# Qualitative Evaluation of Options for Disposal of SNF and HLW

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*Options for disposal of the spent nuclear fuel and high level radioactive waste that are projected to exist in the United States in 2048 were studied. The options included four different disposal concepts: mined repositories in salt, clay/shale rocks, and crystalline rocks; and deep boreholes in crystalline rocks. Some of the results of this study are that all waste forms, with the exception of untreated sodium-bonded spent nuclear fuel, can be disposed of in any of the mined disposal concepts, although with varying degrees of confidence; salt allows for more flexibility in managing high-heat waste in mined repositories than other media; small waste forms are potentially attractive candidates for deep borehole disposal; and disposal of commercial SNF in existing dual-purpose canisters is potentially feasible but could pose significant challenges both in repository operations and in demonstrating confidence in long-term performance. Questions addressed by this study include: is a "'one-size-fits-all' repository a good strategic option for disposal?" and "do some disposal concepts perform significantly better with or without specific waste types or forms?" The study provides the bases for answering these questions by evaluating potential impacts of waste forms on the feasibility and performance of representative generic concepts for geologic disposal*.

## I. INTRODUCTION

This study provides a technical basis for informing policy decisions in the United States regarding strategies for the management and permanent disposal of spent nuclear fuel (SNF) and high-level radioactive waste (HLW) requiring geologic isolation. The scope of the waste in this study included existing SNF from commercial, defense, and research reactors, and SNF from reasonably foreseeable operations of existing reactors (projected to 2048). The study also included existing HLW (e.g., vitrified HLW at Savannah River and West Valley) and waste forms projected to be generated in the future from existing process waste (e.g., projected vitrified HLW from Hanford, Savannah River and the Idaho National Laboratory). In addition, the study included consideration of both direct disposal of waste forms that are not currently planned for disposal without further treatment (e.g., calcine waste at the Idaho National Laboratory), and alternatives to planned treatments. The study acknowledged existing plans, commitments, and requirements where applicable, but the study evaluated disposal options primarily on technical, rather than programmatic or regulatory constraints.

Major assumptions and considerations used in this study included the following:

- HLW and SNF were restricted to existing materials and those materials that can be reasonably expected to be generated by existing or currently planned facilities and processes.
- The inventories of HLW and SNF represent existing materials in the U.S. requiring deep geologic isolation, and were based on the best available information.
- Technologies considered, both for waste treatments and disposal concepts, were limited to those that can be deployed in the near future.
- Programmatic constraints, including legal, regulatory, and contractual requirements, were acknowledged where applicable, but were not included in the evaluations, consistent with the goal of the study to provide technical input to strategic decisions. For example, the identification of wastes requiring deep geologic isolation was based on consideration of overall risk, rather than on specific U.S. legal and regulatory requirements.
- Evaluations were primarily qualitative, and based in large part on insights from past experience in waste management and disposal programs in both the U.S. and other nations.

It should be noted that the set of disposal concepts used in this evaluation was presented as a useful and representative, rather than comprehensive, set of concepts.

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Participants in the study included representatives from the U.S. Department of Energy (DOE), the U.S. Navy, several national laboratories, universities and private sector firms. The contributors have expertise in a broad range of fields, including nuclear engineering, earth sciences, materials science, chemical engineering, materials safeguards and security, and regulatory requirements. The information presented here is a summary of the study, documented in Ref. 1.

## II. DISPOSAL CONCEPTS, WASTES, AND METRICS

A disposal option was defined by the disposal concept being considered and the waste form being disposed of in that concept. Each disposal option was evaluated against a set of six criteria with associated metrics. The disposal concepts, waste forms included, and evaluation criteria/metrics are discussed below.

### II.A. Disposal Concepts Considered

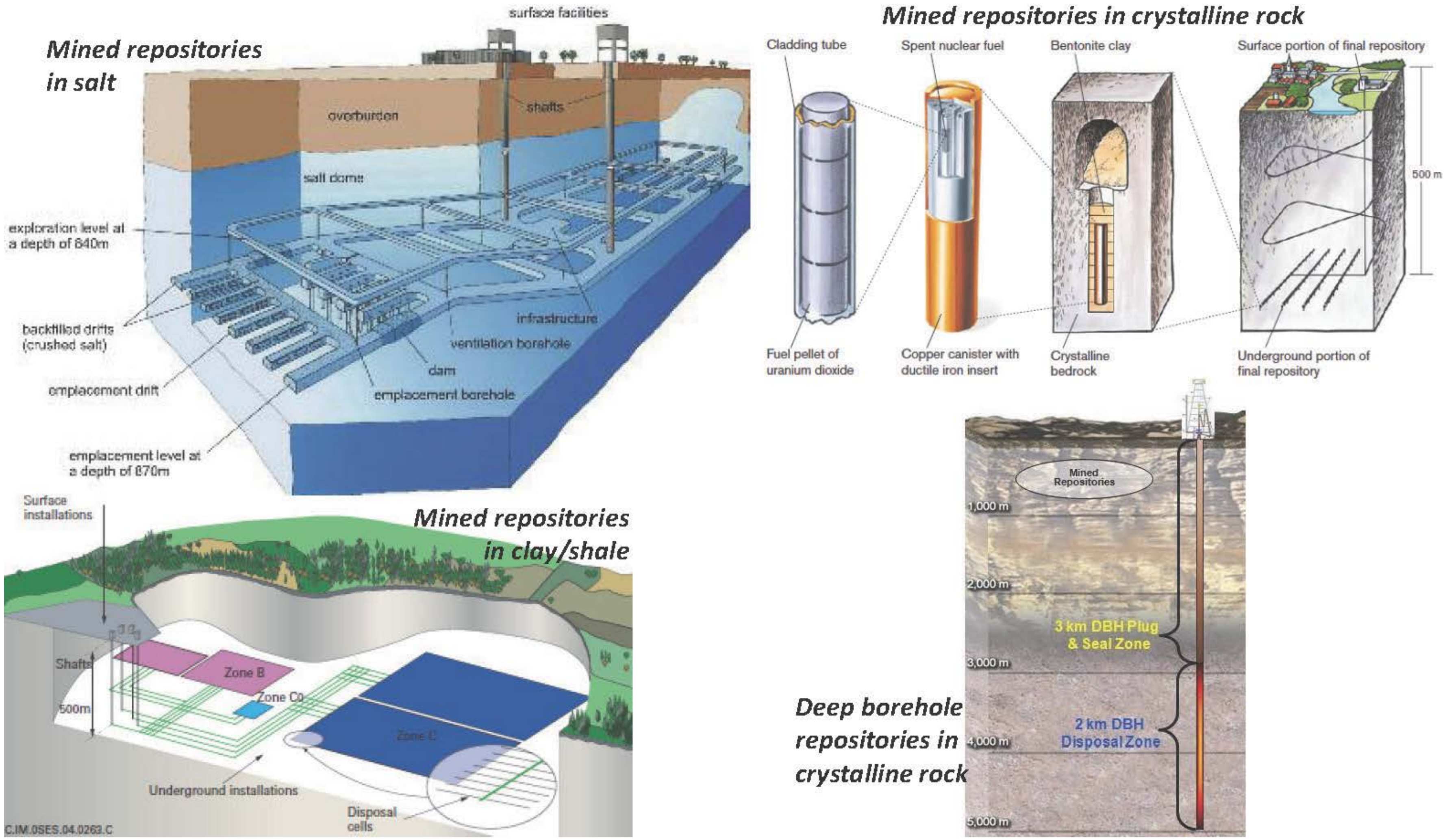
Four representative disposal concepts were included in this study: mined repositories in three geologic media—salt, clay/shale rocks, and crystalline (e.g., granitic) rocks—and deep borehole disposal in crystalline rocks (see Figure 1). These are the four disposal concepts selected for further research and development activities by the DOE Office of Nuclear Energy's Used Fuel Disposition Campaign. Selection of these four concepts began with the observation that options for disposal of SNF and HLW have been evaluated in multiple nations for decades, and deep geologic disposal was recognized as early as the late 1950s to be the most promising approach. By the 1980s, the U.S. waste management program had concluded that multiple geologic media had the potential to provide robust isolation, and that conclusion remains valid today. Experience gained in waste management programs in other nations reinforces that conclusion: for example, Sweden and Finland both have license applications pending for proposed mined repositories for SNF in crystalline rock; the U.S. has an operating repository in salt for transuranic waste at the Waste Isolation Pilot Plant and Germany has extensive experience with the design of a mine for a SNF and HLW repository in salt; and France, Switzerland, and Belgium have completed detailed safety assessments for proposed SNF and HLW repositories in clay and shale media. No nations are currently planning deep borehole disposal, but the concept has been evaluated in multiple programs since the 1970s, and remains viable for waste forms small enough for emplacement.

### II.B. Waste Inventory

This study covered existing and "reasonably foreseeable" projected SNF and HLW inventories. The existing wastes are those that can be inventoried, and the projected are those scheduled to be generated by currently operating reactors (or reactors under construction) and HLW-generating activities through 2048. The boundary of "reasonably foreseeable" was selected to include wastes that can be forecast from current actions by industry or government, but was not intended to include potential waste streams from advanced fuel cycle technologies that may be—or may not be—deployed in the future. This enabled the physical and radiological characteristics of both existing and reasonably foreseeable wastes to be sufficiently defined for evaluation in disposal options. For example, the spent fuels from several prototypical high-temperature gas-cooled reactors that have been built and operated in the U.S. were clearly included in the scope of the study, whereas proposed fuel types for developing reactor technologies that have no firm construction commitment were not included in the scope of the study.

The waste inventory was classified into 43 different waste *types*. For the purposes of the study, a waste *type* was defined as the currently existing materials (in whatever form, abundance, and location they occupy) that are to be disposed of as at least one, and possibly more than one, waste *form* in a deep geologic disposal concept (e.g., Hanford tank wastes; commercial spent fuels, HLW glass). A waste *form* was the end-state material as packaged that is to be disposed of in a deep geologic disposal concept. Some waste *types* had more than one possible alternative waste *form* depending on the processing needed, whereas waste *types* that require no processing other than packaging equated to a single waste *form*. Figure 2 is an illustrative example of waste type, waste form, and waste group for HLW glass.

Including the alternative treatment options for some of the 43 waste types above resulted in 50 waste forms. To facilitate the analysis, these 50 waste forms were aggregated into the ten waste groups listed in Table I. The groups had similar disposal characteristics such as radionuclide inventory, thermal output, physical dimensions, chemical reactivity, packaging of the waste form, and safeguards and security needed for handling, transporting, and disposing of the waste form. The aggregation into waste groups allowed a high-level identification of any waste forms that needed to be considered as a separate group due to outstanding qualities in any one of these characteristics. The alternative waste forms (of a waste type) appeared in various waste groups. For example, cesium/strontium capsules disposed of as-is were in Waste Group 8, while cesium/strontium capsules that were vitrified prior to disposal were in Waste Group 3.




Sources: Ref. 2, Figure 15 (salt repository); Ref. 3 (clay/shale repository); Ref. 4, Figure S-1 (crystalline repository);

Figure 1. Four representative disposal concepts considered in this study.

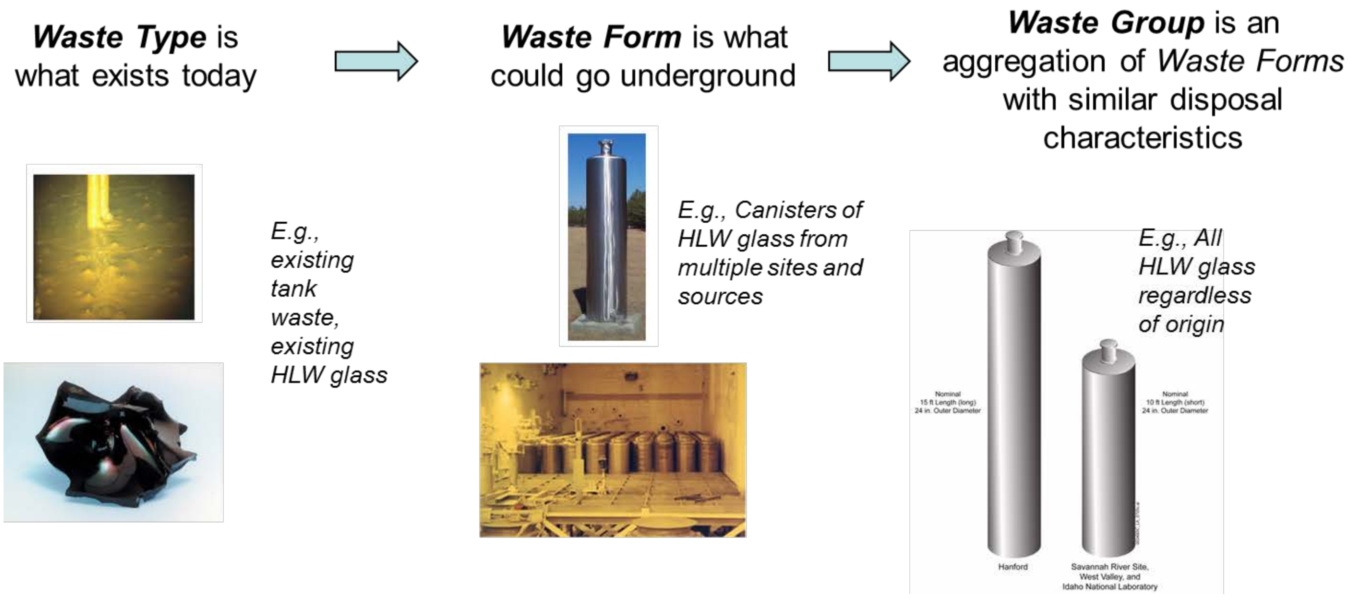



Figure 2. Examples of "waste type," "waste form," and "waste group" using high-level radioactive waste glass.

TABLE I. Waste Group Descriptions

| Waste Group | Description |
|---|---|
| Waste Group 1 | All commercial SNF packaging in purpose-built disposal containers |
| Waste Group 2 | All commercial SNF packaged in dual-purpose canisters of existing design |
| Waste Group 3 | All vitrified HLW (all types of HLW glass, existing and projected, canistered) |
| Waste Group 4 | Other engineered waste forms |
| Waste Group 5 | Metallic and non-oxide DOE spent fuels |
| Waste Group 6 | Sodium-bonded fuels (driver and blanket), direct disposed |
| Waste Group 7 | DOE oxide fuels |
| Waste Group 8 | Salt, granular solids, and powders |
| Waste Group 9 | Coated-particle spent fuel |
| Waste Group 10 | Naval fuel |

### II.C. Evaluation Criteria and Metrics

Each waste group was evaluated against six primary criteria for potential disposal in each of the four disposal concepts. The criteria, and their associated metrics used in the evaluation, are summarized in Table II. Note that in practice not all criteria are equally relevant to all components of a disposal option. For example, secondary waste generation and safeguards and security concerns are primarily relevant to the characteristics of the waste group, whereas confidence in expected performance bases and operational feasibility are more strongly influenced by the disposal concept. Scoring was done qualitatively, using the informed and consensus judgment of a subset of the multidisciplinary team contributing to this study.

## III. STUDY RESULTS

The evaluation of the forty disposal options (defined as a single waste group paired with a single disposal concept) was performed by considering the particular waste form(s) in the waste group and the particular disposal concept in the context of the metrics outlined in Table II. Following the discussion for each metric, a group consensus was reached with regard to the rating for that option for a given metric: strong or positive result, moderate result, weak or uncertain result, or not feasible. In every case, the group was able to reach a consensus regarding the rating for each.

The evaluation results are summarized by waste group and discussed below. This summary was produced by setting the result at the criterion level to the value of the lowest rated metric within a given criterion. Thus, if an option was rated "strong or positive result" for a particular metric and "weak or uncertain result" for another metric associated with the same criterion, then the option evaluation summary indicates a "weak or uncertain result" for that criterion.

With respect to total system level cost, factors that would introduce cost differentials for each option were discussed, but no rating was assigned because the evaluation group concluded that there was not enough information to assign a meaningful rating.

TABLE II. Evaluation criteria and associated metrics

| Evaluation Criteria | Metrics |
|---|---|
| Disposal Option Performance | Likely to comply with long-term standards? |
| Confidence in Expected Performance Bases | Additional components needed above baseline for each design concept.<br><br>Robustness of information bases; simplicity vs. complexity; knowledge gaps |
| Operational Feasibility | Ease in ensuring worker health and safety at all stages<br><br>Special physical considerations at any stages based on physical characteristics |
| Secondary Waste Generation | Amount of low-level waste generated during handling and treatment<br><br>Amount of mixed waste generated |
| Technical Readiness | Status of waste form technologies<br><br>Status of transportation and handling systems<br><br>Status of disposal technologies |
| Safeguards and Security | National security implementation difficulty<br><br>Radiological dispersion device prevention implementation difficulty |

In addition, factors that might need to be considered in a programmatic or regulatory context were discussed, but no rating was assigned. One consent-based siting consideration is that there are many sites around the country associated with each of the four disposal concepts. Another consideration is that there is a significant amount of operational experience in salt mining, and a significant amount of international repository experience in salt, crystalline rock, and in clay/shale, which might make it easier for a community to have confidence in entering into a consent-based licensing agreement. In contrast, there is no operational experience with respect to deep boreholes for disposal, which might present challenges in finding a consenting host community in the absence of further research and development activities.

For the deep borehole disposal concept, it was noted that current disposal regulations did not contemplate deep borehole disposal, and that there may be regulatory issues associated with deep borehole disposal.

It was also noted that for some wastes, there are open regulatory issues with respect to postclosure criticality screening. In addition, some wastes are likely to be subject to RCRA requirements. These concerns are discussed in conjunction with the waste groups for which criticality and/or RCRA requirements are an issue.

### III.A. Disposal in Salt

Overall, mined repositories in salt showed strong results for most waste groups with respect to most metrics. At the level of resolution provided by this evaluation, scores for salt and clay/shale repositories were equivalent. The following pros and cons of disposal in a salt repository were noted:

- Pros:
  - The high thermal conductivity and high temperature limit of salt provide greater flexibility (i.e., larger packages and closer spacing) for disposal of heat generating wastes than other geologic media.
  - The limited far-field radionuclide transport (low permeability) of salt reduces the reliance on the waste form and waste package lifetimes, providing greater confidence in estimates of long-term performance.
  - The low permeability and reducing (oxygen-poor) environment make it easier to keep specific waste packages isolated from each other, should that be necessary.
  - Some untreated waste types may be appropriate for direct disposal in salt, potentially reducing costs and risks associated with waste treatment.
  - The relative lack of water and the high cross-section of chlorine for capture of thermal neutrons make it easier to address criticality concerns (for waste forms for which criticality is relevant).

- Cons:
  - For very large waste packages (e.g., dual-purpose canisters), keeping the large shafts and ramps open during the operational period will present a challenge, as will sealing these large shafts and ramps upon closure.
  - For very large waste packages, technologies for moving and emplacing the waste packages in salt have yet to be developed.
  - Knowledge gaps exist concerning the response of salt to high thermal loads.
  - There may be a greater need for site-specific information regarding this type of disposal medium because of high reliance on the integrity of the host rock.

### III.B. Disposal in Crystalline Rock

Overall, mined repositories in crystalline rock showed strong results for most waste groups with respect to most metrics; however, scores in several areas were lower than for salt or clay/shale disposal concepts suggesting that future research and development needs could be greater for a crystalline repository. The following pros and cons of disposal in a crystalline rock repository were noted:

- Pros:

– There is significant world-wide experience with this medium.

– If waste package retrieval is necessary, it is easiest in this disposal concept.

– Stable rock properties enhance operational feasibility for very large packages (e.g., dual-purpose canisters).

– Would be relatively easy to achieve separation distances between waste forms, if needed.

- Cons

– The lower thermal conductivity of crystalline rock complicates the reliance on bentonite as a buffer for those wastes that generate a significant amount of heat.

– Management of high heat loads could delay emplacing backfill until after a long period of ventilation.

– Strong reliance on waste package lifetime results in lower confidence for high-heat waste forms and readily mobilized waste forms

– Some wastes may need to be segregated from other wastes because of possible corrosive chemical reactions.

– Some of the waste forms, particularly dual-purpose canisters, would need robust overpacks that may pose design challenges.

– Colloids pose a potential for transport in fracture networks

– For very large waste packages, technologies for moving and emplacing the waste packages in crystalline rock have yet to be developed.

– May need to consider adding engineered barrier system component to address criticality concerns for some wastes.

**III.C. Disposal in Clay/Shale**

Overall, mined repositories in clay/shale showed strong results for most waste groups with respect to most metrics. At the level of resolution provided by this evaluation, scores for clay/shale and salt repositories were equivalent. The following pros and cons of disposal in clay/shale repository were noted:

- Pros:

– There is a significant amount of world-wide experience with this disposal medium.

– The limited far-field radionuclide transport in clay/shale (low permeability and high sorption) reduces the reliance on the waste form and waste package lifetimes

– Would be relatively easy to achieve necessary separation distances between wastes, if needed.

- Cons:

– For very large waste packages, keeping the large shafts and ramps open during the ventilation period will present a challenge, as will retrieval during preclosure operations.

– For very large waste packages, technologies for moving and emplacing the waste packages in clay/shale have yet to be developed.

– May need to add engineered barrier system components to address criticality control.

– Some wastes may need to be segregated from other wastes because of possible corrosive chemical reactions.

**III.D. Disposal in Deep Boreholes**

Overall, deep borehole disposal options received mixed scores. For wastes that currently exist either as unpackaged materials (e.g., untreated calcine waste and some DOE-managed SNF) or in small packages (e.g., cesium/strontium capsules), deep borehole disposal may be a feasible and potentially attractive option. For example, untreated cesium/strontium capsules, which represent about 40% of the total radioactivity originally in HLW at the Hanford site, could be disposed of in a single borehole. However, for larger waste forms (e.g., commercial SNF disposed of in dual-purpose canisters and the existing canisters of HLW glass), the option is simply not feasible because the wastes forms are larger than current drilling technology can accommodate. For many waste forms, engineering challenges associated with preparing the waste form in a small enough package for emplacement in boreholes using current standard drilling technology are sufficient to make it a less attractive option. For example, deep borehole disposal of pressurized water reactor SNF could require removal of assembly hardware and consolidation of the rods. Deep borehole disposal of future HLW glass could require redesign of existing vitrification facilities to make smaller canister pours. The following pros and cons of geologic disposal in deep boreholes were noted:

- Pros:

– Thermal load management concerns are minimized by the depth of the disposal concept and the relatively small size of the waste packages.

– Because there is less reliance on waste form and waste package performance, it is easier to have confidence in the performance bases.

– Smaller waste types are good candidates for this disposal concept (e.g., cesium/strontium capsules), allowing for efficient disposal such waste forms.

– Some untreated waste types may be candidates for direct disposal in boreholes (e.g., untreated calcine waste), potentially reducing costs and risks associated with waste treatment

- Cons:

– Currently limited to disposal of very small packages (around 1 ft (30 cm) diameter or less).

– Lack of detailed design or demonstration of this disposal concept limits confidence.

– If considered for disposing of commercial SNF, it would require repackaging and, in some cases, consolidating the spent fuel rods.

– Retrieving waste disposed in deep boreholes could be difficult.

– The transportation capacity and logistics for small volumes of waste likely would limit disposal operations, so surface handling and storage concepts would need further consideration.

– For a given volume of waste, disposing of only very small-diameter packages results in handling more waste packages compared to the other three disposal concepts.

### III.E. Additional Insights

Although some of the criteria provided relatively little discrimination among disposal concepts, the evaluation identified potentially useful insights relevant to waste form properties independent of disposal concept. Specifically:

- Enough information does not currently exist to evaluate the performance of direct disposal of sodium-bonded SNF in any geologic disposal concept. This waste type may require treatment (e.g., electrometallurgical treatment) regardless of the disposal concept.
- None of the disposal concepts considered posed significantly different concerns related to safeguards and security. Only those waste forms containing salts, granular solids, and powders raised moderate security concerns associated with the potential for diversion for radioactive dispersal devices.
- All waste-form treatment options that involve handling or processing waste carry the potential for increased generation of secondary waste. This is most significant, perhaps, in comparing waste group 1 (repackaging of all commercial SNF for disposal in purpose-built container) and waste group 2 (disposal of all commercial SNF in existing dual-purpose canisters without repackaging).
- In general, demonstration of the technical readiness of a specific waste form is independent of the disposal concept being considered.

## IV. CONCLUSIONS

Technical conclusions relevant to each of the three questions posed at the beginning of the study are presented here.

**Is a "one-size-fits-all" repository a good strategic option?**

The study concluded that, from a technical perspective, any of the mined repository concepts could accommodate all of the waste forms with the exception of *untreated* sodium-bonded SNF, for which available information was insufficient to support an evaluation. The study concluded that the deep borehole disposal option is a good option for small waste packages and provides flexibility to a disposal strategy. The study also noted that disposal options that utilize multiple repositories are also technically viable.

**Do different waste forms perform differently enough in different disposal environments to warrant different approaches?**

The study did not identify any waste forms that required a specific disposal environment/concept. Other relevant observations included:

- With the exception of the untreated sodium-bonded SNF discussed above, all waste forms could be accommodated in multiple disposal concepts, although with varying degrees of confidence.
- Some disposal concepts may require segregating some waste forms from each other within a single repository. Specifically, halide-bearing wastes (including salt waste forms and the cesium/strontium capsules) may be corrosive, and if they are disposed of without treatment in disposal concepts that rely on long-lived waste packages they should be isolated from other wastes.
- Small waste forms are potentially attractive candidates for deep borehole disposal. Those wastes forms include salt wastes from electrometallurgical treatment of sodium-bonded SNF, untreated calcine waste, cesium/strontium capsules, and some DOE-managed SNF that has not yet been packaged.
- Salt allows for more flexibility in managing high-heat waste in mined repositories than other media.
- The study did not identify technical issues associated with disposing of mixed waste (i.e., waste containing both radioactive materials and RCRA regulated constituents).
- The study concluded that direct disposal of commercial SNF in existing dual-purpose canisters was potentially feasible but could pose significant challenges

both in repository operations and demonstrating confidence in long-term performance.

**Do some disposal concepts perform better with or without specific waste forms?**

The study concluded that all of the disposal options evaluated have the potential to comply with applicable regulatory requirements that protect both worker and public health and safety, and protect the environment. There were a few disposal options considered that were not evaluated for the full range of criteria. These exceptions are those deep borehole options that are not physically feasible due to size constraints, and the disposal of *untreated* sodium-bonded SNF, for which information is insufficient to support an evaluation. All other disposal options identified in this study could be designed, constructed, and operated to provide safe and robust isolation of the waste forms. However, the evaluation results summarized above show that implementation and demonstration of robust performance may be simpler for some disposal concepts than for others.

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## REFERENCES

1. SNL (Sandia National Laboratories) 2014. *Evaluation of Options for Permanent Geologic Disposal of Used Nuclear Fuel and High-Level Radioactive Waste Inventory in Support of a Comprehensive National Nuclear Fuel Cycle Strategy.* FCRD-UFD-2013-000371. SAND2014-0187P; SAND2014-0189P. Revision 1. Albuquerque, New Mexico: Sandia National Laboratories.
2. BMWi (Federal Ministry of Economics and Technology, Germany) 2008. Final Disposal of High-Level Radioactive Waste in Germany—The Gorleben Repository Project. Berlin, Germany: Federal Ministry of Economics and Technology (BMWi). Available at http://bmwi.de/EN/Service/search.html.
3. ANDRA 2005. Dossier 2005: Argile. Synthesis: Evaluation of the Feasibility of a Geological Repository in an Argillaceous Formation. Châtenay-Malabry, France: ANDRA.
4. SKB (Svensk Kämbränslehantering AB [Swedish Nuclear Fuel and Waste Management Company]) 2011. Long-Term Safety for the Final Repository for Spent Nuclear Fuel at Forsmark, Technical Report TR-11-01. Three volumes. Stockholm, Sweden: Svensk Kärnbränslehantering AB.