SAND2017-0117C

DEEP BOREHOLE DISPOSAL FOR COUNTRIES WITH SMALL NUCLEAR POWER PROGRAMS

John R. Cochran, Patrick V. Brady and Ernest L. Hardin

A Sandia National Laboratories, PO Box 5800 MS 0747
Albuquerque, NM 87185-0747, jrcochr@sandia.gov

Disposal of used nuclear fuel and vitrified high-level radioactive waste (UNF and HLW) in a mined geologic repository is the preferred alternative for the countries with the largest inventories of UNF and HLW. However, deep borehole disposal (DBD) may be especially well suited for countries with small nuclear power programs because DBD is relatively inexpensive and scalable. The economics of scale work against countries with small nuclear power programs – in part because the availability of funds for a mined geologic repository typically scales with the amount of electricity that is sold, whereas the threshold costs to develop a mined geologic repository are quite high and do not scale with the inventory.

Historically, options for countries with small nuclear power programs (programs that individually generate only a few percent of the world total mass of UNF and/or HLW) have been: (1) negotiate to return the UNF to the supplier, (2) conduct off-shore reprocessing, with return and in-country disposal of the resulting vitrified HLW in a mined geologic repository, (3) develop in-country, direct disposal of the UNF in a mined geologic repository or (4) send UNF to a hypothetical multi-national mined geologic repository. However, in-country DBD is likely to be least expensive, and technically achievable with existing technology. In-country DBD is also a viable alternative for disposal of used fuel assemblies from operating and decommissioned research reactors in developing countries – especially if repatriation of the fuel to the country of origin is not viable.

I. INTRODUCTION

Nuclear power is used to generate electricity in 30 countries, providing ~11% of the world's electricity in 2012.[1] In addition to providing relatively carbon-free electricity, the mass of used nuclear fuel (UNF) is exceptionally small, averaging just 0.028 kg of heavy metal per year for each household that receives electricity from a nuclear power reactor (NPR).[2] Some countries plan to dispose of the UNF directly and other countries plan to reprocess the UNF, which recovers the fissile materials and creates high-level radioactive waste (HLW).

Management and disposal of UNF/HLW is especially difficult for countries with small nuclear power programs (programs that individually generate only a few percent of the world total mass of UNF and/or HLW) – in part because of the economics of scale. Typically, the availability of funds for a mined geologic repository scale with the amount of electricity that is sold, whereas the threshold costs to develop a mined geologic repository do not scale with the inventory. Countries with larger nuclear power programs have generated billions of United States (U.S.) dollars (USD) for disposal of UNF/HLW based on a modest tax on the sale of electricity – whereas a similar tax can only generate a fraction of that amount in a country with a small nuclear power program. However, recent work on deep borehole disposal (DBD) demonstrates that DBD of UNF/HLW may be especially well suited for countries with small nuclear power programs, because it has lower per-unit costs, and because the disposal program and the disposal costs scale with the inventory.

II. NUCLEAR POWER PLANTS

Worldwide, 450 NPRs are operating in 30 countries.[3] Figure 1 presents the number of NPRs by country. An additional 60 NPRs are under construction, with 20 of those being built in China.[4] Many of the countries building new NPRs are countries with relatively small generating capacities (e.g., Brazil, Pakistan, Slovakia) and the United Arab Emirates are building their first four NPRs.[4]

Over the past 40+ years these NPRs have produced tremendous amounts of relatively carbon-free electricity, while generating small volumes of UNF; roughly 20 metric tons of heavy metal (MTHM) per year for a typical 1 Gigawatt (GW) NPR operating at 50 GW days per ton of heavy metal.[2]

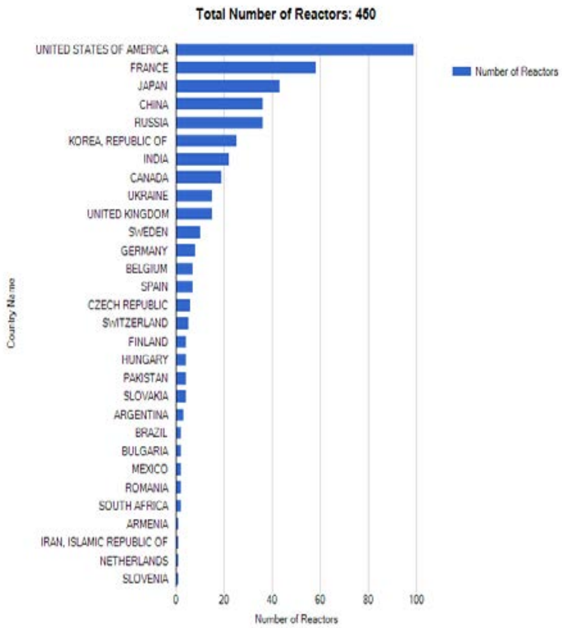

Fig. 1. Number of NPRs per Country in 2016 [3]

Despite the small amount of UNF produced in generating electricity for a household for a year, the cumulative amount of UNF is significant. Approximately 260,000 MTHM had accumulated in storage worldwide in 2006; partitioned between UNF assemblies (~176,000 MTHM) and civilian HLW (~84,000 MTHM).[5] These estimates were prepared by the International Atomic Energy Agency, based on publicly available National Reports submitted to the Second Review Meeting of the *Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management*. Using a global generation rate of 10,000 MTHM/yr,[5] the global cumulative inventory of UNF/HLW today is roughly 360,000 MTHM.

Five countries (Canada, France, Russia, UK and the U.S.) hold ~75% of the global inventory, with the remaining ~25 countries holding ~25% of the global inventory (Tables 4 and 5 of [5]). Importantly, many countries hold only a few percent, or even less than one percent, of the global inventory of UNF/HLW.

III. RESEARCH REACTORS

Fifty-five countries operate about 240 civil research reactors; and some 80 nuclear reactors power ships and submarines.[6] One-third (85) of these operating research reactors are in developing countries.[7] Another 133 research reactors are permanently shut-down and 352 research rectors have been decommissioned.[7] Most of the decommissioned research reactors are in developed countries. Cumulatively there are 60,885 spent fuel assemblies in storage, with 40,222 being low-enrichment uranium assemblies and 20,663 being highly-enriched uranium assemblies.[8]

The nuclear fuel assemblies in operational and shut-down reactors, as well as the fuel assemblies in storage from decommissioned reactors, will all require management and disposal. Many of these research reactors are in countries with NPRs, and management of the research reactor fuel can be leveraged against the waste management programs at the country's NPRs. However, nuclear fuel from older research reactors in developing countries may not have a fuel take-back agreement with the country of origin, and the fuel assemblies may be stranded in the custody of organizations with limited financial or waste management resources. From a technical perspective, repatriation of the used fuel from a developing country to the country of origin is the solution – but if that option is not feasible, then DBD is a viable alternative for dispositioning the UNF within the developing country.

IV. EXISTING OPTIONS FOR MANAGEMENT OF UNF AND HLW

A 1957 U.S. National Academy of Sciences study concluded that HLW could be safely disposed in mined geologic repositories sited in salt formations.[9] Since 1957 many countries have initiated programs to develop mined geologic repositories for the disposal of UNF and HLW in thick bedded salt or other rock types.[10] Conceptually, a mined geologic repository provides a means for physically placing UNF and HLW into quiescent regions of the lithosphere, where rock stability and isolation from groundwater movement will contain the radioactive elements until they decay to safe levels.

Belgium, Canada, Finland, Japan, the Republic of Korea, Russia, Sweden, Switzerland, Taiwan, UK, the U.S. and many other countries have committed to programs to license and build mined geologic repositories for UNF and vitrified HLW.[10] The cost to develop, license and build a mined geologic repository is typically in the billions of USDs.

Some of the countries above have made significant progress in developing and licensing permanent disposal facilities, but delays and redirections are common. At present, no country has succeeded in licensing the operation of a disposal facility for UNF and/or HLW. The worldwide inventory of UNF and HLW remains in storage in pools or dry casks or vaults, at or near the ground surface. This long-term storage of UNF and HLW creates a financial, safety and security liability for each generating country.

Countries with large inventories, and some countries with smaller inventories, have committed to develop mined geologic repositories. However, countries with small inventories of UNF/HLW could in theory:

- negotiate to return the UNF to the supplier
- send the UNF for reprocessing, with return and in-country disposal of the resulting vitrified HLW in a mined geologic repository
- dispose of the UNF in a mined geologic repository sited in-country, or
- develop a hypothetical multi-national mined geologic repository.

In addition to these four options, recent work demonstrates that DBD is a plausible alternative because it is scalable and less expensive than an in-country mined geologic repository. DBD is technically feasible now and might avoid the delay, and attendant expense, of negotiating with other countries for UNF return, reprocessing, and/or development of a mined geologic repository or a hypothetical multi-national mined geologic repository.

V. DEEP BOREHOLE DISPOSAL

Deep borehole disposal is the disposal of packages of solid radioactive waste in a deep borehole with appropriate measures taken to plug and seal the borehole. One conceptual layout of a DBD system is shown below.

DBD isolates radioactive wastes because the deep groundwater/pore fluid is isolated from shallow groundwater resources. Low permeability and the occurrence of hypersaline brine in the deep continental crystalline basement at many locations suggests ancient origin, and exceptionally limited interaction with shallow fresh groundwater resources. Though no single technique is available to determine the age of deep pore fluid, multiple lines of reasoning, based on overlapping measurements, can show that the fluid residence time is millions of years (see, for example, [11] and [12]). Additionally, the geochemically reducing conditions found in such deep fluids limit the solubility and enhance the sorption of many radionuclides. Finally, the density stratification caused by deep hypersaline fluids beneath younger, fresh groundwaters would oppose the relatively short-term convective influence from waste heating or from long-term climate change effects at the ground surface.[13] Using reasonable parameter values for disposal of UNF in deep crystalline basement rocks, analysis by Sandia National Laboratories suggests that radioactive wastes will be safely isolated from the geosphere until they decay to safe levels.[14]

The U.S. Nuclear Regulatory Commission's (NRC's) low-level radioactive waste licensing regulations state that "near-surface" disposal is within 30 m of the land surface (10 CFR 61.2), while siting conditions for a mined geologic repository favor at least 300 m deep (e.g., 10

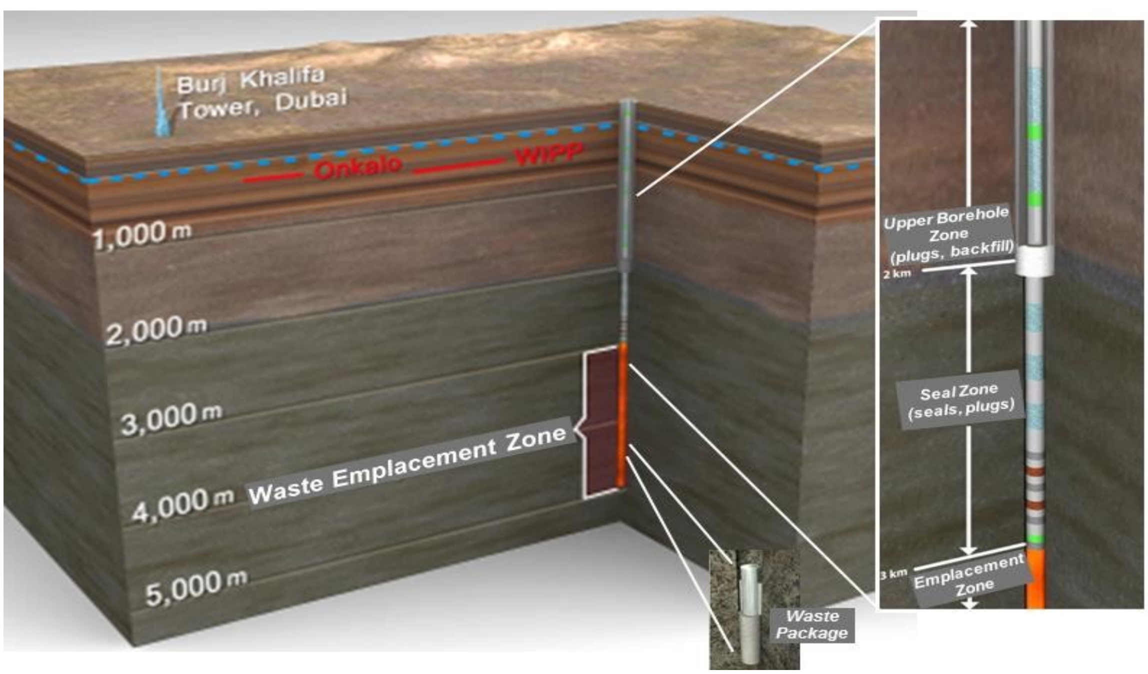

Fig. 2. Conceptual Layout of a Deep Borehole Disposal System

CFR 60.122(b)(5)). However, the minimum depth necessary to qualify a system as being a “deep” borehole disposal system is not defined in U.S. regulation.

The early deep borehole disposal concepts involved smaller diameter boreholes and the injection of liquid radioactive wastes (e.g., in 1957 the U.S. National Academy of Sciences study included the feasible to inject dilute liquid radioactive wastes at depths greater than 1.5 km[9]). Modern capabilities to drill deep, vertical, large-diameter boreholes allow consideration of emplacing solid radioactive waste at multi-kilometer depths below the land surface.

In 1983 and 1984, a deep hole was drilled in sediments in Louisiana, U.S., at a minimum diameter of ~0.66 m, and a string of ~0.51-m casing was installed to the full depth of 3.8 km (English units from the oil and gas industry are used in most DBD documents, and the metric conversions approximate the English units).[15] Other examples of deep, large-diameter drilling, including more recent developments, are provided by [16] and [17].

In 1983, a Woodward–Clyde study concluded that drilling technology might become available by the year 2000 for a deep borehole disposal system based on drilling to 6.1 km in crystalline rock, at an emplacement zone diameter of ~0.5 m.[18] Unfortunately, the Woodward–Clyde disposal concept was never tested.

A recent reference design called for siting a borehole (or an array of boreholes) to penetrate crystalline basement rock to a depth of 5 km.[19] Borehole diameter would be ~0.43 m in the waste emplacement zone from 3 to 5 km depth, and a slightly larger diameter (~0.47 m) in a 1-km seal zone interval directly above (see figure inset). The cost to drill this borehole was estimated to be approximately $20 M USD in 2009,[20] then revised upward in 2011 to $27 M USD for a disposal borehole without characterization sampling or testing.[18] Guidance casing (~0.34 m outer diameter) would be installed in sections from the surface to total depth, to guide the waste packages during emplacement.

The 2011 concept calls for ten intervals of 40 waste packages each, for a total of 400 waste packages per borehole.[19] Borehole seals would consist of alternating layers of compacted bentonite clay and cement, emplaced against the borehole wall rock in an uncased interval.

The 2011 cost estimate was increased to approximately $40 M USD in 2014 using unit rates for drilling equipment and services that reflected the oil-and-gas production boom in effect at the time.[21] Rates have decreased by as much as 50% since then (e.g., back to ~$20 M USD for the reference ~0.43 m borehole to 5 km). Clearly, the cost for field work needed to develop a DBD system will depend on oil-and-gas market conditions. These cost changes could be advantageous for waste disposal because drilling, completion, emplacement, and sealing activities can be scheduled during downturns in the drilling industry.

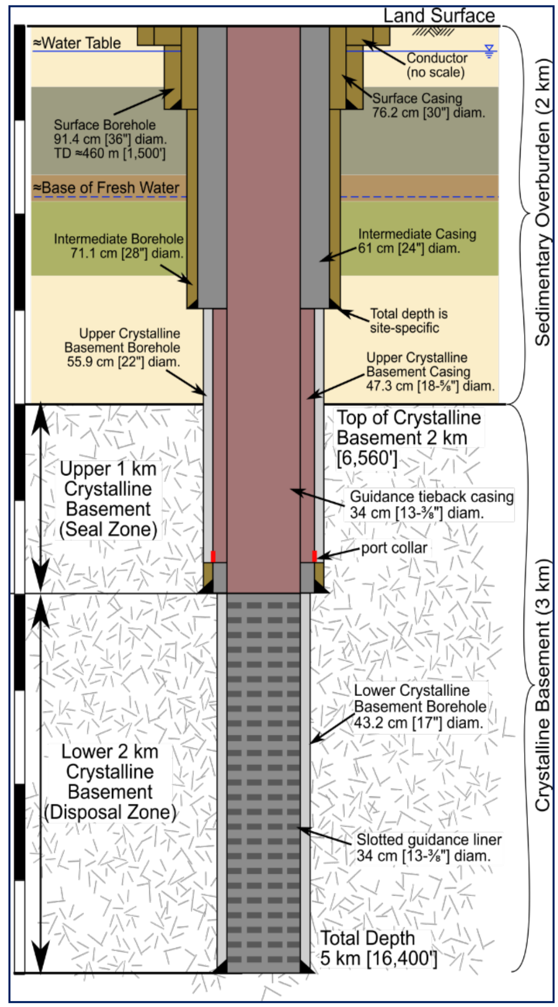

Fig. 3. A deep borehole disposal reference design[19]

The 2011 conceptual design[19] is based on having the lower 3 km of the borehole in continental crystalline basement rocks (e.g., granite), that have low bulk permeability and ancient high salinity groundwater/pore fluids. Crystalline rocks were chosen for this reference design because they:

- are relatively common
- have low bulk permeability (~10^{-19} m^2) at depth
- have low porosity (~1%), and
- lack economic mineral resources.

In addition to the expected characteristics of deep crystalline basement rock, other siting factors would include: limited indications of strongly deviatoric stress conditions, limited geothermal gradient, lack of evidence for fluid overpressure at depth, limited seismic ground motion projections, other indications of tectonic stability, and a lack of geologically recent volcanism. A full set of DBD Field Test siting guidelines was provided in a recent contract solicitation.[22] Note lastly that suitable conditions at depth cannot be assumed, but should be verified, and some countries with small nuclear power programs may not possess suitable sites.

In 2015 Sandia National Laboratories developed reference waste package designs for DBD with a ~0.22 m inside diameter (ID) and an internal length of 5 m.[23, 24] This design could be used for direct disposal of Boiling Water Reactor (BWR) assemblies which are 4.42 m tall, 0.139 m square, and would fit in a cylinder with an ID of 0.198 m. A more recent analysis recommended that vitrified HLW could be disposed of in larger diameter boreholes (up to ~0.91 m) at shallower depth (less than 3 km) depending on site conditions.[16] Borehole drilling and construction could be significantly more feasible at depths of 3 km or less. For purposes of this paper, deep borehole disposal is considered to be at a minimum depth of 2 km from the ground surface, which is two to four times deeper than planned or developed mined geologic repositories. This minimum depth helps to ensure very long transport time to the biosphere, where transport conditions in the basement formations are non-advective and diffusion-dominated. The weight of 2 km of overburden establishes in-situ stress conditions at depth (especially if the minimum stress is vertical) that close fractures and limit permeability.

Beswick, Gibb and Travis (2014) suggest a different DBD reference design based on drilling the emplacement zone to a diameter of ~0.61 m or ~0.66 m from 2.5 km to 5 km.[16] The drilled volume of this borehole at ~0.61 m (2915 m^3) is more than twice the drilled volume of the Arnold et al. (2011) reference design[19] (1,366 m^3), and thus the cost to drill this borehole could be substantially greater (e.g., \$40 to \$50 M USD). The larger borehole could accommodate direct disposal of Pressurized Water Reactor (PWR) assemblies (without rod consolidation) which are 4.8 m tall and would fit in a cylinder with an ID of 0.32 m. A ~0.51 m OD guidance casing would accommodate waste packages with an assumed OD of ~0.43 m and a wall thickness of 5.08 cm.

Smaller boreholes and waste packages could be used for UNF from both BWRs and PWRs, with fuel rod consolidation. Fuel rod consolidation also increases the "efficiency" of the waste packages (e.g., a waste package large enough for direct disposal of a single PWR assembly could accommodate fuel rods from approximately two assemblies). However, a specialized fuel rod consolidation facility would have to be licensed, constructed, operated and decommissioned – which could significantly offset savings won through selection of DBD.

If it is not feasible to site a DBD system in crystalline rocks, a DBD system could be sited in other rock types, so long as there is reasonable assurance the siting criteria (minus crystalline rock) can be met. Low bulk permeability is critical in limiting interaction between groundwater/pore fluids at the disposal horizon, and any shallow groundwater resources. The presence of ancient hypersaline groundwater/pore fluid provides a very strong indicator of such limited interaction.

For a properly sited DBD system, favorable natural conditions (ancient and isolated formation fluid, reducing conditions and density stratification), in addition to a 1-km thick seal zone of compacted bentonite clay and cement plugs, will limit radionuclide transport to diffusion through several kilometers of host rock (and diffusion through the seal zone), ensuring the isolation of the radioactive wastes for hundreds of thousands to millions of years.

Retrieval could be difficult after waste packages are disposed in a borehole at depths > 2 km. Waste packages made from low-alloy carbon steel could be retrieved during operations, and for a few years after placing the seals. More corrosion resistant materials are available that would last longer, but at a higher cost. Grouting waste packages in place would also delay corrosion. After the waste packages corrode, retrieving the waste becomes more difficult. A retrieval system could be based on milling the waste with a once-through circulating fluid, and capturing the waste particles in solid form at the surface. Another option is solution mining, whereby waste could be mobilized by circulating oxidizing and acidic fluids that dissolve and convey the waste to the surface in a retrieval casing. Retrieval of wastes from a DBD system is possible, so long as the retrieval standard is reasonable (e.g., the U.S. standard found in 40 CFR 191.14(f) "... disposal systems shall be selected so that removal of most of the wastes is not precluded for a reasonable period of time after disposal.").

VI. SCOPE AND COST OF A DBD PROGRAM

The scope and cost to implement a program for DBD of UNF will depend on several factors such as: the inventory, the regulatory standard, the licensing process, the availability of suitable drilling resources, the ability to lease or build emplacement equipment, and the availability of information on the geology and the geologic setting. For a country with a small nuclear power program, suitable geology and existing, high-quality geologic information, the siting program could identify one prospective location for site characterization based on technical, social, and other criteria. A single characterization borehole (e.g., ~0.22 m diameter) could then be drilled and characterized to determine if the site is acceptable. Alternatively, the siting program could identify a short-list of prospective sites, and a characterization borehole could be drilled and characterized at each site – to allow the selection of the single preferred location. Then, with a single, preferred location, it may be possible to drill the large-diameter disposal borehole, or it may be desirable to drill one or two more characterization boreholes, followed by the drilling of a large-diameter disposal borehole. The total cost of drilling and testing three characterization boreholes would be roughly $60 M USD at current market rates for drilling equipment, services and characterization. A disposal borehole (without characterization) might be drilled to 5 km for $20 M USD (0.43 m emplacement zone for BWR assemblies) or $50 M USD (0.61 m emplacement zone for PWR assemblies). This estimate is for drilling and characterization costs, and does not include costs for regulatory activities, site selection, or project management.

As many as 400 waste packages could be designed, fabricated, tested, loaded and sealed at a total cost of about $10 M USD, which could be done using an existing fuel pool, but would require acquisition of specialized casks for transfer, temporary storage, and transportation to the disposal site. The program would be scoped to dispose of a number of waste packages, in a series of campaigns lasting 1 to 2 years each. The lifetime of the steel tooling in the disposal borehole would be limited to a few years due to corrosion, so the disposal objectives would need to be accomplished in that time, and the disposal borehole sealed. The cost to emplace 400 waste packages in a borehole was estimated to be approximately $20 M USD,[25] and the cost for final sealing/plugging would be approximately $5 M USD (90 days of rig time for removing casing, and installing clay and cement). In addition, the three characterization boreholes would be sealed and plugged at total cost of about $15 M USD.

Thus, the cost for one initial disposal borehole for 400 waste packages, would be roughly $80 M USD in the simplest case - with a single characterization borehole, a 0.43 m emplacement zone disposal borehole to 5 km and emplacement, sealing and closure costs for BWR waste packages. Subsequent boreholes could be drilled, completed, loaded, sealed and closed for roughly $55 M USD for 400 BWR waste packages. This estimate, and the subsequent estimate, do not include costs for regulatory activities, site selection, or project management.

If there are three characterization boreholes and the emplacement zone is drilled to 0.61 m in diameter to 5 km for 400 PWR waste packages, the cost of the initial borehole is roughly $160 M USD. Subsequent disposal boreholes, each containing 400 PWR waste packages, could be drilled, completed, loaded, sealed and closed for approximately $85 M USD each. Drilling and service costs vary, and may be significantly lower outside the U.S.

The demonstration of post-closure safety will be specific to the site, waste form and regulations; however, U.S. analysis using a conservative model and reasonable parameter values suggests that wastes will be safely isolated from the geosphere until they decay to safe levels.[14]

VII. DBD FIELD TEST

To provide field experience for evaluating DBD as an option for the disposal of radioactive wastes, the U.S. is implementing a Deep Borehole Field Test. Radioactive wastes will not be used in the Deep Borehole Field Test. This science- and engineering-based field test will be conducted in two phases. In the first phase, the program will drill a borehole ~0.22 m in diameter to 5 km to test the ability to characterize the bedrock and groundwater/pore fluids to 5 km. The second phase includes the drilling of a borehole ~0.43 m in diameter from 3 to 5 km to test the ability to drill a deep, large-diameter, vertically straight borehole in crystalline rock and to gain experience in placing and retrieving prototype waste packages.

The first attempt to site the Field Test[22] was met with community concerns that the U.S. Government would require the selected community to accept waste in the future. The program worked to address those concerns, but community opposition developed and the project was withdrawn. Based on this experience, a second program was initiated in late 2016 with the understanding that public engagement and support is paramount, and that the program needs to be very clear that the field test site will not be used for future nuclear waste disposal.[26]

VIII. DEEP BOREHOLE DISOSAL MAY BE IDEALLY SUITED FOR COUNTRIES WITH SMALL NUCLEAR POWER PROGRAMS

Deep borehole disposal may be ideally suited for countries with small nuclear power programs because:

- the initial investment is much lower than the initial investment for a mined geologic repository, and
- total costs are scaled to the inventory, resulting in lower cost per unit of waste.

It is valuable to discuss three of the differences between a mined geologic repository and a DBD system. First, making the emplacement zone in a mined geologic repository safe for workers increases costs significantly. This safety includes radiation safety and mining safety; with requisite excavation and conveyances (e.g., shaft hoists), ventilation, underground utilities, radiation shielding, and so on. Workers do not enter the emplacement horizon in a DBD system, so the added expense is avoided. Second, a properly sited DBD system relies on geologic isolation more than engineered isolation, which should simplify the post-closure safety analysis and allow projections of waste isolation for millions of years. Finally, a mined geologic repository has a lateral orientation, and requires extensive lateral and vertical site characterization and excavation. For example, the proposed Yucca Mountain Project in the U.S. had a subsurface repository footprint of ~8 km^2, and was designed to have ~71 km of emplacement tunnels. For DBD the deep, and diffusion-dominated setting should simplify characterization and safety analysis.

With a suitable geologic setting and pre-existing geologic studies, it may be possible to site a DBD system based on existing information, and a single ~0.22 m in diameter characterization borehole drilled to the design depth. The simplicity of siting and characterization should also allow for relatively fast licensing and implementation. Additionally, it could be far less expensive to close a borehole than to close a mined geologic repository.

More significantly, the costs to implement a DBD system are roughly scaled to the inventory; "pay as you go," with "drill-and-fill." As an example, *a single borehole could accommodate four years' worth of UNF assemblies from a country with 2 GW of nuclear generating capacity*. This estimate is based on PWRs, generating 40 MTHM in ~ 90 UNF assemblies per year, and a deep borehole with a capacity of 400 waste packages. Six countries in the world have a generating capacity in this range (2 GW), and seven countries have a generating capacity that is less than 2 GW.[3] Combined, these 13 countries represent almost ½ of all the countries that have NPRs.[3]

Although the emphasis here has been on DBD for countries with small nuclear programs, it should be noted that DBD could be utilized by countries with larger inventories, for unique waste forms (e.g., excess fissile materials), and/or to reduce long-haul transportation of UNF to a mined repository, and/or to provide regional equity within a country (e.g., by placing the disposal facilities in regions that benefit from the nuclear power).

IX. SUMMARY

Deep borehole disposal should be attractive for countries with small nuclear power programs because it is scalable, and relatively inexpensive. Multiple factors indicate deep borehole disposal of radioactive wastes should be safe for very long time-frames. Low permeability and long residence time of high-salinity groundwater in the deep crystalline basement at many locations suggests very limited interaction with shallow fresh groundwater resources. Geochemically reducing conditions at depth limit the solubility and enhance the sorption of many radionuclides in the waste. Density stratification of saline groundwater underlying fresh groundwater would oppose groundwater convective mixing in response to waste heat input or other future changes (e.g., recharge boundary conditions).

A single deep borehole could accommodate four years' worth of UNF assemblies from a country with 2 GW of generating capacity. The relatively low up-front costs and "pay as you go" nature of DBD should make it far more suitable for countries with small nuclear power programs than a mined geologic repository.

ACKNOWLEDGMENTS

Many thanks to Amir Mohagheghi for his insightful suggestions. Portions of this article were written with internal funding from Sandia National Laboratories' Global Nuclear Assurance and Security, Civilian Nuclear Mission Integration.

REFERENCES

1. Nuclear Energy Institute: http://www.nei.org/Knowledge-Center/Nuclear-Statistics/World-Statistics (accessed on August 31, 2016).
2. Nuclear Energy Institute: http://www.nei.org/Master-Document-Folder/Backgrounders/Fact-Sheets/Quick-Facts-Nuclear-Energy-in-America (accessed on August 31, 2016).
3. International Atomic Energy Agency, *Power Reactor Information System*: https://www.iaea.org/pris/ (accessed on November 30, 2016).
4. International Atomic Energy Agency, *Power Reactor Information System*: https://www.iaea.org/PRIS/WorldStatistics/UnderConstructionReactorsByCountry.aspx (assessed November 30, 2016).
5. International Atomic Energy Agency, *Estimation of Global Inventories of Radioactive Waste and Other Radioactive Materials*, IAEA-TECDOC-1591, Vienna, Austria (2008).

6. World Nuclear Association: http://www.world-nuclear.org/information-library/current-and-future-generation/nuclear-power-in-the-world-today.aspx (accessed November 30, 2016).
7. International Atomic Energy Agency, *Research Reactor Database*: https://nucleus.iaea.org/RRDB/Reports/Container.aspx?Id=A1 (accessed on November 30, 2016).
8. International Atomic Energy Agency, *Research Reactor Database*: https://nucleus.iaea.org/RRDB/Reports/Container.aspx?Id=B6 (assessed on November 30, 2016).
9. U.S. National Academy of Sciences, *The Disposal of Radioactive Waste on Land (1957)* http://www.nap.edu/openbook.php?record_id=10294.
10. P. Hitchin, "Radiating Change" *Nuclear Engineering International*, http://www.neimagazine.com/features/featureradiating-change-4942136/ (July 6, 2016).
11. R.L. Kietäväinen, Ahonen, I.T. Kukkonen , S. Niedermann and T. Wiersberg, "Noble gas residence times of saline waters within crystalline bedrock, Outokumpu Deep Drill Hole, Finland." *Geochimica et Cosmochimica Acta.* 145, 159–174 (2014).
12. M. Gascoyne, "Hydrogeochemistry, groundwater ages and sources of salts in a granitic batholith on the Canadian Shield, southeastern Manitoba." *Applied Geochemistry*. 19, 519–560 (2004).
13. Y.-J. Park, E.A. Sudicky and J.F. Sykes, "Effects of shield brine on the safe disposal of waste in deep geologic environments." *Water Resources*. 32, 1352–1358 (2009).
14. G.A. Freeze, M. Voegele, P. Vaughn, J. Prouty, W.M. Nutt, E. Hardin, and S.D. Sevougian, *Generic Deep Geologic Disposal Safety Case*, SAND2013-0974P, FCRD-UFD-2012-000146 Rev. 1, Sandia National Laboratories, Albuquerque, NM (2013).
15. R.D. Pejac and E. P. Fontenot, Design Testing and Planning Considerations for a 20-in. Record Casing String. *SPE Drilling Engineering*, p. 187- 194 (1998).
16. A.J. Beswick, F. G. F Gibb, and K. P. Kravis, Deep borehole disposal of nuclear waste: engineering challenges. *Proceedings of the Institution of Civil Engineers*, 167, EN12. p.47-66 (2014).
17. M.J. Rigali, S. Pye and E.L. Hardin, *Large Diameter Deep Borehole (LDDB) Disposal Design Option for Vitrified High-Level Waste (HLW) and Granular Wastes*, SAND2016-3312. Sandia National Laboratories, Albuquerque, NM (2016).
18. Woodward–Clyde Consultants, *Very Deep Hole Systems Engineering Studies*, ONWI-266, Office of Nuclear Waste Isolation. Columbus, OH (1983).
19. B.W. Arnold, P.V. Brady, S.J. Bauer, C. Herrick, S. Pye and J. Finger, *Reference Design and Operations for Deep Borehole Disposal of High-Level Radioactive Waste*, SAND2011-6749, Sandia National Laboratories, Albuquerque, NM (2011).
20. P.V. Brady, B.W. Arnold, G.A. Freeze, P.N. Swift, S. J. Bauer, J.L. Kanney, R.P. Rechard, J.S. Stein, *Deep Borehole Disposal of High-Level Radioactive Waste*, SAND2009-4401, Sandia National Laboratories, Albuquerque, NM (2009).
21. B.W. Arnold, P.V. Brady, M. Sutton, K. Travis, R. MacKinnon, F. Gibb and H. Greenberg, *Deep Borehole Disposal Research: Geological Data Evaluation, Alternative Waste Forms, and Borehole Seals*. FCRD-USED-2014-000332. U.S. Department of Energy, Office of Used Nuclear Fuel Disposition, Las Vegas NV (2014).
22. U.S. Department of Energy, Presolicitation Notice – Deep Borehole Field Test. Solicitation Number: DE-SOL-0008071. U.S. Department of Energy, Idaho Operations Office, Idaho Falls ID https://www.fbo.gov/?s=opportunity&mode=form&id=a530c281c15d1c191336a681e69eefe5&tab=core&_cview=0 (2015).
23. J._C. Su and E.L. Hardin, *Conceptual Waste Packaging Options for Deep Borehole Disposal*, SAND2015-6335, Sandia National Laboratories, Albuquerque, NM (2015).
24. J.R. Cochran. and E.L. Hardin, "Waste Handling and Emplacement Options for Disposal of Radioactive Waste in Deep Boreholes - 16277," *Final Proceedings from Waste Management '16*, March 6-10, 2016, Waste Management Symposia, Inc., Phoenix, AZ (2016).
25. E.L. Hardin, *Waste Package Emplacement Cost Estimates for Deep Borehole Disposal*, SAND2015-6372, Sandia National Laboratories, Albuquerque, NM (2015).
26. U.S. Department of Energy, RFP for Deep Borehole Field Test: Characterization, Solicitation Number: DE-SOL-0010181. U.S. Department of Energy, Idaho Operations Office, Idaho Falls ID: https://www.fedconnect.net/FedConnect/PublicPages/PublicSearch/Public_Opportunities.aspx (2016).