Updated Technology Readiness Assessment of Deep Borehole Disposal – 26386

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ABSTRACT

As the demand for nuclear power increases and the global spent nuclear fuel (SNF) and high-level radioactive waste (HLW) inventory grows, the need for disposal solutions also grows. Some countries, such as Finland, Sweden, and Canada, have heavily pursued mined geologic repositories (MGRs) to address SNF and HLW, while other countries are considering alternatives. Deep borehole disposal (DBD) of SNF and HLW has long been considered an alternative and/or supplement to mined geologic disposal. Despite studies showing advantages such as greater modularity, lower cost, and greater siting flexibility for targeted waste forms relative to an MGR, the DBD solution has been hampered by concerns over its technological readiness.

In 2022, Deep Isolation presented a preliminary technology readiness assessment of DBD using the U.S. Department of Energy's (DOE) technology readiness level (TRL) scale. The TRL scale is used to score a system on a 1 to 9 scale through evaluation of sub-processes, where the system TRL is limited to the lowest scoring sub-process. TRL scores between 1 and 3 represent research for a proof of concept, scores between 4 and 6 represent development from lab-scale to somewhat prototypic environment, with a system score of 6 generally considered sufficient for license applications, and scores between 7 and 9 represent efforts toward deployment. Deep Isolation's 2022 TRL assessment scored the least mature of 27 sub-processes at TRL 4 – placing the system as a whole at the Conceptual Design Stage, though the average of all sub-processes was just below 7.

The nuclear, environmental, and drilling industries have made considerable advances since 2022. Additionally, Deep Isolation has made significant progress advancing the readiness of its Universal Canister System (UCS). Specifically, Deep Isolation (with support from its strategic partners) has designed and fabricated UCS prototype canisters and then (under the aegis of the multi-national, non-profit Deep Borehole Demonstration Center) tested their functionality with representative lifting equipment and conducted corrosion testing in a prototypic disposal environment. This paper updates Deep Isolation's 2022 TRL assessment in the light of these advances to the UCS and across industry. The results show all sub-processes now at TRL 6 or higher, with an average TRL right between 7 and 8. This means that DBD as a whole system has moved from the Conceptual Design Stage in 2022 to the Licensing Design Stage in 2025. The paper also evaluates the TRL impact of Deep Isolation's planned large-scale demonstration of horizontal DBD, which would raise the lowest sub-processes to TRL 7 and the average across all DBD sub-processes nearing 8.

The focus of Deep Isolation's TRL assessment is on horizontal DBD, though most sub-processes are also applicable for vertical or deviated boreholes. Though the scoring of this assessment concludes that readiness is sufficient for licensing efforts, further increases to TRL would be beneficial for increasing stakeholder confidence and, per Deep Isolation's cost model methodology, reducing contingency budgets in DBD cost estimates. Following the currently planned demonstration, the areas with the greatest potential for raising DBD TRL include site characterization and monitoring technologies and, if needed for larger inventories in a vertical borehole, axial plugs.

INTRODUCTION

As demand grows for more nuclear power output as a means to sustain consumer electrical demand, enable industrial energy consumers such as data centers, and provide a clean and reliable baseline to offset retiring fossil fuel plants, the need for a permanent disposal solution for spent nuclear fuel (SNF) and high-level radioactive waste (HLW) also grows [1]. Several countries, such as those in the European Union, have even mandated a disposal solution be identified prior to either a set year (e.g., 2050) and/or increasing nuclear power output [2]. Some countries (notably Finland, Sweden, Switzerland, France, and Canada) are investing heavily in mined geologic repositories (MGRs) to fulfill this obligation while others are still considering all options. Deep geologic disposal has long been considered the safest long-term option for addressing SNF and HLW [3], and it comes in two main forms: MGR and deep borehole disposal (DBD). Waste management organizations (WMOs) often consider MGR the default option of deep geologic disposal due to its potential to accommodate SNF and HLW of any geometry and the existing basis of knowledge with projects such as the Waste Isolation Pilot Plant (WIPP) (albeit for defense transuranic waste) [4], Yucca Mountain [5], and Onkalo [6]. Though each MGR will be unique due to geologic, inventory, footprint, and regulatory reasons, many consider the precedent from WIPP and near-operational status of Onkalo [7] to reflect a high technology readiness for MGR. The alternative, DBD, has garnered increasing attention as WMOs, national laboratories, and private industry have studied and noted potential for DBD as modular [8], scalable [9], and potentially much faster to deploy [10] and less expensive [11], [12] than MGR options for a given inventory. While many factors, such as existing national policies and historical precedent, have impeded greater investment in DBD, these factors are largely rooted in the perception of a lower state of technology readiness.

Complex technologies often require programs of research, development, and testing to address technical and programmatic uncertainties prior to full-scale deployment, particularly to address uncertainties with respect to safety. There is international support for collaborative demonstrations to support DBD commercialization [13], [14], [15], [16], [17], [18], though investment in such a demonstration requires confidence in existing technology. Demonstration- and even licensing-readiness are often benchmarked through a technology readiness assessment (TRA). The TRA is a systems engineering approach often used in space [19] and energy [20], [21] sectors in which a system is broken into processes and sub-processes, and each sub-process is assigned a score called a technology readiness level (TRL).

In 2022, Deep Isolation conducted a preliminary TRA [22] for DBD technology, assigning TRLs to each of 27 relevant sub-processes. Though most sub-processes indicated TRLs sufficient for even beginning a license application process, the system TRL is constrained by its lowest scoring sub-processes which were lower. Deep Isolation noted that the lowest scoring sub-processes required some combination of regulatory requirements clarification, technology development, and/or prototype demonstration in relevant and target environments. The lower TRL sub-processes were *Drilling*, *Borehole stability*, *Canister emplacement*, *Retrieval of canisters*, *Axial plugs*, and *Permanent seals*. These findings were consistent with those of Sandia National Laboratories [17], the Nuclear Waste Technical Review Board [23], and the International Framework for Nuclear Energy Cooperation [16].

Since 2022, Deep Isolation has sought to address many of the underlying impediments to the DBD system TRL. Most notably, Deep Isolation has designed, prototyped, tested, and conducted preliminary safety assessments for its universal canister system (UCS) in manners which support revisiting the TRL of *Borehole stability*, *Canister emplacement*, and *Retrieval of canisters* [24], [25], [26]. Additionally, further collaboration with the drilling and adjacent industries have prompted Deep Isolation to revisit Drilling, Axial plugs, and Permanent seals. Though these sub-processes are emphasized, the TRL scores of all 27 sub-processes are considered.

DESCRIPTION

Deep Isolation's TRA, as formulated in 2022, addresses the life cycle of functional and safety relevant processes for DBD. Consistent with systems engineering best practices [27] and IAEA guidance ([28], [29], [30], [31], [32]), Deep Isolation developed a concept of operations for DBD. This concept of operations spans the high-level objectives for each of six key technical processes:

- Site characterization
- SNF storage and handling
- Repository construction (including borehole drilling)
- Canister emplacement
- Pre-closure monitoring
- Closure

From the complete set of structured objectives identified in the concept of operations, 27 sub-processes emerged across the six processes. Each sub-process can be assessed for its technical maturity and, when combined, the assessments culminate in a system-wide assessment. Deep Isolation's generic concept of operations is summarized in Figure 1.

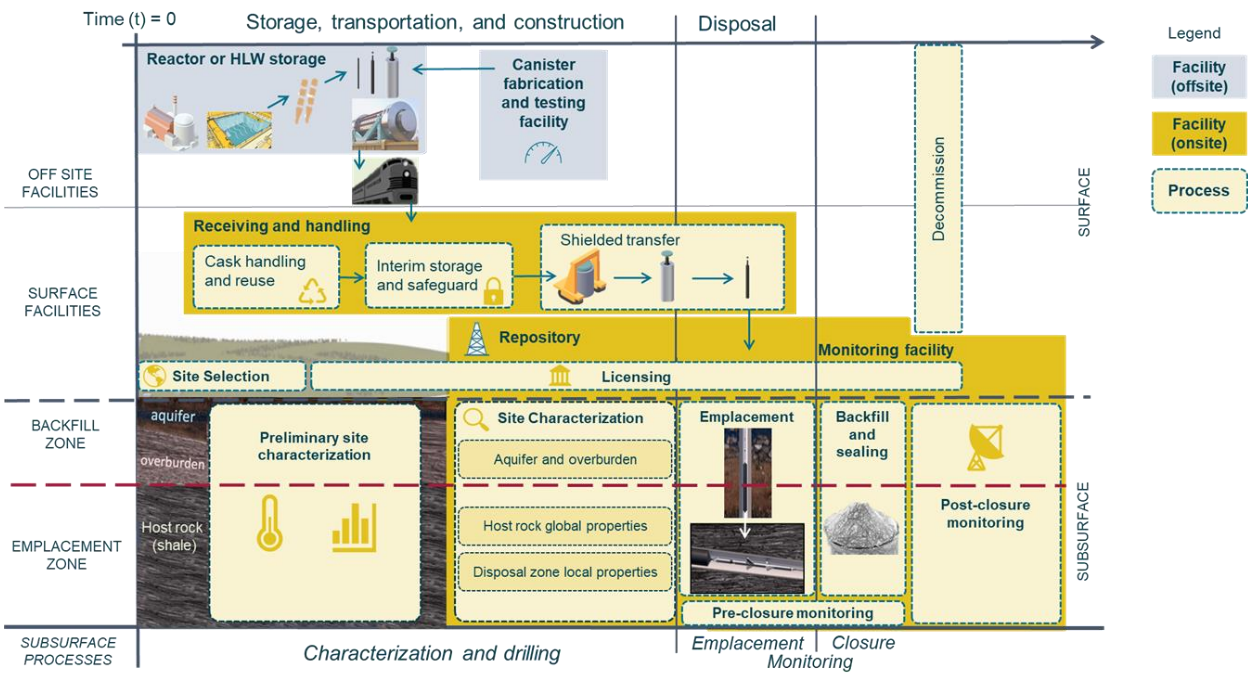

Figure 1. Concept of Operations for a Generic Deep Isolation Borehole Repository [22].

Consistent with the 2022 preliminary TRA, Deep Isolation selected the U.S. Department of Energy (DOE) technology readiness scale due to its broad recognition and acceptance [33]. The DOE TRL scale adapted by Deep Isolation with nomenclature from the U.S. National Aeronautics and Space Administration (NASA) is depicted in Table 1. The stage levels of the 1 through 9 scale indicate that a system merits further, larger-scale concept validation beginning around TRL 3 and that a system is considered ready to initiate a license application process around TRL 6, acknowledging that cost and regulatory approval efficiencies are likely to increase with TRL growth toward 9.

Table 1. Technology Readiness Scale Adapted from US DOE [22].

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)	

*definitions from NASA are used instead of those of U.S. DOE because they are considerably more descriptive [27].

Though elevated TRL scores discussed in this paper through recent advancements in DBD and broader industry research and technology may warrant progression from the *Generic* design stage to either the *Conceptual* or potentially *Licensing* stage of the DOE systems engineering process, Deep Isolation has conducted this TRL update consistent with its 2022 preliminary assessment. This paper does not obviate the need or merit of a formal TRA replete with diverse and, to the extent practicable, independent team members.

DISCUSSION

The 2022 TRL scoring and 2025 updates are juxtaposed by sub-process in Table 2, Table 3, Table 4, Table 5, Table 6, and Table 7 (in chronological process order per the concept of operations). Many sub-processes have not changed in 2025, but for those which have, the change is denoted in **bold**, and the rationale is further elaborated in the paragraph(s) following each respective table.

Table 2. TRL Scoring from 2022 [22] and 2025 for Site Characterization Technologies.

Sub-Process	TRL (2022)	2022 Rationale	TRL (2025)	2025 Rationale
Geological environment	6	Geologic environments (aquifers, host rock, transport paths) have been characterized for Yucca Mountain [34] and rock laboratories [35], however, specific host rock characterization methods may need to be proven at scale and depth for deep boreholes (e.g., fracture connectivity).	**7**	***Increased*** due to site evaluation framework [36] and preliminary acceptance criteria providing confidence parameters are measurable within range.
Surface environment	9	Relevant surface characteristics for many sites are already largely determined.	9	No change.
Subsurface processes	6	Prototypical characterization methods have been demonstrated in a relevant environment [37], [38].	**7**	**Increased** due to similar reasons as *Geological environment*.

Geological Environment and Subsurface Processes: Deep Isolation has constrained its UCS design to depths not exceeding 2 km. This limit is unlikely to be surpassed in horizontal DBD, though additional analysis may be warranted to support vertical or slanted DBD at depths to 3 km. Geological environment and subsurface processes to these depths have been characterized in a wide range of lithologies including shale (envisioned for horizontal DBD) and granite (envisioned for vertical or slanted DBD). Using broad geological data sets as a basis, Deep Isolation developed a comprehensive range of possible values for relevant geologic parameters such as host rock thickness, permeability, and geothermal gradient for use in preliminary and generic post-closure safety assessments [39], [40], [41], [42], [43]. Within these assessments, limiting values across the range of a given parameter are investigated for their influence on peak dose rate to a maximally exposed individual and peak UCS temperature, and results have indicated acceptability of a broad range of potential host rock attributes through normal circumstances and in the presence of potentially credible features, events, and processes. Based on such studies, Deep Isolation published a site evaluation framework in which threshold values for rock properties, proximity to and prevalence of subsurface and surface processes, and economic factors such as drillability and transportability formulate site screening criteria [36]. In feasibility studies for multiple countries since developing the site screening criteria, Deep Isolation has found that after application of these criteria a considerable proportion if not a majority of the country remains viable for DBD. These studies also led Deep Isolation to publish a range of reference shale host rock properties consistent with the studies and enveloping of shales from multiple continents [44]. Thus, while legal and regulatory conditions impede the selection of a specific site and its corresponding geology and processes, there is sufficient basis to conclude that the *Geologic environment* and *Subsurface processes* of locations which could be technically viable for DBD have been adequately characterized with existing technology. Therefore, Deep Isolation considers both of these sub-processes TRL 7.

Table 3. TRL Scoring from 2022 [22] and 2025 for Repository Construction Technologies.

Sub-Process	TRL (2022)	2022 Rationale	TRL (2025)	2025 Rationale
Drilling	5	Deep horizontal drilling is common, but limited examples where large-diameter deep holes (greater than 0.30 m) have been drilled.	**6**	***Increased*** due to detailed design reviews with drilling partners.
Site characterization of excavation disturbed zone (EDZ)	6	EDZs have been characterized for mined repositories (relevant environment). Borehole breakout zones have been characterized for deep boreholes down to 4 km [45].	6	No change.
Site characterization of thermo-mechanical properties of host rock	7	Proven successfully at a full scale in mined repositories (relevant environment) [46]. Relative importance of local thermo-mechanical phenomena in disposal zone for long term safety is likely to be lower for deep boreholes than mined repositories.	7	No change.
Monitoring system insertion	9	Monitoring systems have been inserted for drilling applications.	9	No change.
Borehole stability	4	Depends heavily on required (and variable) pre-closure monitoring and retrievability periods and also on host rock, repository configuration, geometry [45]. Long term stability (>50 years) for horizontal holes at size required for PWR assemblies (~0.34 m) has not been demonstrated (additional study needed).	**6**	***Increased*** due to corrosion testing results [26] providing confidence in structural stability over design life.
Thermal management	9	Proven successfully in drilling industry.	9	No change.
Waste management	7	Proven successfully in drilling industry, but not in presence of SNF.	7	No change.

<u>Drilling</u>: The 2022 TRL scoring of *Drilling* was predicated on the novelty at the time of horizontal borehole drilling and the lack of a representative borehole drilled to-date (in terms of diameter and depth). There is precedent for the depths and diameters associated with vertical DBD [45], making this configuration the least limiting from a TRL perspective. While horizontal drilling remains the limiting method for TRL in this sub-process, discussions with strategic drilling partners have led Deep Isolation to believe that the current lack of precedent for larger diameter and deep boreholes in a horizontal configuration is more a function of insufficient commercial incentive rather than technical hurdles. Deep Isolation does note that horizontal DBD is likely to encounter (at least near-term) diametric limitations before vertical DBD for similar depths. Therefore, the largest diameter UCS design (Class 3) is currently assumed to not be compatible with horizontal DBD. Even without prototypic precedent, however, there appear to be existing horizontal boreholes with diameter and depth profiles exceeding 10% of Deep Isolation's assumed configuration. Thus, *Drilling* warrants a TRL of 6.

<u>Borehole Stability</u>: The required design life of the borehole varies by stakeholder and whether their expectations are tied to MGR design. MGR concepts generally have an increased reliance on engineered barrier performance for operational periods relative to DBD, potentially spanning several decades followed

by some reliance on the repository structure's post-closure performance for hundreds to even thousands of years [5], [47], [48]. For DBD, the only function for which the borehole is relied upon is integrity throughout emplacement and closure operations. Once all canisters are emplaced, closure operations could technically begin. U.S. regulations, however, suggest a pre-closure performance confirmation period of approximately 50 years [49], [50]. This assertion appears rooted in the time estimated to construct, operate, and close the Yucca Mountain repository. Given that construction, emplacement, and closure operations of a single borehole could conceivably be accomplished within a year [10], a shorter performance confirmation period may be warranted and could yield considerable operational, economic, and risk reduction benefits to DBD. Nevertheless, corrosion testing conducted by Deep Isolation and the Deep Borehole Demonstration Center in 2024 and reported in 2025 asserted that *in-situ* corrosion rates of ferrous alloys in borehole disposal conditions are sufficiently low (largely due to anoxic conditions achieved through high hydrostatic pressure) to support a 300-year design life for the casing and canisters following emplacement [26]. This assumption has considerable margin relative to the estimated maximum design life, which accounted for galvanic and general corrosion but did not include radiation embrittlement and microbially-induced corrosion[1]. Given the material testing, regulatory assumptions, and supporting analyses to-date, Deep Isolation asserts that borehole stability is at least TRL 6. Should a WMO require a longer design life, there is sufficient margin in the existing UCS design and flexibility for design modification to support this. Conversely, should stakeholders determine a shorter design life is acceptable, then *Borehole stability* could potentially be prototypically demonstrated at a full scale demonstration in the near future, providing the opportunity for higher TRL and/or potential system cost reductions.

Table 4. TRL Scoring from 2022 [22] and 2025 for Fuel Storage and Processing Technologies.

Sub-Process	TRL (2022)	2022 Rationale	TRL (2025)	2025 Rationale
Fuel storage	9	Fuel storage (wet, dry) has been implemented.	9	No change.
Component reuse	9	Cask decontamination, reuse, and disposal has been implemented.	9	No change.
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.	6	No change.
Fuel handling	9	Operationally proven (at reactors, above surface).	9	No change.

No updates to TRL were identified for *Fuel Storage and Processing Technologies*. Its limiting sub-process, *Fuel packaging*, will not advance until prototypic equipment and procedures are developed to stage, load, and seal SNF and HLW into the UCS.

[1] Microbially-induced corrosion in DBD may be significantly delayed or even arrested due to cement separating the canister and casing. Should microbes eventually contact the casing and/or canisters, higher temperatures nearer the canister may further retard microbial attack through combined heat loading of waste form and ambient temperature, replicating thermal conditions at depths known to impede microbial activity [51].

Table 5. TRL Scoring from 2022 [22] and 2025 for Emplacement Technologies.

Sub-Process	TRL (2022)	2022 Rationale	TRL (2025)	2025 Rationale
Worker safety	7	Operationally proven in a similar environment at reactors and storage facilities.	7	No change.
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.	7	No change.
Canister emplacement	5	Prototype operated in target environment (but not at full scale) and with required reliability.	**6**	***Increased*** with lift testing.
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 SNF.	7	No change.
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.	**6-8**	***Increased.*** May be N/A for horizontal DBD. Applicable for vertical boreholes. For those, filling annular space with cement after stacking several canisters would alleviate concern and be highly precedented (TRL 8). If an engineered removable plug is needed, however, these exist in industry but not currently of the diameter sought (TRL 6).
Canister retrieval	5	Has been demonstrated at a lower scale, not at full geometric or timescales and including effects of seals and monitoring systems.	**6**	***Increased*** with lift testing.

Canister Emplacement and Canister Retrieval: The UCS is designed for compatibility with existing shielding and conveyance equipment in the nuclear dry storage and transport industry (through design work with NAC International, Inc.). Some of these systems may need to be scaled down for application of conveying a single UCS (as opposed to an entire dry storage cask), but this scaling down can be done with high confidence as evidenced by the *Fuel handling* sub-process. The UCS is also designed with a lift adapter capable of engaging and disengaging with multiple tools endemic to the oil and gas industry. The simplest engagement would be with a wireline or coiled tubing unit, and this can be bolstered with a tractor or similar device as needed. The UCS has been prototyped multiple times and tested for engagement and retrieval in various environments, providing adequate representation except for the length of "blind" access to the lift adapter. Upcoming demonstration plans through the Deep Borehole Demonstration Center intend to demonstrate emplacement and retrieval operations in a prototypic deep borehole. Prior to this demonstration, however, Deep Isolation contends that *Canister emplacement* and *Canister retrieval* have been demonstrated at a scale between 10% and 100%, warranting TRL 6 with potential to increase further in the near future. The UCS design analysis has also considered normal and off-normal events such as stuck and dropped canister events and showed sufficient margin in post-event structural integrity to not invalidate the finding of TRL 6 at this time [52].

Axial Plugs: The primary intent of axial plugs is to alleviate stacking loads in vertical or slanted DBD. This sub-process is not necessary for horizontal DBD or for small inventory vertical/slanted DBD in which the quantity of canisters needed is below the limit identified in the UCS stacking analysis (part of the UCS design report, which has not been made public). For DBD scenarios in which axial plugs are necessary, there are two sorts of approaches. The simplest and arguably higher TRL approach would be to cement or otherwise set canisters in place concurrent with the emplacement process prior to stacking beyond the threshold number of canisters. The act of setting items in place with a simple fluid or particle-based filling agent is a well-understood process, particularly in a vertical or near-vertical borehole. Though this may not have been done in the exact circumstance as DBD of SNF/HLW, there is likely enough precedent cementing items in place down hole to justify up to TRL 8. If a longer and/or more restrictive performance confirmation requirement renders this approach untenable, then the axial plug would need to be a mechanical device capable of conveying to a desired depth then engaging with the borehole casing and being able to distribute a stacking load of several canisters. Market research and dialogue with drilling partners have led Deep Isolation to believe such axial plugs exist at a scale between 10% and 100% of the diametric and load-bearing requirements envisioned for use in its DBD concepts. Therefore, *Axial plugs* are considered governed by this state of the art at TRL 6.

Table 6. TRL Scoring from 2022 [22] and 2025 for Pre-Closure Monitoring Technologies.

Sub-Process	TRL (2022)	2022 Rationale	TRL (2025)	2025 Rationale
Seepage rate	9	Proven successfully in drilling industry.	9	No change.
Seismic	9	Operated successfully.	9	No change.
Waste canister integrity	8	Tracers have been operational in the drilling industry in a relevant environment (not in the presence of nuclear waste).	8	No change.
Natural barriers (EDZ)	6	Monitoring systems for host rock and preferential flow paths have been developed for enhanced geothermal systems (relevant environment).	6	No change.

No updates to TRL were identified for *Pre-Closure Monitoring Technologies*. Its limiting sub-process, *Natural barriers (EDZ)*, will require full-scale demonstration in order to advance.

Table 7. TRL Scoring from 2022 [22] and 2025 for Closure Technologies.

Sub-Process	TRL (2022)	2022 Rationale	TRL (2025)	2025 Rationale
Permanent seals	5	Components have been validated in a similar environment (e.g., SKB, Äspö Hard Rock Laboratory [53], FEBEX [46]).	**6-8**	***Increased.*** Near-surface seals for safeguards purposes are highly mature and precedented in the drilling industry (TRL 8). If needed downhole, cementing would also be mature (TRL 8). Alternatives which do not restrain canisters may not yet be at full scale (TRL 6).
Decommissioning	7	Proven successfully (drilling rigs, storage facilities, nuclear reactors).	7	No change.
Risk of human intrusion	6	DOE designed monuments for Yucca Mountain [54] and other technical measures to deter humans have been developed but not deployed [55].	**7**	***Increased*** due to bounding nature of the Finnish ONKALO repository relative to a borehole repository with lower intrusion likelihood (smaller diameter, deeper).

Permanent Seals: The rationale for *Permanent seals* TRL scoring is similar to that of *Axial plugs*. Cementing canisters in place concurrent with or after emplacement would be the simplest approach to downhole sealing and could result in TRL 8. If, however, a requirement exists to avoid sealing canisters in place, then a more elegant solution may required. Such seals could either be mechanically, thermally, and/or chemically activated. Some examples of validation testing were identified in 2022, and upon further consideration after discussions with drilling partners, Deep Isolation considers that drilling industry and laboratory state-of-the-art can accommodate at least 10% of the diametric and environmental scale sought for a prototypic demonstration. Thus, *Permanent seals* are assigned TRL 6.

Human Intrusion: The risk of inadvertent human intrusion has been considered acceptable for MGR concepts to proceed toward operation. While longer institutional control periods and safeguards approaches may be necessary for an MGR relative to DBD, these potential scope additions do not appear to hinder the TRL of the MGR concept. With this in mind and considering that DBD involves depths multiple times that of MGRs with access shafts deliberately smaller than those which could be accessed by humans going to waste disposal zones at depths in which oxygen is scarce and ambient pressures are beyond those of human survivability, inadvertent human intrusion appears implausible, particularly without extensive drilling infrastructure and access to geologic information systems. Moreover, Deep Isolation's site evaluation criteria preclude siting near any known or perceived underground resources for current or future use [36]. Deep Isolation thus considers Risk of human intrusion to be minimal and at TRL 7, acknowledging that this topic will be revisited when specific sites are considered and stands to increase as permanent seals increase.

Based upon these updates to TRL scores, Deep Isolation asserts that the system is at TRL 6 with several sub-processes and even whole processes at TRL 7 and above. The results of this updated preliminary TRA are summarized in Figure 2.

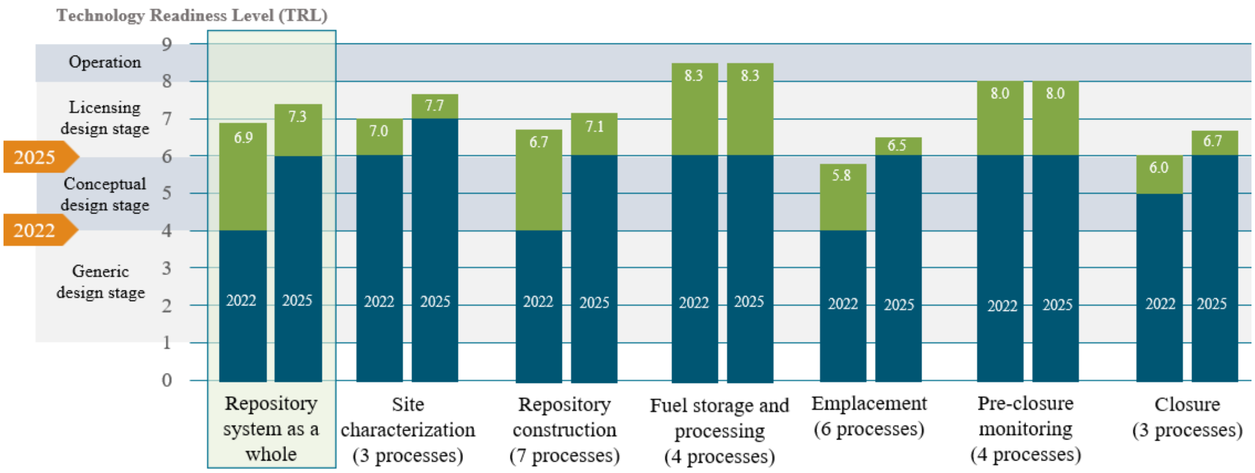

Figure 2. TRL evolution overview displaying limiting sub-process TRL (blue) against average TRL for process (green) between 2022 and 2025.

Though these TRL updates correspond with licensing application readiness, further TRL advancement will bolster the system for technical, economic, and regulatory implementation. To that end, Deep Isolation and the Deep Borehole Demonstration Center are planning a full-scale technology demonstration to complete by 2028 with goals of increasing system TRL, particularly through advancing *Repository Construction* and *Emplacement* processes.

Following a successful demonstration, further TRL advancement may be tailored to a small number of subprocesses (e.g., monitoring technology) or may be system-wide in the case of implementation. First implementation is anticipated to elevate all subprocesses to at least TRL 8, but a system-wide score of TRL 9 is not anticipated until multiple successful disposal programs have been implemented.

CONCLUSIONS

In its 2022 preliminary technology readiness assessment [22], Deep Isolation concluded that the DBD system TRL was limited to TRL 4. Through broad industry advances and specific innovations at Deep Isolation, this DBD system score (lowest scoring sub-process) has advanced to TRL 6 in 2025. This advancement indicates that DBD technology has been validated in a relevant environment and is suited for initiation of a license application process toward full-scale deployment. A license application process for any first-of-a-kind technology, particularly one in the nuclear sector, is likely to be an iterative, multi-year process. To help address technical and programmatic uncertainties prior to and concurrent with such a process, the technological maturity of DBD should continue to advance and the justifications should be refined.

To advance stakeholder confidence in and technological maturity of DBD technology, the Deep Borehole Demonstration Center is planning to drill a representative borehole for non-radioactive testing of DBD sub-processes such as canister emplacement, retrieval, borehole stability, and monitoring. This demonstration effort, coupled with a more comprehensive TRA for the DBD system would be beneficial in illustrating the readiness of DBD for deployment to stakeholders and regulators.

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