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The Need for a Borehole Disposal Field Test for Operations and Emplacement – 21220

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ABSTRACT
Borehole disposal for the geologic isolation of spent nuclear fuel (SNF) and high-level radioactive waste (HLW) has been considered for many years, beginning with evaluations of nuclear waste disposal options in the U.S. in the late 1950s and continuing with recurrent evaluations in several countries. Borehole disposal may be particularly attractive for countries with smaller radioactive waste inventories, where the modular cost of a few boreholes may enable safe and economic geologic disposal due to the lower up-front capital investment compared to a mined repository.

To advance the viability of the borehole disposal concept, a field demonstration is critical for assessing (a) downhole system characterization techniques to inform post-closure safety analyses, and (b) waste container surface handling and downhole emplacement to inform the safety and feasibility of pre-closure operations. In particular, pre-closure operational aspects have not been studied in as much detail as post-closure safety.

This paper identifies field test activities that would enhance confidence in the surface handling and downhole emplacement operations for borehole disposal. Specifically, a surface handling and emplacement demonstration using surrogate waste canisters (i.e., containing no radioactive materials) in a shallow borehole would be sufficient to assess surface handling/emplacement/tracking protocols at the field scale. This type of field-scale test would advance the protocols and implementation of the technology and contribute to the demonstration of safety and viability of the borehole disposal concept.

INTRODUCTION
Depending on the target geologies and waste forms, multiple borehole disposal concepts with different diameters and depths may be considered. These concepts range from low-level waste (LLW) and sealed radioactive sources (SRS) in shallow boreholes (tens to hundreds of meters depth) to intermediate-level waste (ILW) and HLW in intermediate-depth boreholes (≤ ~2,000 m depth) to SNF and HLW in deep boreholes (~2,000 – 5,000 m depth) (Fig. 1). It should be noted that these categorizations are part of a continuum of variation and their delineated depth divisions are meant to provide guidance rather than absolute boundaries. Site-specific disposal depths depend on many of the geologic features of the site, as well as the engineered barriers being utilized within the disposal concept. For comparison, mined geologic repositories for SNF are being proposed at depths ranging from about 250 m to 600 m [1].

Robust post-closure waste isolation can be attained in deep boreholes in low-permeability basement rock that is hydrologically isolated from overlying circulating groundwater systems. Post-closure safety for this deep borehole concept relies almost entirely on the natural system to completely and permanently prevent the waste from being released to the near-surface hydrosphere and biosphere. Engineered seals, emplaced in the borehole above the waste, are relied upon only during the relatively short period of upward flow (< few hundreds of years) due to thermal perturbation from waste form decay heat. This almost exclusive reliance on the deep natural system barriers is unlike that of mined geologic repositories, which are typically located at shallower depths that are within the circulating groundwater systems.

Post-closure safety for shallower mined repositories relies on a combination of engineered and natural barriers to prevent or reduce releases of radioactivity into the near-surface hydrosphere and biosphere for the very long periods of post-closure performance. Similar to mined repository systems, the intermediate-depth and shallow borehole concepts also rely on a combination of engineered barriers (e.g., waste form,

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waste container, borehole fill materials and seals) and natural barriers for substantial periods of the post-closure performance. However, the shallow and intermediate-depth concepts have potential advantages over mined repository disposal because they avoid the significant overhead of construction and operational costs for an underground mined excavation and associated underground infrastructure. Regardless of the depth of the borehole, the construction cost of borehole disposal scales linearly with waste inventory and number of required boreholes to be drilled, resulting in a pay-as-you-go disposal approach.

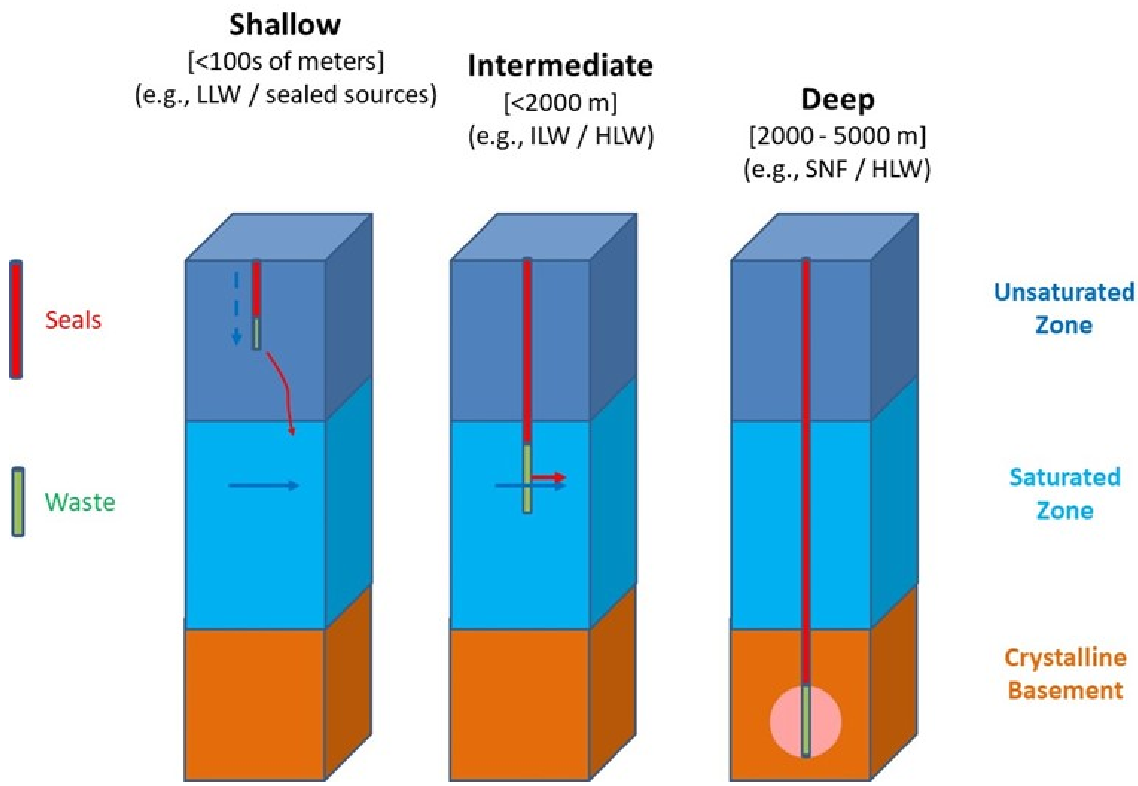
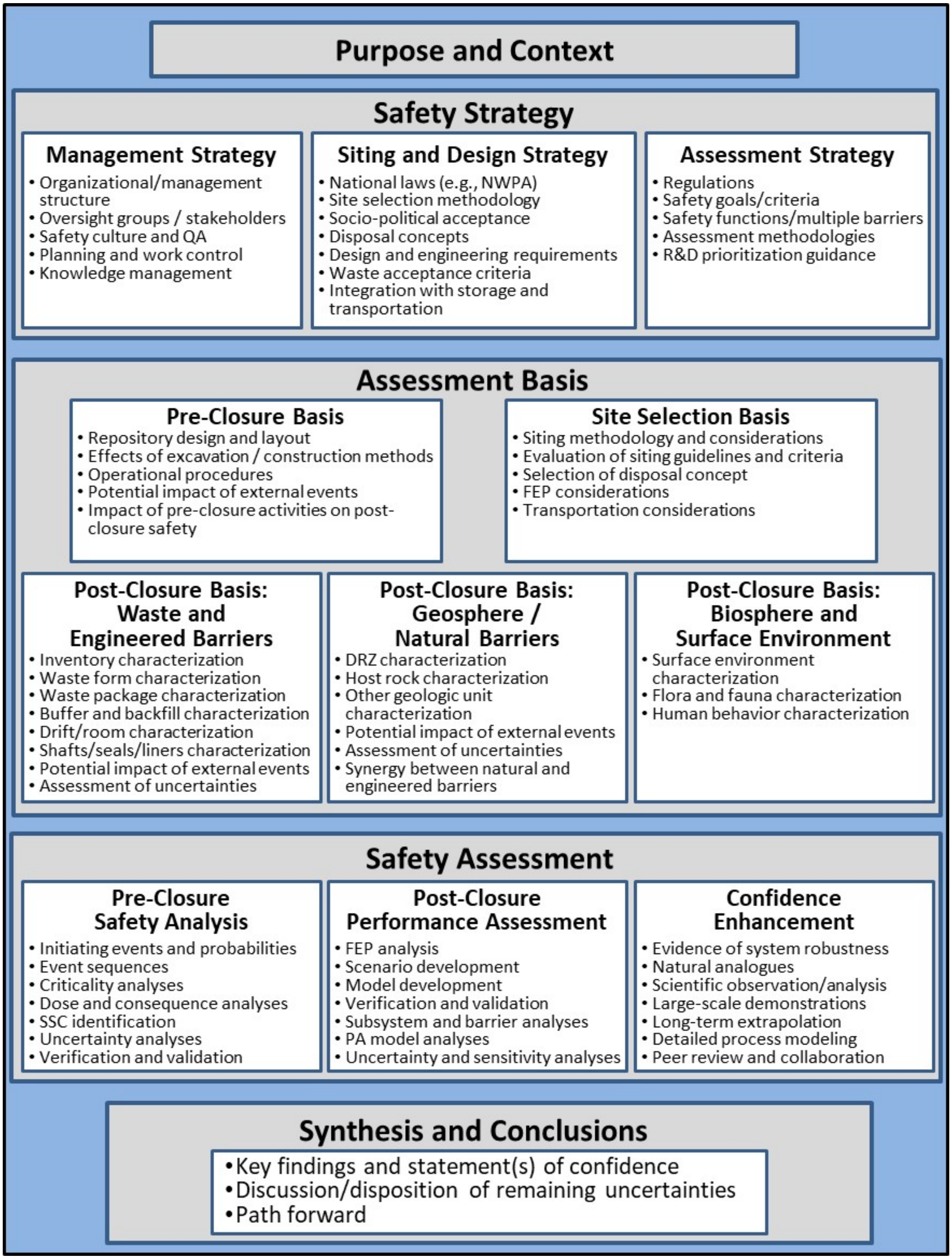


Fig. 1. Borehole Disposal Concepts.

For all of these borehole disposal concepts for SNF, HLW and/or ILW, a field-scale demonstration is still needed as a foundation of concept feasibility, both to assess the feasibility of pre-closure operations and safety and to assess system characterization techniques that would inform post-closure safety analyses.

SAFETY CASE ELEMENTS

A widely accepted approach for documenting the basis for the understanding of a geologic disposal system, describing the key justifications for its safety, and acknowledging the unresolved uncertainties and their safety significance is a structured document, or set of documents, known as a safety case [2, 3, 4, 5]. A safety case includes quantitative (e.g., safety assessments) and qualitative information related to both pre-closure (operational) and post-closure safety [2]. Normally, a safety case and associated safety assessments address (i) a specific repository site, design, and concept of operations, (ii) a well-defined inventory, waste form, and waste package, and (iii) an established regulatory environment. However, this level of specificity does not currently exist for the borehole disposal concept for SNF, HLW, and/or ILW. Instead, the elements of a safety case (Fig. 2) can be used as a checklist for the level of knowledge associated with various components of a borehole disposal system. The key elements of a safety case include the safety strategy, the assessment basis, and the safety assessment.



(Source: [5]; adapted from [2])

Fig. 2. Elements of a Safety Case for Borehole Disposal of Nuclear Waste.

A safety strategy for borehole disposal, which includes national organization, management, and regulations, has not yet been developed by any national waste management organization. However, certain assumptions can be made to guide preliminary research and development (R&D). Two important principles of the safety strategy are (i) public and stakeholder involvement in key aspects of siting, design, and assessment and (ii) alignment of the safety case with the existing legal and regulatory framework [4].

Typically, a safety strategy becomes the basis for communications with stakeholders. Feedback from stakeholders on issues needing to be addressed may help more fully form the safety strategy [2], including siting considerations. The current regulatory framework for radioactive waste management in the U.S. focuses on mined geologic repositories and was not intended to be applied to the long-term performance of borehole disposal facilities. Nevertheless, it is likely that regulations for a borehole disposal facility would be strongly informed by the current standards – general regulations at 10 CFR Part 60 [6] and 40 CFR Part 191 [7]; site-specific regulations for Yucca Mountain at 10 CFR Part 63 [8] and 40 CFR Part 197 [9], and possibly also by internationally recognized standards, such as published by the IAEA [10, 11]. Specific regulatory topics requiring clarification for borehole disposal include retrievability and human intrusion.

The assessment basis elements include information supporting siting, pre-closure safety (design and operational procedures), and post-closure safety (waste and engineered barriers, geosphere and natural barriers, and biosphere and surface environment). The assessment basis describes the quantitative information necessary for site selection and to perform the safety assessments.

Safety assessments provide quantitative indicators of potential safety consequences (e.g., radiological) associated with a range of possible evolutions of a repository or borehole disposal system over time (i.e., for a range of scenarios) both before and after closure [4]. Due to uncertainties in predicting future events, reasonable assurance needs to be provided that the disposal system will perform as it is designed and that compliance with safety criteria will be achieved. The results of the safety assessments provide the necessary technical input to support decision making and form a central part of the safety case [2]. The quantitative evaluation of safety before and during borehole disposal operations is referred to as a pre-closure safety analysis, while the quantitative evaluation of safety after borehole sealing and closure is referred to as a post-closure performance assessment. In addition to these quantitative evaluations, available qualitative information is used to provide further assurance for the safety case in the form of confidence enhancement. These three types of safety assessments are performed and updated iteratively throughout the phases of a repository or borehole disposal project.

Multiple site-specific concepts for shallow borehole disposal have been evaluated [12, 13]. However, no specific sites for borehole disposal of SNF, HLW, and/or ILW have yet been proposed. As a result, the assessment bases and safety assessments for borehole disposal of SNF, HLW, and/or ILW to date have been generic [4, 5]. For the most part, these generic safety assessments have focused on post-closure safety, leveraging information used for post-closure performance assessments for mined repository projects. Because performance assessment modeling of post-closure is reasonably mature [1], generic representations of source terms and near- and far-field radionuclide transport in a borehole disposal system can, and have, leveraged methods and generic data from mined repository post-closure performance assessments. Preliminary generic performance assessments have affirmed that robust post-closure waste isolation can be attained in deep borehole disposal in basement rock that is hydrologically isolated from overlying circulating groundwater systems [4, 5].

Pre-closure operational aspects (e.g., surface handling and downhole emplacement of waste containers) have not been studied in as much detail as post-closure safety; confidence in the viability of the borehole disposal concept would benefit from additional R&D focused on pre-closure operations and safety.

PRE-CLOSURE OPERATIONS AND SAFETY

The operational period for a waste disposal facility begins when waste is first received at the facility and continues up to the final closure of all parts of the facility [3]. This period is subject to pre-closure safety analyses for radiation protection and occupational safety. For a borehole disposal facility, activities during this period include [4]: surface operations (waste receipt and handling); subsurface operations (waste emplacement); and closure (emplacement of seals).

The assessment basis for pre-closure operations, shown in Fig. 2, provides information describing the design features (waste, engineered barriers and their interaction with the natural barriers), construction, operations, and facility closure [4, 14]. The pre-closure safety analysis (PCSA) provides a quantitative evaluation of the potential natural and operational hazards for the pre-closure operational period based on a description of the surface and subsurface facilities and their operation (i.e., the assessment basis), and a comparison with safety standards. Implementation of a pre-closure operations safety analysis methodology (Fig. 2) includes (i) identifying initiating events and event probabilities, (ii) identifying and categorizing event sequences, (iii) performing radiological dose and consequence analyses, (iv) performing criticality analyses, (v) identifying the structures, systems, and components (SSCs) and procedural safety controls intended to prevent or reduce the probability of an event sequence or mitigate the consequences of an event sequence, should it occur, (vi) uncertainty analyses, and (vii) verification and validation [4, 15].

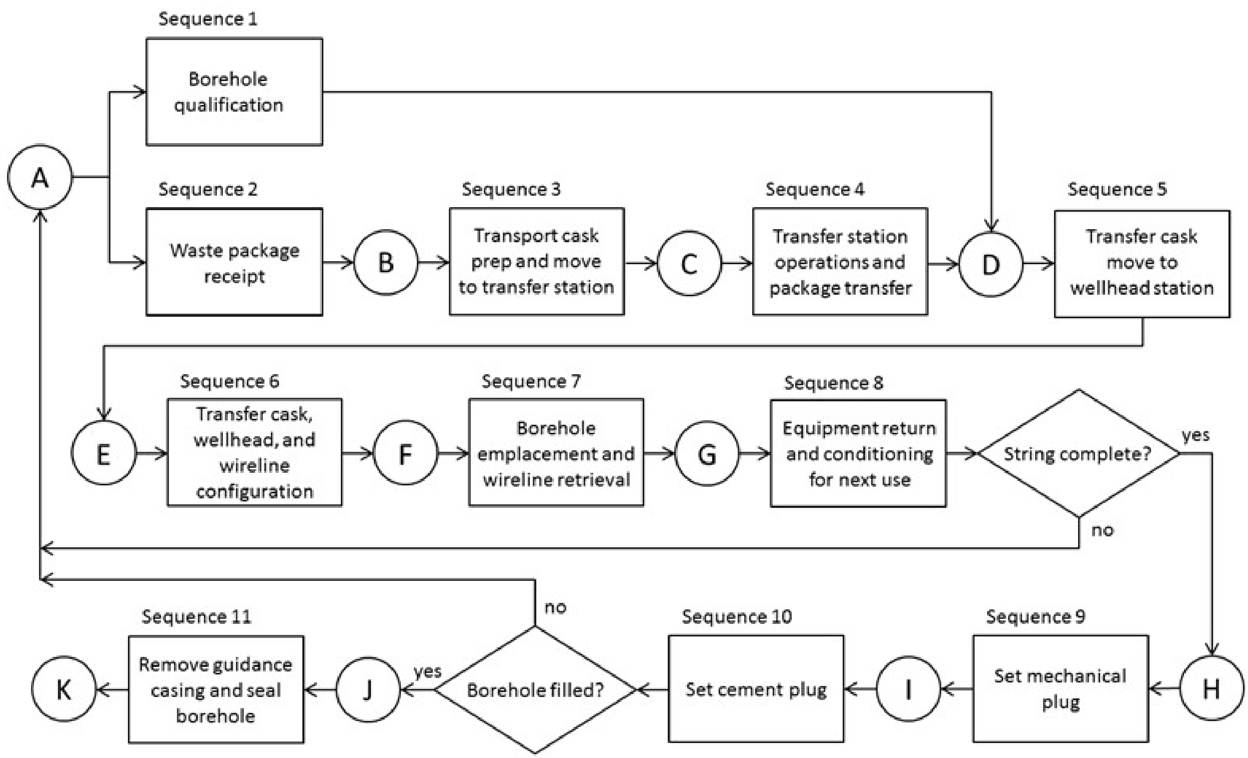
A probabilistic risk assessment (PRA) methodology was developed for a pre-closure radiological safety assessment for deep borehole disposal [16]. The PRA-based pre-closure methodology for borehole disposal is consistent with the approach required by 10 CFR Part 63, and generally consistent with the PCSA for a Yucca Mountain repository [17, 18]. The approach is also consistent with the requirements at 10 CFR Part 60. Implementation of the PRA-based pre-closure safety assessment model uses fault trees, event trees, and probability estimates to calculate results, and the sensitivity of results to key input probability values [19].

The operations for receiving, handling, and emplacing waste packages, and completing a disposal borehole, are described in detail in [19]. To support a PCSA the operations from waste package receipt to borehole closure are diagrammed as a series of activity sequences and nodes, as shown in the process flow diagram in Fig. 3.

The PCSA thus consists of a set of event trees, one for each activity sequence, with each event tree consisting of a number of top events and end states, with failure probabilities for each end state assigned through fault tree analysis [5, 19]. Calculation of the overall probability of successfully completing a borehole disposal campaign is based on the aggregation of the probabilities from each of the activity sequences and possible end states.

Key activity sequences in Fig. 3 include operations associated with surface handling of the waste (Sequences 3 through 5) and downhole emplacement of the waste (Sequences 6 and 7). A preliminary event tree for Sequence 7 (borehole emplacement and wireline retrieval) has been developed [5, 19], but since a full-scale disposal borehole for SNF, HLW, and/or ILW has not yet been implemented, much of the information supporting the fault tree analysis (e.g., failure probabilities) is based on data from other operations where relevant (or quasi-relevant) information was available.

To enhance confidence and advance the viability of the borehole disposal concept, a field-scale demonstration of waste container surface handling and downhole emplacement would significantly increase the available assessment basis information (both qualitative and quantitative) to inform the safety and feasibility of pre-closure operations.



(Source: [19])

Fig. 3. Simplified Process Flow Diagram for Borehole Disposal Operations.

PRIOR PRE-CLOSURE OPERATIONS AND EMPLACEMENT DEMONSTRATIONS

Although waste container surface handling and downhole emplacement methods associated with borehole disposal of SNF, HLW, and/or ILW have not been fully demonstrated, a few field-scale projects with design elements and procedures relevant to borehole disposal have been performed and are summarized below.

Demonstration of Spent Fuel Handling and Borehole Emplacement at Climax Mine (USA)

The Spent Fuel Test - Climax [20, 21], performed on the Nevada Nuclear Security Site (formerly the Nevada Test Site) at the abandoned Climax Mine from 1980 to 1983, demonstrated handling of commercial pressurized-water reactor (PWR) spent fuel in a mined repository environment in crystalline rock. Eleven stainless steel canisters, each containing a single SNF assembly, were lowered by a heavy-duty wireline through a 20-inch (0.51 m) cased borehole into a shielded transfer vehicle in a gallery 1,400 ft (427 m) underground [9]. They were retrieved the same way after 3.5 years of underground storage. Each of the canisters had an outside-diameter (OD) of 14 inches (0.36 m) and length of approximately 15 ft. (4.6 m) [20, 21, 22].

To support the Spent Fuel Test – Climax, a purpose-built, double-ended transportation and transfer cask was developed and deployed [21]. The Climax transportation cask was mounted to a flatbed on pivoting load jacks so that it could be hydraulically upended for loading and for transfer of a canister into the borehole (Fig. 4). Test operations were conducted successfully, with minimal radiation exposure to workers [22].

(Source: [21])

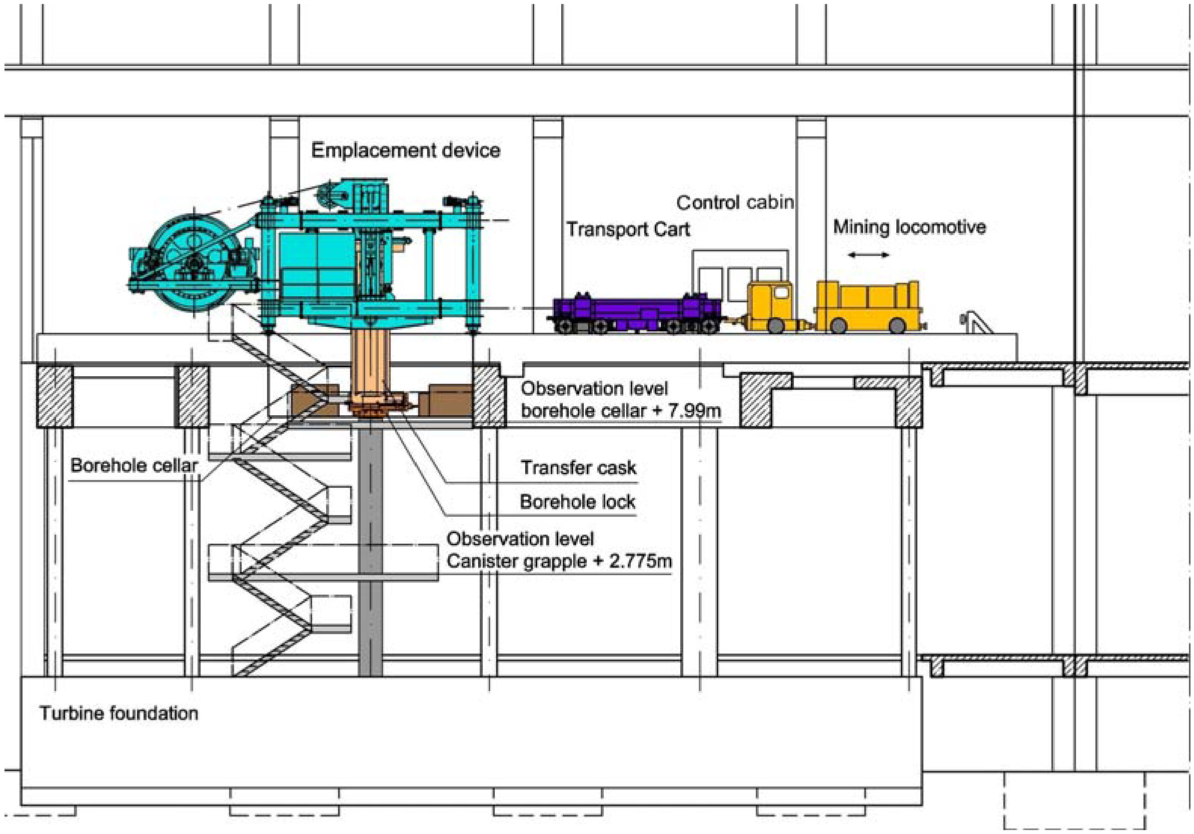
Fig. 4. Waste Package Being Lowered Through Transportation Cask into Climax Mine Borehole.

While the Climax test was not a borehole disposal test, several design elements and procedures relevant to borehole disposal were successfully developed and implemented, such as cask design, surface handling, and wireline emplacement and retrieval. These design elements and procedures are summarized in more detail in [22].

Demonstration of Dummy Spent Fuel Canister Emplacement in Boreholes (Germany)
A demonstration program, at an industrial scale, examining the technical feasibility of the transportation and emplacement of spent fuel canisters in vertical boreholes was planned and performed in Germany in 2008 and 2009 [23]. The German borehole disposal concept includes a transfer and emplacement system that can be used to dispose of heat-generating disposal packages in up to 300-m-deep boreholes emanating from underground drifts in a repository in salt. The concept would use BSK 3 canisters (in accordance with the acronym for the German word for fuel rod canister, i.e. Brennstabkokille) that are ~5 m in length, 0.43 m in diameter, and can be filled with the fuel rods of 3 PWR or 9 boiling-water reactor (BWR) fuel assemblies [23].

The full-scale demonstration tests of the emplacement system were carried out in a surface facility using inert canister dummies with the same dimensions and masses as real BSK 3 canisters. The test facility (Fig. 5), located in a former turbine hall of a power station in Landesbergen, a village near Hanover, Lower Saxony, included (i) a platform erected 10 m above the ground floor of the turbine hall for the emplacement machinery, transport cart and control cabin, and (ii) a 10-m-long vertical steel metal casing simulating the emplacement borehole below the platform [23].

The demonstration tests comprised all the process steps, starting with the acceptance of the BSK 3 canister and concluding with the emplacement of the canister into the simulated vertical borehole. In total, 1,004 complete emplacement operations were carried out by the end of the test program. The entire system and each component proved to be safe, reliable, and robust [23].



(Source: [23])

Fig. 5. Test Site and Emplacement Components for BSK 3 Borehole Emplacement Demonstration.

Deep Borehole Field Test

The U.S. Department of Energy (DOE) initiated R&D for a Deep Borehole Field Test (DBFT) in 2014. The overall goal of the DBFT was to demonstrate and evaluate technologies necessary for determining the safety and feasibility of the deep borehole disposal concept, but without the use or disposal of actual radioactive waste. The overall goal of the DBFT was supported by the following objectives [5]:

- Demonstration of drilling technology and borehole construction to 5,000 m depth in crystalline basement rock with sufficient diameter for cost-effective waste disposal;
- Evaluation of downhole scientific analyses to characterize the thermal-hydrologic-chemical-mechanical (THCM) conditions at a representative location that control waste stability and containment;
- Evaluation of package and seal materials at representative temperature, pressure, salinity, and geochemical conditions;
- Development and testing of engineering methods for test package loading, shielded surface operations, and test package emplacement and retrieval;
- Development and testing of sealing designs and seal emplacement methods; and
- Demonstration of pre-closure and post-closure safety.

The plan for the DBFT included siting and drilling two 5,000 m deep boreholes into crystalline basement rock in a geologically stable continental location [5]:

- An initial Characterization Borehole (CB), with approximately an 8.5-in (0.22 m) bottom-hole diameter, to facilitate examination of downhole scientific testing methods. The objective was to identify (a) the critical downhole measurements needed to determine if conditions favorable to long-term isolation of high-activity waste exist at depth and (b) which testing methods were feasible under conditions encountered in a deep borehole.
- A subsequent Field Test Borehole (FTB), with approximately a 17-in (0.43 m) bottom-hole diameter, to facilitate proof-of-concept of engineering activities using surrogate test packages. The objective was to evaluate the feasibility of package emplacement operations by determining performance envelopes for drilling, package handling, and package emplacement and retrieval. In addition, laboratory testing of borehole sealing materials and designs was planned.

Two Requests for Proposal (RFPs) were initiated by DOE to identify potential sites for the DBFT. In response to the first RFP [24], a contract was awarded in January 2016, which included a proposed test site in Pierce County, North Dakota. After efforts to acquire both the initial test site in North Dakota and an alternative proposed site in Spink County, South Dakota were unsuccessful, activities were suspended [25].

The experiences in Pierce County, North Dakota and Spink County, South Dakota highlighted the importance of public engagement and support for the DBFT, and that relevant levels of government and other public stakeholders should be involved from the beginning [25]. Using these lessons learned, DOE issued a new RFP [26] which emphasized local, state, and tribal (if applicable) government engagement, as well as public and other stakeholder involvement ahead of proposal submittals and throughout the contract execution phases. The new RFP also allowed for multiple initial awards and multiple phases of contract execution, during which down-selects could be made based on contractor team performance and success with local community acceptance, and to ultimately have one contractor team actually execute the DBFT and drill a Characterization Borehole. In response to the second RFP, four contract awards were announced in December 2016: a proposed site in Pecos County, Texas; a proposed site in Quay County, New Mexico; a proposed site in Haakon County, South Dakota; and a proposed site in Otero County, New Mexico [25].

In May 2017, it was announced that "Due to changes in budget priorities, the Department of Energy does not intend to continue supporting the Deep Borehole Field Test (DBFT) project and has initiated a process to effectively end the project immediately" [27].

Although the project was ended prematurely, and the DOE does not currently fund deep borehole disposal work, significant R&D relevant to pre-closure and post-closure safety assessments was completed and documented, including plans and needs for a Field Test Borehole demonstration [4, 5, 19, 22, 28].

PROPOSED NEAR-SURFACE DEMONSTRATION TEST OF PRE-CLOSURE OPERATIONS AND EMPLACEMENT

As noted previously, pre-closure operations have not been studied in as much detail as post-closure performance; to enhance confidence in the viability of the borehole disposal concept for SNF, HLW, and/or ILW a field-scale demonstration focused on waste container surface handling and downhole emplacement would significantly increase the available assessment basis information (both qualitative and quantitative) to inform the safety and feasibility of pre-closure operations.

Information from the DBFT planning and from the Spent Fuel Test – Climax and German BSK 3 demonstrations provides a basis for identifying specific integrated surface handling and downhole emplacement technology and protocols that are important to demonstrating pre-closure operations safety and feasibility at a field scale. Specific field-scale demonstration needs include:

- surface handling of full-scale surrogate waste containers (i.e., containing no radioactive materials)
- repeated emplacement of surrogate waste containers into a full-diameter borehole, and
- repeated removal of surrogate waste containers from the borehole (to partially address concerns about retrieval of a “stuck” waste container).

In addition to using full-scale waste containers and a full-diameter borehole, radiation-shielded equipment and remote handling methods would be employed. In other words, the non-radioactive surrogate waste containers would be handled as if they had the radiation and thermal signatures of actual radioactive waste.

The demonstration borehole would need to have a diameter large enough to accommodate and test emplacement of a full-scale waste container. However, a full-diameter borehole extending to less than full depth would be sufficient to assess surface handling and emplacement protocols at the field scale. It is expected that a test depth of tens to hundreds of meters would suffice. The near-surface demonstration test could be performed at any number of sites (it is not necessary to have a site with favorable long-term isolation characteristics); it could even be performed in laboratory-type conditions in an artificial “borehole” (e.g., representative-sized casing).

Specific details of the near-surface demonstration test would be waste and concept specific. Waste container geometry and materials, shielded surface handing equipment and configuration, and emplacement methods (e.g., drill string, wireline, or coiled tubing) would all need to be specified but can be informed by prior DBFT research [22, 28] and demonstration tests [20, 21, 23].

In addition to the primary objectives of the near-surface demonstration test described above, the demonstration borehole could also be used to test (i) borehole sealing methods and materials, (ii) downhole sensing technologies associated with emplacement monitoring, and (iii) waste tracking devices for materials safeguards. Successful implementation of a near-surface demonstration test would prepare the concept to be tested further, if needed, at full depth and in an integrated fashion with downhole characterization tools.

SUMMARY AND CONCLUSIONS

This paper describes field test activities that would enhance confidence in the surface handling and downhole emplacement operations for borehole disposal. Specifically, a demonstration of surface handling and emplacement demonstration using full-scale surrogate waste canisters (i.e., containing no radioactive materials) in a full-diameter shallow borehole would be sufficient to assess surface protocols at the field scale. This type of near-surface demonstration test would advance the technology and contribute to the demonstration of safety and viability of the borehole disposal concept.

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