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Evaluating Geologic Disposal Pathways for Advanced Reactor Spent Fuels

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INTRODUCTION

All options for generating power from nuclear energy generate radioactive waste products that will require permanent isolation from the biosphere. Choices made regarding nuclear fuel cycle options, including decisions for recovery and re-use of fissile material from irradiated fuel, have the potential to affect waste stream characteristics such as mass, volume, radioactivity, physical form, and thermal power, but do not eliminate the need for robust waste isolation. Beyond the current once-through light-water reactor fuel cycle in the U.S., there is renewed interest in advanced reactor (AR) development and enabling technologies, as well as advanced/accident-tolerant fuels. Development of prototype advanced reactors (and potential AR fuel cycles) may provide both benefits to the energy systems and challenges to the management of the back end of the fuel cycle (BENFC). To address these potential BENFC challenges, the U.S. DOE Spent Fuel and Waste Science and Technology (SFWST) Campaign (DOE NE-81) is developing high-level strategies for evaluating BENFC issues related to advanced reactor (AR) spent nuclear fuel (SNF) waste streams for storage and transportation activities, as well as for delineating pathways to permanent deep geologic disposal. For example, potential AR SNF waste streams may include new physicochemical forms/inventories and may have additional chemical/physical treatments for creating waste forms acceptable for disposal. This work provides our preliminary approaches to the DOE SFWST high-level strategy for disposal considerations of AR SNF.

The recognition that deep geological disposal is the preferred option for achieving safe isolation of high-activity radioactive wastes dates from the 1950s [1] and decades of disposal investigation experience have produced an international consensus that confirms that deep geological disposal is the accepted method for safe isolation of SNF and high-level radioactive waste [2]. Geologic disposal concepts considered include mined repositories in multiple different lithologies in saturated/unsaturated environments and borehole repository concepts (note that the DOE SFWST Campaign ended its activities on deep borehole disposal in 2017 but this is still being evaluated at Sandia National Laboratories and internationally). Mined repositories are in operation for some categories of transuranic and intermediate-level waste [2,3] and a repository for SNF is being readied for operation in Finland. Many countries have active geologic repository programs [4], and published results of safety assessments for geologic repositories proposed in the United States, Canada, Finland, France, Sweden, and other nations, provide insight into the waste form characteristics that most affect the repository system long-term performance[5]. This work utilizes this past experience with nuclear waste disposal safety assessments to assess potential AR fuel cycle (ARFC) waste streams, for strategies on constructing preliminary disposal pathways and illuminate potential geologic disposal issues for further research and development (R&D).

Because similar existing DOE-managed SNF (DSNF) from previous reactors have been evaluated for disposal pathways, we use this knowledge/experience as a broad reference point for initial technical bases for preliminary dispositioning of potential AR SNF. Although AR SNF are similar to some existing DSNF, they will not be identical, so this reference point is being augmented by identifying the potential AR waste stream issues (gaps) that remain to be constrained in a gap analysis. For example, some of the ARFC plan to use high-assay low-enriched uranium (HALEU), where the fuel is enriched to >5 % and <20% ^{235}U, which allows for more efficient reactors that can be run to higher burn-up (longer core duration). HALEU SNF characteristics can differ from similar DSNF in multiple ways including criticality potential, fission product inventories, and thermal loading density. Although some characteristics may be encompassed fairly directly with existing analyses, some disposal considerations may be addressable only with additional R&D. The final portion of this strategy is to perform the gap analyses and define the additional R&D to address those more complex gaps for AR SNF. Once the gaps and associated R&D are identified, the additional R&D would be prioritized for execution to close the gaps for those specific ARFC waste streams.

BACKGROUND ON DISPOSAL CONSIDERATIONS

Swift and Sassani[5] reviewed published safety assessment results for five different disposal concepts: mined repositories in granite [6,7,8], argillite [9,10], salt [11,12,13], volcanic tuff [14], and deep borehole disposal in crystalline rock [15,16,17]. The published safety assessments indicate that all five concepts have the potential to meet regulatory requirements and provide robust long-term isolation for the existing waste forms from the existing fuel cycles in each program, and that various processing considerations may result in moderate changes to disposal concept implementation. That work also provides insights into how specific changes to the waste form that might result from alternative/advanced fuel cycle choices and waste stream processing might affect long-term performance aspects of the disposal concepts considered.

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Swift and Sassani[5] analyzed the potential impacts of different potential future fuel cycles on the implementation of geologic disposal concepts to provide BENFC bases for consideration of potential future fuel cycle alternatives. Though fuel cycle alternatives led to changes in the absolute extent of geologic disposal concepts, no qualitative changes were found to the need for, and basic implementation of, geologic repositories[5]. Those international studies provide useful guidance for considering disposition pathways of future waste streams from potential fuel cycles (e.g., advanced reactors). Those analyzed bases may be used to formulate a strategy to evaluate the SNF coming out of ARFC for direct disposal potential (i.e., provide answers to the question –"Does it appear that the advanced reactor SNF can be directly disposed (without treatment other than appropriate packaging) in a geologic repository?"). In cases where direct disposal does not appear possible, these bases also provide some insight into what characteristics of the advanced reactor SNF need to be addressed prior to disposal (i.e., for gap identification and analysis of R&D for gap closure).

Insights from the published safety assessments for disposal of spent nuclear fuel and high-level radioactive waste suggest that some modifications to waste forms from potential advanced fuel cycles are more beneficial to improving the long-term performance of repositories than are other modifications. In the context of safety assessments Swift and Sassani[5] considered such waste form modifications to draw general conclusions. Their evaluation indicated that changes in the radionuclide inventory of waste forms from the potential recovery and reuse of fissile materials contained in spent fuel are unlikely to drive significant impact on the estimates of long-term performance for most disposal concepts (in the absence of disruptions that expose the waste directly to the biosphere such as human intrusion) because the long-lived fission product I-129 has relatively higher mobility in most disposal system environments. Additionally, they[5] indicated that waste form volume reductions, unless they are accompanied by the separation and removal of heat-generating radionuclides (which may still require deep geologic disposal), tend to increase the thermal power per unit volume of waste. The decrease in waste volume has potential to reduce the size of the repository and therefore reduce disposal costs, but such increases in thermal power of the waste could counter those savings by increasing spacing between waste packages to meet repository design temperature constraints. They[5] noted modifications that reduce the thermal power of the waste or that reduce waste volume without increases to thermal loading have potential for more efficient use of underground mined repository galleries, and potentially also offer pathways to developing waste forms that would fit within deep borehole disposal systems. All of those possible modifications provide potential for flexibility in disposal concept design and operations. Swift and Sassani[5] also showed that waste form modifications for durability may improve estimated peak dose performance of repositories only if the modified waste-form lifetime becomes relatively long compared to the geosphere transport time, and/or approaches the period of performance (e.g., on the order of hundreds of thousands of years). Relatively smaller improvements in waste-form lifetime (e.g., on the order of thousands or tens of thousands of years) may simply delay the time of the estimated peak release to the biosphere.

In addition to the insight from detailed safety assessments for geologic disposal, the disposal options study[2] evaluated disposal for the range of existing US nuclear waste forms (both commercial and non-commercial, including DSNF which are similar to some potential AR SNF) in four generic disposal concepts—mined repository concepts in crystalline, argillite, and salt host rocks, and deep borehole disposal in crystalline basement. That work delineated multiple disposal options (defined as a waste form and disposal concept pair) for the range of existing waste streams with consideration of the standard waste form production methods for vitrification of liquid high level wastes, electrometallurgical treatment for Na-bonded fuels, and flexible packaging for waste forms. The disposal options evaluation[2] analyzed the back end of the fuel cycle system pros and cons (including considerations for storage/transportation/security and safeguards) for each disposal option and delineated disposition pathways for the wide range of waste forms analyzed.

Section 3.2 of the disposal options evaluation[2] discusses the various characteristics that were considered in creating waste groups for that evaluation. Those waste form characteristics include radionuclide inventory, thermal output, chemical characteristics, physical characteristics, packaging of the waste form, as well as safeguards and security needed for handling, transporting, and disposing of the waste form. In general, any waste forms that are largely similar in these characteristics were lumped together into a single waste group. These waste form characteristics are also useful for assessing the direct disposability of waste forms anticipated to be produced by ARFC. These characteristics can be used for grouping AR SNF/waste forms in the context of the disposal concepts being considered.

<u>Radionuclide Inventory</u>: the radionuclide inventory of each waste form is the essential hazard that is being made safe via deep geologic disposal and, as such defines the primary nature of the hazard of any one particular waste form. There is a range of variation regarding fission product content. In addition, some waste forms are either highly enriched in fissionable radionuclides to start with, or may consist primarily of short-lived, high activity radionuclides

<u>Thermal Output</u>: the thermal output of the waste form is related to the radionuclide inventory discussed above, but presents an additional consideration in terms of both handling and managing heat within a disposal concept. As such, these characteristics focus on thermal limits for repository environments and thermal management strategies for storage and disposal systems leading up to disposal.

Chemical Characteristics: the bulk chemistry of a waste form is considered from a number of standpoints for delineating waste groups. First, in terms of waste form lifetime for a disposal concept, the bulk chemistry defines the reactivity of the waste form under differing environmental conditions. Reduced oxide waste forms disposed of in a reducing repository concept may have extremely long lifetimes if there is no ready source of oxidants (e.g., spent fuels that have radiolytic oxidants scavenged by hydrogen formed from metal corrosion), whereas some waste forms (e.g., salt waste electro-refined from sodium-bonded fuel) dissolve readily and have very short lifetimes once exposed to water. A second set of chemical characteristics also related to the bulk composition of the waste form is reactivity and ability to affect the bulk chemistry of solutions in the regions of the source term. For example, borosilicate glass waste imparts a relatively alkaline pH to water that reacts with it, so if the glass is in a condition where very slow groundwater flow exists, fluids may become alkaline in the region around the reacting waste form. Such bulk chemical effects should be considered relative to interactions with engineered materials lifetimes in that region, as well as for potential to affect the lifetime of any other proximal waste forms. An extreme example, which relates both to this and the waste form lifetime above, is the pyrophoric nature of the sodium-bonded metallic fuel (especially in consideration for direct disposal of that waste form). Additionally, there are some trace constituents that may be detrimental to engineered barriers/waste forms nearby. Examples include fluoride that may be more abundant and labile in some waste forms compared to the composition of the hosting geologic formation, and may drive corrosion of some materials.

Physical Characteristics: the physical aspects of the waste form, including the overall dimensions and mass of the un-packaged waste form (length, radius, weight, volume) are relevant for disposal (and handling) considerations. Also, the condition of the waste form (e.g., glass log, intact cladding, fine-grained broken pieces), is relevant to waste form lifetime once the package breaches. The dimension/scale of the packaged waste form is a consideration for placement into a disposal concept.

Packaging: some packaging may require substantially unique handling considerations, like the dual purpose canisters (DPCs) because of size and weight constraints, and possibly thermal constraints also. For example, DPCs are large and heavy and may present particular challenges to hoist technology to lower them to the disposal level of a repository, and their large size would preclude placing DPCs in a deep borehole. In addition, for some waste forms (e.g., direct disposed salt wastes from electro-refined sodium-bonded fuel), the packaging may be the primary (longest lived on average) aspect of the waste form that controls the rate of release of the radionuclides from the waste package (i.e., the source-term).

Beyond the above considerations are specific considerations of potential for post-closure criticality, which may also impact performance due to energetic degradation/evolution of the waste form generating both heat (with gas evolution) and changes to radionuclide content of the inventory. Such aspects, as well as pyrophoric processes of waste form evolution, may matter in terms of the relative fraction of the repository inventory. For example, instantaneous degradation for a small percentage of SNF inventory (e.g., DSNF is <~4% of the inventory included in the Yucca Mountain Safety Analysis Report (SAR); DOE 2008) may have negligible impact on the performance of a repository, however this may not be the case for that same material if it is a greater fraction of the inventory (and future new SNF perhaps should be assessed at 10% and 50% levels as well, with the latter being effectively commensurate with 100% for performance assessment purposes).

OVERVIEW OF ADVANCED REACTOR DEVELOPMENTS

There is renewed interest in nuclear energy in the US, with various initiatives in the past few years indicating an expansion of commercial nuclear energy generation. The FY20 U.S. Department of Energy (DOE) budget included nearly $1.5B for nuclear energy research at the DOE Office of Nuclear Energy (NE), which supports advanced reactor programs, accident tolerant fuels, high-assay low-enriched uranium, disposal and storage requirements (including potential for recycling used fuel), and the demonstration of producing hydrogen on-site at a nuclear power plant to open up new markets.[1] In August 2019, DOE also announced the launch of the National Reactor Innovation Center, an Idaho National Laboratory (INL) led initiative that will assist with the development and commercialization of advanced nuclear energy technologies by harnessing the capabilities of the DOE national laboratory system.[2] The U.S. Nuclear Regulatory Commission (NRC) is also engaged in the process of licensing advanced reactor technologies, and DOD is advancing microreactors through Project Pele.[3] Additionally, the DOE Advanced Research Projects Agency – Energy (ARPA-E) formulated a workshop in December 2020[4] to bring together National Laboratories, industry partners, and university researchers to formulate and launch an ARPA-E program for research and development on the impacts of advanced reactor waste streams on the back end

[1] https://www.energy.gov/ne/articles/analysis-fy2020-spending-bill-points-nuclear-resurgence

[2] https://www.energy.gov/ne/articles/energy-department-launches-new-demonstration-center-advanced-nuclear-technologies

[3] https://clearpath.org/our-take/one-of-worlds-largest-energy-consumers-embracing-advanced-nuclear/

[4] https://arpa-e.energy.gov/events/reducing-impact-used-nuclear-fuel-advanced-reactors-workshop

of the fuel cycle. ARPA-E enlisted a multi-lab consortium to provide background to prepare for this workshop, with Sandia National Laboratories covering primarily the disposal options and desirable waste form characteristics for such waste streams. In 2021 ARPA-E released a funding opportunity announcement, ONWARDS related to enhancements for advanced reactors to address aspects of disposal [5] and has awarded a number of grants. Lastly, the DOE (DOE NE-81) has funded a National Academy of Sciences study[6] to evaluate existing and future advanced reactor fuel cycles and examine their waste streams potential to impact the BENFC.

Partnerships are an important component to advanced reactor companies' reactor development efforts, with many partnering with other companies and/or national laboratories (particularly through the Gateway for Accelerated Innovation in Nuclear program[7]) to advance their technology and plan for deployment. This is especially true for companies whose reactor technology is further into the regulatory process. For example, under the Advanced Reactor Demonstration Program, the DOE has awarded $80 million each to TerraPower LLC and X-energy to build advanced nuclear reactors that can be operational within seven years.[8] TerraPower will demonstrate the Natrium reactor, which is a sodium-cooled fast reactor using metal fuel and a molten salt energy storage system. X-energy will deliver a commercial four-unit nuclear power plant based on its high-temperature gas-cooled reactors using tristructural isotropic (TRISO) particle fuel. Both of these companies have formally notified the NRC of their intent to engage in regulatory interactions with the NRC. Other vendors that have notified the NRC of their intent to engage in regulatory interactions with respect to non-LWRs include General Atomics (helium-cooled fast reactor with ceramic matrix composite fuel), Kairos Power LLC (molten fluoride salt coolant and TRISO fuel in pebble form), TerraPower LLC (molten chloride fast reactor), Westinghouse Electric Company (eVinci™ Micro-Reactor), and Terrestrial Energy (integral molten salt reactor(MSR)).[9]

Including small-modular and micro-reactors indicates that the potential variability in new reactor technology and variability in readiness/development levels are vast. To focus work on developing strategies for the potential BENFC, our focus is on a subset of AR types which have AR SNF that span those ranges of variabilities. Three example AR SNF types are selected from a range of representative AR for preliminary strategy development for evaluating the potential direct disposal impact from those AR SNF. These representative AR SNF span ranges of expected waste form lifetime, expected potential chemical reactivities, and projected compositional variability. Note that in some cases, there may be advantages for treatment/waste form development versus direct disposal of these AR SNF. The three example SNF for these prototype AR SNF are:

<u>TRISO particle fuels</u> – Examples of these AR SNF fuels may consist of 15.5% enriched uranium-oxy-carbide kernel coated by multiple layers of carbon- and ceramic-based materials to prevent the release of fission products. The TRISO particles may be bonded together into graphite compacts, and the fuel compacts would be loaded into prismatic fuel blocks. The graphite compacts could be irradiated up to an average burnup of ~120 GWd/t. Variations include different kernel compositions (U/Th oxides – e.g., Ft. St. Vrain[2]) and/or TRISO particles embedded in graphite spheres [e.g., 18,19]. Such SNF from AR may be He-gas cooled, or molten salt cooled.

<u>Metallic fuel</u> – This fuel may consist of a U-10Zr binary metallic fuel that is enriched to about 13.5 % U-235. The fresh metallic fuel may be irradiated to an average burnup of 101 GWd/t in the reactor. The fuel is commonly Na-bonded (e.g., EBR-II and Fermi[2]) if Na cooled, or may also be He-bonded.

<u>Molten salt fuel</u> - This fuel example may consist of UCl_3 and $PuCl_3$ fuel salts in a NaCl carrier salt (e.g., see TerraPower above). Either enriched UCl_3 or the $PuCl_3$ fuel may be used for initial startup, while natural UCl_3 fuel may be used as external material feed. The concept may be for the fuel salt to undergo continuous online treatment to remove fission products and minor actinides. Alternatives include fluoride-based salt fuel (e.g., the MSR Experiment at ORNL[20]).

DOE-managed SNF for TRISO particle spent fuels from reactors such as Ft. St. Vrain (FSV, a high temperature gas-cooled reactor; HTGR) were included in previous disposal evaluations[2,14] and the TRISO particles themselves appear to have reasonably robust waste form lifetimes[e.g., 21]. Those FSV fuels consist of numerous coated fuel particles, slightly less than 1 mm in diameter, that are embedded in graphite cylinders (i.e., compacts), which are then loaded into hexagonal-columns of graphite fuel elements[22]. In other cases, the TRISO particles are embedded in graphite spheres called pebbles[e.g., 18].

For the FSV spent fuel about 5,580 TRISO particles are embedded in graphite compacts (graphite cylinders 4.928 cm long and 1.245 cm in diameter)[21,22]. The TRISO particles

[5] https://arpa-e-foa.energy.gov/Default.aspx#FoaId7912e4f9-4475-47d7-9a2c-2993e369c410
[6] https://www.nationalacademies.org/our-work/merits-and-viability-of-different-nuclear-fuel-cycles-and-technology-options-and-the-waste-aspects-of-advanced-nuclear-reactors
[7] https://gain.inl.gov/SitePages/Home.aspx
[8] https://www.energy.gov/ne/articles/us-department-energy-announces-160-million-first-awards-under-advanced-reactor. Accessed 9/20/21.
[9] https://www.nrc.gov/reactors/new-reactors/advanced/ongoing-licensing-activities/pre-application-activities.html Accessed 9/20.21.

themselves consist of a micro spherical fuel kernel (U-Th-carbide for FSV; or U-Th-Ox for others) that is ~500-600 μm in diameter, surrounded by four layers/coatings[19,21]. Some advanced reactor concepts use TRISO embedded in graphite spheres cooled by high-temperature gas[10]. Other TRISO AR plan to use molten salt[11] rather than helium gas for cooling. As such, different considerations may apply to those spent fuels (e.g., dependent on adherence/contamination of the coolant materials to the spent fuel), and potentially to the coolant depending on its radionuclide content (e.g., from contamination/activation). Potential differences may include less volume (disposed without the hexagonal graphite fuel element) or higher relative volume (the compact/pebble graphite beyond just the TRISO particles), effects of hotter or cooler operational temperatures, differing fuel kernel composition/enrichment and/or differing burn-up resulting in different fission product concentrations, and chemical effects. Such differences would be assessed initially as part of preliminary performance assessment (PA) analyses of features, events, and processes for generic disposal concepts to see which may not be important and which should be included in safety/gap analyses for further R&D on those systems.

PRELIMINARY STRATEGY APPLICATION EXAMPLES

Our strategy for developing fully-formed gap analyses for AR SNF entails the primary step of first obtaining all the defining characteristics of the AR SNF waste stream from the AR developers. Utilizing specific and accurate information/data for developing the potential disposal inventory to be evaluated is a key principle for success. Once the AR SNF waste stream is defined, the initial assessments is based on comparison to appropriate existing SNF/waste forms previously analyzed to make a determination on feasibility of direct disposal, or the need to further evaluate due to differences specific to the AR SNF. Presented here are three example preliminary assessments of direct disposal for the representative AR SNF from above. Note that these are for a range of generic disposal concepts similar to those considered in the disposal options evaluation[2] and including a generic unsaturated repository concept.

TRISO Particle Fuels

TRISO particle fuels were included in disposal options analyses[2] as part of waste Group 9 that was defined as the set of DOE spent fuels that are particle fuels that are carbide-based fuel particles with graphite/carbon coatings. For Fort St. Vrain fuel the particles are contained in hexagonal graphite blocks. In some cases, these have not yet been packaged for disposal and are small enough for deep borehole disposal (e.g., Peach Bottom fuel particles). This waste group covers the waste forms from used coated particle fuels originating at Fort St. Vrain and Peach Bottom. The Fort St. Vrain TRISO fuel is expected to be a robust waste form[21] with long waste form lifetimes and these materials include fuels with uranium enrichments above 20%.

These TRISO fuels appear to be directly disposable in any of the disposal concepts considered[2], unless the prismatic blocks holding the compacts are too large to fit into the deep borehole diameter constraints. Although additional work may be needed to better define waste form lifetime and radionuclide release mechanisms, it was suggested[21] that the TRISO particles themselves likely have lifetimes from about 10,000 to 100,000 years based on a relatively robust layer of SiC. Additionally, the graphite of the Fort St. Vrain is free of issues regarding Wigner energy [23,24] due to its high operating temperature and the Fort St. Vrain TRISO fuel has more criticality margin than other DSNF with moderation from the graphite being overwhelmed by that of water entering the canister[25].

Metallic fuel (U-TRU-Zr alloy)

Metallic fuel (U-TRU-Zr alloy) from the sodium cooled fast reactor likely falls into either Waste Group 5 or Waste Group 6 that were defined[2] as follows.

Waste Group 5 consists of a number of DOE spent fuels that, in many cases, have not yet been packaged for disposal. In general, the state of the wastes is highly variable and in some cases consists of scrap, tubes, rods, cylinders, and or plates. The range of waste forms included here covers those that contain varying levels of uranium enrichment (with possible natural uranium or depleted uranium in some of these). These waste forms are not expected to have particularly robust lifetimes in post-closure environments either because of their physical state (small broken pieces) or their reactivity (e.g., metallic waste forms), though the expected lifetimes would be longer in reduced environments versus oxidizing conditions

Waste Group 6 is a single DOE spent fuel waste form: metallic sodium-bonded fuel. Conditions of these fuels are variable. Direct disposal of these fuels has not been considered in safety assessments for deep geologic disposal previously. Because of the reactive nature of these spent fuel waste forms and the challenges that they present, they have been separated from Waste Group 5.

The essential difference between Waste Group 5 and Waste Group 6 is that Waste Group 6 metallic fuels are sodium-bonded fuels, and if there is metallic sodium as part of the fuel, no direct disposal pathway has been identified[2]. These fuels are candidates for treatment, as discussed below.

For Waste Group 5, metallic fuels there are considerations of relatively short waste form lifetimes, as

[10] https://x-energy.com/reactors/xe-100 ; and https://x-energy.com/fuel/triso-x[11]
https://kairospower.com/technology/

[11] https://kairospower.com/technology/

well as high reactivity with oxidizing environments and water (potential pyrophoric behavior), making direct disposal of such waste forms in large amounts less likely. Generally, these materials are treated in post-closure safety assessments as having instantaneous degradation rates[2,14]. Although this is not an issue for Waste Group 5 spent fuels when they comprise a very small component of the inventory, and an entire repository of these materials likely would have larger source-term releases compared to one comprised of oxide fuels. It is likely that these would need a treatment pathway for a more stable waste form. Although deep boreholes do not rely on the waste form lifetime or waste package performance post-closure, direct disposal of Waste Group 5 spent fuel in a deep borehole concept would benefit from some research and development regarding the other thermal and chemical interactions/behaviors of these reactive materials in a large number of boreholes.

Molten Salt Reactor SNF

MSR SNF is directly related to Waste Group 8[2] that was defined as the set of waste forms that are salt waste forms, granular solids or powdered waste form materials and are expected to have either short waste form lifetimes once exposed to the post-closure environment, or only moderate lifetimes. One of these waste forms, small capsules containing cesium chloride and strontium fluoride, are very hot in short time frames (~300 years), but also contain ^{135}Cs that is long lived. Because they are relatively small in size and total mass, their thermal mass can be spread out within the disposal system if necessary. In addition, these waste forms are characterized by constituents (e.g., halides and halogenated organics) that would potentially be corrosive to other metallic barriers or other waste forms in a disposal system. This corrosive chemistry may result in a requirement to separate these from other waste packages sufficiently (via backfill or location or both).

Because of their very short waste form lifetimes, these Waste Group 8 materials are generally not directly disposable in most mined geologic repository concepts unless they are a very small fraction of the total radioactive waste being disposed. In such a case, they might be placed/isolated in their own portion of any repository, so they do not chemically affect engineered barriers of other waste forms. The two repository concepts in which Waste Group 8 wastes could likely be disposed directly are salt and deep borehole. The limited far-field radionuclide transport in a salt repository concept reduces the importance of the waste form and waste package lifetime in evaluating the safety of the disposal option and increases confidence in the information bases for waste forms such as these. These Waste Group 8 wastes may be directly disposed in a deep borehole concept (as long as they can be loaded into smaller diameter disposal packages). If there are numerous boreholes needed (i.e., fields of dozens to hundreds), thermal aspects may need to be assessed, especially if fission products are concentrated in the waste form.

It should be noted that the above preliminary direct disposal assessments are based on previous work[2,14] for existing similar DSNF to some potential AR SNF and are meant only as a guide to further specific analyses based on the actual detailed definition of the AR SNF characteristics. Those specific analyses would also be used to identify further issues/gaps for additional R&D activities to close them.

Reprocessed or Treated SNF from ARFC

If the SNF produced by an ARFC is not directly disposable, then it would be reprocessed or treated prior to disposal, producing different waste forms for which disposal options would be evaluated. Based on published safety analyses of the geologic disposal concepts discussed above, the safety assessment context for changes to the waste forms for different processing schemes provides a method for understanding magnitudes of potential changes to generic repository concept logistics/performance. In addition to the first cut at disposal options, the details of each AR SNF and/or waste form would be evaluated for assessing additional issues/gaps to be considered and then prioritized for closure via additional R&D. Recent preliminary analyses of AR waste streams to assess potential issues for further R&D have been performed for both AR SNF and other reactor materials waste streams that by be dispositioned for deep geologic disposal[26,27]. These analyses identify a number of additional radiologic and chemical considerations for the handling, storage, and disposal of the potential waste streams and underline the import for precise definition of the physical, chemical, and radionuclide characteristics of AR SNF, as well as other potential specific AR waste streams.

Beyond the performance safety evaluations for a disposal option, there are considerations regarding the potential for criticality that should be examined for each ARFC waste form. Such criticality considerations for pre-closure would focus primarily on fissile content, burn-up credit, packaging configuration, and the presence of engineered neutron absorbers in the packaging. For post-closure criticality, analyses would focus on those same aspects together with the potential for post-closure conditions promoting critical conditions (moderators, etc.).

SUMMARY

As presented above, because similar existing DOE-managed SNF (DSNF) from previous reactors have been evaluated for disposal pathways, we use this knowledge/experience as a broad reference point for initial technical bases for preliminary dispositioning of potential AR SNF. The strategy for developing fully-formed gap analyses for AR SNF entails the primary step of first obtaining all the defining characteristics of the AR SNF waste stream from the AR developers. Utilizing specific and accurate information/data for developing the potential disposal inventory to be evaluated is a key principle start for success. Once the AR SNF waste streams are defined, the initial assessments would be based on comparison to appropriate existing SNF/waste forms previously analyzed (prior experience) to make a determination on feasibility of direct disposal, or the need to further evaluate due to differences specific to the AR SNF. Assessments of criticality potential and controls would also be performed to assess any R&D gaps to be addressed in that regard as well. Although some AR SNF may need additional treatment for waste form development, these aspects may also be constrained and evaluated within the context of disposal options, including detailed gap analysis to identify further R&D activities to close the gaps.

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