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A Framework to Assess Advanced Reactor Spent Fuel Management Facility Deployment

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INTRODUCTION

There is significant interest in the development and deployment of advanced nuclear reactors, which can offer various advantages over light-water reactors (LWRs) including safety, efficiency, and natural resource utilization, among others. This next generation of nuclear reactors will produce spent nuclear fuel (SNF) with a wide range of forms and characteristics. Each advanced reactor SNF type potentially poses unique challenges different than those dealt with in the management of the current LWR SNF inventory.

Previous planning and prioritization for LWR SNF management investigated the risks and uncertainties of deploying facilities such as consolidated interim storage [1, 2, 3, 4]. As part of that work, activities and milestones were collected into success precedence diagrams that charted a path to achieving facility deployment [1]. In that framework, activities are any research, development, design, or decision required to achieve an intermediate goal; milestones are activity endpoints and mark the completion of deliverables. Milestones can be thought of as achievements required to reach the final goal of facility deployment; activities are the means by which milestones are accomplished. In planning, activities and milestones are compiled into comprehensive flow charts that visualize the steps necessary for deployment. This framework has been used to quantify risks, timelines, and costs of deploying SNF management facilities.

The activity and milestone framework can also be applied to the hypothetical deployment of facilities managing SNF from advanced reactors. Advanced reactor SNF management requires some of the same types of facilities as LWR SNF, and at a high level, the same milestones will apply to the deployment of any facility. However, advanced reactor and SNF characteristics could present new challenges that will determine whether new types of facilities are required and could affect the activities on the deployment path.

As a preliminary demonstration, this paper applies the facility deployment activities/milestones framework to advanced reactor SNF management. The goal of this paper is to point out how advanced reactor SNF characteristics could pose challenges for facility deployment, thereby highlighting issues for research and development. First, a generic set of facilities which could be required to manage any type of SNF is proposed. Each facility is assumed to share the same set of generic, high-level milestones and activities along the critical path to deployment. These generic sets of facilities and milestones are then conceptually and qualitatively examined in the context of managing SNF produced by various advanced reactor technologies.

First, the paper provides an overview of a hypothetical, generic SNF management system and a broad set of major milestones and activities that apply to the development of any facility. The following sections present case studies that apply this hypothetical system to three types of advanced reactors: sodium-cooled fast reactors (SFRs), high-temperature gas-cooled reactors (HTGRs), and molten-salt reactors (MSRs). This report makes no recommendations or conclusions about any specific reactor type or system, but only uses specific systems for illustrative purposes. The case studies illustrate deployment challenges and how they affect different milestones for different facilities. Finally, the paper concludes with overarching takeaways and opportunities for future work.

GENERIC SNF MANAGEMENT FACILITY MILESTONES AND ACTIVITIES

The direct-disposal fuel cycle for any reactor or SNF form can be generalized conceptually with a few key operations. After fuel is discharged from the reactor, some or all of the following operations are required: on-site cooling and storage, transportation, fuel treatment or stabilization, interim storage, and final disposal in a deep geologic repository. Different advanced reactor types may not require all generic steps, and facilities would need to be tailored to specific types of fuel or processes. Fig. 1 shows a generalized flow sheet of these operations arranged linearly to create a hypothetical back-end system. Transportation would be required between some, but perhaps not all, steps. If

Fig. 1. Generic advanced reactor SNF management flowsheet for direct disposal fuel cycle (no reprocessing), assuming stabilization step and transportation between all facilities.

necessary, repackaging into disposal canisters could occur at the repository.

A broad overview of the primary purposes for each of the operations is outlined in Table 1. These general considerations must be accounted for in the planning of each facility, regardless of SNF type. In addition to accomplishing their stated task(s), all facilities must address safety considerations including those related to fuel and clad integrity, maintaining subcriticality, dissipating decay heat, and providing adequate shielding.

Seven major milestones are necessary to implement any of the facilities needed to perform the operations described. These are listed in Table II along with the high-level activities required to achieve them. Despite the limited number of major milestones, the activities are numerous, complex, and highly coupled [1]. The milestones and activities reported in Table II are abstracted from those borne out of subject matter expert input as part of the process reported in Ref. [1]. Each high-level activity can itself be broken down into smaller milestones and activities, but this level of detail is not presented in this preliminary effort and can be built out in the future.

The following sections trace the pathway of SNF from three advanced reactor types through this generic SNF management system. Characteristics of the SNF are used to inform which management facilities may be required. The cross-product of all major milestones and all required operations results in a conceptual matrix of milestones and facilities. Based on SNF characteristics, management challenges are identified and qualitatively studied according to facility type and major milestone. This exercise highlights which combinations of facilities and milestones appear to be

TABLE I. Primary purposes for facilities fulfilling generic SNF management operations

Operation	Purpose
On-site cooling and storage	Allow discharged SNF to initially cool prior to subsequent process steps; provide storage until SNF is transported off site
Fuel treatment or stabilization	Produce waste forms more amenable to storage, transport, and/or disposal, e.g. by removing reactive, toxic, or otherwise undesirable materials from the SNF [(a)] (or, alternatively, by achieving volume reduction if desired)
Interim storage	Provide consolidated storage prior to transport to a geologic repository for final disposal
Transportation	Move SNF from one geographic site to another
Final disposal	Provide permanent isolation of radioactivity hazard from the biosphere by leveraging engineered and natural barriers in a geologic repository

[(a)] Potentially required if the fuel contains hazardous or reactive materials as defined by the Resource Conservation and Recovery Act (RCRA) [5] and determined by 40 CFR 261.23 [6]; will depend on repository waste acceptance criteria

TABLE II. Generic major milestones and activities to develop SNF management facilities

Major milestone	Major activities required
Establishing responsibility	• Formal authorization of organization to site and develop facility (potentially via legislation) • Determine organization management structure; determine financial responsibility
Siting	• Develop siting process; request and evaluate volunteer sites; identify alternatives • Negotiate consent agreements with host communities, ultimately designating a site
Establishing transportation infrastructure	• Design and test rolling stock • Design and obtain NRC approval of transportation casks • Manufacture and procure transportation fleet • Identify maintenance needs, design maintenance facilities • Planning: select routes; obtain approvals from authorities; contract with railroads
NEPA compliance	• Complete site-specific draft environmental report and NRC prepares environmental impact statement (EIS), considering alternative sites, designs, transportation requirements, and other necessary facilities • Hold public hearings, receive comments, finalize EIS
Design	• Establish facility scope, design, acceptance criteria; complete safety analysis
Licensing	• Prepare and submit license applications for nuclear facilities to NRC for review • Respond to NRC requests for additional information • Obtain necessary licenses and permits from local, tribal, state, and federal authorities
Construction	• Prepare site; construct facility, ancillary facilities, and transportation infrastructure (e.g. rail spur)
Testing	• Perform inspections and testing to verify construction quality, safety, and compliance with regulation • Potentially include pilot-scale demonstration operation prior to full-scale operation

most challenging. These identifications may provide direction for near term R&D to begin tackling the challenges most critical to advanced reactor SNF management.

SODIUM FAST REACTOR SNF MANAGEMENT

Sodium-cooled fast reactors (SFRs) use liquid sodium as coolant, allowing for higher operating temperatures and increased thermal efficiencies. Fast fission results in extra neutrons that can be used to breed new fissile material or transmute fissionable actinides. Historically, SFRs were envisioned for use in a closed fuel cycle that recycled fertile uranium and actinides. By contrast, the fuel cycles of many currently proposed SFRs do not rely on close coupling with fuel reprocessing, although for all the option remains a technical possibility. Instead, these projects are focusing on achieving longer refueling cycles and higher burnup to increase resource utilization without reprocessing.

SFR fuel is typically metallic Zr-alloy clad in stainless steel (e.g. HT9). Many past designs have relied on Pu as fissile fuel, but newer designs use high-assay low-enriched uranium (HALEU). Sodium may be used as a thermal bond material between the fuel and cladding to improve heat transfer; during operation, the fuel will swell to contact the cladding and sodium will migrate into the fuel. Among proposals for new SFR fuels are concepts that do not require sodium bond [7]. Fuel pins are arranged in a hexagonal lattice which is bundled in a hexagonal, stainless steel duct.

SFR SNF has numerous characteristics that distinguish it from LWR SNF. As an example, Table III compares the fuel characteristics of Westinghouse AP1000 PWR fuel with different phases of the TerraPower Natrium SFR [7]: "Natrium" as initially commercialized, and "Natrium-U", which supports the long-term vision for a sustainable fuel cycle. The Natrium fuels have a significantly shorter active fuel height and operate at higher thermal efficiency and to higher burnup, resulting in lower heavy metal discharge per electricity generated. It should be noted that the amount of heavy metal that is expected to be discharged from operating an initially deployed Natrium-DEMO (13.7 t/GWe-y [7]) is greater than that from Natrium and Natrium-U due to lower burnup. Natrium fuel assemblies are smaller than AP1000 fuel assemblies, so despite the significantly lower uranium loading per assembly, Natrium reactors discharge less SNF volume per electricity generated.

Sodium is reactive with water and might be considered a RCRA hazard. Although direct disposal has been considered for sodium-bonded SNF [12, 13], sodium bond will likely need to be removed by a fuel treatment process before disposal in a deep geologic repository. Relative to LWR SNF, the higher burnup of SFR SNF will result in elevated radioactivity and decay heat. High burnup may also result in structural degradation of assembly components. Compositionally, the spent fuel will be fundamentally different from LWR spent fuel, potentially requiring new assessments of nonproliferation safeguards and criticality safety.

On-site SNF storage at the SFR

Storing sodium-bonded SFR SNF is more complex than storing LWR spent fuel, so on-site storage warrants discussion in this section.

The U.S. has decades of experience storing sodium-bonded SNF from legacy reactors in pool and dry storage at Idaho National Laboratory (INL). The Department of Energy (DOE) is responsible for managing approximately 60 metric tons heavy metal (MTHM) of sodium-bonded SNF [14]. Some of these fuels have been damaged or failed while in storage [14, 15]. It is likely that lessons-learned from this experience could be applied to benefit the storage of future SFR SNF.

The storage facility is expected to provide cooling while ensuring that no water or humid air contacts the fuel. Because

TABLE III. Comparison of SFR and PWR fuel assembly characteristics

Characteristic	Unit	Natrium [7]	Natrium-U [7]	AP1000 [8]
Assembly dimensions	m	Height = 4.7 Duct flat-to-flat = 0.16		Height = 4.583 Side length = 0.214
Assembly volume	m^3	0.104		0.210
Fueled height	m	1.2	2.0	4.267
Thermal Power	MW	841.5	841.5	3415
Electric Power	MW	345.0	345.0	1110
Thermal efficiency	%	41.0	41.0	32.5
Burnup	GWd/t	150.0	200.0	50.0
Discharged mass (HM + FP) [(a)]	t/GWe-y	5.93	4.45	22.46
HM (U) mass per assembly	t/asm	0.09 [(b)]	0.15 [(b)]	0.44 [(c)]
Discharged SNF volume [(d)]	m^3/GWe-y	6.72	3.02	10.72

[(a)] Calculated: 1 GWe / Thermal efficiency / Burnup [GWd/t] * 365 [d/y]

[(b)] Calculated: Fueled vol. [m^3] * 0.283 * 16.3 [t/m^3] * 0.75; where 0.283 and 0.75 are the fuel vol. frac. and smear density from S-PRISM, respectively [9], and 16.3 t/m^3 is the fabrication density for U-10Zr (from Table 8 in [10])

[(c)] Calculated based on 2017 data from [11]

[(d)] Calculated: Discharged HM mass [t/GWe-y] / HM mass per asm [t/asm] * Assembly volume [m^3]

the sodium bond is reactive with water, moisture ingress through any cladding defect is of great concern. Until recently, the Experimental Breeder Reactor II (EBR-II) driver SNF was in wet storage in steel canisters, but DOE is working to transfer it to dry storage [16]. New facilities for storing sodium-bonded SNF may avoid water or will need to guarantee canister seals.

Licensing on-site storage of sodium-bonded SNF may be challenging but will be part of the license granted to construct and operate the SFR. The NRC has never licensed a storage installation for sodium-bonded SNF, as all is currently managed by DOE. Most was also produced by DOE or its predecessors in EBR-I, EBR-II, the Fast Flux Test Facility (FFTF), and the Sodium Reactor Experiment (SRE). The only private SFR was Fermi-1, which shut down before the NRC was established; Fermi-1 SNF is managed by DOE.

Even if the SFR SNF contains no sodium bond, cooling will still be critical due to the higher burnup during breed-and-burn operation. Increased burnup results in increased decay heat and radioactivity. The cooling time requirement will be longer as burnup is increased, affecting facility design and operation strategy.

Fuel treatment to remove sodium bond

Although direct disposal has been considered for sodium-bonded SNF, it is likely that treatment to remove sodium will be required. Because the bond sodium enters the fuel during operation, its removal is more complicated than simple mechanical stripping [17]. Three treatment options are available, described in Refs. [14] and [18] and summarized here. Key considerations are whether reprocessing is allowable as a follow-on process and what waste forms are preferable for final disposal.

1. Pyroprocess: metal fuel is separated in a molten salt electrolytic cell, removing bond sodium in the process. The chopped fuel is electrochemically dissolved. Noble metals remain in the anode basket, uranium collects on a steel cathode, and bond sodium and most fission products form salt compounds. Two waste forms are produced: a metal containing materials from the anode basket, and a ceramic with materials dissolved in the salt.
2. Melt-drain-evaporate-carbonate (MEDEC): the fuel is exposed to heat and low pressure to melt and vaporize bond sodium. Once sodium has been removed, the cleaned rods are packaged for disposal or immobilized with/without cladding via a process such as melt-dilute to produce a metal waste form.
3. Alcohol wash: fuel is removed from the cladding and soaked in alcohol to remove the sodium. The recovered fuel could then be packaged for disposal or immobilized with or without cladding via a process such as melt-dilute to produce a metal waste form.

Of these methods, pyroprocessing is the most mature and is being utilized to treat EBR-II SNF at INL. However, pyroprocessing is technically a form of reprocessing. The MEDEC process was explored as recently as 2003 in testing on EBR-II blanket fuel and unirradiated Fermi-1 fuel [19], but there is no recent experience available for the alcohol wash process [14].

A fuel treatment facility will require front-end facilities to receive, store, and prepare SNF for treatment, a hot cell facility for the treatment itself, and back-end facilities to produce stable waste forms that meet decay heat and criticality safety constraints. The facility must be able to store wastes until they can be transported to centralized storage or a geologic repository. The designation of responsibility for fuel treatment is a crucial concern. Additionally, licensing may be challenging: all previous sodium-bonded fuel treatment activities have been carried out by DOE, and the NRC has never licensed a private fuel treatment facility.

Interim storage of SFR SNF (or treated HLW)

With the sodium-free SFR spent fuel or treated HLW in a disposal-ready form, interim storage should be straightforward. The same storage requirements are expected to apply to SFR and LWR SNF, although the storage cask design must accommodate the elevated decay heat and radioactivity.

Transportation of SFR SNF (or treated HLW)

Because no colocation can be assumed, transportation may be required between any facilities for SNF in a variety of forms: as assemblies with/without sodium bond, and as HLW after sodium bond removal. No fundamental challenges are envisioned. Transportation of sodium-bonded SNF has been performed by DOE (for example, to bring SNF from Fermi-1, FFTF, and SRE to Idaho). The presence of reactive sodium in the fuel may create challenges for package design. This will likely increase hurdles associated with licensing. Elevated decay heat, radioactivity, and potentially fissile enrichment will be accommodated in canister and cask design.

Final disposal of SFR SNF (or treated HLW)

Disposal of SFR SNF in a geologic repository raises similar challenges as disposal of LWR SNF. In particular, elevated decay heat from SFR SNF may constrain repository design and operations, as heat can impact the effectiveness of temperature-sensitive barriers such as bentonite clay.

The impact of including SFR SNF in a repository performance assessment is unclear. If in its original form, the SNF may be metallic, whereas LWR SNF is an oxide. Ref. [20] reviewed past uranium metal corrosion experiments in oxic (oxidizing) and anoxic (reducing) water and used linear regression to obtain curve fits, as plotted in Fig. 2. For

comparison, the degradation rates for commercial LWR SNF used for the Yucca Mountain Repository (YMR) Total System Performance Assessment [21] are included at various pH values. (YMR was above the water table in oxidizing conditions.) Degradation rates for uranium metal are greater than those for uranium oxide, especially at higher temperatures in the repository due to decay heat. Further research is needed to understand metallic SNF waste form performance in a geologic repository.

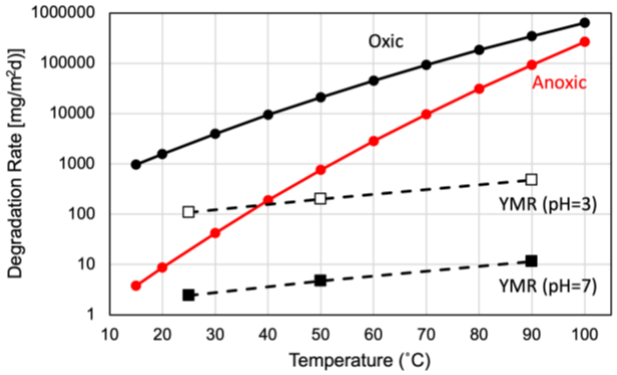

Fig. 2. U-metal degradation rate from Ref. [20] compared to the LWR SNF degradation rate from the YMR TSPA [21].

The ceramic and metal waste forms produced by the pyroprocess are expected to be acceptable for disposal and perform successfully as engineered barriers. Little research has been performed on the suitability for disposal of the other treatment process waste forms.

SFR management facility milestones and challenges

The goal of this summary section is to highlight the combinations of facilities and milestones that appear particularly challenging relative to the equivalent operation for LWR SNF. Table IV shows three critical challenges identified in the previous sections that affect the potential deployment of SFR SNF management facilities.

First, if SFR SNF is to be treated prior to disposal, organizational responsibility for implementing a fuel treatment facility for sodium-bonded SNF would need to be identified. Because all other waste management facilities may rely on fuel treatment, it is foundational to the success of the system. If direct disposal of sodium-bonded SNF is a preferred management pathway, further research and development will be necessary to prove viability.

The second challenge pertains to the need to design facilities that can accommodate the unique features of SFR SNF. Due to higher burnup, SFR SNF will have higher decay heat, higher radiation dose rate, and potentially lower structural integrity than LWR SNF. Any SFR SNF with sodium bond may require special handling. These factors will constrain design for every facility type.

TABLE IV. Selected SFR SNF management challenges, associated milestones, and affected facilities

Challenge	Relevant Milestones	Affected Facilities
Ownership	Establishing responsibility	• Fuel treatment
Design and environmental impact	Facility design; NEPA compliance	• On-site storage • Fuel treatment • Transportation • Interim storage • Final disposal
Licensing new technologies	Licensing	• On-site storage • Fuel treatment • Transportation

Finally, licensing of new technologies is the third challenge. The facilities required to accommodate SFR SNF – in particular, on-site storage, fuel treatment, and transportation – will be new, and neither the vendors nor the NRC has experience licensing them.

At least one challenge applies to each type of facility required for managing SFR SNF. However, there are milestones that may not be affected relative to LWR SNF. In particular, facility siting, construction, and testing are likely to be common hurdles for any SNF management facility. As previously mentioned, it is important to acknowledge that this analysis is preliminary and high-level. As such, it is not exhaustive and will need to be enhanced and expanded by future work that includes surveys of subject matter experts.

HIGH-TEMPERATURE GAS-COOLED REACTOR SNF MANAGEMENT

High-temperature gas-cooled reactors (HTGRs) have garnered significant interest due in part to their high thermal efficiency. Most HTGR designs plan to use fuel based on tristructural-isotropic (TRISO) coated fuel particles. TRISO fuel is significantly different than LWR fuel. In a TRISO fuel particle, a central kernel of uranium oxycarbide (UCO) is surrounded layers of porous carbon, pyrocarbon, and silicon carbide. The spherical particles are embedded in a graphite matrix in the form of prismatic blocks or fuel pebbles. Due to the relatively low density of fissile material in TRISO fuels and the high-temperature durability and heat transfer properties of graphite, HTGR fuels are extremely robust [22].

To exemplify the differences between LWR and HTGR SNF, Table V compares SNF characteristics of two HTGRs – the X-energy Xe-100 pebble bed reactor [23] and the Framatome Steam-Cycle HTGR [24] – with those from the Westinghouse AP1000 PWR. The heavy metal mass per unit energy discharged from the HTGRs is much less than that from the AP1000 due to increased burnup and higher thermal efficiency. Fuel volume data is not available for the SC-HTGR; however, the volume of the Xe-100 SNF pebbles is much larger than that of AP1000 SNF assemblies due to the

TABLE V. Comparison of HTGR and PWR fuel assembly characteristics

Characteristic	Unit	Xe-100 [23]	SC-HTGR [24]	AP1000 [8]
Dimensions	m	Radius = 0.030	---	Height = 4.583 Side length = 0.214
Volume (per unit)	m^3	1.13e-4	---	0.210
Thermal Power	MW	200.0	625	3415
Electric Power	MW	80.0	272	1110
Plant efficiency	%	40.0	43.5	32.5
Burnup	GWd/t	168.5	160.0	50.0
Discharged mass (HM + FP) [(a)]	t/GWe-y	5.42	5.24	22.46
HM (U) mass per assembly	t/asm	7.0e-6	---	0.44 [(b)]
Discharged HM volume [(c)]	m^3/GWe-y	87.5	---	10.72

[(a)] Calculated as: 1 GWe / Thermal efficiency / Burnup [GWd/t] * 365 [d/y]
[(b)] Calculated based on 2017 data from [11]
[(c)] Calculated: Discharged HM mass [t/GWe-y] / HM mass per asm [t/asm] * Assembly volume [m^3]

low fissile loading of the pebbles; the Xe-100 pebbles contain 7 gHM/pebble [23] whereas AP1000 fuel assemblies contain roughly 440 kgHM/assembly [11]. Higher thermal efficiency and lower core power density (due to lower density of fissile material in the pebbles) imply significantly lower decay heat density in HTGR SNF than LWR SNF.

For HTGR SNF pebbles in particular, the size and number of fuel elements will vary significantly from LWR SNF. Whereas an LWR contains several hundred large fuel assemblies, a pebble-bed HTGR core contains hundreds of thousands of fuel pebbles. Despite fundamental differences in form and composition between TRISO-bearing HTGR SNF and LWR SNF, experience and extensive testing indicates that management of spent fuel pebbles or spent prismatic block fuels will be straightforward. After discharge from the reactor, HTGR SNF will need to be cooled, stored, and eventually disposed of in a geologic repository; these are the same steps required for management of LWR SNF. For both pebble and prismatic block SNF, treatment could be pursued to achieve volume reduction, but it is not required and may not be desirable due to added risk and cost.

On-site SNF storage at the HTGR

Spent pebbles from pebble bed reactors will be continuously processed by an automated fuel handling system whereas spent prismatic blocks will be withdrawn during shutdowns. Storage experience from other past HTGRs will be instructive; for example among others: the AVR [16] and THTR-300 [25] in Germany; the HTR-10 [26] in China; and Fort St. Vrain and Peach Bottom [22] in the U.S.

Decay heat management for HTGR SNF is less complicated than for LWR SNF due to the low heat density, the effective heat transfer properties of TRISO particles and graphite, and their robustness at high temperatures. In the case of pebbles, the spherical shape offers a large surface area to volume ratio to aid in heat dissipation. HTGR SNF contains no highly reactive materials. Graphite combusts in air, but this is a surface reaction that only occurs above 1600˚C [22]; reasonable protections include isolation from air and/or adequate heat dissipation.

HTGR SNF may be stored under a variety of conditions, including in pools or in sealed containers, either cooled by liquid or gas. Storage in liquid coolant enhances heat removal and shields radiation, allowing for larger collocated storage of blocks or pebbles. However, the coolant may become contaminated and require treatment, creating another waste stream. Dry storage of pebbles or blocks in canisters filled with helium reduces risks of contamination but heat dissipation is less effective and fewer elements can be stored together [27].

Criticality controls during storage may be necessary, especially for SNF pebbles in wet storage. One option is to include boron-doped pebbles in the pool or canister. Dose rate considerations may dictate when and how pebbles are moved to dry storage. Recent work explored these issues for TRISO-fueled pebbles from the Fluoride High temperature Reactor [27].

Another unique aspect of pebble management is their small size and regular movement prior to being sealed in canisters, which poses unique material accounting risks compared to LWR SNF. Whereas the several hundred fuel assemblies in an LWR are immobile during operation, regular operation of a pebble-bed HTGR will involve movement of hundreds of thousands of pebbles. LWR assemblies are large, heavy, and highly radioactive, which deters potential theft. By comparison, pebbles are small and light with relatively low radiation dose rates. Additionally, each LWR assembly is uniquely identified; this is not possible for the HTGR SNF pebbles. Although some aspects of material control and accounting for LWRs are applicable to pebble-bed reactors, these differences warrant special consideration to prevent pebble diversion [28]. Importantly, any recovery of fissile material would require obtaining a significant number of pebbles and an industrial recycling process, but the risk of diversion should be considered nonetheless.

Interim storage of HTGR SNF

Based on previous experience, interim storage of HTGR SNF should be straightforward. For example, the SNF from Fort St. Vrain and Peach Bottom [22] in the U.S. has been stored safely for decades, as have the nearly one million pebbles from AVR and THTR-300 in Germany [29]. As for all SNF interim storage, canister integrity must be maintained to prevent radionuclide release. The SNF pebbles and blocks themselves are chemically stable in air at temperatures expected of an acceptable storage environment. One potential hazard is graphite dust, which may be radioactive due to the buildup of C-14 and its release should be avoided. Dust is primarily an issue for pebble bed reactors and is considered as part of reactor design [30, 31] If this is found to be an issue, potential mitigation strategies could include in-canister structures to reduce contact and friction. As previously mentioned, decay heat management of HTGR SNF is less of a concern than for other types of SNF.

Transportation of SFR SNF (or treated HLW)

The structural robustness of the HTGR SNF is a benefit for transportation system design requirements. However, pebble or block fracture is possible, and notably, pebble fracture mechanics and stress tests are a part of fuel design [32, 33]. These details should be factored into the transportation system design.

Prismatic HTGR fuel has been shipped in the U.S.; in particular, SNF from Peach Bottom and some from Fort St. Vrain was shipped to INL for research and storage. However, there is limited experience transporting spent fuel pebbles. For example, the spent AVR and THTR-300 pebbles are still stored on-site [29], although transportation from Germany to the Savannah River Site has been explored [34]. The pebbles are stored in canisters, which are housed in CASTOR storage casks [35]. These efforts lend confidence to the prospect of successfully shipping HTGR SNF pebbles.

Although not a fundamental challenge, large-scale HTGR deployment will result in more SNF shipments relative as compared to LWR SNF due to the increase in discharged SNF volume. Increasing the number of shipments may impact planning and deployment of transportation infrastructure.

Final disposal of HTGR SNF

The same considerations applied to LWR SNF disposal in a geologic repository are relevant HTGR SNF disposal. Because HTGR SNF will have lower decay heat density than LWR SNF, disposal packages may be larger, placed closer together, or require shorter cooling time prior to emplacement without violating repository thermal constraints; all of these factors can benefit repository size and cost [37].

Early scoping calculations assessing the repository performance of prismatic block HTGR SNF indicated its acceptability as a waste form for disposal in a geologic repository and may be superior to LWR spent fuel. It was noted that these conclusions should not differ significantly for SNF pebbles [38]. The TRISO particles provide multiple barriers to contain radionuclides; in particular, the stable silicon carbide layer in the TRISO particles may last for more than one million years [22]. Additionally, the graphite itself in the TRISO particles and in the pebbles or fuel compacts does not degrade underground or in running water [22].

HTGR SNF management facility milestones and challenges

As was done in the previous section for SFR SNF, generic milestones and required facilities are cross referenced and examined based on the challenges identified by tracing HTGR SNF through a hypothetical back-end system. This qualitative, preliminary examination serves to highlight the combinations of facilities and milestones that appear to pose the greatest difficulty.

HTGR SNF management will not require specific facilities other than those co-located with the reactor, a situation shared with the LWR SNF management. Not every combination of milestone and facility has been judged to pose an enhanced challenge relative to the same milestone-facility pair for managing LWR spent fuel. The robustness of the SNF and prior experience successfully handling spent TRISO-based fuels reduces the scale of challenges facing management facility design and deployment.

The primary challenge identified for HTGR SNF management is material accountancy of SNF pebbles, which is relevant to diversion and nonproliferation controls at the reactor site. Once pebbles are sealed in a canister for storage, transportation or disposal, the risk of diversion is greatly decreased. Until then, while pebbles are recycled into the reactor or are undergoing initial cooling prior to canister loading, they pose a unique diversion risk. HTGR pebbles are a more attractive target for diversion than LWR spent fuel assemblies, and due to the large number of pebbles and their frequent handling, material accounting procedures will be different than for LWR. The challenge arises due to the combination of a more attractive fissile material target and a need for new material accounting procedures.

Importantly, both pebble and prismatic HTGR SNF will have higher volume than LWR SNF per energy generated. However, it is not clear that the need for more storage space, more packages, or more shipments will be a fundamental hurdle facing HTGR SNF management or facility deployment, although these factors may result in increased costs. HTGRs will also produce graphite waste which must be managed but is not classified as SNF.

Notably, many milestones may not be affected considering the management of HTGR and LWR SNF. Both likely share similar challenges in facility siting, construction, and testing. Additionally, differences in characteristics between TRISO-based and LWR SNF may be offset by the

robustness of the former, which lead to comparable SNF management pathways. If that is the case, the establishment of transportation infrastructure may be comparable for TRISO-based and LWR SNF. These conclusions are preliminary, however, and future assessment is warranted to identify additional risks.

MOLTEN SALT REACTOR SNF MANAGEMENT

Liquid-fuel molten salt reactors (MSRs) use molten salt as both the coolant and the fuel. Fissile fuel is dissolved in liquid salt that flows through the primary system. The fuel salt is critical in the core region but subcritical as it circulates to heat exchangers. MSRs operate at atmospheric pressure and are able to accommodate online refueling and fuel treatment. MSRs are extremely versatile and can vary in size, fuel salt chemistry (e.g. fluoride vs. chloride salt), fuel type (Pu- vs. HALEU-fueled), and neutron spectrum (thermal vs. fast).

Relatively few details are available about potential MSR spent fuel salt characteristics. Table VI compares PWR SNF characteristics with those of two MSRs, the TerraPower Molten Chloride Fast Reactor (MCFR) [39] and the Terrestrial Energy Integral Molten Salt Reactor (IMSR) [40, 41]. Two values are provided for the MCFR burnup depending on its operation. "Once-through" means that the entire core is discharged as SNF at end of reactor life; "twice-through" is similar except that the discharged fuel salt is transferred to start a new reactor. The primary fissile material in the re-used fuel salt is primarily Pu from several decades of U-238 transmutation. Table VI shows that based on thermal efficiency and target burnup, the MCFR will produce 5-9 times less heavy metal relative to the AP1000. The IMSR achieves lower burnup and therefore the discharged heavy metal mass is about the same or greater than that from the PWR, depending on the fuel cycle. However, the thermal-spectrum IMSR is much smaller than the fast-spectrum MCFR, as indicated by thermal and electric power capacity. Without information about fuel salt composition, density, and heavy metal loading, it is difficult to compare discharged spent fuel volumes. MSR waste volumes will depend on how the spent fuel salt is treated and immobilized.

An overarching challenge is that there is little prior experience with MSR SNF management. Only three small salt-fueled MSRs have been operated: the Aircraft Reactor Experiment (ARE) in 1954, the Pratt and Whitney Aircraft Reactor (PWAR-1) in 1957, and the Molten Salt Reactor Experiment (MSRE) from 1965-1969. As a prototypic power generation reactor and the MSR with the longest operating history, the MSRE is most relevant to inform MSR spent fuel salt management. Although the MSRE fuel salt (uranium-bearing FLiBe) was treated to remove uranium [43], it remains in tanks at the facility and has not been processed into a form suitable for disposal.

The use of liquid fuel in MSRs is fundamentally different than that of solid fuel assemblies in LWR. Actinides and fission products exist throughout the fuel salt. MSRs require online salt processing to remove species that do not form stable compounds in the salt. During operation, noble gases and volatile fission products are removed via gas sparging and noble metals and insoluble fission products are mechanically filtered. As a result, some of the radionuclides normally present in solid spent fuels will be removed from the fuel salt during operation and will not be present at discharge. Therefore, the near-term decay heat per electricity generated from spent MSR fuel salt may be less than that of LWR SNF. Fission products that are stable in the salt will be allowed to accumulate until it is discharged as SNF. Separated fission products will be managed in other waste streams, for which additional planning is necessary for safe storage and disposal. Additionally, whereas LWRs periodically discharge SNF assemblies, MSRs may directly discharge an entire reactor's worth of fuel salt at once. In general, salt is not considered a suitable waste form for disposal in a geologic repository because it is soluble in water. The one exception is for disposal in a salt repository, although it may be prudent to avoid anticipating availability of a particular repository type. Given this, it is assumed that MSR SNF management will require on-site cooling and storage, fuel treatment, interim storage, and final disposal, with transportation between some or all of these steps.

On-site SNF storage at the MSR

Cooling, shielding, and subcriticality of spent fuel salts must be maintained during storage. After discharge from the reactor, spent salt will be heavily poisoned with neutron absorbers and pumped into subcritical-geometry canisters or

TABLE VI. Comparison of MSR and PWR fuel assembly characteristics

Characteristic	Unit	MCFR [39]	IMSR [40]	AP1000 [8]
Thermal Power	MW	2222.2	440	3415
Electric Power	MW	1000.0	200	1110
Plant efficiency	%	45.0 [(a)]	45.5	32.5
Burnup	GWd/t	183.0-334.0 [(b)]	14.3-31.9 [(c)]	50.0
Discharged mass (HM+FP) [(d)]	t/GWe-y	4.43-2.43	55.99-25.14	22.46

[(a)] From Ref. [42]

[(b)] From Ref. [39]; the two options are for once-through or twice-through operation, respectively

[(c)] From Table 1 in Ref. [41]; the two options are for once-through or "feed, seed, and breed" fuel cycles, respectively

[(d)] Calculated as: 1 GWe / Thermal efficiency / Burnup [GWd/t] * 365 [d/y]

tanks. Canisters could then be cooled to solidify the salt. Later, the canisters could be shipped to centralized fuel treatment, reprocessing, or storage facilities [42]. If pumped into storage tanks, the tanks must have the capability to reheat the salt to ensure it can be pumped out for processing.

Fuel salts are chemically inert and do not react exothermically with air or water, but previous experience from MSRE shows that storage conditions are essential for safety. After final shutdown, the MSRE fuel salt was drained into tanks. An annual annealing procedure was performed by reheating the salt to recombine fluorine that had been released from the salt due to radiolysis [44]. Over time, evidence of radioactive material migration was detected throughout the drain tank piping and off-gas system. The source of the radiation was UF_6, and large quantities of F_2 gas were observed in the drain tanks and piping. As a result, the MSRE Remediation Project was launched to remove uranium from the system and stabilize the salts [45]. The MSRE fuel salt storage experience exemplifies the potential for unforeseen challenges caused by the interaction of chemical, radioactive, and thermodynamic processes in the salt.

Because fuel salt is pumped as bulk material, it poses unique material accounting challenges relative to LWR SNF [46]. In an LWR, the fuel assemblies are immobile; in MCFR, the fuel salt will be continuously flowing throughout the reactor system. Whereas LWR fuel assemblies are individual units that can be counted, MCFR fuel salt is a bulk material. Advanced accountancy methods will be required for ensuring that no fuel salt is diverted during operation or after discharge, prior to waste form preparation. Such methods will also need to ensure that fissile material is not accumulated anywhere in the system due to differential material migration caused by the various processes affecting the salt. However, clandestine diversion of spent fuel salt is anticipated to be difficult, and the risk perceived to be low. Due to the integration of the system, it will be difficult to modify once contaminated. Additionally, the salt freezes at relatively high temperatures, so reheating systems would need to be activated to remove discharged salt [42].

Fuel salt stabilization into a disposable waste form

Treatment of spent fuel salt will almost certainly be required to prepare a waste form suitable for geologic disposal. In general, regardless of the process chosen, treatment facilities will require front-end facilities to receive, store, and prepare the spent fuel salt for treatment, and back-end facilities to produce stable waste forms. The processing operations will require hot cell facilities. Technically, the waste forms produced by the process are HLW, not SNF, but they share the same requirements for storage, transportation, and disposal. The facility must account for on-site storage until waste can be transported to a centralized storage facility or a geologic repository.

The remainder of this section focuses on options available for treatment of spent fuel salts, which can occur by one of two pathways: (1) the salt may be directly immobilized and disposed of without any separations; or (2) the carrier salt may be recovered from the waste stream. The following subsections discuss both of these potential pathways. Much of this section is based on a recent, comprehensive review of MSR waste management options [47].

Unseparated fuel salt treatment

If a salt repository were available, fuel salt could potential be directly disposed without processing. Otherwise, the salt would need to be converted to a robust waste form suitable for disposal in a repository in any geologic environment. For a generic fuel cycle approach, then, fuel salt immobilization would be required. Immobilization could take place at the reactor site or at a centralized facility.

Although there are numerous options available for MSR waste forms, many unknowns remain. In general, spent fuel salt will be mixed with an immobilizing matrix to improve its resistance to leaching by water. The ratio of salt to immobilizer depends on many factors, including (but not limited to): chemical compatibility; waste decay heat rate and thermal limits; and waste form robustness. Available options can be broadly categorized as: mineral-based, including sodalite ceramic [48], apatite [47], or Synroc [47, 49]); metal composites, such as cermet or halmet [47]; and glass-based, such as tellurite glass [47].

Fuel salt separation and processing

An alternative to direct immobilization is to process fuel salt to recover the carrier salt and partition waste species. The radioactive products from salt separations will still need to be immobilized for geologic disposal. If multiple waste streams are produced, each can have a waste form tailored to its chemical characteristics.

Carrier salt removal may be desirable to increase the radionuclide loading in the final waste forms. An additional incentive for removing carrier salt is that it can be recycled. Some carrier salts are enriched; for example, chloride fuel salts may be enriched in Cl-37. Isotopic enrichment is expensive, so it could be advantageous to recover and reuse the salt. Vacuum distillation is a common technology to separate mixtures based on differences in vapor pressure [47], which could be used to recover the carrier salt.

Many processes are available to further separate species in the salt or change their chemical composition (e.g. from chlorides to oxides). The benefit of such operations is that oxides and metals can be more easily processed into robust waste forms. Process options include reductive extraction, oxidative precipitation, melt crystallization, dehalogenation, phosphorylation, ion exchange, and the Glass Material Oxidation and Dissolution system (GMODS). Ref. [47] contains a comprehensive review of these processes.

Interim storage of MSR SNF

As for on-site storage, lessons learned from MSRE will be valuable for the storage of any spent fuel salt. Canister integrity must be maintained to prevent release of harmful radionuclides or chemicals. Generation of chlorine or fluorine gas by radiolysis in the salt or waste form should be avoided, mitigated, or accounted for. The canisters, waste forms, and storage facility must be designed to accommodate the decay heat load and provide shielding from radiation.

An interim storage facility for spent fuel salt from commercial nuclear power generation would likely be regulated by the NRC. Licensing for a facility to store spent fuel salt itself might be more challenging than licensing for one to store the HLW created by treating the salt.

Transportation of MSR SNF

Frozen fuel salt (rock salt) is structurally robust and can be shipped like any other waste form [42]. The salt is chemically inert in air and water. Similarly, any final waste form will be dense, compact, and structurally robust to withstand shipping. In both cases, canister and cask designs will need to accommodate the unique decay heat, radiation, and criticality safety risks posed by the waste.

Final disposal of wastes produced from MSR SNF

Final disposal of MSR spent fuel salt waste forms in a geologic repository raises similar challenges as disposal of LWR SNF. Decay heat management and compliance with thermal constraints will depend on decay heat rate and waste form loading. The waste form must be acceptably resistant to leaching. Many volatile fission products that contribute to repository dose, such as cesium and iodine, may be released as gases during MSR operation or spent fuel salt processing; if so, these will be disposed of in a different waste form than the bulk spent fuel salt. MSRs that use chloride salts will need to dispose of Cl-36, formed by neutron absorption on Cl-35. Cl-36 is a long-lived radionuclide (301,000-year half-life) and is highly soluble in water. The contribution of Cl-36 to repository dose may be significant in a clay repository but will not be an issue in a salt repository [42].

MSR SNF management facility milestones and challenges

This section cross-references generic milestones and facilities, examining them based on the challenges identified for MSR SNF management. This preliminary study highlights combinations of facilities and milestones that intersect with challenges for MSR SNF management relative to LWR SNF management. Table VII connects challenges with relevant facilities and milestones for deploying management facilities for MSR spent fuel salts. Challenges are primarily due to the limitations of current experience and the many outstanding decisions about available options and management pathways. As such, the list of potential challenges is longer than for the other advanced reactor types.

That MSRs may discharge their entire fuel salt inventory as SNF means that management facilities may need to be larger to accommodate higher throughput. Further, because they will not be used until final shutdown, operational experience would not be gained until long after reactors are constructed, although a demonstration unit could help lead the way. MSR SNF management could dominate the reactor decommissioning plan and timeline.

The experience with storing MSRE fuel salt has shown the need to plan for salt instability. In the MSRE fuel salt, radiolysis drove the production of fluorine gas and allowed fluorinated uranium to migrate through the system. Chloride-based salt may experience similar vulnerabilities that must be accounted for during the design of storage systems.

Fuel treatment of MCFR spent fuel salt poses multiple challenges. The organizations responsible for financing and executing fuel treatment facility deployment would need to be identified. There are many promising options for salt treatment, but significant research and development is necessary to identify the best path forward. As a spent fuel salt and a final waste form, MSR wastes will have unique characteristics that need to be accounted for, but it is currently unclear how they will compare with those from LWR SNF. Characteristics such as decay heat, radioactivity, chemical form, material properties, and fissile material loading will impact all aspects of waste management.

Finally, the lack of experience with MSR technology means licensing facilities could be challenging. The NRC

TABLE VII. Selected MSR SNF management challenges, associated milestones, and affected facilities

Challenge	Relevant Milestones	Affected Facilities
Size/scope of spent fuel salt management	Facility design, licensing, and construction	• On-site storage • Fuel treatment • Transportation • Interim storage • Final disposal
Salt stability during storage	Facility design	• On-site storage • Interim storage
Ownership	Establishing responsibility	• Fuel treatment
Process options	Facility design, licensing	• Fuel treatment
Design and environmental impact	Facility design; NEPA compliance	• On-site storage • Fuel treatment • Transportation • Interim storage • Final disposal
Licensing new technologies	Licensing	• On-site storage • Fuel treatment • Transportation

does not have experience licensing the types of facilities or operations required for managing MSR spent fuel salts. Operations for which licensing is new or expected to be notably more challenging for MSR SNF than for LWR SNF include on-site storage, fuel treatment, and transportation.

All facilities required for managing MSR SNF face challenges, but they are not uniformly distributed across milestones. Milestones for which MSR SNF management is not uniquely difficult include facility siting, construction, and testing; these may be similarly difficult for managing LWR SNF. Importantly, these challenges and milestones only pertain to the spent fuel salt that must be dealt with after the reactor reaches its operational lifetime. Additional considerations and planning are needed to manage separate fission product waste streams produced during operation.

CONCLUSIONS

This work presents a preliminary exploration that applies the activity/milestone framework to the development of advanced reactor SNF management facilities. The goal is to consider high-level activities and milestones and generic SNF management while accounting for the unique characteristics of advanced reactor spent fuels and their management requirements. To that end, the steps for managing any generic SNF were described, starting from initial on-site cooling and storage, and culminating in deep geological disposal. Alongside that, a set of generic, high-level milestones for realizing any waste management facility were presented. The waste management system and the high-level milestones were then applied to the development of hypothetical management pathways for spent fuel from three advanced reactor types: SFRs, HTGRs, and liquid-fuel MSRs. These case studies exemplify the unique challenges associated with the management of new waste types and the combinations of milestones and facilities that appear to pose development challenges relative to LWR SNF management.

Some commonalities were observed considering SNF management facility deployment challenges for all three advanced reactor types. In all cases, challenges are not equally distributed among facilities or milestones. Facilities early in the management process – on-site storage and fuel treatment, specifically – have barriers to deployment that are more urgent because they must account more immediately for unique SNF characteristics as the possibility of deployment approaches.

Another theme across all case studies is that the challenge to achieve some milestones is independent from the waste being managed. Facility siting, construction, and testing are important milestones but could be similar in difficulty for the management of any SNF, including that from the advanced reactors investigated in this paper. In other words, it is not clear that achieving a milestone for one type of waste will be any more challenging than for an analogous facility for another type of waste. Conversely, establishment of responsibility, facility design, and licensing could pose more challenges because their operations directly accommodate challenging characteristics of different SNF types.

Finally, there is potential to improve efficiency if an integrated waste management system anticipates new SNF types and addresses common challenges. For example, standardized transportation, storage, or disposal casks with interchangeable inserts could be leveraged for different SNF assemblies. Standardizing options for fuel treatment or waste form processing could provide benefit to multiple reactor projects that may require them and reduce total system cost.

This assessment is preliminary, high-level, and not exhaustive. It represents a first step in the planning process for managing advanced reactor SNF. As a follow-on effort, the activities and milestones could be expanded, refined, and analyzed to produce quantitative conclusions about risk and cost. Adding more levels of detail could produce new insights about planning and research needs. Collaboration between subject matter experts in industry, academia, national laboratories, and the NRC could highlight new questions and provide direction. In particular, SNF management regulations should be scrutinized considering advanced reactor SNF.

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DISCLAIMER

This is a technical paper that does not account for contractual limitations or obligations under the Standard Contract for Disposal of Spent Nuclear Fuel and/or High-Level Radioactive Waste (Standard Contract) (10 CFR Part 961). For example, under the provisions of the Standard Contract, spent nuclear fuel in multi-assembly canisters is not an acceptable waste form, absent a mutually agreed to contract amendment. To the extent discussions or recommendations in this report conflict with the provisions of the Standard Contract, the Standard Contract governs the obligations of the parties, and this presentation in no manner supersedes, overrides, or amends the Standard Contract. This report reflects technical work which could support future decision making by the U.S. Department of Energy (DOE or Department). No inferences should be drawn from this presentation regarding future actions by DOE, which are limited both by the terms of the Standard Contract and a lack of Congressional appropriations for the Department to fulfill

its obligations under the Nuclear Waste Policy Act including licensing and construction of a spent nuclear fuel repository.

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