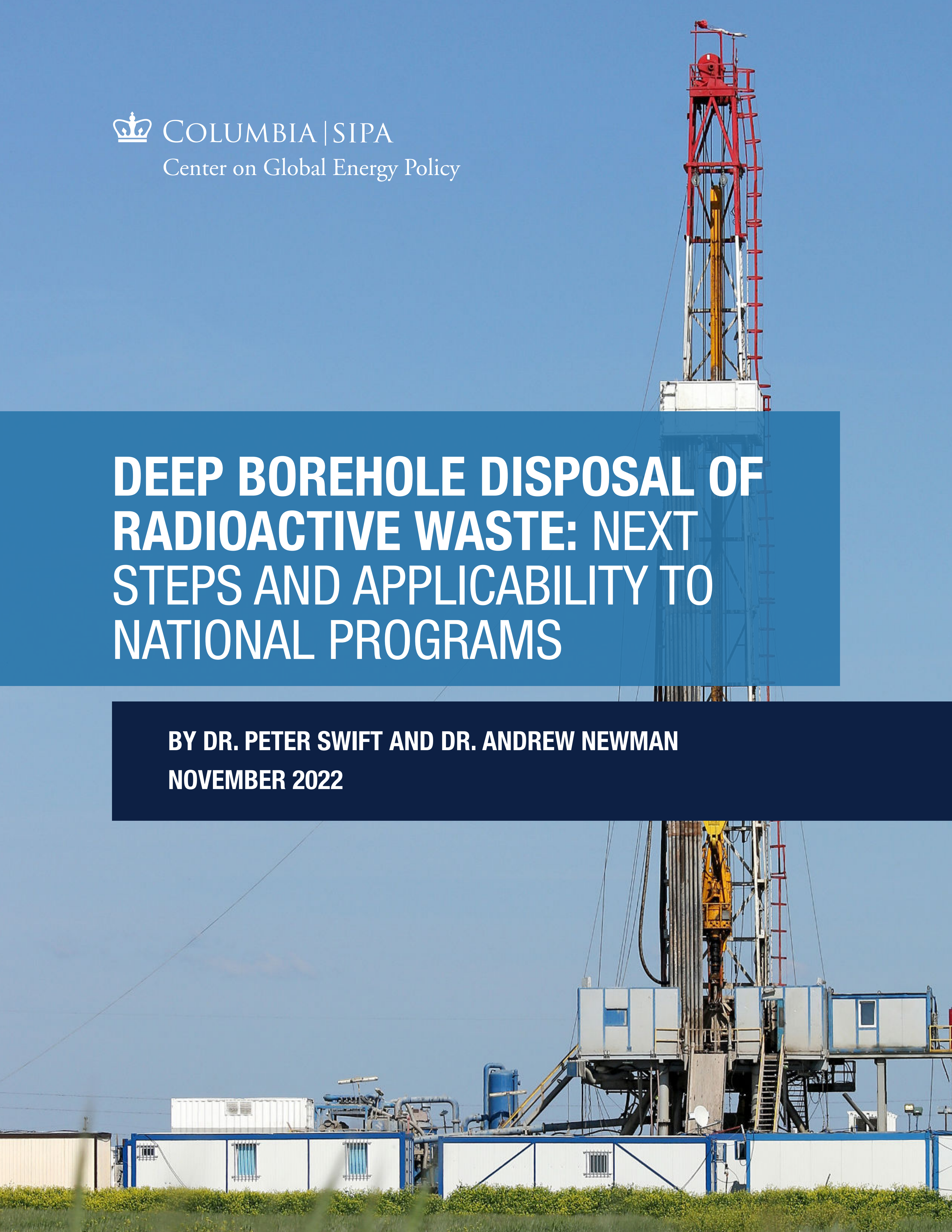

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DEEP BOREHOLE DISPOSAL OF RADIOACTIVE WASTE: NEXT STEPS AND APPLICABILITY TO NATIONAL PROGRAMS

BY DR. PETER SWIFT AND DR. ANDREW NEWMAN

NOVEMBER 2022

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EXECUTIVE SUMMARY

Deep borehole disposal of high-level radioactive waste has been proposed repeatedly and in multiple countries over the last several decades, but the concept remains unproven in the field. A straightforward research, development, and demonstration test program could provide answers to basic questions about the viability of the concept. This program would involve the construction of two or perhaps more boreholes to test disposal concepts using surrogate, nonradioactive waste. Field tests would focus on the engineering and operational feasibility of deep borehole disposal, the availability of favorable rock types at depth, appropriate designs for waste forms and waste packaging, and the long-term performance of borehole repositories. Because of the scale of the project, it might best be undertaken as an international collaboration, perhaps led by the US Department of Energy but with participation from multiple national programs to ensure it meets a wide range of needs.

Mined geologic repositories, which have been the preferred approach for permanent disposal of high-level radioactive wastes for most national programs for many decades, will likely remain the preferred disposal option for countries with large inventories of commercial spent nuclear fuel. If deep borehole disposal can be demonstrated as a viable concept, however, it may be an attractive alternative disposal option for countries with small inventories of materials requiring permanent geologic isolation. For example, national programs with limited amounts of waste from research or medical isotope production reactors may not need to incur the cost of a full-scale mined repository. Other countries may find borehole disposal a useful option for permanently disposing of small quantities of waste that could otherwise pose security risks, including both fissile materials and high-activity sealed radioactive sources used in industrial and medical applications. For programs committed to disposing of large inventories of spent nuclear fuel and high-level waste in mined repositories, deep boreholes may provide options for prompt disposal of small volumes of specialty wastes that may otherwise have to wait for repository construction.

This report reviews the borehole disposal concepts proposed to date, identifies potentially suitable waste forms worldwide, and proposes a field-testing program that could resolve many remaining technical questions and inform future programmatic decisions. The report also summarizes the potential benefits of borehole disposal in terms of public acceptance, cost, and security. The main takeaways from this report are the following:

- For countries such as the US with large inventories of spent nuclear fuel and vitrified high-level radioactive waste, mined repositories remain the best disposal option.
- If technical feasibility and safety are demonstrated, boreholes could provide a complementary disposal pathway for small, highly radioactive waste forms in the US and other countries when mined repositories are not available.
- If technical feasibility and safety are demonstrated, boreholes could also provide a cost-effective and safe alternative to mined repositories for countries with nascent or

small nuclear power programs, particularly those with limited financial, institutional, technical, and/or geographic resources.

- If boreholes prove viable technically, economically, and sociopolitically in countries where they may be preferable to mined repositories, getting spent fuel into the ground more quickly provides significant security and nonproliferation benefits, particularly in politically unstable regions of the world.
- The authors propose a multinational two-phase borehole field test program, performed sequentially or in parallel, with nonradioactive surrogate waste materials to address unresolved technical questions related to engineering feasibility and host rock performance.
- Such a collaborative research, development, and demonstration project could help decision makers in participating (and observing) countries determine whether borehole disposal is an appropriate disposal method for a portion or all of their high-activity radioactive waste inventory.

INTRODUCTION

Beginning with work in the US in the 1950s (NAS 1957), most national nuclear programs have viewed mined repositories as the preferred approach for permanently disposing of high-level radioactive waste. Such repositories have been studied intensively, with sites identified and characterized in multiple countries and extensive underground research conducted over decades. For countries that have large inventories of spent nuclear fuel from nuclear power reactors or large amounts of high-level waste from defense programs or commercial reprocessing, mined repositories very likely remain the best option, despite the slow progress in licensing and constructing such facilities.

One alternative to such repositories that is worthy of further consideration is deep boreholes. Unlike mined repositories, deep borehole disposal concepts remain untested in the field despite having been proposed since at least the early 1970s (Schneider and Platt 1974; USDOE 1980; Juhlin and Sandstedt 1989; MIT 2003; Gibb and McTaggart 2008; Brady et al. 2009; US DOE 2015; Muller et al. 2019) and the possibility of implementation still seems remote. If field tests can demonstrate their viability, however, they can represent an attractive alternative to mined repositories for countries with relatively small amounts of radioactive waste requiring deep geologic disposal. Specifically, borehole disposal could avoid some of the high up-front costs and decade-scale lead times required for mined repositories and could prove particularly useful in reducing security and nonproliferation risks associated with small volumes of enriched or high-activity nuclear material in countries without nuclear defense programs.

A note on the US context

The authors do not propose that the United States should consider disposing of commercial spent fuel or packaged, high-level defense waste in boreholes. In 2009, Sandia National Laboratories (SNL) estimated that it would require over 950 boreholes, each spaced 200 meters apart to avoid thermally affecting one another, to dispose of a then-projected inventory of 109,300 metric tons of heavy metal comprised of spent nuclear fuel and high-level waste (Brady et al. 2009). (This inventory estimate was based on projections used by the US DOE in 2008 [US DOE 2008]; more recent projections suggest that the country's inventory is significantly larger [Peters et al. 2020]). If deployed at a single site, a disposal system of this magnitude could require up to 40 square kilometers (approximately 16 square miles), a footprint significantly larger than that of mined repositories. In addition, spent fuel already in dry storage in the US would need to be removed from canisters and repackaged in smaller dedicated borehole disposal packages (Brady et al. 2009), a step that may potentially be avoided for some mined repository concepts. Boreholes could, however, perhaps provide a complementary disposal pathway for small, specialized waste forms in the US (US DOE 2014). With extensive experience in waste disposal research as well as oil and gas drilling,

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the US could provide critical leadership and state-of-the-art technology to an international research program designed to address both a small but highly radioactive portion of the DOE waste inventory with no current disposition pathway as well as the spent fuel and high-level waste disposal needs of other countries with small volume or similarly problematic waste streams, strengthening the DOE's global nuclear safety and security mission.

This report has two objectives. The first of these is to review the current status of deep borehole disposal concepts and identify research gaps that could be addressed through a well-defined set of field tests. Because such field tests would require a substantial commitment of resources, they might be best performed through international collaboration, perhaps led by the US Department of Energy (DOE). The second objective is to explore the potential sociopolitical, economic, security, and nonproliferation benefits that might lead some countries with relatively small existing and projected inventories of spent fuel, high-level waste, and possibly long-lived intermediate-level radioactive waste to choose boreholes as a cost-effective and safe alternative to mined repositories for their disposal needs. These potential benefits should be considered by decision makers, including those within the US DOE and other national programs, when evaluating the prospect of a multi-year field-testing program.

The authors note that decision makers must also address public opposition to many aspects of nuclear waste management, including, in the US at least, site-specific opposition in the past to deep borehole disposal testing (US DOE 2015). Social and political considerations of nuclear waste disposal are outside the scope of this paper, but public acceptance should be acknowledged as a major, and perhaps the most important, factor in moving forward with any permanent disposal options. Borehole disposal concepts are not unique in this regard and there may be ways for any future program to avoid mistakes of the past while helping to build public confidence in the intent of and technical basis for evaluating options. As discussed below, two of these could be decoupling the two phases of the program and selecting a test drill site known a priori to be unsuitable for disposal.

RESEARCH GAPS FACING DEEP BOREHOLE DISPOSAL

Existing analyses of hypothetical design concepts strongly suggest that if suitable rock can be found and if a borehole can be constructed, operated, and sealed as proposed, borehole disposal may provide excellent long-term isolation of radioactive waste (Brady et al. 2017; Freeze et al. 2019; Deep Isolation 2020). Proposed technologies remain unproven, but most remaining questions could be addressed through a straightforward research, development, and demonstration (RD&D) project. Broadly, these questions fall into two categories: engineering feasibility and the contribution of host rock performance to long-term safety.

- First, is borehole disposal feasible from an engineering and operations perspective? Specifically, can boreholes of an appropriate depth and diameter be constructed using readily available technologies? Can radioactive waste be emplaced in a borehole repository remotely, with sufficient shielding to ensure safe operations? Can boreholes be sealed to ensure permanent isolation? Can all of these operations be done with the extremely high level of reliability and safety required for nuclear activities? Can disposal be reversed during operations, allowing recovery of waste in the event of problems during emplacement?

A note on what deep borehole disposal in this context is not

Borehole disposal concepts discussed here differ in substantive ways from two other types of past and ongoing borehole disposal operations. Specifically, this paper does not address borehole disposal of liquid radioactive wastes, which has been implemented in the past for both low-level and high-level wastes (e.g., Stow and Hasse 1986; Kedrovskii et al. 1990). Concepts discussed here are limited to the disposal of solid wastes, and are intended to avoid concerns associated with the mobility of liquid wastes in groundwater. In addition, concepts discussed here do not include disposal of solid low-level and shorter-lived intermediate-level radioactive wastes in relatively shallower boreholes at depths of tens to hundreds of meters. Safe disposal of lower-level and shorter-lived wastes in intermediate-depth boreholes has been demonstrated in multiple locations worldwide (Cochran et al. 2001; IAEA 2011), and the remaining research gaps for intermediate-depth borehole disposal are unlike those facing deep borehole disposal of higher-level wastes.

- Second, can suitable host rocks be found at appropriate depths that will provide high confidence in the long-term performance of disposal systems? Disposal concepts can be designed specifically for available rock types and a variety of waste forms and there may be more than one rock type that provides robust isolation for a given borehole repository design. For some disposal concepts, isolation might rely on siting the facility in extremely low-permeability rock at depths of multiple kilometers, assuming such rocks can be found. In these concepts, the slow rate of radionuclide diffusion through the host rock and the borehole seals might provide robust isolation with little reliance on the longevity of the waste package and the waste form. In other concepts, long-lived waste packages or durable waste forms might provide a primary part of the isolation system, allowing for disposal at shallower depths or in more permeable rock types. Regardless of the specific details of the disposal concept, suitable rock types need to be identified and tested.

Definitive answers to these questions would allow decision makers to proceed based on the best available information regarding the technical feasibility and long-term safety of borehole disposal. If an RD&D project were designed to encourage international collaboration, national programs would have the opportunity to engage in first-of-a-kind field-based research to test disposal concepts specifically relevant to their waste forms and potential host rocks.

SUMMARY OF DEEP BOREHOLE DISPOSAL CONCEPTS TO DATE

The deep borehole disposal concepts that have been proposed to date all call for emplacing waste in relatively narrow-diameter cylindrical volumes up to thousands of meters long. They also all rely on some combination of natural (i.e., geologic) and engineered barriers to provide long-term isolation of the waste. In general, the primary natural barrier for borehole disposal is the thickness of low-permeability rocks between the waste and the land surface, determined both by depth and rock characteristics. In many concepts, favorable water chemistry at depth is also important because it provides (1) reducing conditions that lower the solubility of most radionuclides and (2) high salinities that both lower the potential for colloidal transport and create a density gradient that helps counter the potential for thermally driven buoyant convection in the borehole or surrounding rock. All borehole disposal concepts rely on the ability to demonstrate the absence of fast flow paths from the disposal zone to the surface. As noted above and by others (e.g., Krall et al. 2020), favorable rock properties and water chemistry at depth cannot be assumed and must be demonstrated independently for each site. Engineered barriers can include durable waste forms (e.g., vitrified, grouted, or hot isostatically pressed wastes), long-lived waste packages, and grouts or buffers to help control permeability and long-term water chemistry in the borehole. Low-permeability permanent seals are an important component of all deep borehole disposal concepts. Although details of local vadose-zone hydrology are essential to shallower disposal concepts in unsaturated rocks and sediments, they are less important for deep disposal far below the water table.

Factors that *discriminate* among proposed deep borehole disposal concepts include the following:

Depth, emplacement geometry, host rock, and reliance on engineered barriers: Over the last roughly two decades, deep borehole disposal has been proposed at depths that range from approximately one km (Muller et al. 2019) to five km (Brady et al. 2009). Emplacement has been proposed in vertical holes, most commonly in crystalline basement rocks at depths of three to five km (Freeze et al. 2019), in inclined holes drilled at depth from a vertical access hole (Gibbs et al. 2011), and in subhorizontal holes drilled in shale and other rock types at depths of one km and greater from a vertical access hole (Crichlow 1998; Muller et al. 2019). The diameter of the proposed boreholes is typically limited by available technology and cost considerations, but in all cases boreholes must be large enough at the disposal horizon to accommodate the proposed waste forms and waste packaging as well as the steel casing that lines the holes. As noted above, one proposed design concept calls for downhole diameters of 445 mm, consistent with current drilling practices and large enough to accommodate waste packages of up to approximately 273 mm in diameter (Arnold et al. 2011). Larger- diameter boreholes may be possible at these depths but have not been demonstrated in current drilling practice (Beswick et al. 2014). Proposed disposal concepts include relatively different levels of reliance on waste form and waste package durability and analyses of vertical emplacement in crystalline basement have shown robust long-term isolation assuming no contribution from waste form or waste package performance. In general, shallower disposal concepts (Muller et al. 2019) are likely to require greater reliance on waste form and package performance.

In the absence of detailed information from engineering demonstration and site-specific characterization data, there is no need to define a priori a preferred depth and design concept for deep borehole disposal. Any disposal concept will need to be evaluated in detail for both operational feasibility and long-term performance before decisions can be made regarding implementation.

Characteristics of the waste selected for disposal: The first characteristic to be considered in identifying waste for a specific borehole disposal concept is its size. Is the waste already in a form that is small enough in geometry to be emplaced in a borehole drilled to the proposed depth using readily available technology? If not, can it be packaged with appropriate dimensions following minimal treatment? Other attributes of the waste must be known in sufficient detail to support safety analyses for a specific design, including radionuclide inventory and bulk chemistry, physical and chemical stability during operational handling, and the long-term performance of the waste form in the disposal environment. For most purposes, though, waste form geometry is likely to be the limiting factor in disposal concept design.

Operational emplacement strategies: Downhole emplacement of the waste packages in a cased borehole has been proposed with multiple approaches using off-the-shelf drilling industry technology. Emplacement in vertical holes can be accomplished with assemblages of multiple waste packages linked together at the end of a continuous column of drilling pipe (drill-string emplacement), or by lowering packages one at a time on a cable (wireline emplacement) (SNL 2016; Hardin et al. 2019). In principle, it could also be done by free fall, with velocity limited by the viscosity of the fluid filling the drill pipe (Bates et al. 2011), but the lack of control over the package during descent makes this a less desirable approach (Beswick et al. 2014). Emplacement in horizontal or subhorizontal boreholes has been proposed by pushing with drill pipe or coiled tubing (Hardin et al. 2019), or, as demonstrated at a reduced scale with existing downhole tools, a wireline tractor (Muller et al. 2019). The operational feasibility and safety of remote handling emplacement of radioactive materials remains to be demonstrated for all emplacement techniques.

Sealing strategies: Most proposed sealing concepts rely on removing casing from the upper portion of the borehole and emplacing thick sequences of packed bentonite clay supported and isolated by concrete plugs (Arnold et al. 2011; Bates et al. 2014). Vertical emplacement concepts also call for concrete "bridge plugs" between zones of multiple waste packages to reduce vertical loads on the lower packages and prevent crushing during the operational period. Achievement of exceptionally low-permeability permanent seals has been proposed by introducing sufficient heat into the borehole to melt the seal material and surrounding host rock (Gibb and Travis 2015). Available system-level analyses suggest, however, that robust isolation can be achieved without rock melting (Freeze et al. 2019; Deep Isolation 2020).

CANDIDATE WASTES FOR DEEP BOREHOLE DISPOSAL

Worldwide, multiple types of radioactive wastes may be candidates for deep borehole disposal, including the following:

- *Spent nuclear fuel from existing light water reactors (LWR) used for electric power generation.* This waste form represents the largest single component by volume and radioactivity of the world's high-activity radioactive waste requiring deep geologic disposal; much of it, however, may not be a good candidate for borehole disposal because of geometric considerations. Typical pressurized water reactor (PWR) assemblies, which account for nearly three-quarters of the world's spent fuel inventory, have diagonal cross-sections of 300 mm or more. With packaging and casing, direct disposal of intact PWR assemblies would require borehole diameters beyond what is typically available with current drilling practices at proposed disposal depths for spent fuel. Russian-designed water-water energetic reactor (VVER) assemblies are comparable in size to other PWR assemblies, so similar constraints for borehole disposal apply. Typical boiling water reactor (BWR) assemblies are smaller and with packaging and casing could fit into a 445-mm-diameter borehole, with disposal limited to a single assembly per waste package. In principle, LWR fuel rods could be removed from their assemblies and consolidated into smaller-diameter packages to support borehole disposal, but this would require additional facilities for waste-handling operations.

- *Spent fuel from Canada Deuterium Uranium (CANDU) reactors.* Given the small size of individual CANDU fuel bundles, with typical diameters between 82 and 102 mm, this waste form is a good candidate for borehole disposal, particularly for programs that have a relatively small inventory of spent fuel.

- *Vitrified high-level radioactive waste (HLW) from reprocessing spent nuclear fuel.* Most existing vitrified waste worldwide is in cylinders of 430 mm or more in diameter (e.g., US vitrified HLW at the Savannah River and West Valley sites is in canisters that are 610 mm in diameter [Peters et al. 2020] and vitrified HLW from La Hague in France is in 430 mm diameter canisters [ANDRA 2005]), which exceeds interior casing diameters for boreholes currently drilled to depths of three or more kilometers. The robust properties of vitrified waste could potentially support disposal at shallower depths where construction of larger-diameter boreholes is routine. Analysis and testing are needed to evaluate the feasibility of borehole disposal of vitrified wastes.

- *High-activity sealed radioactive sources.* Disused sealed radioactive sources are already being disposed of in intermediate-depth boreholes worldwide and remain an excellent candidate for borehole disposal (IAEA 2011). For programs with a small total inventory of high-activity radioactive waste requiring deep geologic disposal, it could make sense to include disused sealed radioactive sources in the inventory for deep borehole disposal.

- *Spent fuel from research or isotope production reactors.* Depending on reactor-specific geometry, spent fuel from civilian nonpower reactors is a good candidate for deep borehole disposal.
- *Spent fuel from advanced reactors.* For the purposes of this discussion, advanced reactors include both small modular reactors based on LWR designs and new designs (i.e., "Gen IV" reactors) based on a range of proposed technologies. Given that nearly all proposed advanced reactor concepts have already existed as prototype experimental reactors, the characteristics of this waste form are broadly understood. The most important consideration for disposing of it in a deep borehole is likely its geometric properties (i.e., spent fuel dimensions). Fuel forms that pose significant operational handling risks, such as those incorporating spontaneously reactive metallic sodium, are unlikely to be good candidates for borehole disposal without treatment (SNL 2014).
- *Defense-related wastes other than vitrified HLW.* Countries with active nuclear defense programs may have wastes that are suitable for deep borehole disposal and there may be circumstances in which borehole disposal could be preferred to commingling defense materials with civilian wastes or waiting for a civilian repository to become available.

DESIGNING A BOREHOLE RD&D PROJECT WITH BROAD INTERNATIONAL RELEVANCE

An RD&D project could efficiently address research gaps associated with deep borehole disposal with a two-phase field-testing program done entirely with nonradioactive surrogate waste materials. The test program described here is similar to one proposed by the US DOE in 2015 but never completed (US DOE 2015; SNL 2016; NWTRB 2016; Kuhlman et al. 2019), except in two important respects. First, the new program explicitly decouples the two phases of the test in both time and location, with the first phase focused on engineering feasibility and the second focused on identifying and characterizing suitable host rocks (reversing the order proposed by the US DOE). The two phases are described here as if they were to be performed sequentially, but there is no compelling reason why they could not be performed in parallel. They do not need to be done in the same location and, in fact, decoupling them geographically may have the advantage of allowing for the characterization of multiple rock types. Importantly from the perspective of international collaboration, testing could be done in multiple countries, with individual national programs taking the lead in hosting portions of the program. For example, a test of engineering feasibility could be designed and implemented in a country with a significant oil and gas drilling industry, while rock characterization tests could be done in another country with specific interests in potential host media. The decoupling of the two phases also has the potential to help alleviate, at least for the first phase, the loss of trust in some potential host communities that resulted in major setbacks for the US DOE program before its termination.

Second, and as indicated already, the project described here would specifically be designed to encourage international collaboration, increasing its value for programs outside the US, while retaining benefits for the US nuclear waste disposal program. Indeed, a comparable collaborative endeavor for the disposal of long-lived intermediate-level waste already exists at the technical level, without participation from the US DOE. An Australian Commonwealth Scientific and Industrial Research Organization (CSIRO), Australian Nuclear Science and Technology Organization (ANSTO), and Sandia National Laboratories international partnership, supported by regional experts from the Pacific Rim Spent Fuel Management Partnership, is working toward the execution of a full-scale borehole RD&D project in Australia (Mallants et al. 2021).

Phase 1: The Engineering Feasibility Demonstration Test

Phase 1 of the borehole RD&D project would focus on constructing a single large-diameter (nominally 445 mm at depth) test hole for demonstrating technologies for borehole completion, remote emplacement and retrieval of surrogate (i.e., nonradioactive) waste packages, and permanent borehole sealing. Testing engineering feasibility should be a relatively straightforward extension of technologies that already exist in the drilling and nuclear industries, but it should not be viewed as trivial, in part because emplacement operations must meet nuclear industry expectations and regulatory requirements for reliability and safety.

A vertical test hole is recommended to enable evaluation of the most straightforward and widely applicable design concepts. To reduce costs, the test hole does not need to be drilled to the full depth proposed for all disposal concepts; it must, however, be deep enough to allow high confidence that the same technologies could be used at greater depths. The test hole does not need to be drilled in a site that might ultimately be used for disposal; in fact, as mentioned previously, selecting a site known a priori to be unsuitable for disposal for any reason can reassure host communities of the project's focus on research. The goal of this phase of the project is not to find suitable host rocks or a potential disposal site. Rather, it is to demonstrate that the technology could be deployed if and when a site is found. Individual components of Phase 1 should be designed by participating programs to ensure transferability of results to a broad range of waste-form-specific disposal concept designs. Research on suitable waste forms, including geometry and physical characteristics, could be done in parallel within participating programs to help inform the design of the field test.

Phase 2: The Host Rock Characterization Test

Phase 2 of the borehole RD&D project would focus on drilling one or more boreholes in potentially suitable host rocks at one or more locations. Currently available data from deep boreholes do not, in general, come from sites that are specifically chosen because of their potential to be favorable for disposal and sites with favorable conditions at depth remain to be identified (Krall et al. 2020). Rock characterization tests can be completed most effectively in small-diameter holes (e.g., 203 mm in diameter at full depth) that would be significantly less expensive to construct than the large-diameter hole needed for the engineering feasibility test. Multiple holes in different rock types at different locations (perhaps hosted by different national programs) would allow for evaluating a range of concepts proposed for various waste forms. Research to develop improved techniques for downhole rock and fluid characterization in low-permeability media could be carried out in parallel within participating programs to help inform the design of the field test. All characterization test holes should be drilled to the full depth proposed for the relevant disposal concept, and if suitable rock is found, these locations could become candidate sites to be considered for disposal operations. Because of the relatively small diameter of the characterization boreholes, however, they would be unsuitable for disposal of most waste forms. Should a participating program choose to proceed to disposal operations after reviewing results from both phases of the project, full-diameter holes would need to be constructed and rock suitability reevaluated.

The two-phase RD&D project described here could offer a wide range of benefits to international participants. The demonstration of engineering feasibility at a single location could be completed with participation from multiple international programs and insights from the demonstration would be readily transferable to a broad range of locations and borehole concepts. All participants could benefit equally.

With respect to the Phase 2 rock characterization tests, drilling of lower-cost narrow-diameter host rock characterization holes could be tailored to specific disposal concepts that can benefit all participants while furthering individual national goals. Insights would be most applicable to the specific locations and rock types that were tested, providing an incentive for participants to propose tests in their own candidate rock types. All participants would benefit, however, from the knowledge gained about any rock types evaluated.

APPLICABILITY OF BOREHOLE DISPOSAL

As noted previously, mined repositories remain the best disposal option for countries with large inventories of spent nuclear fuel from power reactors or large amounts of high-level waste from defense programs and/or commercial reprocessing. But borehole disposal could provide meaningful benefits to countries with nascent or small nuclear power programs, particularly those with limited financial, institutional, technical, and/or geographic resources. Borehole disposal also has the potential to make a significant contribution to regional and international security.

Sociopolitical and Economic Considerations

Because boreholes can be drilled using off-the-shelf oilfield technology, the concept may prove relatively straightforward to describe to potential host communities that will, presumably, be largely comprised of nonengineers. By relying primarily on strong natural barriers, particularly if situated in very low-permeability rock, it depends less on long-lived waste forms and robust waste canisters (i.e., engineered barriers) compared to other disposal concepts. A borehole's surface footprint could be as small as an area with a radius of perhaps 1–2 km around the borehole itself, allowing for on-site waste-handling facilities, equipment for downhole emplacement operations, and related support facilities, with a security perimeter constituting the outer boundary. This means the overall environmental impact of a single borehole or even a small array of boreholes would be significantly less than that of a repository. The smaller surface footprint and minimal geological disturbance created by a small repository may also translate to a wider choice of potential candidate sites, which in turn may increase the chances of finding a willing host community.

This relative simplicity and small size, at least for a small facility, has the potential to reduce characterization, excavation, disposal operations, closure, and passive long-term monitoring costs compared to a repository. The inherent modularity of borehole disposal also creates a financial advantage for programs that may need more than one borehole to accommodate their inventory. Construction costs for a borehole repository could be incurred on an as-needed basis, avoiding the large up-front costs of a mined facility. In 2009, SNL estimated that one five km borehole with a 445 mm downhole diameter would cost about $20 million (in 2008 dollars), not including emplacement operations, licensing, etc., and could take about 110 days to construct (Brady et al. 2009). Construction costs and timelines depend on the details of the design concept and will vary from country to country and geology to geology, but enabling earlier access to disposal facilities will reduce spent fuel and HLW storage costs. Licensing, however, may be costly and the process time-consuming, particularly if the regulator has a small staff and little to no experience with this technology.

Security and Nonproliferation Considerations

Despite decades of effort worldwide to construct repositories and thorough documentation of the financial burdens and sociopolitical complexities associated with the failure to permanently dispose of spent fuel and HLW, these wastes remain in temporary storage above ground (see BRC 2012 and Bowen 2021 on the US case). Specific to security and nonproliferation concerns, the reasons for disposing of spent fuel underground remain unchanged and the goals remain unmet worldwide. The benefits of drilling deep and getting spent fuel/HLW underground sooner rather than later are magnified in politically unstable regions of the world.

In a once-through fuel cycle, spent fuel needs to be securely stored for extended periods of time until it has cooled sufficiently for disposal. Given that the allowable thermal and radiation limits for transportation are often substantially lower than those for storage, increasingly high-burn-up fuel and large dry storage canisters require an extended period of aging before the canisters have cooled enough to be moved. In most countries, it will be decades before repositories are open and able to accept waste in sufficient quantities to begin to significantly draw down the inventory. The longer spent fuel is stored, the more the shorter-lived, "self-protecting" isotopes decay and the less radioactive it becomes, the greater the security risk that it presents. In light of the demonstrated willingness of some nonstate actors to disregard self-preservation in the pursuit of their objectives, the current self-protection standard—one gray/hour at one meter unshielded, a threshold used by the US Nuclear Regulatory Commission, DOE, and IAEA—might not be sufficient to deter the unauthorized removal of material (NRC 2015). However, unless the objective is on-site radiological dispersal by breaching a pool or dry cask, the operational and technical complexities of acquiring spent fuel rods or assemblies, transporting them off-site, and then fabricating an improvised nuclear device suggest that the most plausible nonstate theft scenarios would present at facilities where security has completely broken down.

In addition, spent fuel contains plutonium—approximately 1 percent by weight—that can be separated by chemical or metallurgical processes to make mixed oxide (MOX) fuel or to build nuclear weapons. Because the production or acquisition of fissile material is the biggest challenge for a state developing nuclear weapons or a nonstate actor developing an improvised nuclear explosive device, the separation and stockpiling of plutonium poses real proliferation and security risks.

For a variety of reasons, some countries have chosen to reprocess their spent fuel domestically or abroad. The purpose of doing so is primarily to separate the plutonium and then recycle it as MOX fuel. However, Japan's accumulation of 46.1 tons of separated plutonium as of the end of 2020 (8.9 tons stored domestically and 37.2 tons stored in the UK and France) is a reminder of the risks of reprocessing decoupled from either the use of the recovered material as new reactor fuel or a disposal pathway (Japan Office of Atomic Energy Policy 2021). Other countries have defaulted to foreign reprocessing, often with an agreement that the high-level waste will be returned at a future date, which is a way of buying time to find a long-term storage and/or disposal solution. The Taiwan Power Company, for example, tried unsuccessfully in February 2015 to have a relatively small batch of spent fuel reprocessed overseas, with the vitrified high-level waste to be returned 20 years later, to prevent one of its power plants from running out of pool storage capacity (Newman 2021). If boreholes prove viable technically, economically, and politically in countries where they may be preferable to mined repositories, getting spent fuel into the ground more quickly could further disincentivize reprocessing and thus reduce opportunities for state or nonstate diversion, theft, or sabotage.

Spent fuel disposed of in a borehole or mined repository is, by definition, "retrievable" from a nonproliferation perspective in the sense that, given time and resources, some portion of the radioactive material could be brought back to the surface. However, drilling back into a plugged borehole to retrieve spent fuel is expensive, time-consuming, and extremely difficult to conceal from outside observation. Boreholes will likely be easier and cheaper to safeguard than repositories and other methods of either eliminating plutonium (such as transmutation in reactors or accelerators) or recycling for reuse as MOX reactor fuel are more complicated to safeguard and arguably pose greater proliferation risks (Lyman and Feiveson 1998).

Indeed, nuclear facilities can face risks unrelated to attempts to divert radioactive material. For example, during the 1990s at the closed nuclear weapons test site in Semipalatinsk, Kazakhstan, "hundreds of miles of copper cabling and tracks that crisscrossed the test site provided a lure for many out of work Kazakhs. Familiar with the situation at the test site, residents of the city of Kurchatov and the rural settlements surrounding the testing grounds began scavenging the site in search of metal to sell" (Davydov 2014). More dramatically, Russia's shelling and seizure of the Zaporizhzhia nuclear plant in Ukraine in 2022 provides a graphic illustration of the risks of collateral damage to nuclear facilities, reactors, and spent fuel in war zones. Disposal of spent fuel several kilometers down a plugged borehole makes state or nonstate human intrusion or disruption scenarios, whether inadvertent or deliberate, extremely unlikely.

CONCLUSIONS

An RD&D project supported by multiple national nuclear waste disposal programs could inform decision makers worldwide regarding the potential for safe, permanent disposal of high-activity radioactive waste in deep boreholes. The project proposed here involves drilling two or more boreholes in separate locations (and perhaps in separate countries), with a first borehole that demonstrates the engineering feasibility of the concept, accompanied either subsequently or in parallel by one or more separate rock characterization holes. The latter holes can help to advance the fundamental science underlying deep borehole disposal concepts and demonstrate the ability to find and characterize potentially suitable rock types at appropriate depths. Deep borehole disposal research can produce first-of-a-kind information that would be available to all interested parties worldwide and provide participating programs with an opportunity to plan and implement field tests relevant to specific disposal concepts appropriate for their candidate waste forms and available rock types.

This project would also enable countries with relatively small inventories of commercial spent fuel and other high-activity wastes, as well as larger nuclear programs with specialized waste forms not suitable for colocation in a repository, to make informed decisions about the cost-effectiveness, safety, security, and timeliness of boreholes as a primary or complementary disposal method. As a world leader in nuclear waste disposal RD&D and commercial oil and gas drilling as well as an architect of the nuclear nonproliferation regime and efforts to strengthen global nuclear security, the United States is uniquely positioned to help steward an international research program, including by providing critical technology and expertise. Such an international borehole initiative could help lead to a disposal pathway for a small, specialized portion of the US DOE waste inventory and promote US global nuclear safety and security goals.

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