Preliminary Technology Readiness Assessment of Deep Borehole Disposal – 22338

Ethan Bates*, Mark W. Frei**, John Midgley***, John Mathieson***, Rod Baltzer*
*Deep Isolation, Inc. 2001 Addison St, Suite 300 Berkeley, CA 94704
**Frei Solutions LLC 426 N. George Mason Dr., Arlington, VA 22203-2502
***Deep Isolation, Inc., 1, Northumberland Avenue, Trafalgar Square, London, WC2N 5BW, U.K.

ABSTRACT

There is growing worldwide interest in the advancement of deep borehole disposal (DBD) technology as a supplement to mined repositories for the disposal of higher activity radioactive waste. Deep boreholes offer a scalable, modular, and more economical disposal solution for spent nuclear fuel and vitrified high-level waste, particularly for countries with smaller waste inventories or those with waste products which may compromise the safety case for a mined facility. Deep Isolation's specific borehole designs could further increase the available options for disposal sites by leveraging directional drilling and geosteering techniques to emplace disposal canisters in either vertical, inclined, or horizontal orientations in various rock formations geologically isolated from the biosphere.

Although spent nuclear fuel handling and deep drilling technologies are mature in their own contexts, there are aspects of DBD which will require additional technology maturation prior to full-scale deployment. Typically, this issue is addressed using a technology readiness level (TRL) scale such as the ones used widely by the Department of Energy [1], [2] and NASA [3] in the U.S., and by the Nuclear Decommissioning Authority in the U.K. [4] to assess the similarity between prior experience and the projected application of the technology during its deployment.

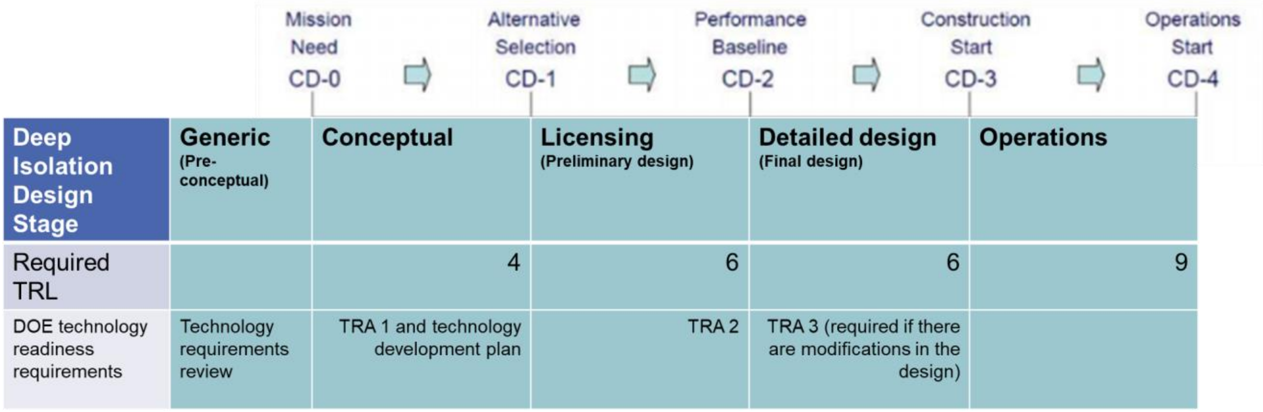
To provide a foundation for a technology development plan, this paper provides a preliminary evaluation of technology readiness level assessments for each aspect of DBD operations. Overall, the assessment concludes that spent nuclear fuel handling above ground is the most mature technical process and that demonstrating borehole stability and canister emplacement should receive the highest priority in terms of technology development planning. Other processes such as pre-closure monitoring, canister retrieval, and borehole sealing may also require additional development and demonstration, but the extent will depend on regulatory and risk-informed engineering requirements that are still being developed.

INTRODUCTION

Need for Technology Readiness Assessments

Most modern complex technologies require programs of testing and development to reduce technical uncertainties prior to full-scale deployment. In the case of DBD technologies, the international consensus amongst waste management organizations (WMOs) is that there should be a collaborative demonstration to support DBD industrialization [5]–[9]. Recent research by Deep Isolation [10] found a consensus across regulators, national policymakers, and WMOs that DBD offers significant opportunities to all national waste management programs and draws on mature technologies and processes – but that it is currently less mature than the mined repository concept because it has not been fully demonstrated as an integrated system.

Systems engineering practices are well established and highly suited to address technology risks and have been used throughout the nuclear industry [11]–[13]. Specifically, these methods aid with two fundamental aspects of technology maturation: 1) quantitatively measuring the technology readiness level (TRL) and 2) implementing a technology development plan. The systems engineering approach strategically phases product development into distinct design stages separated by critical decisions (CD) in which various aspects of the design are defined in greater detail. For example, according to the U.S. Department of Energy's (DOE) systems engineering practices [1], at least two complete technology readiness assessments (TRAs) should occur in the product development process. The first required TRA occurs within the conceptual stage of design and identifies TRLs lower than 4. This forms the basis of the technology development plan which is needed to bring TRLs to level 6 (via demonstration or other means of deploying prototypes) during the preliminary design stage (i.e., licensing design stage). Fig. 1 summarizes the technology readiness requirements and progression of the DOE systems engineering process adapted by Deep Isolation.



Deep Isolation Design Stage	**Generic** (Pre-conceptual)	**Conceptual**	**Licensing** (Preliminary design)	**Detailed design** (Final design)	**Operations**
Required TRL		4	6	6	9
DOE technology readiness requirements	Technology requirements review	TRA 1 and technology development plan	TRA 2	TRA 3 (required if there are modifications in the design)	

Fig. 1. DOE Technology readiness assessment requirements [1], [14]

Deep Isolation's DBD concept is at a generic stage of design and thus a formal TRA will be completed once design requirement uncertainties, such as those governing retrievability and monitoring [15], have been addressed, and the design has been defined in greater detail. For now, this study presents a preliminary TRA that will be revised within the conceptual design stage.

METHODS

Concept of Operations (COOP)

In line with best practices of systems engineering [3] and IAEA guidance [16]–[20], Deep Isolation has developed a concept of operations (COOP) for a deep borehole repository. This covers the high-level objectives for each of the key technical processes:

- site characterization
- spent nuclear fuel storage and handling
- repository construction (including borehole drilling)
- canister emplacement
- pre-closure monitoring
- closure

Based on the complete set of structured objectives identified in the COOP, the maturity of all technologies involved in each process (and thus the entire technological system) was assessed. Post-closure monitoring was not included in this TRA due the significant regulatory uncertainty and international variation on requirements. For example, according to the IAEA [20], geological disposal in principle should not require post-closure monitoring; however, ultimately it may be required for as long as society considers it beneficial. Deep Isolation's generic concept of operations is summarized in Fig. 2.

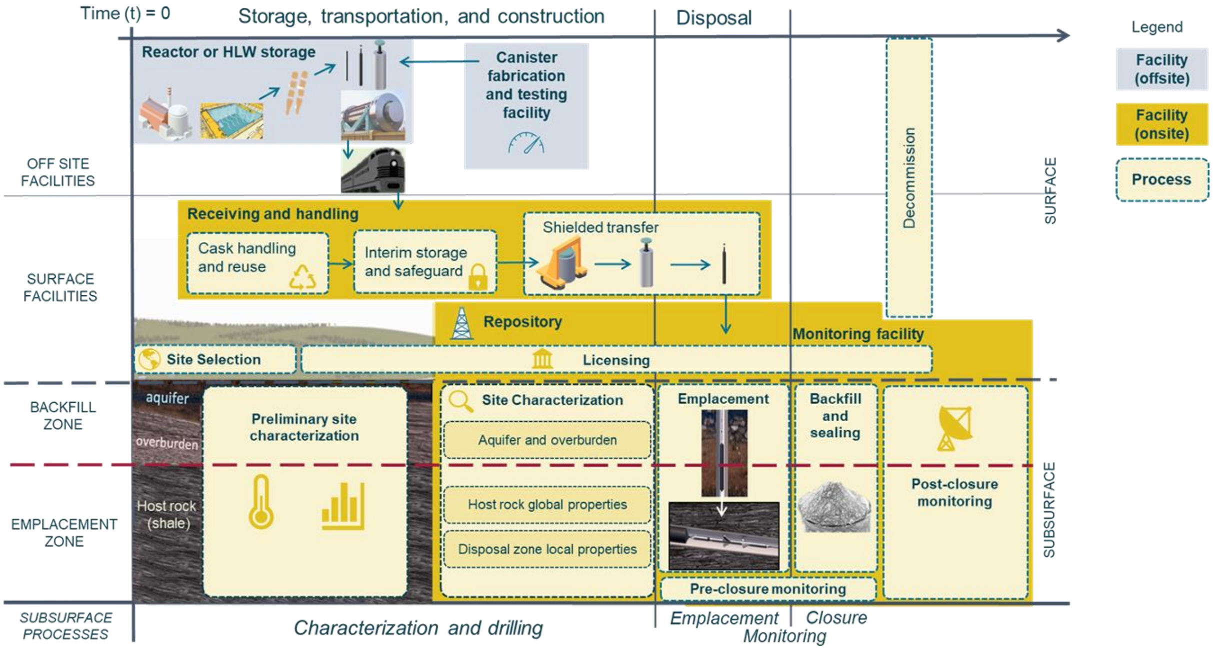


Fig. 2. Concept of operations for a generic Deep Isolation borehole repository

Technology Readiness Scale Definition

Although there are recently published adaptations of the technology readiness scale for geologic repositories [14], Deep Isolation opted to use the existing DOE technology readiness scale due to its more widespread use. Table I summarizes DOE's TRL definitions as adapted by Deep Isolation.

TABLE I. Technology readiness scale adapted from the DOE [1]

Stage of development	**TRL**	**TRL Definition**	**Scale of testing**	**Fidelity* (configuration)**	**Environment**
System operations	9	Actual system operated over the full range of expected mission conditions.	Full	Identical	Operational, full range of actual waste
System Commissioning	8	Actual system completed and qualified through test and demonstration.	Full	Identical	Operational, limited range of actual waste
	7	Full-scale, similar (prototypical) system demonstrated in relevant environment	Full	System prototype	Relevant
Technology demonstration	6	Engineering/pilot-scale, similar (prototypical) system validation in relevant environment	Engineering/ Pilot scale (10%<system <100% scale)	System/subsystem model or prototype	Relevant
Technology development	5	Laboratory scale, similar system validation in relevant environment	Lab/bench (<1/10 of full scale)	Components	Relevant
	4	Component and/or system validation in laboratory environment	Lab (<1/10 of full scale)	Components	Simulated
Research to prove feasibility	3	Analytical and experimental critical function and/or characteristic proof of concept	Lab	Analytical and experimental proof of concept	Simulated
Basic technology research	2	Technology concept and/or application formulated	None	Paper (no hardware)	Simulated
	1	Basic principles observed and reported	None	Paper (no hardware)	

*NASA [3] definitions are used because they are significantly more descriptive

DISCUSSION

Error! Reference source not found.e II through Table V summarize the preliminary technology readiness assessments across the full range of technical processes identified in the COOP for DI’s generic deep borehole design. A more detailed TRA will be conducted as the conceptual design is optimized through trade studies and the specific technologies involved are selected and comprehensively documented.

Some lower TRL areas identified here (e.g., drilling, borehole stability, axial plugs, seals) will depend significantly on site-specific geological conditions. More ideal host rock isolation characteristics could enable shallower configurations at a higher overall TRL than the current generic design (with a horizontal disposal zone at a depth of 1.5 km). Furthermore, the necessary level of characterization of the host rock and excavation disturbed zone (EDZ) will be derived and coupled to ongoing performance assessments and design choices (i.e., risk informed). DI’s recent performance assessments in vertical [21] and horizontal [22] configurations in crystalline rock and shale suggest that the details of host rock fracture networks, EDZ, and seal behaviors have a low impact on performance, potentially easing performance, development, and demonstration requirements for these technologies.

Several engineering requirements (e.g., pre-closure monitoring, and retrievability) are based on uncertain or variable regulatory requirements that can be addressed by developing performance envelopes (i.e., defining a range of feasible options) within the conceptual design stage. The conceptual design stage will further explore the complex trade-offs between maximizing technical readiness, suitability to other waste forms, site availability, and other performance characteristics by varying key design parameters such as geological conditions, disposal depth, diameter, and configuration.

TABLE II. Preliminary technology readiness assessment for site characterization and repository construction technologies

Process	**Goal**	**TRL**	**Comments**
Site characterization technologies	Geological environment	6	Geologic environments (aquifers, host rock, transport paths) have been characterized for Yucca Mountain[23] and rock laboratories [24]; however, specific host rock characterization methods may need to be proven at scale and depth (e.g., fracture connectivity in crystalline rock). Deep boreholes are generally expected to have lower requirements for site investigations compared to the detailed fracture characterization that are required for mined repositories [21], [25].
	Surface environment	9	Relevant surface characteristics for many sites are already largely determined.
	Subsurface processes	6	Prototypical characterization methods have been demonstrated in a relevant environment [26], [27].
Repository construction technologies	Drilling	5	Deep horizontal drilling is common, but there are limited examples where large-diameter (> 0.4 m) and deep (>1.5 km) horizontal holes have been drilled. Depends on disposal depth, host rock, repository configuration [28], and geometry.
	Site characterization of excavation disturbed zone (EDZ)	6	EDZs have been characterized for mined repositories (i.e., a relevant environment). Analogous borehole breakout zones have been characterized for deep boreholes down to 4 km [28]. Current performance assessments suggest that the necessary level of detail in characterizing the EDZ will likely be lower [22] for deep boreholes.
	Site characterization of thermo-mechanical properties of host rock	7	Proven successfully at a full scale in mined repositories (i.e., a relevant environment) [29]. Relative importance of local thermo-mechanical phenomena (e.g., fracturing) in disposal zone for long term safety is likely to be lower for deep boreholes than mined repositories.
	Monitoring system insertion	9	Monitoring systems have been inserted for drilling applications.
	Borehole stability	4	Depends on required (and variable) pre-closure monitoring and retrievability periods and also on host rock, repository configuration, and geometry [28]. Long term stability (>50 years) for horizontal holes at size required for PWR assemblies (~0.34 m) has not been demonstrated (additional study is needed).
	Thermal management	9	Proven successfully in drilling industry.
	Waste management	7	Proven successfully in drilling industry, but not in presence of spent nuclear fuel.

Table III. Preliminary technology readiness assessment for spent fuel storage and processing and emplacement technologies

Process	**Goal**	**TRL**	**Comments**
Fuel storage and handling technologies	Fuel storage	9	Fuel storage (wet, dry) has been implemented.
	Component reuse	9	Cask decontamination, reuse, and disposal has been implemented.
	Fuel packaging	6	Proven successfully in relevant environment (effects of long aging periods on cladding integrity are still being determined). Possibility of failure of cladding during repackaging may increase fission gas release to the facility compared to fresher fuels.
	Fuel handling	9	Operationally proven (at reactors, above surface).
Emplacement technologies	Worker safety	7	Operationally proven in a similar environment at reactors and storage facilities.
	Monitoring systems	7	Monitoring systems (e.g., calipers) have been inserted into production wells. However, more novel monitoring systems may be required to accelerate emplacement process.
	Canister emplacement	5	Prototype operated in target environment (but not at full scale) and with required reliability.
	Canister integrity-buffer material	7	Replacement of borehole fluids is routine in drilling industry, but conditions may differ. For example, some neutron activation may occur with spent nuclear fuel.
	Axial plugs	4*	Has been demonstrated in a laboratory environment. Axial plugs may be required for vertical boreholes (to facilitate retrievability) and may not be necessary for the horizontal boreholes.
	Canister retrieval	5	Has been demonstrated at a lower scale, not at full geometric or timescales and including effects of seals and monitoring systems.

*Depends on repository configuration

TABLE IV. Preliminary technology readiness assessment for pre-closure monitoring technologies

Technology	**TRL**	**Comments**
Seepage rate	9	Proven successfully in drilling industry.
Seismic	9	Operated successfully.
Waste canister integrity	8	Tracers have been operational in the drilling industry in a relevant environment (not in the presence of nuclear waste).
Natural barriers (EDZ)	6	Monitoring systems for host rock and preferential flow paths have been developed for enhanced geothermal systems (relevant environment).

TABLE V. Preliminary technology readiness assessment for pre-closure monitoring technologies

Technology	TRL	Comment
Permanent seals	5*	Components have been validated in a similar environment (e.g., SKB, Äspö Hard Rock Laboratory[30], FEBEX [29]).
Decommissioning	7	Proven successfully (drilling rigs, storage facilities, nuclear reactors).
Prevention of inadvertent human intrusion	6	DOE designed monuments for Yucca Mountain [31] and other technical measures to deter humans have been developed but not deployed [32].

*Depends on design requirements placed on permanent seals which have not been determined

CONCLUSIONS

This paper summarizes the results of the first published technology readiness assessment completed across the entire life cycle of a deep borehole repository. Overall, the deep borehole concept is at a sufficient technical maturity (TRL>4) to proceed to the conceptual level of design. Some technical processes, such as fuel storage and handling and certain monitoring techniques, are technically mature and would not require further demonstration; however, there would be value in demonstrating the full end-to-end solution including these mature technologies. The key items identified for regulatory requirements clarification, technology development, and prototype demonstration in relevant and target environments are validated and broadly consistent with those independently identified by previous investigations and meetings, such as those by Sandia National Laboratories [9], the Nuclear Waste Technical Review Board [33], and the International Framework for Nuclear Energy Cooperation (IFNEC) [8], and can be summarized as follows:

- **Drilling and borehole stability:** This will be affected by currently uncertain and variable requirements for long-term pre-closure monitoring and retrievability, as well as the borehole geometry, configuration, and site-specific host rock properties and stress environment.

- **Emplacement and retrieval of canisters:** Emplacement of canisters at engineering scale (>10%) should be demonstrated in a relevant environment. As with the point above, modifying the required canister retrieval time period will significantly impact TRL.

- **Emplacement of axial plugs (in the disposal zone):** In a horizontal configuration, current performance assessments show that axial plugs would have a small and potentially negligible effect on long-term safety [22], [34]. Axial plugs may be necessary for the vertical variation of the deep borehole disposal concept (e.g., to avoid canister crushing and thus facilitate retrieval).

- **Closure (permanent seals):** Components of borehole seals (specialized cements, clay mixtures) have been studied in the laboratory [35], [36] and in other configurations[37], [38], but long-term performance with prototypical diameters, depths, and chemical conditions has not been demonstrated. The TRL also depends on design requirements placed on permanent seals, which are suggested by current performance assessments to be lower than for mined repositories [22], [34]. Carbon capture and sequestration projects could provide relevant data.

This represents a first pass at quantitatively assessing the technology readiness of DI's proposed deep borehole disposal concepts and future iterations will add and further refine the TRA.

REFERENCES

[1] "Technology Readiness Assessment Guide," U.S. Department of Energy, DOE G 413.3-4A, 9-15-2011, 2011.

[2] "Program and Project Management for the Acquisition of Capital Assets," Department of Energy, DOE O 413.3B, Chg 5, Apr. 2018.

[3] "NASA systems engineering handbook," Diane Publishing, NASA SP-2016-6105 Rev2, 2010.

[4] "Guide to Technology Readiness Levels for the NDA Estate and its Supply Chain," Nuclear Decommissioning Authority (NDA), EDRMS No. 22515717, Nov. 2014.

[5] B. W. Arnold *et al.*, "Research, development, and demonstration roadmap for deep borehole disposal," *SAND2012− 8527P Albuq. NM Sandia Natl. Lab.*, 2012.

[6] B. W. Arnold *et al.*, "Deep Borehole Disposal Research: Demonstration Site Selection Guidelines Borehole Seals Design and RD&D Needs.," Sandia National Lab.(SNL-NM), Albuquerque, NM (United States), 2013.

[7] A. Sowder, R. McCullum, and V. Kindfuller, "Why demonstration of a deep borehole disposal concept matters to the nuclear industry," presented at the Proceedings of the International High-Level Radioactive Waste Management Conference, 2015.

[8] S. Tyson and T. Zagar, "Understanding Deep Borehole Disposal Technology in the context of Spent Fuel and High-Level Radioactive Waste Disposal: History, Status, Opportunities and Challenges," presented at the IFNEC Reliable Nuclear Fuel Services Working Group, Nov. 04, 2020.

[9] G. Freeze, D. Sassani, P. V. Brady, E. Hardin, and D. Mallants, "The Need for a Borehole Disposal Field Test for Operations and Emplacement," presented at the Waste Management Symposia, Pheonix, Arizona, Mar. 2021.

[10] C. Parker, B. Madru, F. Brundish, J. Mathieson, and N. A. Chapman, "Implementing Deep Borehole Disposal of Radioactive Waste: preliminary results from a study of stakeholder views across the regulatory, policy and practitioner communities," Vienna, Austria, Nov. 2021.

[11] D. J. Hill, "Global Nuclear Energy Partnership Technology Development Plan," Idaho National Laboratory (INL), 2007.

[12] Z. Liu and J. Fan, "Technology readiness assessment of small modular reactor (SMR) designs," *Prog. Nucl. Energy*, vol. 70, pp. 20–28, 2014.

[13] W. Carmack, L. Braase, R. Wigeland, and M. Todosow, "Technology readiness levels for advanced nuclear fuels and materials development," *Nucl. Eng. Des.*, vol. 313, pp. 177–184, 2017.

[14] S. D. Sevougian and R. J. MacKinnon, "Technology Readiness Assessment Process Adapted to Geologic Disposal of HLW/SNF.," Sandia National Lab.(SNL-NM), Albuquerque, NM (United States), 2017.

[15] J. Bahr *et al.*, "Geologic Repositories: Performance Monitoring and Retrievability of Emplaced High-Level Radioactive Waste and Spent Nuclear Fuel," Nuclear Waste Technical Review Board, May 2018.

[16] IAEA, "Disposal of Radioactive Waste, Specific Safety Requirements No. SSR-5," 2011.

[17] IAEA, "Geological disposal facilities for radioactive waste," *Specif. Saf. Guide Int. At. Energy Agency Saf. Stand. Ser. No SSG-14*, p. 124, 2011.

[18] "Design Principles and Approaches for Radioactive Waste Repositories," International Atomic Energy Agency (IAEA), No. NW-T-1.27, 2020.

[19] "Geological Disposal of Radioactive Waste: Technological Implications for Retrievability," International Atomic Energy Agency (IAEA), No. NW-T-1.19, 2009.

[20] "Monitoring of Geological Repositories for High-Level Radioactive Waste," International Atomic Energy Agency (IAEA), IAEA-TECDOC-1208, 2001.

[21] S. Finsterle, R. A. Muller, J. Grimsich, E. A. Bates, and J. Midgley, "Post-Closure Safety Analysis of Nuclear Waste Disposal in Deep Vertical Boreholes," *Energies*, vol. 14, no. 19, 2021, doi: 10.3390/en14196356.

[22] S. Finsterle, C. Cooper, R. A. Muller, J. Grimsich, and J. Apps, "Sealing of a Deep Horizontal Borehole Repository for Nuclear Waste," *Energies*, vol. 14, no. 1, p. 91, 2021.

[23] R. P. Rechard, H.-H. Liu, Y. W. Tsang, and S. Finsterle, "Site characterization of the Yucca Mountain disposal system for spent nuclear fuel and high-level radioactive waste," *Spec. Issue Perform. Assess. Propos. High-Level Radioact. Waste Repos. Yucca Mt. Nev.*, vol. 122, pp. 32–52, Feb. 2014, doi: 10.1016/j.ress.2013.06.020.

[24] R. Stanfors, I. Rhén, E.-L. Tullborg, and P. Wikberg, "Overview of geological and hydrogeological conditions of the Äspö hard rock laboratory site," *Appl. Geochem.*, vol. 14, no. 7, pp. 819–834, 1999.

[25] T. Baldwin, N. A. Chapman, and F. Neall, "Geological Disposal Options for High-Level Waste and Spent Fuel," Jan. 2008.

[26] R. A. Couture and M. G. Seitz, "Movement of fossil pore fluids in granite basement, Illinois," *Geology*, vol. 14, no. 10, pp. 831–834, 1986.

[27] M. Coates, B. Haimson, W. Hinze, and W. Van Schmus, "Introduction to the Illinois deep hole project," *J. Geophys. Res. Solid Earth*, vol. 88, no. B9, pp. 7267–7275, 1983.

[28] J. Beswick, "Status of technology for deep borehole disposal," *Rep. NDA Contract NP*, vol. 1185, 2008.

[29] E. E. Alonso *et al.*, "The FEBEX benchmark test: case definition and comparison of modelling approaches," *Int. J. Rock Mech. Min. Sci.*, vol. 42, no. 5–6, pp. 611–638, 2005.

[30] M. Laaksoharju and S. Wold, "The colloid investigations conducted at the Äspö Hard Rock Laboratory during 2000-2004," 2005.

[31] "Yucca Mountain Safety Analysis Report Chapter 5: Management Systems," U.S. Department of Energy, DOE/RW-0573 Update No. 1, Nov. 2008.

[32] J. Schröder, "Preservation of Records, Knowledge and Memory (RK&M) Across Generations: Final Report of the RK&M Initiative," 2019.

[33] R. Ewing, "Technical Evaluation of the U.S. Department of Energy Deep Borehole Disposal Research and Development Program," Nuclear Waste Technical Review Board, Jan. 2016.

[34] S. Finsterle, "Spent Nuclear Fuel Disposal in a Deep Horizontal Drillhole Repository Sited in Shale: Numerical Simulations in Support of a Generic Post-Closure Safety Analysis," Deep Isolation, DI-2020-01-R0, May 2020. [Online]. Available: https://www.deepisolation.com/wp-content/uploads/2020/03/NumericalSimulations-for-Generic-Spent-Nuclear-Fuel-Disposal-in-Deep-Horizontal-Drillhole.pdf

[35] E. A. Bates, A. Salazar, M. J. Driscoll, E. Baglietto, and J. Buongiorno, "Plug design for deep borehole disposal of high-level nuclear waste," *Nucl. Technol.*, vol. 188, no. 3, pp. 280–291, 2014.

[36] "Sealing deep site investigation boreholes: Phase 2. Final Report," Amec Foster Wheeler, RWM/03/046, Mar. 2018.

[37] R. Pusch, L. Boergesson, and G. Ramqvist, "Final report of the borehole, shaft, and tunnel sealing test - Volume 3: Tunnel plugging," Switzerland, 1987. [Online]. Available: http://inis.iaea.org/search/search.aspx?orig_q=RN:19079185

[38] "News story: First seal of success for borehole project," Radioactive Waste Management, Jun. 2021. [Online]. Available: https://www.gov.uk/government/news/first-seal-of-success-for-borehole-project