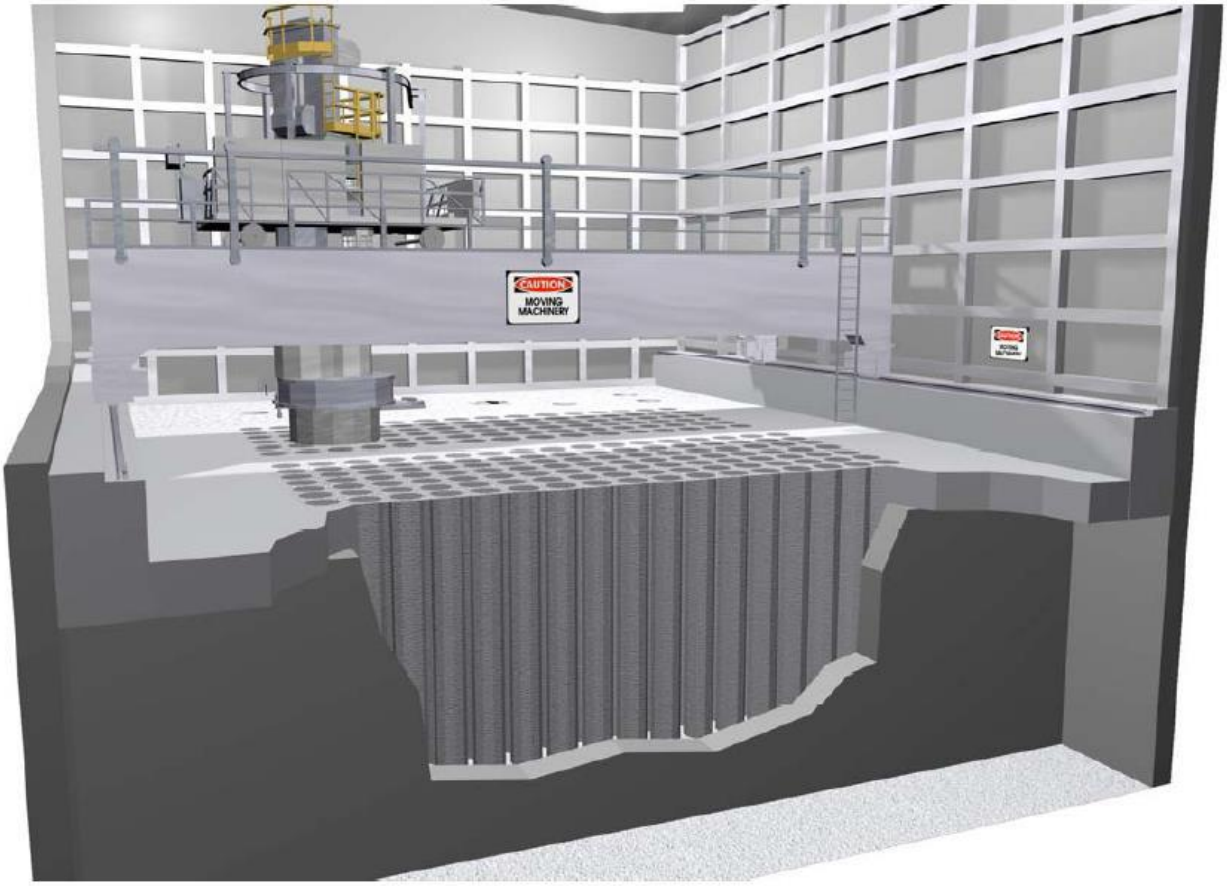

Figure 20: Cutaway view of several storage tube assemblies loaded with ISF canisters.

5. MICROREACTOR DISPOSITION OPTIONS

The following discussion of conceptual strategies for the disposition of microreactor SNF by microreactor demonstrations at INL is predicated on the information currently available. Assumptions were made to bridge any existing information gaps. Therefore, the following discussion is provided for microreactor SNF with specific commentary for the selected microreactor fuel concepts.

Where microreactor SNF demonstrably falls within the analytical envelop of a fuel type currently stored by DOE at INL, there is significant confidence current technology can be applied to provide safe and secure storage, transportation and disposition of that microreactor SNF. For microreactor SNF with significantly different characteristics from the SNF currently stored at INL, further investigation would be required. Nevertheless, for all microreactor SNF generated at INL in microreactor technology demonstrations, a complete set of engineering and safety analyses will have to be performed.

Table 5 shows the SNF that is currently stored at INL that are potentially analogous to the selected HTGR and sodium-cooled microreactor fuel concepts. The Peach Bottom and FSV SNF serve as examples of TRISO based fuel types. The Fermi-1 and EBR-II SNF serve as examples of examples of uranium metal sodium bonded fuel.

Table 5: HTGR and Sodium-Boned SNF at INL

SNF Type	Storage Facility	Storage Type	Main Source of SNF	SNF Characteristics (fuel type and cladding type)
HTGR	INTEC CPP-749	Dry	Peach Bottom Unit 1, Core 1	Thorium-uranium carbide fuel in a graphite matrix
	INTEC CPP-603	Dry	Fort St. Vrain commercial nuclear power reactor Peach Bottom Unit 1, Core 2	Thorium-uranium carbide fuel in a graphite matrix
Sodium bonded	INTEC CPP-749	Dry	Fermi-1 fast breeder reactor blanket assemblies	Uranium-molybdenum alloy fuel with sodium bonding between the fuel and the stainless-steel cladding
	MFC RWSF	Dry	Experimental Breeder Reactor-II blanket assemblies	Low-enrichment uranium metal fuel with sodium bonding between the fuel and the stainless-steel cladding
	MFC RWSF	Dry	Experimental Breeder Reactor-II driver assemblies	High-enrichment uranium-molybdenum alloy fuel with sodium bonding between the fuel and the stainless-steel cladding
	MFC HFEF	Dry	Hanford Fast Flux Test Facility fuel assemblies	Uranium–oxide fuel with sodium bonding between the fuel and the stainless-steel cladding

5.1 Interim Storage

After sufficient cooling, the SNF may be transferred to dry interim storage or to other processes along the disposition path (packaging, treatment, material recovery, or extended dry storage).

Many microreactor concepts propose a modular mode of operation whereby fueling and defueling operations are performed in the manufacturing facility and away from the microreactor deployment site. For demonstration microreactors deployed at INL, it is assumed there will be many prototypical, research and development, operational and first-of-a-kind activities performed at the microreactor deployment site that would otherwise be performed in the manufacturing facility once the microreactor reaches full scale commercial deployment. Therefore, an interim storage capability would have to be provided at INL for the demonstration micro reactor. The following are interim storage options for microreactor demonstrations at INL:

- **In microreactor-envelope interim storage.** This option involves either in-core storage of SNF or SNF storage facilities built as part of the microreactor design. For microreactors operating under the traditional paradigm of co-located reactor and spent fuel pools at the site of deployment, this option does not represent a new challenge. For reactors operating under the modular mode of operation, the design may be intended to provide interim storage in the reactor module onsite until it is defueled for final disposition. In this scenario, the reactor module becomes the storage module. If it is retained on site in Idaho, it is assumed that INL would provide facilities necessary to remove the fuel from the reactor module and containerize them for final disposition. Storing SNF within the microreactor envelope during technology demonstrations becomes challenging for fuel declared spent prior to the end of life of the reactor. Examples of fuels declared spent prior to end of life of the microreactor include prototypical fuels and damaged fuels (whether by accident or as a result of intended testing). It is likely that demonstration microreactors deployed at INL will produce both prototypical fuel elements and damaged fuel elements. Any fuel declared spent before the conclusion of the demonstration activities will likely complicate or limit the availability and capability to perform other testing and demonstration activities
- **In facilities specifically built for microreactor demonstrations.** It is assumed that many of the facilities and capabilities representative of a microreactor manufacturing requirements will be approximated at INL in support of the microreactor demonstration program. This includes capabilities to load and unload the reactor and to store fresh, intact damaged and spent fuel. Should additional facilities be built in support of the microreactor program, an interim storage capability should be prioritized.
- **In existing INL facilities.** SNF generated in microreactor demonstration activities may be stored in existing INL facilities in accordance with legal, regulatory, operations and scheduling requirements for the transfer and storage of these fuels. The diverse nature of SNF stored at INL supports the likelihood of SNF generated from most microreactor designs falling with the analytical envelope of existing SNF at INL and as such requiring minimal modifications of existing facilities to provide interim storage. Transfer to existing facilities will be predicated on the appropriate analyses/procedures and may require some degree of immediate storage within the microreactor program prior to transfer.

- **In new INL facilities.** SNF generated in microreactor demonstration activities may be stored in in newly constructed INL facilities that will be necessary as INL SNFs are packaged and consolidated in preparation for shipment off site (i.e. to a final repository or subsequent interim storage facility). Transfer to new facilities will be predicated on the appropriate analyses/procedures and may require some degree of immediate storage within the microreactor program prior to transfer.

5.2 Treatment

Treatment and conditioning of SNF while packaging may be necessary to ensure safe storage, transport and disposal. For highly enriched fuel types, supplemental neutron absorbers may be included in the disposal package for criticality control. These materials need to be carefully selected as their inclusion could further complicate the chemistry inside the package and repository and could impact package performance for future transportation and extended interim storage.

Drying is a critical conditioning process performed as part of the packaging process and is necessary for all microreactor SNF that may have come into contact with water as part of reactor operation or interim storage. For SNF stored underwater, the SNF is typically dewatered and dried using the vacuum drying process, with or without added heat. Once the system is adequately dry, the canister is backfilled with an inert gas (such as helium) for applicable pressure and leak testing.

Sodium-bonded SNF requires special consideration and treatment due to the potential for chemical reaction between elemental sodium and air and water. Thus, sodium bearing SNF would require deactivation or removal of the sodium before disposal. Treatment and sodium removal via the melt-drain-evaporate-carbonate (MEDEC) process have been studied and demonstrated for sodium-bonded fuels. INL currently treats sodium-bonded EBR-II assemblies at MFC using pyroprocessing, and this can be applied to all types of sodium-bonded fuel. The MEDEC process has been demonstrated at the laboratory and engineering scale. Treatment processes may produce various waste streams of HLW and LLW that must be dispositioned in addition to the actinide-bearing waste forms.

5.3 Material Recovery

Material recovery as part of the disposition pathway of commercial microreactor SNF is unlikely but remains a possibility for SNF generated at INL in microreactor technology demonstrations. Material recovery may prove desirable for several reasons: (1) recovery of valuable isotopes in microreactor SNF, (2) microreactor SNF could provide unique R&D opportunities as feed stock in the demonstration of various conditioning technologies, (3) implemented as a result of treatment of microreactor SNF (for example pyroprocessing of sodium-bonded fuels), and (4) reduction of the volume of microreactor SNF requiring disposal in a permanent repository. Whatever the case, INL's facilities and ongoing activities can support material recovery initiatives for microreactor SNF, including the HTGR and sodium-bonded fuel types selected above. Material recovery processes may produce various waste streams of HLW and LLW that must be dispositioned in addition to the actinide-bearing waste forms.

5.4 Packaging

Packaging of SNF serves three necessary purposes, (1) preparation of SNF for extended dry storage, 2) preparation of SNF for transport, and (3) preparation of SNF for eventual disposal in a permanent repository. The DOE Standard Canister provides a high-integrity leak-tight barrier that satisfies the necessary safety functions and facilitates storage, transport, and disposal operations Per the current DOE SNF disposition strategy, and considering the variety of potential microreactor design concepts, microreactor SNF is expected to be disposed of using DOE Standardized Canister once the appropriate evaluation and analyses are performed. At present no facility exists at INL for the repackaging of microreactor SNF into the DOE Standardized Canister which would be the preferred repackaging option since this configures the microreactor SNF into a configuration that is ready for shipping to an independent fuel storage or permanent repository.

INL has several facilities with fuel handling and packaging capabilities. However, their suitability to proposed microreactor SNF requires further investigation regarding feasibility and safety of such activities. For the selected TRISO and sodium-bonded heat pipe microreactor fuel concepts, existing INL facilities currently have the capability to package the identified analogous fuels in the INL SNF inventory. Therefore, it is likely that these fuel forms can be handled with the appropriate modifications to these facilities. For more exotic microreactor fuel designs where an analog is not applicable, existing capabilities would need to be evaluated and custom packaging capabilities may need to be constructed as part of the microreactor technology demonstration program or as part of the DOE Standardized Canister packaging facility.

5.5 Extended Dry storage

Several options exist for the extended dry storage of microreactor SNF at INL. For some microreactor SNF types, interim storage and extended dry storage may be the same. However, for other microreactor SNF types that require treatment and conditioning, extended dry storage (different to interim storage) may be required after packaging the fuel in preparation for transport to a permanent repository. Extended dry storage options for microreactor SNF are as follows:

- **In microreactor-specific storage casks.** The anticipated applications and modes of deployment and operation for most microreactor designs suggest that requirements for safe and secure storage and transport will be incorporated into most microreactor designs. If true, this provides an option for extended dry storage of microreactor SNF in a custom microreactor storage cask. This cask could include the entire microreactor envelope or require transfer of the microreactor SNF into a custom designed cask. Demonstration of such a capability would constitute a key part of any microreactor technology pursuing such an extended storage capability.

- **In facilities specifically built for microreactor demonstrations.** As discussed, it is assumed that many of the facilities and capabilities representative of a microreactor manufacturing requirements will be approximated at INL in support of the microreactor demonstration program. Extended dry storage capabilities should be considered and included as part of these new facilities.

- **In existing INL facilities**. SNF generated as part of microreactor demonstration activities may be stored in existing INL facilities so far as the legal, regulatory, operational, and scheduling requirements for the transfer and storage of these fuels in existing facilities are met. The diverse nature of SNF stored at INL supports the likelihood that SNF generated from most microreactor designs will fall within the analytical envelope of existing SNF at INL while requiring little to no modifications of existing facilities in order to provide extended storage for microreactor SNF. Transfer to existing facilities will be predicated on the appropriate analyses/procedures and may require some degree of immediate storage within the microreactor program prior to transfer. This includes transfer to commercial dry storage cask systems currently on offer from dry cask vendors.

- **In new INL facilities.** SNF generated in microreactor demonstration activities may be stored in in newly constructed INL facilities that will be necessary as INL SNFs are packaged and consolidated in preparation for shipment off site (i.e. to a final repository or subsequent interim storage facility). Transfer to new facilities will be predicated on the appropriate analyses/procedures and may require some degree of immediate storage within the microreactor program prior to transfer.

These options apply to extended dry storage of microreactor SNF both before and after packaging for transport to a permanent repository. Existing INL facilities are available to provide extended dry storage for the selected TRISO and sodium-bonded fuels, so long as the necessary set of engineering and safety analyses are performed.

5.6 Permanent Disposition

As with all spent nuclear fuels at present, the question of permanent disposition of microreactor SNF is directly dependent on the identification and licensing of a permanent repository for SNF in the United States. However, given the diversity of existing SNFs that must be prepared and packaged for direct disposal, it is not anticipated that microreactor fuels will pose any new challenges.

6. CONCLUSIONS

Microreactor disposition options include all processes necessary to support safe and secure storage of the spent microreactor fuel in a configuration that is ready for transport to a permanent repository. This includes options for interim storage, treatment, material recovery, packaging and extended dry storage pending final transport to a permanent repository. INL currently safely stores and manages a wide variety of DOE-owned SNF that span the range of nuclear reactor technologies such as fast and thermal spectrum, light water, gas, liquid metal cooled, various enrichments (depleted, LEU, HEU), various fuel forms (metallic, ceramic, alloys) and cladding options (zirconium alloy, stainless steel, graphite matrix, aluminum). The DOE-owned SNF have been categorized into 34 SNF groups and for each group, the number and type of packages that could be used for off-site transportation have been identified. This group structure constitutes the analytical envelop for evaluation of DOE SNF and could be applied to SNF generated in demonstrations of microreactor technology to identify disposition options.

In the absence of detailed microreactor design information, a TRISO fueled HTGR concept and a sodium/potassium-bonded heat pipe reactor concept were considered. INL currently has analogous SNF in its inventory. The Peach Bottom and FSV SNF serve as examples of TRISO based fuel and the Fermi-1 and EBR-II SNF serve as examples of sodium bonded uranium metal fuel. As such it is expected that INL can safely manage, store, package and transport similar microreactor fuel types.

Several existing INL facilities and capabilities as well as new facilities developed as part of the microreactor program, or as part of DOE’s overall strategy for packaging and consolidation of INL SNF may be applicable to disposition of SNF generated in demonstrations of microreactor technology. As part of the overall strategy for disposition of all DOE-owned SNF at INL, these fuels are anticipated to be packaged and transported to a final repository using the DOE Standardized Canister system. The details of any disposition option are highly microreactor design specific and further investigation, evaluation and analyses must be performed once this information is available. Furthermore, in the unlikely event of a microreactor fuel concept that does not fit into the DOE SNF group structure, the same processes and approaches used to create the 34 DOE SNF groups could be applied to create additional groups that characterize this new DOE-owned SNF and disposition options identified with the appropriate analyses.

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