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A White Paper: Disposition Options for Sodium-Cooled Fast Reactors

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SUMMARY

The sodium-cooled fast reactor (SFR) design concept is one of the six classes of nuclear reactors in the GenIV initiative. SFRs are uranium or plutonium-fueled reactors operating in the fast neutron spectrum using liquid sodium as the coolant. SFRs can be designed as a breeder reactor or actinide-burning reactor in addition to operating the thorium fuel cycle. While having different fuel designs, the anticipated waste streams, and the necessary management strategies for spent nuclear fuel (SNF) and radioactive wastes from SFRs are very similar. This includes the SNF, activated sodium coolant, in-core stainless-steel components, piping, resins and filters, solidified liquid waste, contaminated equipment, and other radioactive wastes. Modern SFR designs are based on a long and rich operating history of several liquid-metal-cooled fast reactors with sodium coolant. Several of these reactors have been shut down, the fuel has been placed in safe storage, and they have undergone some degree of decommissioning. As such, there is significant experience in the management of the SNF and radioactive wastes associated with operating these reactors.

This white paper will identify the definitions and regulations that apply to the safe and secure management, storage, and disposal of radioactive waste and identify the key radioactive waste streams from SFRs. Idaho National Laboratory has significant experience in the management of the SNF from the SFR predecessors. This experience should form the basis for the management and disposition efforts of the radioactive waste from any new SFR-type small modular reactor or microreactor intended for deployment at the Idaho National Laboratory Site.

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ACRONYMS

AEA	Atomic Energy Act of 1954, as amended
CFR	Code of Federal Regulations
DOE	U.S. Department of Energy
EMT	electrometallurgical treatment
GenIV	generation IV
GTCC	Greater-Than-Class C
HLW	high-level waste
INL	Idaho National Laboratory
LLW	low-level waste
LWR	light water reactor
MEDEC	melt-drain-evaporate-carbonate
NWPA	Nuclear Waste Policy Act of 1982, as amended
SFR	sodium-cooled fast reactor
SNF	spent nuclear fuel
TRU	transuranic

A White Paper:

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1. INTRODUCTION

The sodium-cooled fast reactor (SFR) under the Generation IV (GenIV) initiative is a uranium or plutonium fueled fast reactor concept using liquid sodium as the coolant. The SFR can be designed as a breeder[a] reactor or actinide-burning[b] reactor in addition to operating the thorium fuel cycle. The thermal properties of the liquid sodium coolant allow for smaller core geometries and higher power densities, when compared with light-water reactors (LWRs). The high boiling point of sodium also allows for low-pressure operation just above atmospheric pressure, minimizing the likelihood of the complete loss of coolant inventory. Sodium reacts chemically with air and water, introducing a category of accident scenarios not encountered with LWR systems. Figure 1 shows a schematic of the SFR layout under the GenIV initiative.

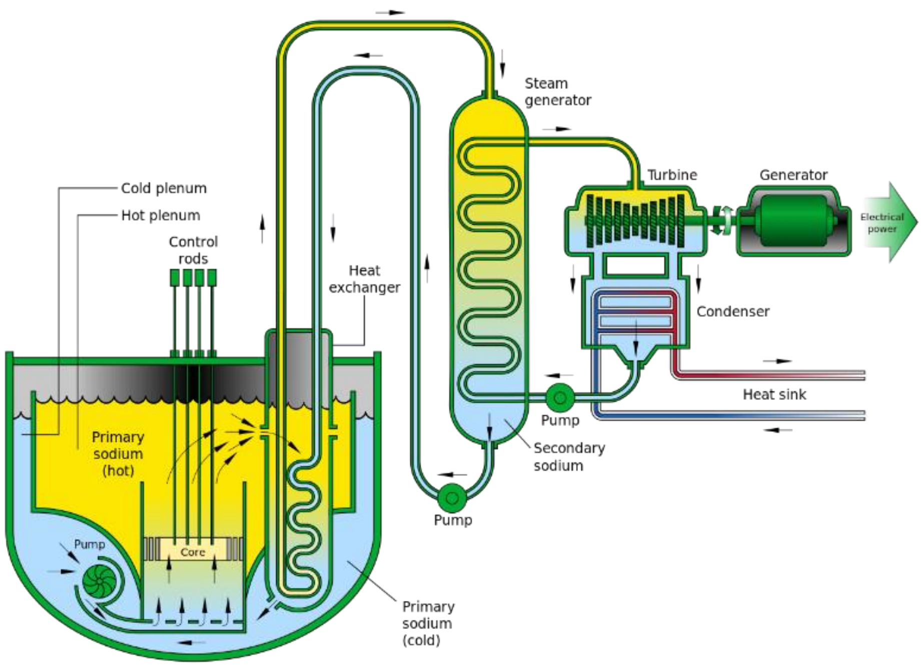

Figure 1. Pool-type SFR concept under the GenIV initiative

The SFR is the result of decades of operating experience with liquid-metal-cooled fast reactors in general, and sodium-cooled fast reactors in particular. Table 1 shows the location, thermal power output and years of operations of several experimental, prototypic, and commercial sodium-cooled fast reactors. While they have different fuel designs, the anticipated waste streams, and necessary management strategies for SNF and radioactive wastes from SFRs are very similar. This includes the SNF, activated sodium coolant, in core stainless-steel components, piping, resins and filters, solidified liquid waste, contaminated equipment, and other radioactive wastes. Indeed, there is significant experience in the management of the spent nuclear fuel (SNF), and radioactive wastes associated with operating SFRs. Of the reactors referenced

[a] Breeder reactors are designed to produce more fissile material than they consume.

[b] Actinide-burning reactors are designed to incinerate long-lived radioactive isotopes.

in Table 1, only the BN-600, BN-800, CEFR, FBTR, and Jōyō are still in operation. The remaining reactors have been shut down and are in various stages of decommissioning.

Section 2 discusses the classification of radioactive waste and how they may apply to SFR waste streams. Section 3 identifies the key classes of SFR radioactive waste streams. Idaho National Laboratory (INL) has significant experience in the management of SNF from the SFR predecessors; specifically, Fermi-1 (34 metric tons), EBR-II (25.6 metric tons), and FFTF (0.25 metric tons). This experience should form the basis for the management and disposition efforts of the radioactive waste from any new SFR-type reactor intended for deployment at the INL Site. Section 4 presents the conclusions of this paper.

Table 1. Overview of sodium-cooled fast reactors with significant years of operation

Reactor	Country	Thermal Power (MW)	Year of Operation
EBR-1	United States	1.4	1950–1964
SRE	United States	20	1957–1964
Fermi 1	United States	200	1963–1975
EBR-2	United States	62.5	1965–1994
Rapsodie	France	40	1967–1983
Jōyō	Japan	150	1971–Operational
BN-350	Soviet Union	~850	1973–1999
Phénix	France	590	1973–2010
PFR	United Kingdom	500	1974–1994
FFTF	United States	400	1980– 2003(cold standby)
BN-600	Soviet Union	1470	1980–Operational
FBTR	India	40	1985–Operational
SNR-300	Germany		1985–1991
Superphénix	France	3000	1986– 997
Monju	Japan	714	1995–2010
CEFR	China	65	2012–Operational
BN-800	Soviet Union/ Russia	2100	2015–Operational

2. RADIOACTIVE WASTE CLASSIFICATION

The disposition options for radioactive waste streams from SFR operations will be dictated by the classification of the radioactive waste streams as either SNF, high-level waste (HLW), low-level waste (LLW), transuranic (TRU) waste, or byproduct material. The applicable definitions for the various categories of radioactive waste in the U.S. are established by the U.S. Department of Energy (DOE), the Atomic Energy Act of 1954 (AEA) (Atomic 1954), and the Nuclear Waste Policy Act of 1982 (NWPA) (Nuclear 1982). The following are the terms as defined in the relevant laws.

- **Spent nuclear fuel (NWPA 1982)** – *Fuel that has been withdrawn from a nuclear reactor following irradiation, the constituent elements of which have not been separated by reprocessing.*
- **High-level waste (NWPA 1982)** – *(A) the highly radioactive material resulting from the reprocessing of spent nuclear fuel, including liquid waste produced directly in reprocessing and any solid material derived from such liquid waste that contains fission products in sufficient concentrations; and (B) other highly radioactive material that the Commission, consistent with existing law, determines by rule requires permanent isolation.*
- **Transuranic waste (DOE Order 435)** – *radioactive waste containing more than 100 nanocuries (3700 becquerels) of alpha-emitting transuranic isotopes per gram of waste, with half-lives greater than 20 years, except for: (1) High-level radioactive waste; (2) Waste that the Secretary of Energy has determined, with the concurrence of the Administrator of the Environmental Protection Agency, does not need the degree of isolation required by the 40 CFR Part 191 disposal regulations; or (3) Waste that the Nuclear Regulatory Commission has approved for disposal on a case-by-case basis in accordance with 10 CFR Part 61.*
- **Low-level waste (NWPA 1982)** – *radioactive material that (A) is not high-level radioactive waste, spent nuclear fuel, transuranic waste, or by-product material as defined in section 11e(2) of the Atomic Energy Act of 1954 [42 U.S.C. 2014(e)(2)]; and (B) the Commission, consistent with existing law, classifies as low-level (C) radioactive waste.*
- **Byproduct material (AEA 1954)** – *(1) any radioactive material (except special nuclear material) yielded in or made radioactive by exposure to the radiation incident to the process of producing or utilizing special nuclear material.*

There are four classes of LLW: Class A, Class B, Class C, and Greater-Than-Class C (GTCC). These classes are based on waste form requirements and the activity per unit volume of specific radioisotopes, as defined in title 10, Part 61 of the Code of Federal Regulations (10 CFR 61).

There are four categories of byproduct material: (1) radioactive material that results from the fission, or splitting apart, of enriched uranium or plutonium in nuclear reactors; (2) tailings or waste produced by processing uranium or thorium from ore; (3) certain processed radium-226 or material that becomes radioactive in a particle accelerator used for a commercial, medical, or research activity; and (4) a naturally occurring radioactive source that is processed to increase its concentration and that the NRC decides could pose a threat to people and the environment similar to that of radium-226.

Depending on the operations at the SFR plants, it is expected that some of the waste streams could be classified as LLW. This has been done for byproduct material, such as the components of the primary loop, drainable liquids, resins, filters, solidified liquid waste, contaminated equipment, delayed beds for capturing and holding short lived radioactive gases and allowing them to decay away, decontaminated piping, the containment vessel, and refueling equipment, to name a few.

The disposition of some SFR HLW waste as TRU or LLW may be possible following the recent DOE interpretation of HLW (DOE 2018, DOE 2019). DOE interprets that reprocessing waste may be determined to be non-HLW if the waste meets either of the following two criteria: *1) does not exceed concentration limits for Class C low-level radioactive waste as set out in section 61.55 of title 10, Code of Federal Regulations, and meets the performance objectives of a disposal facility; or 2) does not require disposal in a deep geologic repository and meets the performance objectives of a disposal facility as demonstrated through a performance assessment conducted in accordance with applicable requirements*.

All contaminated sodium-bearing wastes from SFRs would be classified as a mixed waste. Hazardous wastes are materials known or tested to exhibit one or more of the following hazardous traits: ignitability, reactivity, corrosivity, or toxicity as per 40 CFR 261. Mixed wastes are regulated by both the Resource Conservation and Recovery Act (RCRA) (Resource 1976) and AEA.

3. SFR RADIOACTIVE WASTE STREAMS

The radioactive waste streams from SFRs can be categorized into the following groups:

1. Spent nuclear fuel
2. Sodium wastes
3. Other radioactive wastes.

Any SNF and HLW will require disposal in a deep geological repository. Depending on the waste acceptance criteria of the final repository, hazardous wastes as defined by RCRA could be deemed unacceptable. For materials containing a potentially reactive component, as is the case of SFR SNF or sodium-bonded SNF, RCRA regulations in 40 CFR 261.23 must be used to determine if those materials require treatment prior to disposal. Since elemental sodium is known to violently react with water and produce a potentially explosive gas (hydrogen), the sodium component would be classified as a characteristic reactive waste. Treatment for this type of reactive waste requires deactivation to remove the hazardous characteristic of a waste. Based on these regulatory requirements, SFR SNF and sodium-bonded SNF disposal will require chemical deactivation or physical removal of the sodium. There are a range of options for sodium deactivation, though their applicability and effectiveness are strongly dependent on the amount of sodium that becomes infused into the fuel element. This infusion can happen in metallic fuel elements where fission products can cause fuel elements to swell and develop porosity. The sodium can then become infused into the fuel elements. Significant infusion of sodium in the fuel prevents either chemical deactivation or physical removal of sodium and requires dissolution or melting of the fuel. The SNF can also be treated to recover desirable materials using various processes, such as aqueous separation and electrometallurgical treatment (EMT).

Sodium-bearing wastes not considered SNF or HLW will require disposition at LLW disposal sites. These wastes will also require chemical deactivation or physical removal of sodium prior to disposal. The bulk sodium coolant can often be decontaminated and reused. The wastes from this decontamination will require storage until disposal either as HLW or LLW. Some of these structures may exceed the activity limits for class C LLW at which point they would be considered GTCC wastes, for which there is no clear disposition path at present. These would have to be stored temporarily to allow the radioactivity to decay away below the class C activity limits before disposal.

Other radioactive waste streams include metal, carbon, operating, decontamination, and decommissioning waste streams. In general, these wastes can be treated and disposed of in the same manner as similar wastes from other nuclear reactors.

3.1. Spent Nuclear Fuel

The DOE preferred disposition path for EBR-II driver and blanket fuel and FFTF driver fuel is the EMT process (DOE 2000) A decision is to be made in the future for other SFR SNF and sodium-bonded SNF. Other disposition paths are direct disposal without sodium removal, direct disposal following sodium removal, melt and dilute following sodium removal, melt and dilute following sodium and cladding removal, and aqueous processing following sodium and cladding removal.

3.1.1. Direct Disposal without Sodium Removal

As mentioned, this is only an option if the repository is designed to accept reactive materials like sodium without prior treatment. Under this regime, the SNF could be packaged into standard repository disposal canisters. Should the fuel be damaged in any way, the SNF would be packaged into high-integrity cans to provide an additional level of containment for SNF. These canisters would have to be compatible with the standard repository disposal canisters.

3.1.2. Direct Disposal following Sodium Removal

This alternative would require the packaging of SNF into high-integrity cans to provide an additional level of containment for SNF after the removal of the sodium from the SNF. This is necessary since the cladding will have to be compromised to access and extract the sodium. These canisters would have to be compatible with the standard repository disposal canisters. This option is only viable for fuel types where the sodium is not infused within the fuel meat. This can happen in metallic fuel elements where fission products can cause fuel elements to swell and develop porosity. The sodium can then become infused into the fuel elements. Significant infusion of sodium in the fuel prevents either chemical deactivation or physical removal of sodium and requires dissolution or melting of the fuel.

The sodium can be removed using the melt-drain-evaporate-carbonate (MEDEC) technology initially developed in the early 2000s to remove sodium from unirradiated EBR-II fuel elements. Since then, further development has shown that the process can be applied to irradiated fuel as well. The process uses a combination of heat and reduced pressure to melt and vaporize the bond sodium, removing it from the metal fuel. After melting, the sodium evaporates and is condensed in a separate container. Radioactive cesium and trace amounts of plutonium were measured in the evaporated elemental sodium (DOE 2007).

An alternative to MEDEC is sodium removal through an alcohol wash process. In this process, the fuel element cladding is cut to expose the fuel slugs, which are washed in an alcohol wash solution. This removes the sodium as sodium carbonate, which can be disposed of as LLW.

3.1.3. Melt-Dilute following Sodium Removal

This alternative involves melting the fuel elements after the sodium removal through alcohol wash or the MEDEC process, but without prior removal of the cladding. The result is metal-based waste forms that can be packaged in high-integrity cans compatible with the standard repository disposal canisters for disposal.

3.1.4. Melt-Dilute following Sodium and Cladding Removal

This alternative involves melting the fuel elements after sodium removal through alcohol wash or the MEDEC process and cladding removal. The result is metal-based waste forms that can be packaged in high-integrity cans compatible with the standard repository disposal canisters for disposal.

3.1.5. Aqueous Processing following Sodium and Cladding Removal

This alternative involves chemical processing of the SFR SNF via conventional processing techniques that allow for the recovery of the U, Pu, and Th (if the Th fuel cycle is used). To do so, the sodium and cladding must first be removed. The separated fission products can then be encapsulated in glass or any other appropriate waste form that meets the repository waste acceptance criteria.

3.1.6. Electrometallurgical Treatment (Pyroprocessing)

The electrometallurgical treatment (EMT) process also known as pyroprocessing is a chemical process developed for DOE by Argonne National Laboratory in the 1980s that oxidizes sodium into sodium chloride while separating SNF into a uranium and transuranic product and acceptable HLW forms that must be packaged in repository acceptable HLW packages. Sodalite is a glass-bonded ceramic waste form that has been demonstrated as a waste form option for the electrolyte salts from pyroprocessing of the EBR-II fuel. The residual steel cladding has been demonstrated to form a consolidated metallic ingot suitable for geologic disposal. The DOE preferred disposition path for EBR-II driver and blanket elements and FFTF driver fuel. (DOE 2000) A decision is to be made in the future for other SFR SNF and sodium-bonded SNF.

3.2. Sodium Wastes

The sodium wastes from SFR operations will be in two forms, the bulk sodium from the primary and secondary coolant loops and the residual sodium on SNF, piping, and other such components. Sodium bearing wastes not considered SNF or HLW will require disposition at LLW disposal sites. These wastes will also require chemical deactivation or physical removal prior to disposal. The bulk sodium coolant can often be decontaminated and reused. The wastes from this decontamination will require storage until disposal either as HLW or LLW. The EBR-II bulk sodium measured a final concentration of cesium within the primary coolant of approximately 370 Bq/g of cesium before it was decommissioned (Newton et al. 2002). The contamination can be remediated with a suitable cesium trap system. The traps act as a filter for the sodium passing through it, trapping the cesium. Successive traps are installed until acceptable levels of cesium are achieved. The cesium traps will require shielding and storage and eventual disposition either as LLW or GTCC depending on the activity limits. The bulk sodium can then be drained and converted into anhydrous sodium hydroxide, which is a solid form that can be stored in drums. After the draining of the sodium, the primary coolant loop and the reactor vessel will still have residual sodium that must be chemically deactivated or physically removed to prevent hydrogen gas build-up.

3.3. Other Radioactive Waste Streams

Other radioactive waste streams include stainless-steel components, piping, operating, and decontamination and decommissioning waste streams. Operating radioactive waste includes contaminated equipment, solidified liquid waste, material containers, personal protective equipment, resins and filters, waste cleanup resins, and glove box gloves. In general, these radioactive wastes can be treated and disposed of in the same manner as similar wastes from other nuclear reactors. These waste streams are likely to produce some HLW but a majority are likely to be LLW.

4. CONCLUSIONS

In conclusion, the SFR design concept is one of the six classes of nuclear reactors in the GenIV initiative and is the result of several decades of research, development, and operation of liquid-metal-cooled fast reactor technology. The SFR can be designed as a breeder or actinide-burning reactor in addition to operating the thorium fuel cycle. While having different fuel designs, the anticipated waste streams, and the necessary management strategies for SNF and radioactive wastes from SFRs are very similar. This includes the SNF, activated sodium coolant, in-core stainless-steel components, piping, resins and filters, solidified liquid waste, contaminated equipment, and other radioactive wastes. Indeed, many SFRs have been built and operated around the world, with over 10 sodium-cooled fast reactors are in various stages of decommissioning. As such, there is significant experience in the management of the SNF, and radioactive wastes associated with operating these reactors.

Depending on the waste acceptance criteria of the final repository, hazardous wastes as defined by RCRA could be deemed unacceptable. Materials containing a potentially reactive component, such as the sodium in SFR SNF or sodium-bonded SNF, will require chemical deactivation or physical removal of the sodium to remove the hazardous characteristic of the waste. The DOE preferred disposition path for EBR-II driver and blanket fuel and FFTF driver fuel is the EMT process that oxidizes sodium into sodium chloride while separating the SNF fuel into a uranium and transuranic product and acceptable HLW forms. This approach is preferred over other alternatives, such as direct disposal with and without sodium and cladding removal, melt-dilute with and without sodium and cladding removal, and conventional aqueous processing following sodium and cladding removal.

The sodium waste streams from SFRs will be largely composed of bulk sodium from the primary and secondary coolant loops and residual sodium on SNF, piping, and other such components. The bulk sodium can often be decontaminated and reused in future SFRs but not in non-nuclear applications. The wastes from this decontamination will require storage until disposal either as HLW or LLW. Sodium-bearing wastes from residual sodium removal will also require chemical deactivation or physical removal before disposition at LLW disposal sites.

Other radioactive waste streams include metal, carbon, operating, and decontamination and decommissioning waste streams. In general, these wastes can be treated and disposed of in the same manner as similar wastes from other nuclear reactors.

INL has significant experience in the management of SNF from the SFR predecessors, specifically Fermi-1 (34 metric tons), EBR-II (25.6 metric tons), and FFTF (0.25 metric tons) and is currently treating EBR-II SNF ND using the EMT process, and evaluating a modified MEDEC process for EBR-II and Fermi blanket materials.. This experience should form the basis for the management and disposition efforts of the radioactive waste from any new SFR-type reactor intended for deployment at the INL Site

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