Microreactor Spent Nuclear Fuel Transportation, Management, and Disposition Options

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Disclaimer

SUMMARY

The U.S. Department of Energy (DOE) is supporting the U.S. advanced reactor industry through funding, legislation, and regulatory development to actively pursue several microreactor design concepts. Microreactors are very small nuclear reactors with a power output of 20 MWe or less and are designed to be factory-built, modular in nature, and highly portable. This report, led by INL and supported by PNNL, identifies options for the transportation, management, and disposition of microreactor spent nuclear fuel (SNF) generated in the demonstrations of microreactor technology.

The details of any component of an identified transportation, management, and disposition option are highly microreactor design specific, and, as such, those details are not provided here in the absence of comprehensive design information on a particular microreactor. Thus, the approach taken is to present a general overview of transportation, management, and disposition options, the regulations pertinent to transportation, management and disposition, and options for onsite transportation and management of microreactor SNF at INL. This approach is viable due to the variety in potential microreactor SNF based on open literature information, being reflected in the diverse nature of DOE-owned SNF currently managed at INL, making it highly probable that DOE currently manages fuels that are analogous to most microreactor fuel concepts and have transported such fuel under normal operations.

Transportation options for microreactor SNF can be categorized under two broad scenario sets— separate from the microreactor or together with the microreactor, within the microreactor envelope. Both scenarios are subject to the regulations related to the transport of fissile and radioactive. The first scenario set fits within the current paradigm for SNF transport and represents a well characterized operation for a wide variety of fuel types. The second scenario set represents a significant paradigm shift away from the existing paradigm and would require significant effort to achieve. Probabilistic risk assessment has been identified as a potential method that could be used to demonstrate the equivalent safety of transporting microreactor SNF within the microreactor envelope.

Microreactor management 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 manages a wide variety of DOE-owned SNF and 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 management of SNF generated in demonstrations of microreactor technology.

As demonstrative cases, two proposed microreactor fuels were selected—the Project Pele microreactor and INL's Microreactor Applications Research Validation and Evaluation (MARVEL) microreactor. The Project Pele microreactor is a 1 – 3 MWe TRISO fuel based high-temperature gas reactor and the MARVEL microreactor design concept is a sodium-cooled 20 kWe reactor utilizing a sodium bonded fuel design. INL currently has within its SNF inventory, examples of analogous SNF in the Peach Bottom and Fort St. Vrain TRISO based fuels and the Fermi-1 and EBR-II sodium bonded fuel for which transportation and management options are well understood. As such it is expected that INL can safely manage, and transport similar microreactor fuel types.

As with all SNF 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 SNF that must be prepared and packaged for direct disposal, it is not anticipated that microreactor fuels will pose any new challenges.

Future microreactor transportation work should be focused on building the framework for a transportation PRA that would provide the basis for approving the transport of microreactor SNF within the microreactor envelope by transportation regulators. It is recommended that the framework first be developed for onsite shipment at a DOE site, before expanding to offsite transportation requiring NRC approval, with the ultimate goal of achieving international transport which would require approval of a foreign competent authority.

Future microreactor SNF management and disposition work should be focused on structural, thermal, shielding, criticality and other necessary analyses that will inform the identification of concrete options for each step of the management process. The objective being, to arrive at microreactor SNF in a configuration that is ready for transportation to an independent spent fuel storage installation or permanent repository.

The details of any transportation, management, and disposition plan are highly microreactor design specific and the necessary investigation, evaluation and analyses can only be performed once this information is available. As such, detailed microreactor design information, including geometries, configurations, materials, and material properties are key to perform a more detailed assessment of the transportation and management options identified thus far.

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ACRONYMS

AAR	Association of American Railroads
AEC	Atomic Energy Commission
ANPP	Army Nuclear Power Program
ATR	Advanced Test Reactor
ANSI	American National Standards Institute
BWR	Boiling water reactor
CFA	Central Facilities Area
CFR	Code of Federal Regulations
CO	Certifying Official
CoC	Certificate of Compliance
COI	Certificate of Inspection
CVSA	Commercial Vehicle Safety Alliance
DoD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOE-NE	U.S. Department of Energy Office of Nuclear Energy
DOT	U.S. Department of Transportation
EBR	Experimental Breeder Reactor
FDPA	Fluorinel Dissolution Process Area
FSA	Fuel Storage Area
FSV	Fort St. Vrain Nuclear Reactor
HAC	hypothetical accident conditions
HADR	Humanitarian Assistance and Disaster Relief
HALEU	high-assay low enriched uranium
HFEF	Hot Fuel Examination Facility
HLW	high-level radioactive waste
HRCQ	highway route controlled quantity
HTGR	high temperature gas reactor
IAEA	International Atomic Energy Agency
IFSF	Irradiated Fuel Storage Facility
INL	Idaho National Laboratory
INTEC	Idaho Nuclear Technology and Engineering Center
IP	industrial package
ISFF	Idaho Spent Fuel Facility
ISFSI	Independent Spent Fuel Storage Installation
ISO	International Organization for Standardization
LEU	low enriched uranium
LLW	Low-level radioactive waste
MARVEL	Microreactor Applications Research Validation and Evaluation

MEDE	melt-drain-evaporate
MFC	Materials and Fuels Complex
ML-1	Mobile Low Power Plant
MTHM	metric tons of heavy metal
MTR	Materials Test Reactor
NCT	normal conditions of transport
NEPA	National Environmental Policy Act
NNSA	National Nuclear Security Administration
NORAD	North American Air Defense Command
NRC	U.S. Nuclear Regulatory Commission
OCO	Overseas Contingency Operations
OFSF	Outdoor Fuel Storage Facility
PWR	Pressurized water reactor
REV	Rail escort vehicle
RNA	Regulated Navigation Areas
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
TSD	Transportation Safety Document
USCG	U.S. Coast Guard

1. INTRODUCTION

According to the U.S. Nuclear Regulatory Commission (NRC), advanced reactors involve designs that leverage coolants such as molten salt, high-temperature gas, and liquid metal as opposed to traditional light-water reactors that use water in primary and secondary heat exchange loops. Advanced reactor designs are designed to be inherently safer, incorporating features such as reduced reactivity with increasing temperature. Some designs may not require safety-related backup electrical systems to operate. Advanced reactor designs are being considered that will offer a broad range of sizes and associated application-specific power outputs, from more than 1,000 megawatts (like traditional reactors) down to a single megawatt for more niche applications. This will allow for the selection and tailoring of the application to be performed based on specific or localized energy demands.

A subset of these advanced reactors, providing 20 megawatts electrical (MWe) or less, are commonly referred to as microreactors. Microreactors are very small nuclear reactors designed to be factory-built, modular in nature, and portable— whether by road, rail, barge, or air. 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. As a result, microreactors are typically intended for independent operation in off-grid remote locations but can also be operated as part of a local microgrid.

The U.S. Department of Energy (DOE) is supporting the U.S. advanced reactor industry through funding, legislation, and regulatory development 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 the demonstration of microreactor technology due to its well-established track record of nuclear facility operations. INL has world-class nuclear research and development experimental facilities and capabilities to support demonstration needs, a well-characterized site with a controlled emergency planning zone and mechanisms for the necessary 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. Two examples of microreactor concepts working towards near term demonstration at INL are the Project Pele microreactor and INL's Microreactor Applications Research Validation and Evaluation (MARVEL) microreactor.

The microreactor being designed and developed for Project Pele is a 1 – 3 MWe tristructural isotropic (TRISO) fueled high-temperature gas reactor (HTGR) that will use high-assay low-enriched uranium (HALEU) as the fuel composition. The design concept requires a small ruggedized mobile nuclear reactor that can be fully enclosed in a standard certified 20'-long ISO-688 freight container due to the Army's significant familiarity with deploying these containers. Such a reactor would make the DoD's domestic infrastructure resilient to an electric grid attack and fundamentally change the logistics of Overseas Contingency Operations (OCO), both by making higher density energy sources available and by drastically simplifying the complex fuel logistic lines, which currently support existing power generators operating mostly on diesel fuel. It would enable a more rapid response during Humanitarian Assistance and Disaster Relief (HADR) operations and could also reinvigorate the commercial nuclear industry through commercial investment and development of demand-centric, modular, and scalable high energy density power for industrial and technology parks or other localized need. Figure 1 illustrates TRISO fuel particles, fuel compacts, prismatic graphite blocks, and spherical fuel pebbles.

The MARVEL microreactor design concept is a sodium-cooled 20 kWe reactor utilizing a SNAP-10A reactor-style pin design. The MARVEL design concept uses a sodium-bonded uranium zirconium hydride (UZrH) fuel design that also uses HALEU. It is specifically targeted to provide a test platform for component and subsystem development as well as demonstration. It will be utilized to elevate the technology readiness level of nuclear-derived electric power generation and associated enhancing technologies. MARVEL is currently anticipated to be a fixed reactor definition that takes advantage of an accommodating research and testing safety environment. Its components are envisioned to be shop fabricated and delivered by truck. Final assembly, fueling, and operation will be conducted within the research and testing safety environment. Figure 2 illustrates a SNAP-10A fuel pin.

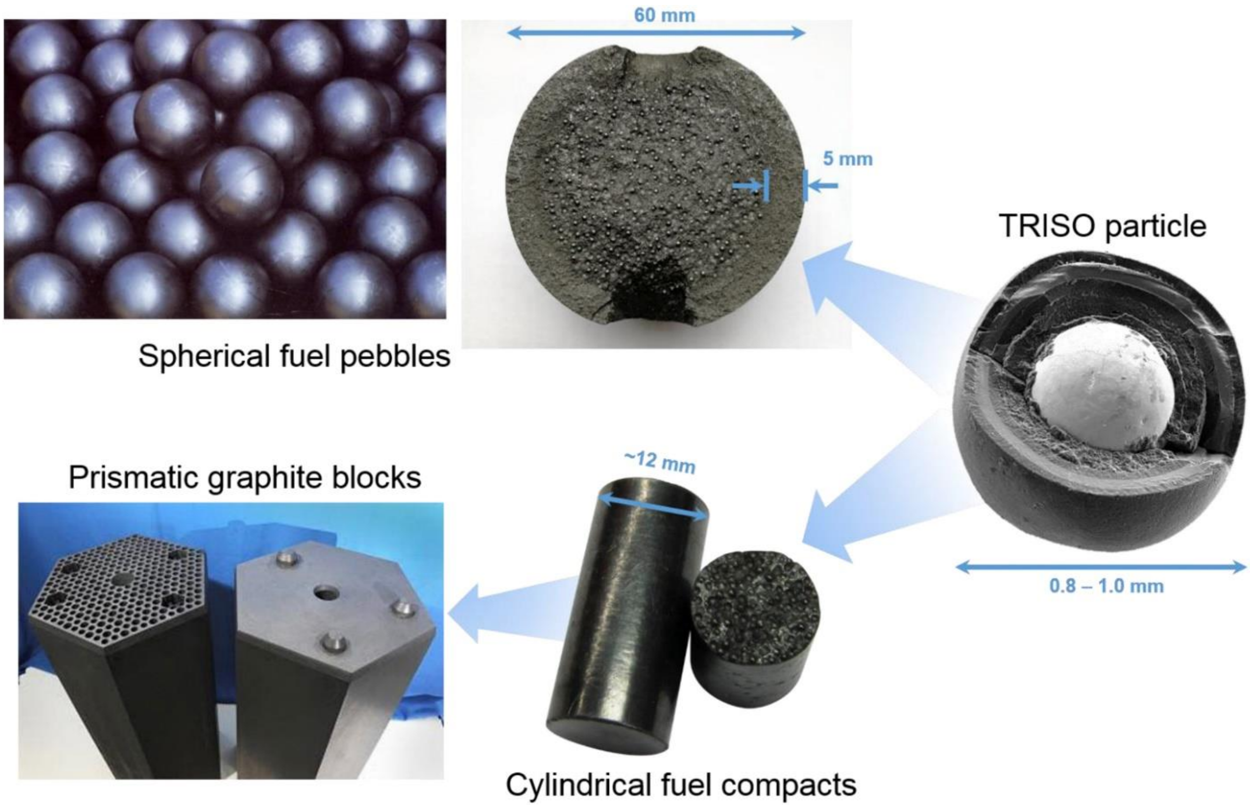


Figure 1. TRISO particles, fuel compacts, prismatic graphite blocks, and spherical fuel pebbles. (Demkowicz et al. 2019)

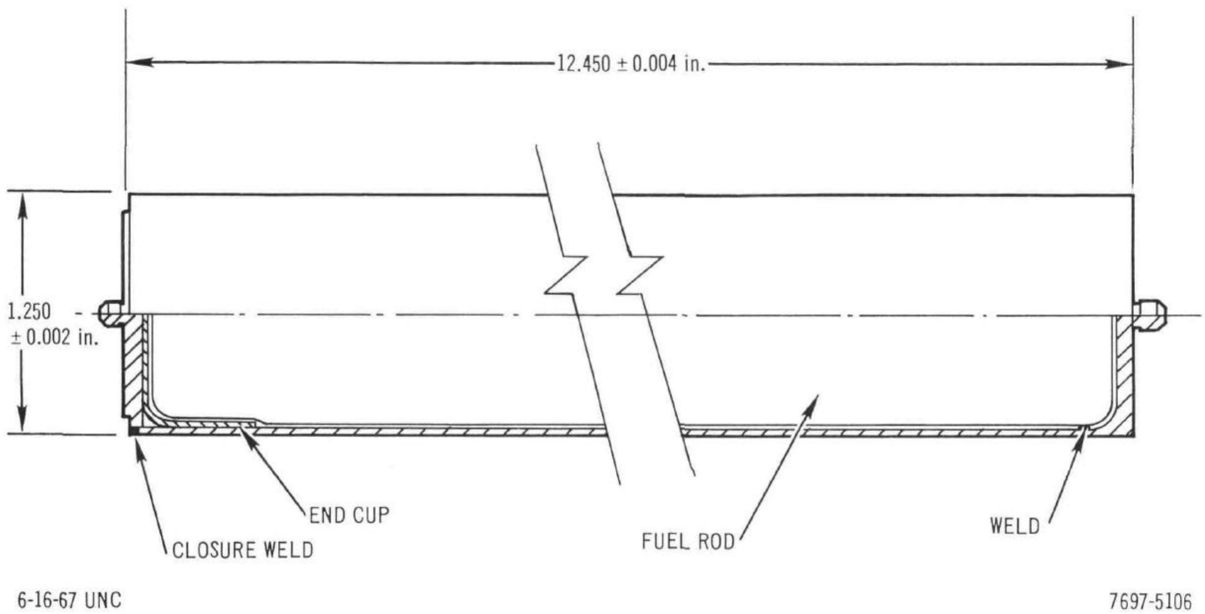


Figure 2. SNAP-10A fuel pin schematic. (Golding 1967)

In support of such demonstrations and any subsequent microreactor or advanced reactor concepts, the DOE Office of Nuclear Energy (DOE-NE) is supporting research and development as well as programmatic efforts in multiple areas related to microreactor technology. This includes the safe and secure transportation, management, and disposition of spent nuclear fuel (SNF) generated in microreactor technology demonstrations. The purpose of this report is to identify options for the transportation, management, and disposition of SNF generated in demonstrations of microreactor technology. Transportation will include both onsite and offsite transport of SNF. Management and disposition will include all the processes necessary to support the safe and secure storage of the microreactor SNF in a configuration that is ready for transportation to an independent spent fuel storage installation (ISFSI) or permanent repository. This establishes the scope of this report to only include microreactor fuel that has been declared spent and waiting final disposal. As an initial evaluation, the transportation, management, and disposition options identified are not specific to any single reactor type or design. When more detailed information on possible origins, destinations, favorable transport modes, and reactor definitions are known, documentation will be updated to reflect a more detailed framework. Furthermore, facility operations, changing SNF inventories, and storage space availability can also affect the identification of management options. Many issues can affect disposition pathways, including regulatory and policy changes. This report, in conjunction with future detailed analyses, will allow INL and DOE-NE to perform in-depth analyses of the identified transportation and management options.

Section 2 provides a general overview of microreactor transportation, management, and disposition identifying various transportation modes and the processes involved in management and preparation for disposition options of SNF. Section summarizes regulations relevant to reactor transportation, management, and disposition. Section 4 discusses onsite transportation and storage of SNF at INL. Section 5 identifies options and potential issues associated with the transportation and management of microreactor SNF at INL and Section 7 provides the conclusions of the report

2. OVERVIEW OF SNF TRANSPORTATION, MANAGEMENT, AND DISPOSITION

This section provides a general discussion of SNF transportation management and disposition options that may be applicable to microreactors intended for demonstration at INL. The discussion focuses on post-operation implications for transportation and onsite management of microreactor SNF. Options for transportation via highway, railway, barge/ship, and air are considered, with modal-specific transport information, possible generic container considerations, and related cargo container and tie-down information. Options for management address all necessary steps for SNF to be in a configuration that is ready for shipping to an ISFSI or permanent repository. This includes interim storage, SNF treatment, potential material recovery, packaging for extended dry storage or transport to a repository and extended dry storage.

2.1 Microreactor Transportation

A unique feature of microreactors is their small size and proposed operational mode whereby the reactor can be operated, transported, and operated again at multiple locations before decommissioning. A demonstration of this unique feature of microreactor operations would provide confidence of the ability of microreactors to fulfil niche application arenas for which they are being specifically designed. There are several transportation scenarios that could be used to support a microreactor demonstration at the INL. Many of these involve the transport of unirradiated or irradiated fuel that is still considered in service under the demonstration program. Such scenarios lie beyond the scope of this report. The scenarios of interest to this report are those where the fuel has been declared spent.

Options for the transport of microreactor SNF can be categorized under two broad scenario sets. The first set of scenarios involves the transportation of the microreactor SNF separately, either offsite for storage or disposal, or onsite for storage and management. In this set of scenarios, the SNF package would require the application of the schedules related to the transport of fissile and radioactive material. This scenario is representative of the paradigm under which SNF is currently transported and represents a well characterized scenario set for a wide variety of fuel types. The second scenario set involves the transport of the microreactor SNF together with the reactor or within the reactor envelope. In this set of scenarios, the microreactor envelope would have to meet the same transport requirements, which would be met by the microreactor design supplemented additional controls. This set of scenarios represents a significant paradigm shift in the way SNF is currently transported and would require significant effort to achieve. Under both set of scenarios, microreactor SNF transportation options include transport by highway, rail, barge or ship, and air.

2.1.1 Cargo Containers

One option for the transport of a microreactor and its components is to place the microreactor and its components in a cargo container. The ability of a microreactor and its components to fit in a cargo container would be advantageous, and this capability is listed as an objective in the Project Pele Phase I Request for Solutions (DoD 2019). Cargo containers are transport equipment designed and constructed to facilitate the international and intermodal exchange of goods, and can be used for highway, rail, barge, and air transport. They are designed to be used repeatedly and to provide security during transport. Also, their fittings readily permit handling and transfer from one transport mode to another (TEA 2005). International Standard ISO 688

(ISO 2020) contains the dimensions and ratings for cargo containers (see Table 1). If the microreactor is designed for transport between operations at different sites using a cargo container, it is possible that this could provide an avenue for transport of the SNF as well.

Table 1. Cargo container external dimensions and gross weights

Freight Container Designation	Length (mm)	Width (mm)	Height (mm)	Gross Weight (lb.)
1EE	13,716	2,438	2,591	67,200
1AA	12,192	2,438	2,591	67,200
1BB	9,125	2,438	2,591	67,200
1CC	6,058	2,438	2,591	67,200
Source: ISO (2020)				

2.1.2 Highway

Highway transport of SNF occurs regularly in the U.S. and according to the NRC, from 1979 to 2007, 1,285 SNF shipments accounting for 930,000 shipment-miles were made by highway (Garrett et al. 2010). If the microreactor and microreactor SNF are to be transported separately, highway transport would represent a well characterized transportation mode. In the U.S., the federal maximum gross vehicle weight limit for trucks is 80,000 lb. The minimum trailer length is 48 ft and widths are limited to 102 in. There is no federal height standard. States may set a longer length standard and impose a maximum height. Figure 3 summarizes these standards. State laws and regulations set varying size and weight limits and permitting requirements for vehicles that exceed these limits and that operate on highways and bridges. For example, states' length standards vary between the minimum federal standard of 48 feet and 65 feet for a semitrailer. Vehicles that exceed these dimensions and weights are known as oversize or overdimension (see Figure 4) (GAO 2015).

49 CFR 385, Subpart E contains the requirements for hazardous materials safety permits. A highway route controlled quantity truck shipment requires a hazardous materials safety permit (49 CFR 385.403[a]). Operational requirements associated with this permit include a written route plan and a pre-trip Commercial Vehicle Safety Alliance (CVSA) Level VI inspection. 49 CFR 397, Subpart D contains requirements for the routing of Class 7 (radioactive) materials, including requirements for motor carriers and drivers (49 CFR 397.101) and requirements for state routing designations (49 CFR 397.103). 49 CFR 397.101(a) contains requirements for the routing of placarded shipments, and 49 CFR 397.101(b) contains requirements for highway route controlled quantity shipments.

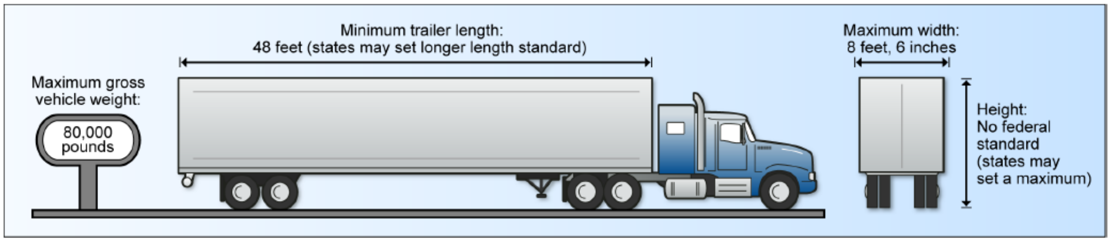


Figure 3. Federal size and weight standards. (GAO 2015)

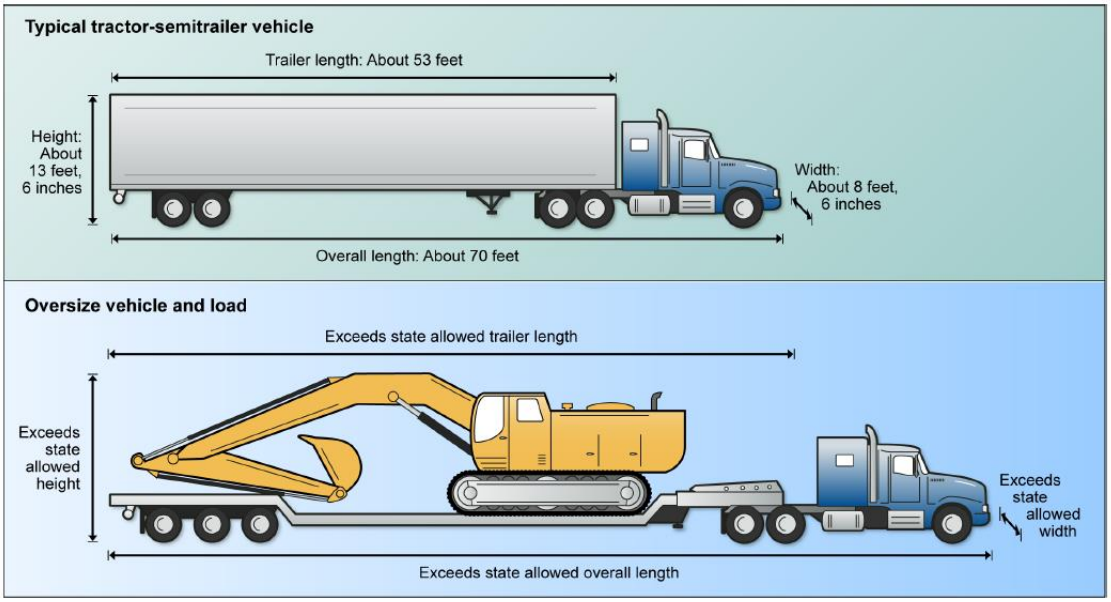


Figure 4. Typical and oversize vehicles and loads. (GAO 2015)

For oversize and overdimension vehicles, states issue and enforce permits, and practices vary by state. Table 2 summarizes the permitting practices for oversize and overweight vehicles. Vehicles that are extremely heavy, long, wide, or tall are known as "superloads" and are typically subject to additional permitting requirements. A summary of the permitting practices for superload vehicles by state is provided in (GAO, 2020).

Table 2. Summary of permit processes for oversize and overweight vehicles in the 50 states and District of Columbia

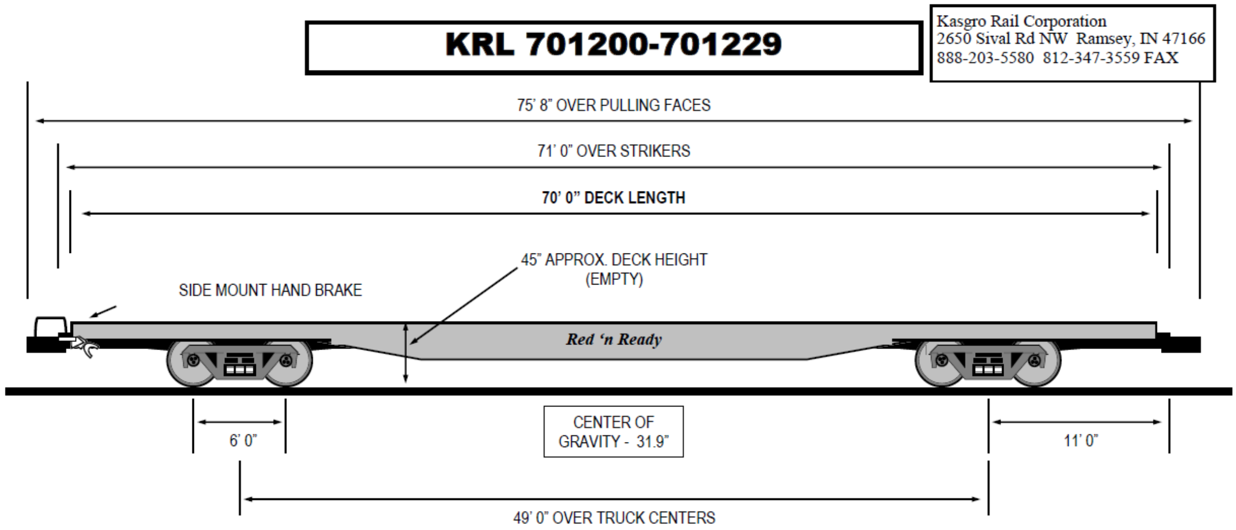
Permit Processes	Description
Permit issuing agency	32 issue permits from Departments of Transportation. In other states, Departments of Motor Vehicles, Departments of Revenue, or others issue permits.
Permit system	45 offer online permit applications.
Automated routing system	23 offer automated truck routing.
Escort vehicles	44 may require escort vehicles above a certain height. 51 may require escort vehicles beyond a certain width.
Certification of escort drivers	38 do not require certification for escort drivers.
Source: GAO (2015)	

2.1.3 Rail

A second option for the transport of microreactor SNF is by rail. Rail transport of SNF has occurred in the U.S., and according to the NRC, from 1979 to 2007, 269 SNF shipments accounting for 74,000 shipment-miles were made by rail (Garrett et al. 2010). In the U.S., typical 4-axle freight railcars have a gross rail limit of 286,000 lb and a nominal capacity of about 110 tons. Figure 5 illustrates an example of a typical 4-axle freight railcar manufactured by Kasgro Rail Corporation. Freight railcars that are acceptable for unrestricted interchange must meet the dimensional requirements contained in American Association of railroads (AAR) standard AAR Standard S-2056, Plate B (AAR 2017a), which limit the width of the railcar and its cargo to 10 ft 8 in. If the microreactor and its components were shipped in an intermodal container (i.e., an ISO container), a specialized intermodal railcar could be used.

AAR Standard S-2043 (AAR 2017b) establishes performance guidelines for trains carrying SNF and/or HLW. This standard applies to transportation in cask-carrying railcars, buffer cars, and railcars containing security escorts (known as a rail escort vehicle or REV). While the use of railcars that comply with AAR Standard S-2043 is not a regulatory requirement imposed by the Federal Railroad Administration, it is the expectation of the railroads that SNF shipped to a repository or interim storage site would be moved using railcars that comply with AAR Standard S-2043. The DoD and DOE have also signed settlement agreements with three of the Class 1 railroads (Union Pacific, Norfolk Southern, and the BNSF) that require the use of AAR approved equipment to take advantage of the rates in the settlement agreements.

U.S. Navy shipments of SNF are currently being made using cask-carrying railcars that meet AAR Standard S-2043, and the U.S. Navy is currently developing a REV that meets AAR Standard S-2043. The DOE is also developing the 12-axle Atlas railcar, a buffer railcar, and an 8-axle railcar to meet AAR Standard S-2043 (DOE 2018). Figure 6, Figure 7, and Figure 8 show the Atlas railcar, the buffer railcar, and the REV, respectively.



LENGTH OF LADING (ft)	LOAD LIMITS (lbs)	CAR NUMBERS	LOAD LIMITS (lbs)	LIGHT WEIGHTS (lbs)	MAXIMUM GROSS (lbs)	SPRING TRAVEL (in)	DECK LENGTH (ft-in)	DECK HEIGHT (ft-in)	JOURNAL SIZE BEARING TYPE
2	187,500	**701200 - 701229**	224,000	62,000	286,000	3 11/16"	70' 0"	3' 9"	6 1/2" X 9" ROLLER
6	195,650					WHEEL DIAMETER (in)	DECK WIDTH (ft-in)	DRAFT GEAR	
10	204,550								
14	214,290					36"	10' 0"	15" EOC	
18 & OVER	LOAD LIMIT								

KRL 701200-701229
112 Ton - 70' Flat Deck Car
Drawing No. A19643, Rev. B

Figure courtesy of Kasgro Rail Corporation

Figure 5. Typical 4-axle freight railcar.

Figure 6. Atlas railcar with test weights.

Figure 7. Buffer railcar.

Figure 8. Rail escort vehicle.

2.1.4 Barge

A third option for the transport of microreactor SNF is by barge or ship. Transport of SNF by barge or ship has occurred in the U.S. For example, lightly irradiated fuel has been shipped from the Shoreham nuclear power plant site to the Limerick nuclear power plant site using a barge. In addition, foreign research reactor SNF is routinely shipped to the U.S. by ship. The transport of large components, such as reactor pressure vessels, steam generators, and pressurizers, by barge to and from nuclear power plant sites is also routinely done in the U.S.

The U.S. Coast Guard (USCG) has published Navigation and Vessel Inspection Circular No. 2-87, Domestic Barge Transportation of Radioactive Materials/Nuclear Waste (USCG 1987). This circular references American National Standards Institute (ANSI) Standard N14.24-1985, Highway Route Controlled Quantities of Radioactive Materials – Domestic Barge Transport, which identifies the organizations, equipment, operations, and documentation involved in barge shipments of radioactive materials between U.S. ports by inland waterways and in coastwise and ocean service. The Standard includes requirements pertaining to selection of the cask, barge, and towing vessel, certification and documentation, radiological and non-radiological operations, insurance, emergency planning and physical protection and security of the shipment. It should be noted that a Coast Guard–issued Certificate of Inspection (COI) is required to move hazardous materials by barge, including Class 7 Radioactive Material, and 90 percent of barges do not have a COI (Feldman et al. 2019).

2.1.5 Air

A fourth option for the transport of a microreactor and its components is by air. In addition, the Project Pele Phase I Request for Solutions specified that the mobile nuclear reactor developed under Project Pele be transportable in a single C-17 aircraft. Table 3 lists the design limits for equipment to be transportable in the C-17.

Table 3. C-17 Transportability design limits

Height	**142 inches**
Width	196 inches 204 inches if the height is less than 136 inches
Length	784 inches (cargo deck) 238 inches (ramp)
Maximum payload	167,400 lb 130,000 lb (for a range of 3,200 nautical miles)
Source: TEA (2005)	

2.2 Microreactor Management and Disposition

Management of SNF includes all processes necessary to support the safe and secure storage of the SNF in a configuration that is ready for shipping to an ISFSI or permanent repository. This includes the: (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. Disposition refers to the permanent disposal of the SNF. Figure 9 shows how these processes are related.

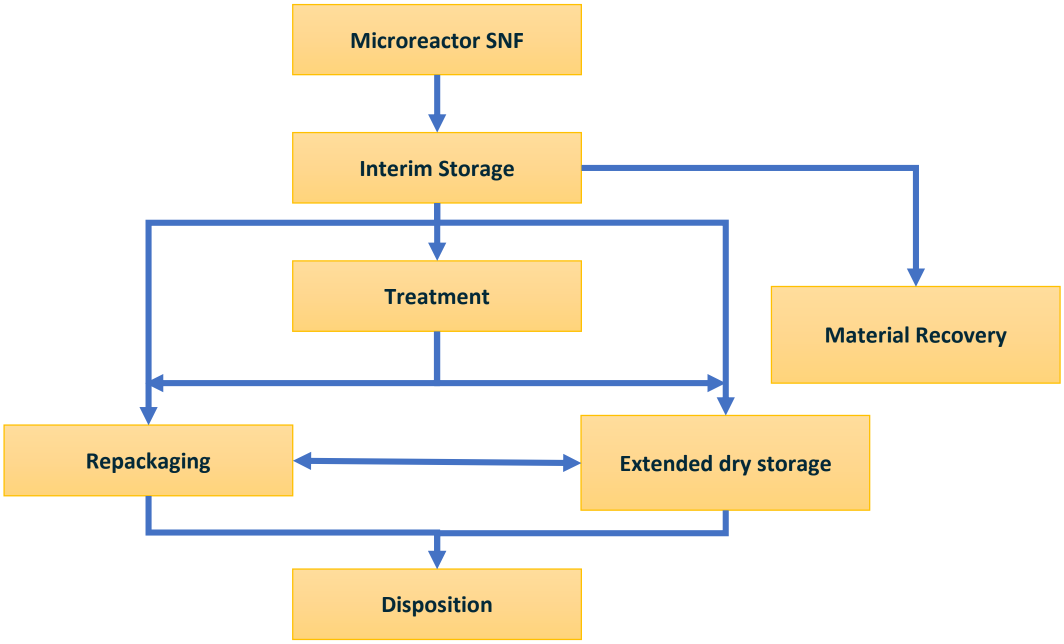


Figure 9. Processes for the management of microreactor SNF.

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 an out-of-core wet storage capacity will be provided in commercial microreactor designs. Wet facilities may be necessary for the disassembly and handling of prototype and/or demonstration microreactors. 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 meets the functional criteria for dry storage and transportation. If the microreactor design is not compatible with interim storage and transportation, additional capabilities will have to be developed for the interim and extended dry storage of microreactor 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 that is able to confine the radioactive material to prevent a 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 (NRC 1997). Dry storage design requirements depend on various 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.

Material recovery as part of the management pathway of commercial microreactor SNF is unlikely but remains a possibility for any DOE-owned 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 research and development opportunities as feed stock in the demonstration of various conditioning technologies, (3) implemented as a result of the 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.

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 SNF that must be prepared and packaged for direct disposal, it is not anticipated that microreactor fuels will pose any new challenges.

3. REGULATIONS RELEVANT TO TRANSPORTATION, MANAGEMENT, AND DISPOSITION OF MICROREACTORS

This section summarizes the regulations relevant to the transportation, management, and disposition of microreactor SNF and associated radioactive wastes. Outlines of relevant regulations are provided primarily on U.S. Department of Transportation (DOT) and NRC requirements for transportation and DOE, NRC, and the U.S. Environment Protection Agency (EPA) requirements for management and disposition. For transportation, the focus is on fissile material packages and Type B packages, which are expected to be most applicable to the transport of the fuel and/or a fueled microreactor before and after irradiation.

3.1 Regulations Relevant to Transportation of Microreactors

The regulations relevant to microreactor transportation options are recorded as schedules in the code of federal regulations. The schedules contain specific regulatory requirements for the transport of fissile material packages and Type B packages. Schedules for common provisions of transportation regulations and radioactive material package design and testing also apply.

The schedules do not include the requirements for low specific activity shipments, surface contaminated object shipments, uranium hexafluoride shipments, import and export shipments, shipments by passenger aircraft, or special form shipments (i.e., shipments were assumed to be normal form) because these types of shipments are unlikely to be relevant to microreactor shipments. In addition, requirements for Industrial Packages (IP) (i.e., IP-1, IP-2, and IP-3) or empty packages are not listed because these packages are not likely to be relevant to microreactor shipments. The NRC physical protection requirements specified in 10 CFR Part 37 are also not listed because these requirements are unlikely to be relevant to microreactor shipments containing irradiated fuel. However, this assumption will be revaluated when more detailed information is available on the activation of the microreactor structural material for the case where the microreactor is defueled and the irradiated fuel and the microreactor are shipped separately.

The key schedules dealing with the transportation of fissile material packages and radioactive materials are contained in 49 CFR 173 Subpart I which deals are DOT regulations on transportation of radioactive materials and 10 CFR 71 which captures NRC regulations on packaging and transportation of radioactive material. In general, the schedules are organized into sections on materials, packaging/package, radiation, contamination, decontamination, mixed content, loading and segregation, marking and labeling, placarding, transport documents, storage and dispatch, carriage, and other provisions for various form of transportation. This is the same for Type B packages, which at present appears to be the most likely package for microreactor fuel transportation. The military has additional requirements for the shipment of fissile material and Type B packages.

3.2 Regulations Relevant to Management of Microreactor SNF

The regulations relevant to the storage of microreactor SNF are recorded as schedules in the code of federal regulations. The key schedules dealing with the storage of SNF is 10 CFR 72 which deals with the packaging and storage of SNF, HLW, and reactor-related greater than class C waste. The schedule is organized into sections on general provisions, license applications, issuance and conditions of license, records, reports, inspections, and enforcement, siting evaluation factors, general design criteria, quality assurance, physical protection, training and certification of personnel, storage installation information to state governments and Indian tribes, general license for storage of spent fuel at power reactor sites and approval of spent fuel storage casks. In addition, INL manages SNF in accordance with the numerous DOE Records of Decision (ROD) and Environmental Impact Statements (EIS) on SNF management, including the *"Programmatic Spent Nuclear Fuel Management and Idaho National Engineering Laboratory Environmental Restoration and Waste Management Programs"*. This ROD records a department-wide decision on for DOE-owned SNF management and contains decisions dealing with site-wide environmental restoration and waste management programs at INL. These decisions include the continuation of environmental restoration activities, development of cost-effective treatment technologies for SNF and waste management; and implementation of projects and facilities to prepare waste and treat SNF for interim storage and final disposition (DOE, 1995a).

3.3 Regulations Relevant to Final Disposition of Microreactor SNF and Other Radioactive Wastes

The regulations relevant to the final disposition of SNF and HLW are contained in 40 CFR 197 and 10 CFR 63 for the disposal of SNF and HLW at the Yucca Mountain site and 40 CFR 191 and 10 CFR 60 for disposal at sites other than Yucca Mountain. The EPA regulations are organized into sections on public health and environmental standards for storage, public health and environmental standards for disposal, and ground water protection standards.

10 CFR 60 and 10 CFR 63 have sections on general provisions, licenses, participation by state governments and affected Indian tribes, records, reports, tests, and inspections, technical criteria, performance confirmation program, quality assurance, training and certification of personnel, emergency planning criteria, and violations. In addition, 10 CFR 63 has preclosure public health and environmental standards, postclosure public health and environmental standards, postclosure individual protection standard, human-intrusion standards, groundwater protection standards, and additional provisions

DOE Order 435 contains the DOE requirements for the management of radioactive materials. The associated DOE manual describes the requirements and specific responsibilities for implementing DOE O 435.1, Radioactive Waste Management, for the management of DOE high-level waste, transuranic waste, low-level waste, and the radioactive component of mixed waste. This order sets the requirements for the management of HLW, LLW, TRU waste, and other radioactive waste generated from microreactors at INL. The manual contains sections on definitions, management of specific wastes, complex-wide high-level waste management program, site-wide radioactive waste management program, radioactive waste management basis, quality assurance program, contingency actions, corrective actions, waste acceptance, waste generation planning, waste characterization, waste certification, waste transfer, packaging and transportation, site evaluation and facility design, storage, treatment, disposal, monitoring, closure and specific operations.

4. MICROREACTOR SNF TRANSPORTATION AND STORAGE AT INL

This section discusses onsite microreactor SNF transportation and storage at INL. For transportation, the emphasis is on the process through which a transportation plan can be prepared and revised for hazardous material transport, which would apply to advanced reactor and microreactor SNF and related radioactive materials. For storage, the section details existing INL facilities used for the storage and management of the current INL SNF inventory which could potentially be used for management of microreactor SNF.

4.1 Microreactor Transportation at INL

For onsite transport at DOE sites, DOE Order 460.1D allows for the preparation of a Transportation Safety Document to demonstrate equivalent safety for deviations from hazardous materials transportation requirements. The INL Transportation Safety Document (INL 2017) describes the INL packaging and transportation program and explains the methodology for complying with the rules, laws, and regulations governing onsite and offsite transportation functions at the INL site. The INL Transportation Safety Document addresses organizational structure and responsibilities, transport regulations, site-specific standards, procedures, and instructions, safety assessment methodology, routine and nonroutine shipments, personnel qualification and training, documentation and recordkeeping incident reporting and emergency response and transport vehicle operation.

Nonroutine shipments are shipments that do not fully comply with DOT hazardous material regulations and require the preparation of a Transport Plan. Cases that require the preparation of Transport Plans include variations to packaging requirements (such as the use of a packaging not authorized by DOT for shipping the material), packaging limits (such as radiation or contamination limits), and any other DOT requirements that cannot be met. The INL Transportation Safety Document requires that Transport Plans identify, as applicable, the specific DOT requirement(s) not met, hazard category, safety analysis, technical safety requirements, administrative controls, hazard controls, engineered barriers, and site-mitigating conditions that ensure a level of safety equivalent to that afforded by DOT requirements for routine shipments. Figure 10 shows the process flow for developing a new transport plan. INL allows an alternative to preparing Transport Plans for nonroutine shipments. This alternative consists of preparing a Documented Safety Analysis that includes transportation activities at nonreactor nuclear facilities. If the Documented Safety Analysis addresses all transportation hazards and controls necessary to provide safety equivalent to DOT regulations, then the requirements of DOE Order 460.1D are met and a Transport Plan is not required for the transportation of the material covered by the Documented Safety Analysis. The INL report *Safety Analysis Report for Intra-INL and MFC Inter-Facility Transfers* (INL 2019b) is an example of a Documented Safety Analysis prepared in lieu of a Transport Plan. The technical safety requirements derived from INL (2019b) are contained in the INL report

Technical Safety Requirements for Intra-INL and MFC Inter-Facility Transfers (INL 2019c). An example of an approved container/payload for INL intra-facility transfers between the Idaho Nuclear Technology and Engineering Center (INTEC) and the Materials and Fuels Complex (MFC) is the NAC-LWT transportation cask containing Materials Test Reactor (MTR) canisters (INL 2019d).

In terms of potential sites at the INL for an advanced reactor or microreactor demonstration, INL has evaluated 32 sites and has identified nine preferred locations on the INL (Connor et al. 2020). One site is located at the INTEC, five of these sites are located at or near the MFC, two sites are located in the vicinity of the Central Facilities Area (CFA), and one site is located near the Advanced Test Reactor (ATR) Complex. It should be noted that CFA is connected to the national rail network through the Union Pacific Railroad Mackay Branch Line and the Scoville Spur, located in the southern part of the INL site. A DOE-owned railroad track connects the Scoville Spur to CFA and to INTEC (Griffith and Holland 2015). None of the other locations have rail access. This would make truck a more viable mode of transport between most of the preferred sites identified in Connor et al. (2020).

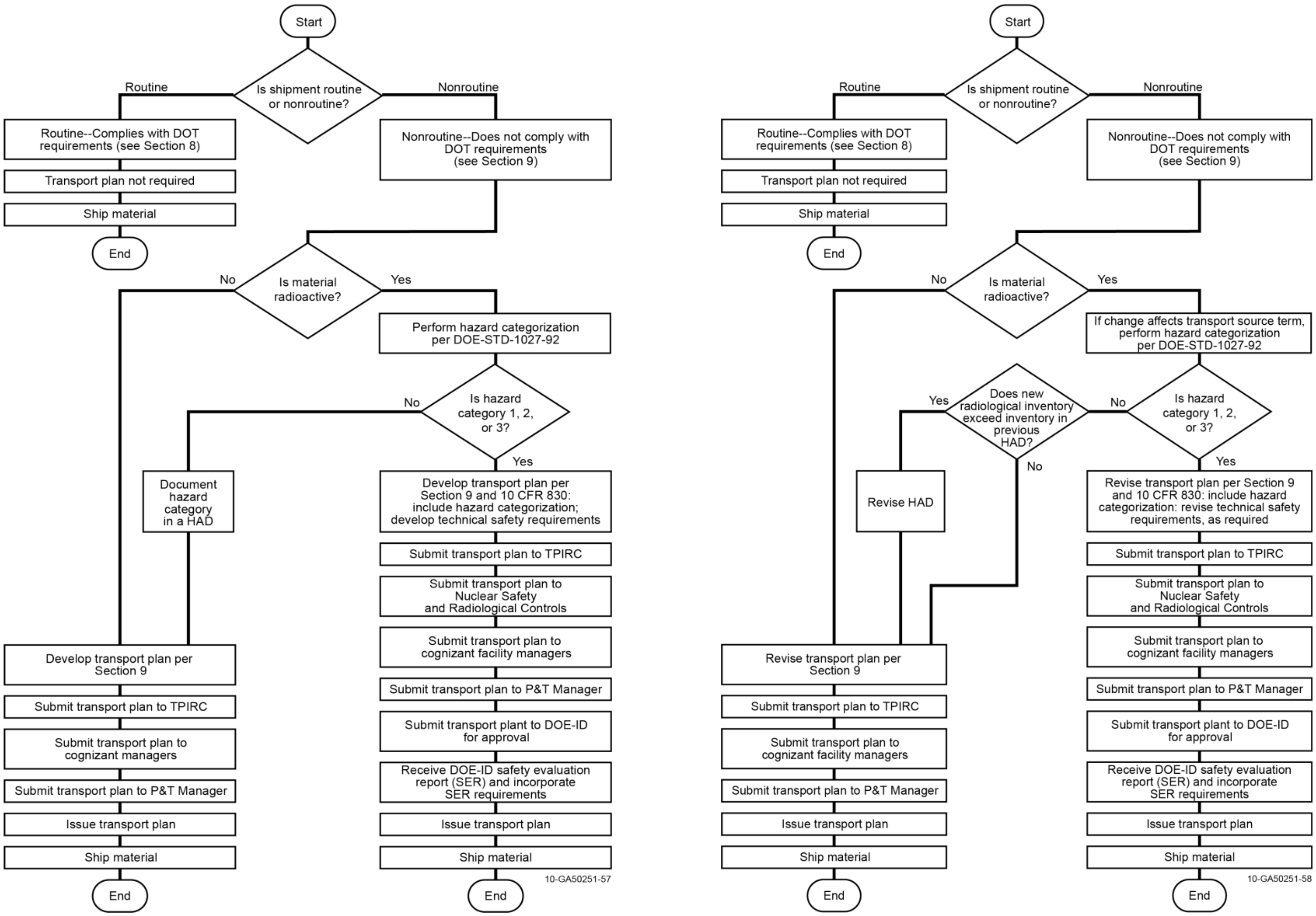


Figure 10. Process flows for developing and revising transport plans.

4.2 Onsite Storage

The current SNF inventory at INL includes over 250 different types of SNF (Hill and Fillmore 2005). Figure 11 shows some of the different fuel types managed at INL. Disposal options for many of these fuels were identified as part of the Yucca Mountain Repository project, including all necessary treatment packaging and transportation requirements for final disposal. The characteristics of the current INL SNF inventory vary greatly and were 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 potential release of radionuclides from DOE-owned SNF and are important to nuclear criticality (DOE 2009). 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 offsite 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). Such a comprehensive analysis of the existing INL SNF inventory and indeed other DOE-owned SNF at other sites should provide an analytical envelope for many of the new proposed microreactor SNF. In the unlikely case of a microreactor with SNF not enveloped by existing DOE-owned SNF, the Yucca Mountain Repository License Application Safety Analysis Reports represents a proven methodology and framework by which new SNF with radically different characteristics can be addressed.

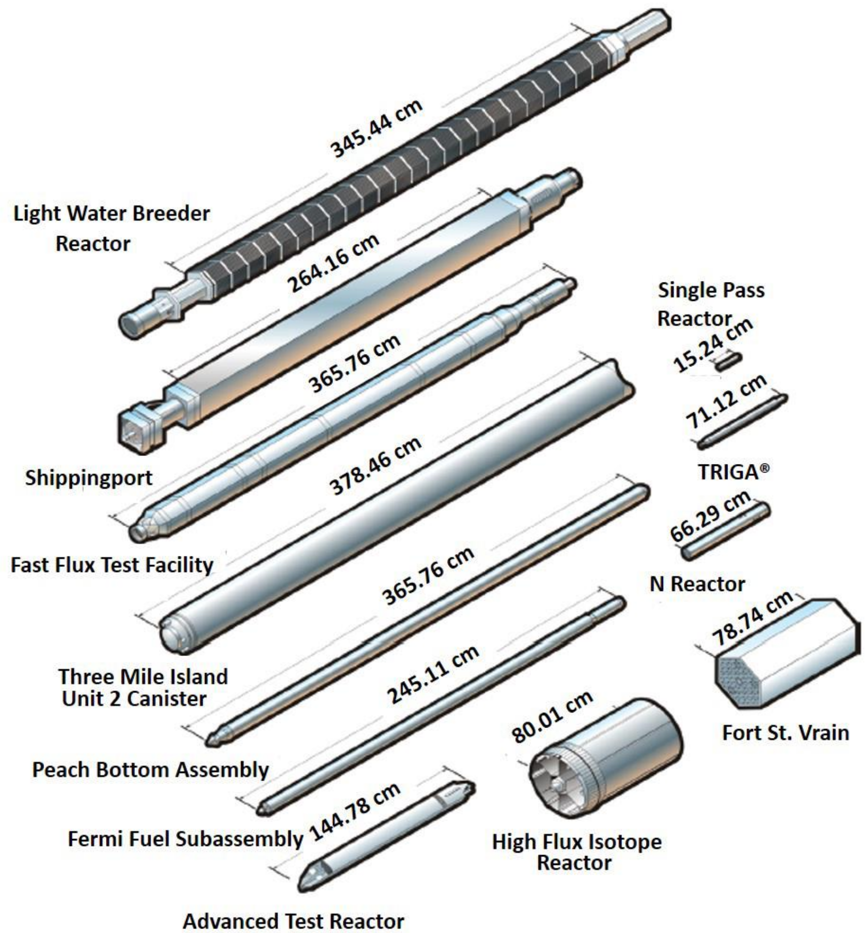


Figure 11. Some of the SNF types managed at INL.

As stated, the INL site currently manages over 250 types of SNF. Its SNF inventory totals approximately 315 MTHM (INL 2019) stored in both wet and dry storage facilities at INTEC, MFC and the 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 (HFEF) 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 12 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 these facilities and Table 5 lists the main source and distinguishing characteristics of the SNF in these facilities (NWTRB 2017b). Only the most prevalent types (by mass) are described in Table 5.

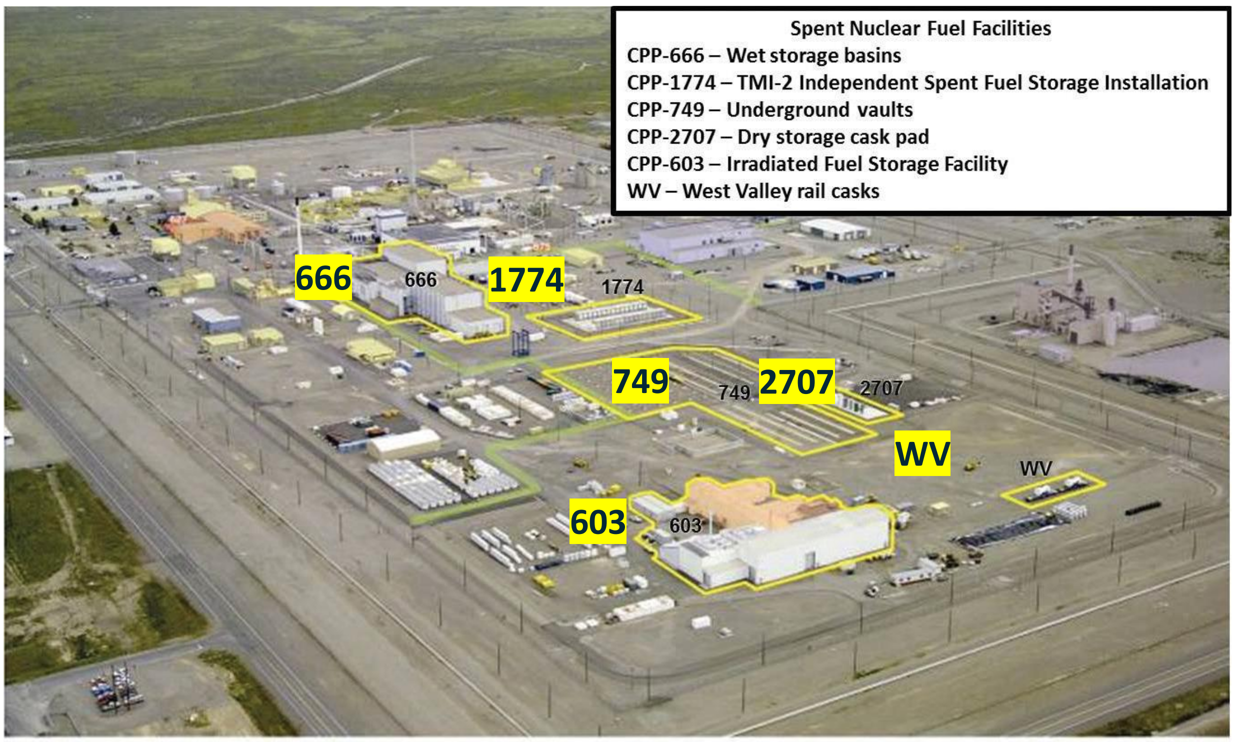


Figure 12. Aerial view of storage facilities at INTEC at the INL site.

Table 4. Characteristics of INL SNF storage facilities

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

Table 5. Main source of SNF at identified INL SNF storage facilities

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

4.2.1 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 ×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 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 13 shows remote handling of a canister in the fuel storage area (Davis 2009).

Figure 13. Remote handling of a storage canister in the CPP-603 vault.

The fuel handling cave was designed for the 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. 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 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 ATR, FSV, and Peach Bottom cask types (Bohachek et al. 2013).

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.

4.2.2 CPP-749 – Underground Fuel Storage Facility

The CPP-749 storage facility is an outdoor storage facility designed to safely store fuel and equipped with 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). 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 were loaded in September 1971. However, corrosion issues from moisture intrusion resulted in a 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 14 shows rows of second-generation vaults at CPP-749 (Davis 2009).

Figure 14. Second-generation underground vaults at the Underground Fuel Storage Facility.

4.2.3 CPP-2707 – Cask Pad Facility

The CPP-2707 Cask Pad Facility is part of the OFSF, which also includes CPP-749. The OFSF is designed to provide the safe storage of fuel and to provide retrieval capabilities for eventual transfer of the fuel out of the facility. 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 Castor V/21, Westinghouse MC-10, Ridihalgh, Eggers, and Associates, Inc. (REA)-2023, (5) Transnuclear, Inc. (TN)-24P 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 15 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 reprocessing facility in New York 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 16 shows one of the two rail casks at CPP2707 (Beller 2013).

Figure 15. Dry storage casks on the Cask Pad Facility.

Figure 16. One of two West Valley rail casks stored at CPP-2707.

4.2.4 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 the 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, which provides the bulk of interim SNF storage at MFC. The carbon steel–lined silos are 2ft in diameter and 12ft long (Smith et al. 2001; Gonzales- Stoller Surveillance 2012). Figure 17 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).

4.2.5 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 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 a microreactor demonstration as a facility in which to perform the post-irradiation disassembly of fuel that may contain reactive material such as sodium but is not suitable as a storage option for microreactor SNF

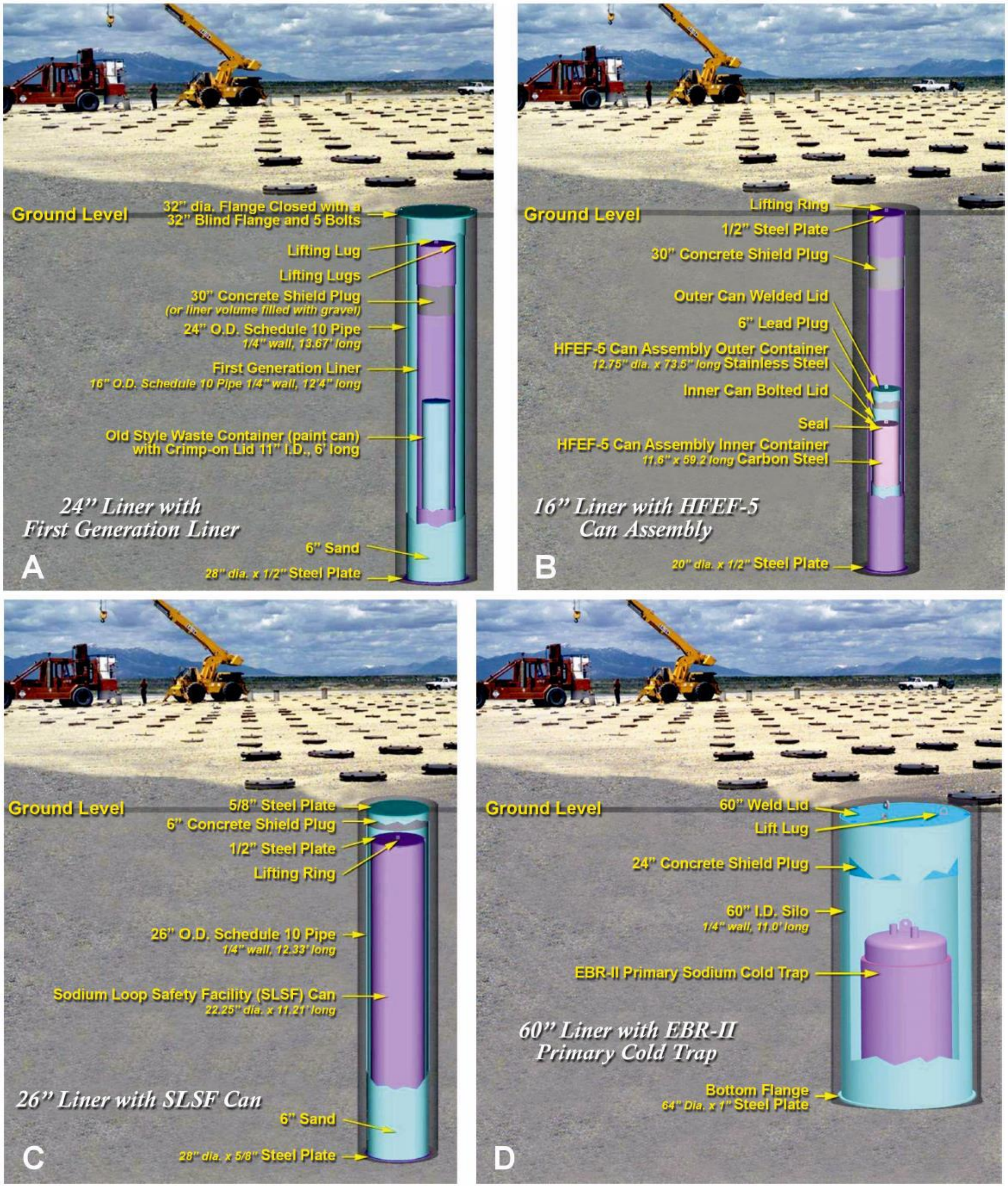


Figure 17. Four of the eight different steel liner configurations in the RSWF.

4.2.6 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 offsite disposal criteria. Figure 18 shows the general layout of the areas within the FSA.

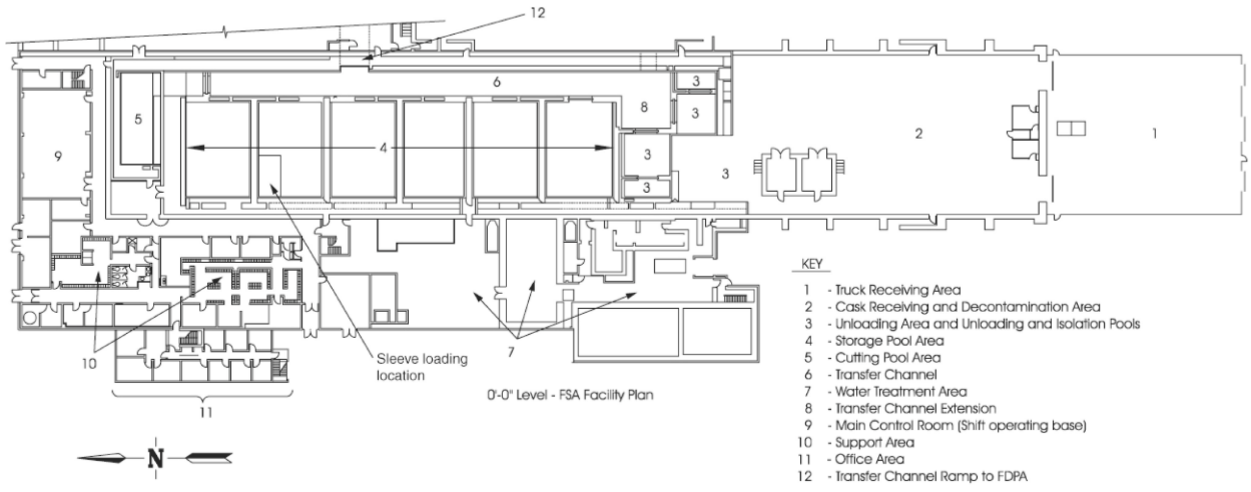


Figure 18. Plan view of the Fuel and Storage Facility.

The fuel storage pool area is shown in Figure 19 (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 19. 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.

4.2.7 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, for transportation out of Idaho in accordance with the 1995 Settlement Agreement. In 2001, Foster Wheeler Environmental Corporation, a DOE contractor, applied to the 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 offsite 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 20. 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 20 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 21 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. If constructed, a facility such as the ISFF, with some modifications (most notably increased storage capacity), may be able to meet the needs for the management of SNF from microreactor technology demonstrations at INL.

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

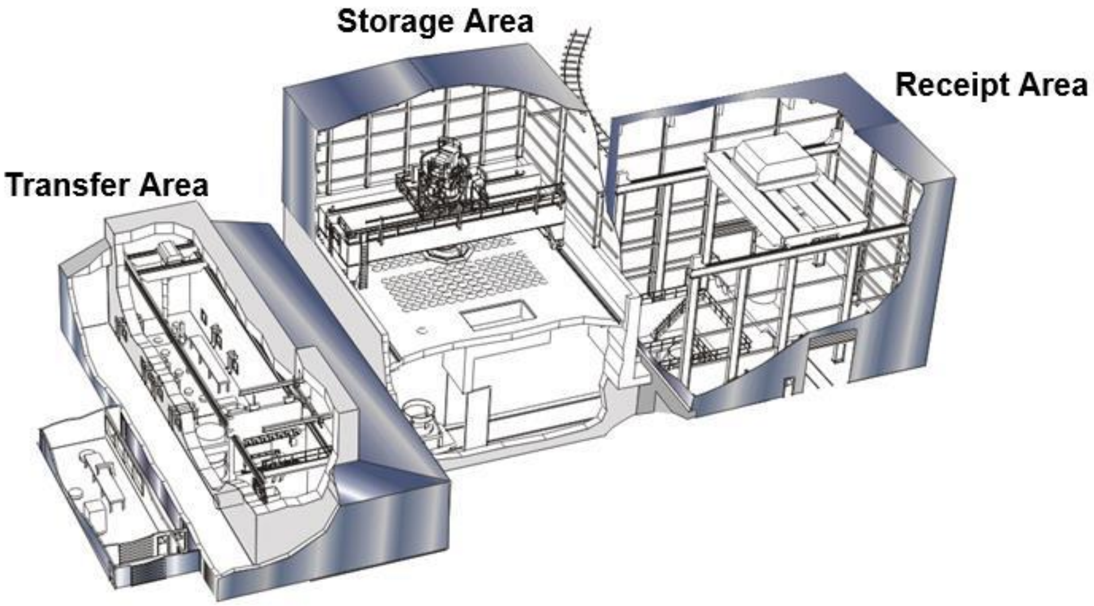


Figure 20. Cutaway view of ISFF storage vault configuration.

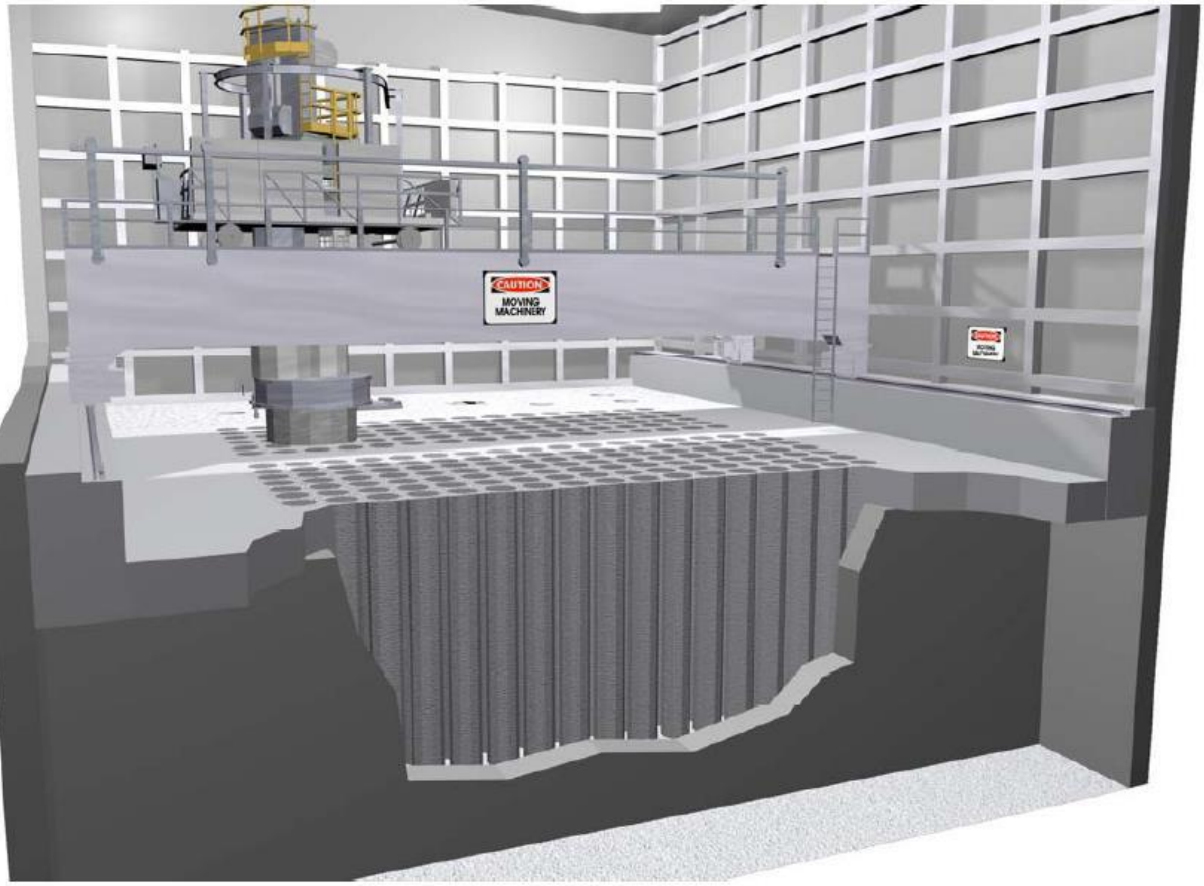


Figure 21. Cutaway view of several storage tube assemblies loaded with ISF canisters.

5. MICROREACTOR SNF TRANSPORTATION, MANAGEMENT, AND DISPOSITION OPTIONS

This section discusses options for transportation, management, and disposition of microreactor SNF and identifies issues associated with the identified options. Transportation options include transporting the microreactor and microreactor SNF separately or together. Management options are discussed for interim storage, treatment, material recovery, packaging, extended dry storage, and permanent disposition.

5.1 Microreactor Transportation Options at INL

In general, transporting a microreactor without its contents prior to irradiation would not be an issue, as the microreactor would not be a hazardous material shipment. Shipping a microreactor without its contents after irradiation by highway, rail, or barge would also not be an issue because it would be similar in concept to shipping an irradiated commercial nuclear power plant reactor vessel. Shipping of these reactor vessels has been done intact, such as from the Trojan nuclear power plant or the La Crosse nuclear power plant, or segmented, such as from the Rancho Seco nuclear power plant. The most significant issues are associated with shipping the microreactor together with its contents by any transport mode or shipping microreactor fuel by air.

Potential areas for issues include fissile material and Type B packaging applications, issues stemming from microreactor shielding and weights, issues associated with use and disposition of the current proposed microreactor fuel types, transportation mode specific issues (highway, rail, barge, and air), and necessary packaging evaluations (structural, thermal, containment, shielding, and criticality). Defense-in-Depth as well as associated issues stemming from this approach will also be discussed.

Packages used to ship microreactor SNF must meet the fissile material requirements in 10 CFR 71, including requirements for normal conditions of transport and hypothetical accident conditions. In their white paper (NEI 2018), the Nuclear Energy Institute discusses the need to develop criticality benchmark data to be used in certifying HALEU transport packages. At present, there is insufficient microreactor design detail to evaluate the structural, thermal, containment, shielding and criticality issues associated with microreactor transport. These analyses will be required to show that a microreactor will meet the requirements for the normal conditions of transport and hypothetical accident conditions in 10 CFR Part 71 in their microreactor designs.

5.1.1 Transport Microreactor and SNF Separately

One option for addressing most of the issues associated with transporting a microreactor is to ship the microreactor and SNF separately. New transportation packages would have to be designed based on the fuel type of the microreactor, but for TRISO and sodium bonded fuel, these types of packages have been designed and certified by the NRC or DOE and there is no reason to believe that it would not be feasible to design and certify new transportation packages for these fuel types. The ability to ship an irradiated reactor vessel either intact or segmented has been demonstrated numerous times in the commercial nuclear power industry. Shipping the microreactor without irradiated fuel would be like shipping an irradiated reactor vessel and there is no reason to believe that it would not be feasible to ship a microreactor without irradiated fuel either intact or segmented. For transport by air, shipping the SNF separately from the microreactor might simplify the design and certification of the fissile material package for the fuel because the design would not have to consider the design of the microreactor, but the fissile material packages would still have to meet the enhanced testing standards for transport by air.

For cases where the microreactor was shipped separately from SNF, no structural, thermal, containment, shielding, or criticality issues unique to microreactors were identified. In addition, shipping the microreactor without irradiated fuel would be like shipping an irradiated reactor vessel, except that the microreactor would likely be smaller and weigh less. Because the ability to ship irradiated reactor vessels either intact or segmented has been demonstrated numerous times in the commercial nuclear power industry no structural, thermal, containment, shielding, or criticality issues unique to shipping an irradiated microreactor without its fuel are expected.

The TN-FSV transportation cask (Docket No. 71-9523) is currently certified to ship irradiated high-temperature gas-cooled reactor TRISO fuel elements from the Fort St. Vrain nuclear power plant and BISO fuel elements from Peach Bottom Unit 1, Core 2. The TN-FSV is a Type B(U)F-96 package. The FSV-3 package (Docket No. 71-6347) was certified to ship unirradiated high-temperature gas-cooled reactor TRISO fuel elements from the Fort St. Vrain nuclear power plant. The FSV-3 was a Type AF package. The certificate of compliance for the TN-FSV and FSV-3 did not authorize the air transport of fissile material. Based on the ability of the TN-FSV transportation cask to transport Fort St. Vrain TRISO and Peach Bottom BISO fuel elements, and the ability of the FSV-3 package to transport Fort St. Vrain unirradiated fuel elements, it is likely that transporting microreactor TRISO fuel elements separately from the microreactor is achievable with the appropriate analyses showing adherence to the requirements of 10 CFR Part 71.

The T-3 transportation cask (DOE Certificate No. 9132) is currently certified to ship irradiated sodium bonded fuel pins with enrichments up to 40 percent. These fuel pins would be similar in design to SNAP-10A fuel pins that could be used in some microreactor designs. As with TRISO fuel elements, it is likely that transporting microreactor sodium bonded irradiated fuel elements separately from the microreactor is achievable. However, structural, thermal, shielding, and criticality analyses will be required to show that a microreactor containing sodium bonded irradiated fuel elements will meet the requirements of 10 CFR Part 71, particular for very short cooling times.

For cases where the microreactor was shipped separately from its SNF, no structural, thermal, containment, shielding, or criticality issues unique to microreactors were identified. In addition, shipping the microreactor without SNF would be like shipping an irradiated reactor vessel, except that the microreactor would likely have smaller dimensions and mass. Because the ability to ship irradiated reactor vessels either intact or segmented has been demonstrated numerous times in the commercial nuclear power industry no structural, thermal, containment, shielding, or criticality issues unique to shipping an irradiated microreactor without its fuel are expected.

5.1.2 Transport Microreactor and SNF Together

A second option for transporting a microreactor is to ship the microreactor together with its SNF. This option is likely to be much more challenging than shipping the microreactor and its fuel separately because the microreactor and its contents would likely not be designed or certified as a fissile material package or as a Type B package and would not meet the standards for these packages in 10 CFR Part 71. It should be noted that NRC has approved special package authorizations for Type B packages with a containment that is not leak tight but that demonstrated compliance with 10 CFR Part 71 leakage dose rates for normal conditions of transport (NCT) in 10 CFR 71.51(a)(1) and with hypothetical accident conditions (HAC) in 10 CFR 71.51(a)(2) (NRC 2015).

Probabilistic risk assessment (PRA) is one method that could be used to demonstrate the equivalent safety of transporting a microreactor together with its contents. PRA has been conducted since the 1970s for nuclear reactors, (NRC 1975, NRC 1990, Chang et al. 2012), dry cask storage systems at a nuclear power plant (NRC 2007) and transportation of SNF (Fischer et al. 1987, Sprung et al. 2000, NRC 2014). PRAs for transporting radioactive materials would be based on accident event trees that represent a set of possible transportation accidents. These event trees include accidents involving collisions and accidents that do not involve collisions. Collision accidents include accidents with non-fixed object (trains, trucks, other vehicles, etc.) and fixed objects (bridges, buildings, walls, etc.). Non-collision accidents include fires and explosions, jackknifes, rollovers, etc. Event trees are typically constructed using transportation accident data and geographic information system data. As such, event trees can be made country-specific and modified to include additional branches or exclude branches that are not applicable or of no interest.

5.2 Microreactor SNF Management and Disposition Options at INL

Where microreactor SNF demonstrably falls within the analytical envelop of a fuel type currently managed by DOE at INL, there is significant confidence that the current technology can be applied to provide safe and secure management of that microreactor SNF. For microreactor SNF with significantly different characteristics from the SNF currently managed 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 6 shows the SNF that is currently managed at INL that are potentially analogous to the selected TRISO 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 6. 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 RSWF	Dry	Experimental Breeder Reactor-II blanket assemblies	Low-enrichment uranium metal fuel with sodium bonding between the fuel and the stainless-steel cladding
	MFC RSWF	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

5.2.1 Interim Storage

After sufficient cooling, the SNF may be transferred to dry interim storage or to other processes involved with SNF management (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. In this scenario, the reactor module becomes the storage module. If it is retained on site, 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 part 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 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 managed 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 SNF 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.

5.2.2 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 comes 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 HLW and LLW waste streams that must be dispositioned in addition to the actinide-bearing waste forms.

5.2.3 Material Recovery

Material recovery as part of the management 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 HLW and LLW waste streams that must be dispositioned in addition to the actinide-bearing waste forms.

5.2.4 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 Standard 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 Standard Canister which would be the preferred repackaging option since this configures the microreactor SNF into a configuration that is ready for shipping to an ISFSI 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 Standard Canister packaging facility.

5.2.5 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 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 managed 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 managed 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 SNF 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.

5.2.6 Permanent Disposition

As with all SNF 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 SNF that must be prepared and packaged for direct disposal, it is not anticipated that microreactor fuels will pose any new challenges.

6. CONCLUSIONS

Microreactors are defined as a subset of advanced reactors, providing 20 MWe or less. Microreactors are designed to be factory-built, modular in nature, and portable— whether by road, rail, barge, or air. 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.

DOE is supporting the U.S. advanced reactor industry through funding, legislation, and regulatory development to actively pursue several microreactor design concepts with the objective of near-term demonstration of microreactor technology. As the nation's lead nuclear engineering laboratory, INL is strategically positioned to support near term demonstrations of advanced nuclear reactor technology including microreactor technology. The safe and secure transportation, management, and disposition of microreactor SNF generated in microreactor technology demonstrations in compliance with transportation, management and disposition regulations is a critical component of the successful deployment of microreactors in the U.S. The objective for this project is to identify and address issues related to the transport, management of microreactor SNF in general and at the INL site, as well as final disposition of the microreactor SNF offsite.

Transportation options for microreactor SNF can be categorized under two broad scenario sets. The first set of scenarios involves the transportation of the microreactor SNF separately, under the regulations related to the transport of fissile and radioactive material in 49 CFR 173, 10 CFR 71 and other pertinent regulations. This is representative of the paradigm under which SNF is currently transported and represents a well characterized operation for a wide variety of fuel types. The second scenario set involves the transport of the microreactor SNF together with the reactor or within the reactor envelope. This set of scenarios represents a significant paradigm shift in the way SNF is currently transported and would require significant effort to achieve. At present, without detailed design and operational information on microreactor SNF, it is unlikely that a microreactor without additional transportation packaging would meet the codified regulatory requirements for transportation. Probabilistic risk assessment is one method that could be used to demonstrate the equivalent safety of transporting microreactor SNF within the microreactor envelope.

Microreactor management 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 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). 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 management 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 Standard Canister system.

Two examples of microreactor concepts working towards near term demonstration at INL are the Project Pele microreactor and INL's Microreactor Applications Research Validation and Evaluation (MARVEL) microreactor. The Project Pele microreactor is a 1 – 3 MWe TRISO fuel based high-temperature gas reactor being developed for DoD, through the Strategic Capabilities Office to provide DoD's domestic infrastructure resilient to an electric grid attack and fundamentally change the logistics of Overseas Contingency Operations. The MARVEL microreactor design concept is a sodium-cooled 20 kWe reactor utilizing a sodium bonded fuel design. The MARVEL reactor is specifically designed to provide a test platform for microreactor component and subsystem development as well as demonstration. INL currently has within its SNF inventory, examples of analogous SNF in the Peach Bottom and Fort St. Vrain TRISO based fuels and the Fermi-1 and EBR-II sodium bonded fuel for which transportation and management options are well understood. As such it is expected that INL can safely manage and transport similar microreactor fuel types.

As with all SNF 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 SNF that must be prepared and packaged for direct disposal, it is not anticipated that microreactor fuels will pose any new challenges.

Future microreactor transportation work should be focused on building the framework for a transportation PRA that would provide the basis for approving the transport of microreactor SNF within the microreactor envelope by transportation regulators. It is recommended that the framework first be developed for onsite shipment at a DOE site, before expanding to offsite transportation requiring NRC approval, with the ultimate goal of achieving international transport which would require approval of a foreign competent authority.

Future microreactor SNF management and disposition work should be focused on structural, thermal, shielding, criticality and other necessary analyses that will inform the identification of concrete options for each step of the management process to arrive at microreactor SNF in a configuration that is ready for transportation to an independent spent fuel storage installation or permanent repository. In this respect, the diverse nature of DOE-owned SNF currently managed at INL, provides a reasonable bases to expect that INL currently manages SNF that are analogous to most microreactor fuel concepts. Therefore, the existing transportation, management, and disposition options for the current INL SNF inventory will serve as a model for the management of new microreactor SNF. In the case of microreactor SNF that is not represented by SNF in the current inventory, well established methodologies and approaches can be applied to develop the necessary transportation, management, and disposition plan.

The details of any transportation, management, and disposition plan are highly microreactor design specific and the necessary investigation, evaluation and analyses can only be performed once this information is available. As such, detailed microreactor design information, including geometries, configurations, materials, and material properties are key to perform a more detailed assessment of the transportation and management options identified thus far.

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