A Framework for Streamlining RD&D Activities for Deep Borehole Disposal

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ABSTRACT

Australia is evaluating deep borehole disposal as a potential solution for its long-lived intermediate level waste. The project will aim to demonstrate by means of a comprehensive RD&D program the technical feasibility and the long-term safety of vertical borehole disposal. The RD&D activities include demonstration of surface handling and full-scale field testing of waste/seal emplacement capabilities in a demonstration borehole whose dimensions are nominally put at 0.7 m diameter and 2000 m deep. Pre- and post-closure safety assessments and safety case development are an integral part of the project. The paper introduces a preliminary msulti-barrier system for deep borehole disposal and assigns safety functions to each of its components. We then provide an overview of the framework that has been developed to streamline the RD&D activities. Several example activities are briefly introduced, while more detailed reports on these RD&D activities are provided in several companion papers.

INTRODUCTION

Deep borehole disposal (hundreds to thousands of metres) is being considered around the world for high-level waste (HLW), spent nuclear fuel (SNF), separated plutonium wastes and some very high specific activity fission-product wastes - its modularity being one of the major advantages over traditionally mined geologic disposal facilities (GDF) [1, 2, 3]. In Australia, long-lived intermediate level waste (ILW) from research reactors and radiopharmaceutical production represents the principal waste stream that requires deep geologic disposal. Whilst the Australian Government has not yet made a decision on its preferred strategy for ILW disposal, it is anticipated that deep borehole disposal of small volumes of appropriately conditioned ILW would be a more cost-effective, and modular, solution compared to a conventional GDF. In a recent review of the state of the science and technology in deep borehole disposal, the recommendation was made that “there was a sufficient knowledge base to plan and execute field-based demonstration projects that address key elements of borehole disposal, including deep drilling of wide-diameter holes, waste emplacement testing and seal emplacement and performance monitoring” [3]. The waste emplacement testing could be undertaken in a phased manner, initially using a shallow borehole with surrogate canisters to test surface handling, emplacement, and safety protocols before moving to a full-scale field-testing in a deeper borehole [4].

CSIRO (Commonwealth Scientific and Industrial Research Organisation) – Australia’s National Science Agency –, ANSTO (Australian Nuclear Science and Technology Organisation), and SANDIA National Laboratories (USA) have therefore created an international partnership to work towards the execution of a full-scale borehole research, development and demonstration (RD&D) project in Australia.

The project will aim to demonstrate the technical feasibility, operational and post-closure safety of borehole disposal in deep geological formations. The RD&D includes demonstration of surface handling and waste/seal emplacement capabilities, basic research on foundational science areas, and full-scale field testing in a large-diameter demonstration borehole. Currently the maximum borehole depth has been put at 2000 m, while a borehole diameter of approximately 0.7 m or 27.5 inch is considered, and (1) suitable to accommodate disposal containers with an estimated diameter of approximately 0.53 m [5] and (2) technically feasible based on reviews of available drilling technology [6].

The preliminary design of a deep vertical borehole concept for disposal of Australia's long-lived ILW has so far been focused on those waste packages that will likely have the highest concentration of long-lived radionuclides, i.e., the vitrified waste from the reprocessing of research reactor fuel from the HIFAR (High Flux Australian Reactor) and OPAL (Open Pool Australian Light water reactor) reactors at ANSTO, Lucas Heights (NSW). This waste stream will produce an estimated 100 CSD-U stainless-steel containers (Conteneurs Standards de Déchets Vitrifiés/CSD-U: verres UMo), each 180 L. It is anticipated that for those appropriately conditioned wastes, relatively deep boreholes will be a feasible and safe solution. It is of note that the total expected volume of the CSD-U waste (approximately 20 m^3), represents a small fraction (i.e., < 1%) of the total estimated ILW volume generated by ANSTO (about 3060 m^3, comprising legacy and future arisings [7]). Other waste streams that may require deep borehole disposal include Synroc wastes (about 150 m^3) from the treatment of liquid waste streams from Mo-99 production [8] and spent uranium filter cups from Mo-99 production (between ~10 - 20 m^3, depending on conditioning method). The volumes of these waste streams are estimated to be less than for ILW waste streams with a much smaller activity concentration of long-lived radionuclides; therefore, shallower disposal in silo-type facilities may be anticipated.

To prepare for a field-based deep borehole demonstration test in Australia, generic post-closure performance and safety assessments have commenced to evaluate the effect of disposal depth and geological environment on radiological impact, and to identify influential parameters [5, 9]. The assessments also facilitate establishing a modelling framework that, while initially generic, can be gradually refined with site-specific data once the demonstration project evolves from being generic to becoming more site-specific.

The paper first discusses the multi-barrier system for the deep disposal borehole concept for long-lived ILW and the safety functions associated with each barrier. Next, the framework is introduced that will streamline the RD&D activities that will be undertaken as part of the demonstration test, and that will support future siting efforts and ultimately the development of a safety case. Results from several such foundational research activities will be discussed in several companion papers [10, 11, 13, 14, 15].

MULTI-BARRIER SYSTEM AND SAFETY FUNCTIONS

In analogy with the multi-barrier system for conventional GDFs, the multi-barrier system specific to a deep borehole disposal concept is defined. In the current concept for ILW disposal, five barriers are considered for CSD-U canisters containing vitrified waste from reprocessing of spent research reactor fuel (Fig. 1) (for barrier #1 and #2 different materials are expected for different waste streams, e.g., a Synroc immobilization matrix for waste streams from Mo-99 production):

- #1: The borosilicate glass matrix of the CSD-U canister, with a very slow dissolution rate, is expected to fulfil its safety function throughout the isolation phase for a period of at least 10,000 years [16, 17];
- #2: The stainless-steel primary package of the CSD-U canister, with a slow corrosion rate, will also contribute to long-term safety during the isolation phase for a similar period as barrier #1 [16, 17];

- #3: The disposal container or overpack, considered to have a mild steel structural component with a corrosion resistant coating, expected to be functional at least during - and possibly beyond - the thermal phase (which is rather short for the CSD-U ILW, see further);
- #4: Borehole seals may have a mechanical function (concrete) or a hydraulic function (compacted bentonite), and are expected to fulfil their safety function during the isolation phase, for at least 10,000 years [18];
- #5: The geological environment, which is the deep host rock with a very thick geological coverage, provides for the geological isolation, typically millions of years.

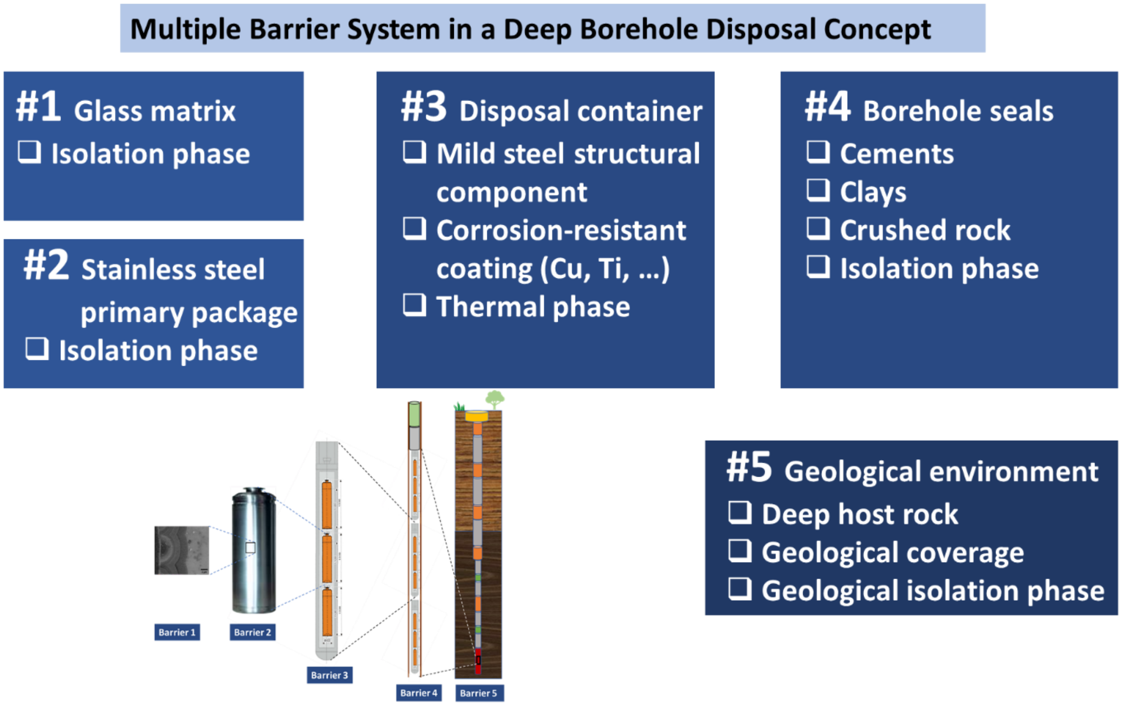


Fig. 1. Multi-barrier system for deep borehole disposal of long-lived ILW.

For each of the barriers identified above, safety functions are defined. There are typically three safety functions [19]:

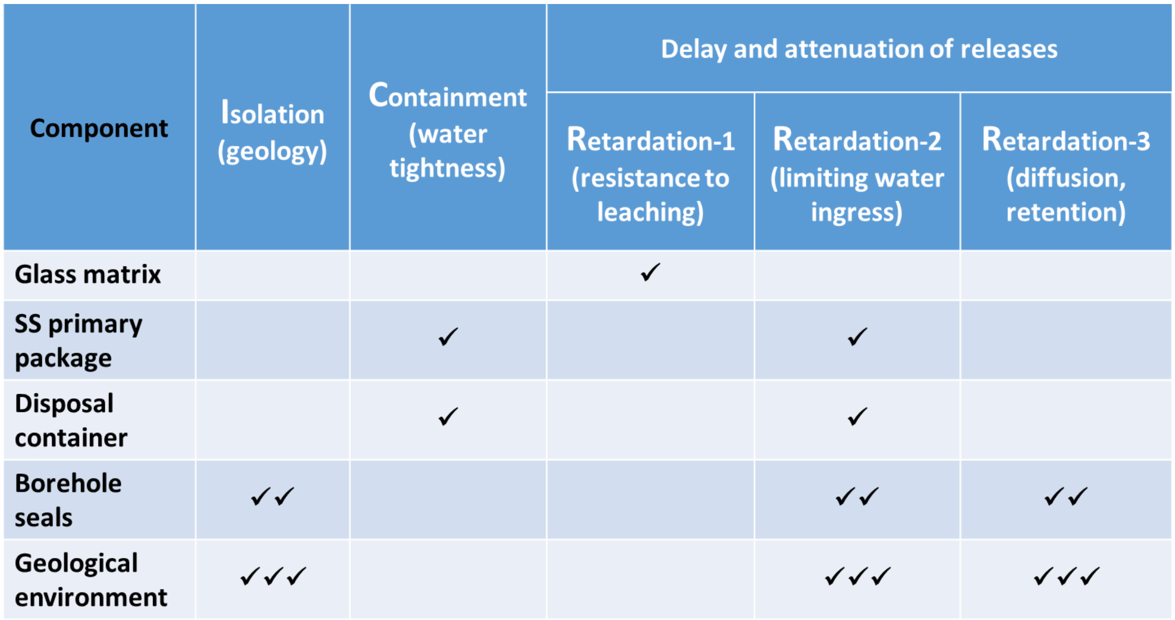
- The I safety function or isolation of the waste from the human environment;
- The C safety function or engineered containment;
- And the R safety function which refers to delay and attenuation (diffusion and retention) of radionuclide releases.

Each component of the multi-barrier system contributes to one or more safety functions (TABLE 1; ✓ = depth independent; ✓✓,✓✓✓ = scalable with depth, where geology has overall greatest contribution compared to seals):

- The glass matrix contributes to the “Resistance to leaching” safety function owing to its very slow dissolution;
- The stainless-steel primary package contributes to “Engineered containment” because of its water tightness during the thermal period and beyond and also contributes to “Delay and attenuation” (that is limiting water ingress) over the very long term;

- The disposal container contributes to “Containment” during the thermal period and contributes to “Limiting water ingress” beyond that period;
- Borehole seals provide for the “Isolation function” and contribute to “Limiting water ingress” and “Slow transport due to diffusion and retention (adsorption)”;
- The geological environment provides for “Isolation” at the geological timescale, contributes to “Limiting water ingress” because of its low permeability at great depth, and also contributes to “Diffusion and retention (adsorption)”.

TABLE I. Safety functions for the deep borehole multi-barrier system.



Component	Isolation (geology)	Containment (water tightness)	Delay and attenuation of releases		
			Retardation-1 (resistance to leaching)	Retardation-2 (limiting water ingress)	Retardation-3 (diffusion, retention)
Glass matrix			✓		
SS primary package		✓		✓	
Disposal container		✓		✓	
Borehole seals	✓✓			✓✓	✓✓
Geological environment	✓✓✓			✓✓✓	✓✓✓

A unique feature of deep borehole disposal is that the contribution of borehole seals and the geological environment is scalable with depth, i.e., the deeper the borehole the greater the contribution of these two components to long-term safety. Finally, note that in this concept, other than the glass matrix, primary package, and disposal container, there are no other engineered barriers at the disposal zone. This is justified once the borehole is deep enough such that the main contributors to isolation and containment are the geology and the seals.

The above multi-barrier system and safety functions were derived for vitrified waste from the reprocessing of research reactor fuel. Other waste streams with long-lived ILW will likely be immobilized with the Synroc technology which also provides for a very durable waste form [6]. The demonstration project will in due course develop a slightly modified multi-barrier concept and safety functions for Synroc and other waste forms.

STREAMLINING RD&D ACTIVITIES

Streamlining of the RD&D activities is driven by the safety functions which the borehole concept must fulfil. For the five safety functions defined previously to be useful and practical to implement, they require translation into pragmatic and measurable system and component behaviour. By analogy with the Safety and Feasibility Statements trees developed by NIRAS/ONDRAF for geological disposal of HLW and SNF in Belgium [19], we define a framework for streamlining the RD&D activities based on Safety and Feasibility Statements specific for deep borehole disposal.

Additional RD&D activities that will further support the safety case with both qualitative and quantitative evidence as per the NEA safety case framework [20] and its adaptations for deep borehole disposal [2] are grouped under Confidence Enhancement activities (Fig. 2). The traffic lights in Fig. 2 refer to the progress in each of these activities, where red means work has not yet commenced, amber means work is in progress and green refers to work being completed. This version of the framework is preliminary while also traffic lights will be progressively updated as the RD&D program matures.

SAFETY STATEMENTS

Three safety statements are considered that underpin the confidence in the long-term safety of deep borehole disposal (Fig. 2):

- Safety functions will provide long-term passive safety by contributing to containment and isolation;
- Performance and safety of the borehole disposal system meets regulatory and external requirements and the evolution of the borehole disposal system (including the waste) and its environment are sufficiently known;
- Residual uncertainties about the disposal borehole and its environment will not impair the long-term safety; any unresolved issues can be addressed by future RD&D.

The RD&D activities to confirm the I, C, and R safety functions of the different elements will focus on:

- For the I safety function: demonstrate how the seals and the geological environment will contribute to long-term isolation of the waste isolated from humans.
- For the C safety function: demonstrating sufficiently long containment of the primary package (stainless steel canister) and overpack/disposal container.
- For the R safety function: demonstrating diffusion dominated transport for the host rock and seals, quantifying sorption potential of the host rock, and testing disposability of the glass and synroc waste matrices under deep borehole conditions (extreme conditions of T, P, and C),

Isolation provided by seals

Borehole seals provide for the “Isolation function”, while also contributing to “Limiting water ingress” and “Slow transport due to diffusion and retention (adsorption)”. The long-term performance of clay-based and cement-based seals in a deep borehole environment has recently been reviewed [21]. These reviews considered only investigation boreholes, without the complexities typical of a large-diameter disposal borehole (e.g. longer isolation times required, heat production from waste, etc). An RD&D program on borehole seals specific for disposal boreholes is being planned.

Containment provided by the primary package

For deep disposal of various long-lived ILW wastes, a one-size-fits-all disposal container or overpack in accordance with the multi-barrier systems is considered (Fig. 1). One such potential canister design involves a relatively inexpensive carbon steel canister (as structural component) with a durable corrosion resistant coating. Cold spray of copper onto disposal canisters is a potentially economic way to add corrosion and wear resistant coatings. An experimental program is underway to test the performance of various cold spray coatings under chemical and mechanical stresses characteristic of a deep borehole environment [10].

Demonstrating diffusion-dominated transport for the host rock and seals

Several activities have commenced to demonstrate diffusion-dominated transport for a potential host rock, including determination of petrophysical properties (permeability, porosity) on crystalline rock samples [11, 12], the measurement of noble gases in mineral fluid inclusions [15], and the measurement of hydrogen diffusion through bentonite.

A key feature of a suitable host rock for borehole disposal is to have a very low permeability and diffusion dominated chemical transport, such that the containment of radionuclides is guaranteed for a sufficiently long time (safety function Delay and Attenuation, TABLE I). The permeability is also an important input parameter for post-closure safety assessments, where numerical models of flow and transport are used to estimate the radionuclide migration from the disposal zone into the surrounding host rock and geosphere. To this end, permeability and porosity measurements of granite rock samples from 700 – 1900 m depth have been undertaken. Results at 17.3 MPa effective pressure show very low permeabilities of around 0.5-7,5 micro Darcy ($2\times10^{-12} – 3\times10^{-11}$ m/s) with very low porosity in the range 0.02-1.2%. Results further show that porosity and permeability increase and rocks becoming more stress sensitive as mineral alterations of feldspars into Muscovite or Kaolinite increase [11, 12]. As no site for a test borehole has been identified yet, the results will mainly be used to inform concept development and site selection.

A second method to confirm diffusion-dominated chemical transport is by determining the age of pore fluids to confirm absence of recent groundwater flow at the disposal zone by using environmental tracers. Hard rocks such as granite typically have a very low porosity with insufficient pore fluid for conventional tracer sampling and analysis. The only solution then is to isolate mineral fluid inclusions and extract tracers such as noble gases (e.g. the isotope ratios $^{21}Ne/^{20}Ne$ and $^{3}He/^{4}He$). Measurements from fluid inclusions may indicate the provenance, evolution history as well as ages of geofluids [15], as a means to confirm the rocks have been isolated from recent groundwater.

Sorption potential of rocks and sealing materials

Computational methods such as Molecular Dynamics (MD) simulations have previously been used to study mobility and adsorption capacity of radionuclides onto various materials. The MD simulation-based approach allows estimation of sorption parameters at the initial stage of a disposal project when rock material for more conventional lab tests is not yet available. To examine radionuclide transport in complex fluids emanating from a nuclear waste repository sealed with bentonite clay seals, MD simulations were used based on smectite as the sorbent. Smectite is a so-called 2:1 clay with tetrahedral alumina sheets alternating with octahedral silica sheets. The aqueous phase contained a 0.16 M uranyl carbonate solution. Based on the MD simulations, the sorption parameter K_D was calculated to be in the range 58.3 to 150.9 mL/g (depending on pore size) [22]. This study also identified various polynuclear uranyl carbonate complexes on clay surfaces (e.g., $[Na(UO_2)_3(CO_3)_3]^+$) and in aqueous solution (e.g., $[Na_2(UO_2)_5(CO_3)_6]^0$) [20].

Testing disposability of waste matrices

The disposability of glass and synroc waste matrices has not been investigated yet for specific deep borehole conditions. However, considerable R&D has been devoted to understanding glass matrices under environmental conditions typical for conventional GDF [23]. Initial disposability investigations have also been reported for the synroc waste [8].

Glass and synroc matrices contribute to the “Resistance to leaching” safety function owing to their very slow dissolution. The “Resistance to leaching” is characterised by a leaching model which can be incorporated in post-closure safety assessment models. The dissolution rate of glasses used for incorporation of radionuclides designated for final disposal is very slow, on the order of $10^{-5} – 10^{-6}$ g/cm^2.day [23]. The leaching rates are representative for temperatures typical of depths of conventional geological repositories. For the leaching model in Boom Clay, this was 16 °C. For higher temperatures leaching rates were 1 µm/y (10^{-6} g/cm^2.day) at 40 °C and 2 µm/y (2×10^{-6} g/cm^2.day) at 90 °C [24]. The pH of the material surrounding the glass is another influential parameter: for every increase of two pH units (in the pH range 8-12), dissolution rates increase by a factor between 5 – 10 [25].

In situ temperatures in a hypothetical borehole were estimated to be between 30-45 degrees at 1000 m and between 70-100 degrees at 3000 m depth [5]. In other words, the 1 μm/y leaching rate could be considered representative for the 1000 m depth and 2 μm/y could be considered representative for 3000 m depth. Future studies will include establishing a hydrochemical database for potentially suitable host rocks to determine the chemical conditions relevant to estimate glass and synroc dissolution rates.

FEASIBILITY STATEMENTS

Three feasibility statements are considered that will support the claim that a deep disposal borehole can be constructed, waste can be emplaced and the borehole can be sealed in a manner that meets operational and long-term safety requirements, while being cost-effective. RD&D will be undertaken to demonstrate:

- Practicability of drilling, waste emplacement, and sealing;
- Operational safety of borehole disposal: demonstrated safety of workers, the public and the environment throughout the different operational phases;
- The costs for drilling, waste emplacement and borehole sealing and monitoring are in agreement with best value-for-money principles, while also considering non-financial costs and benefits. This includes cost comparisons with alternative disposal options such as mined repositories at intermediate depth, similar to those already in operation in Sweden (SFR repository), Finland (VLJ repository, Olkiluoto), or Hungary (Bataapati).

At this stage of the program, no site or host rock type has been selected. To facilitate the design of a deep disposal borehole at this stage, a generic workflow was developed that considers all key parameters that influence the final design. The workflow included the following parameters: rock type (crystalline, clay, salt), disposal canister diameter, borehole casing requirement, and minimal annular gap between disposal canister and casing or borehole wall [26]. This workflow will also help better understand the complexity of developing a deep disposal borehole facility.

Feasibility and safety statements are developed concurrently, with intermediate hold points to assess progress and knowledge transfer between them to ensure the most up-to-date information is available to continue develop both statements. The gradual compilation of the necessary evidence to substantiate the different feasibility statements involves a number of activities (in chronologic order):

- Undertake a state-of-the-art review of the science and technology regarding each feasibility statement (e.g., [3]);
- Identify key data and knowledge gaps that are deemed fundamental to provide the underpinning evidence for each feasibility statement (e.g., [4]);
- Undertake a prioritisation exercise of the data and knowledge gaps based on the degree to which they would impact borehole disposal feasibility, and the confidence in making inferences about such impact;
- Design, plan, and execute RD&D activities to address the prioritised data and knowledge gaps;
- Critical evaluation of the findings from the RD&D studies and updating the evidence underpinning the feasibility statements;
- Identify any remaining uncertainties, and assess if they need further consideration, or whether they are immaterial and therefore can be closed off.

As with the safety statements, this series of activities is undertaken in an iterative manner until there is sufficient confidence to conclude a given phase in the step-wise development of the disposal solution.

CONFIDENCE ENHANCEMENT

The safety case for geological disposal facilities has provisions for so-called confidence enhancement activities. Such activities provide additional qualitative and/or quantitative support for the pre-closure and post-closure safety assessments, especially where it concerns the long-term predictions of disposal facility components [2]. Examples include geological analogues of mineral alterations as models for engineered barrier material (e.g. bentonite or cement) evolution [27], simulation model benchmarking for complex coupled thermo-hydro-mechanical-chemical processes [28], the role of redox and immobilization processes in radionuclide mobilization and retardation [29], etc. Industrial analogues from deep oil and gas wells and geothermal wells can provide evidence about casing corrosion and cement dissolution [29]. Collaboration with regional experts from the Nuclear Threat Initiative Pacific Rim Partnership and the Horonobe International Project are being planned to share experimental facilities for the execution of benchmark test cases.

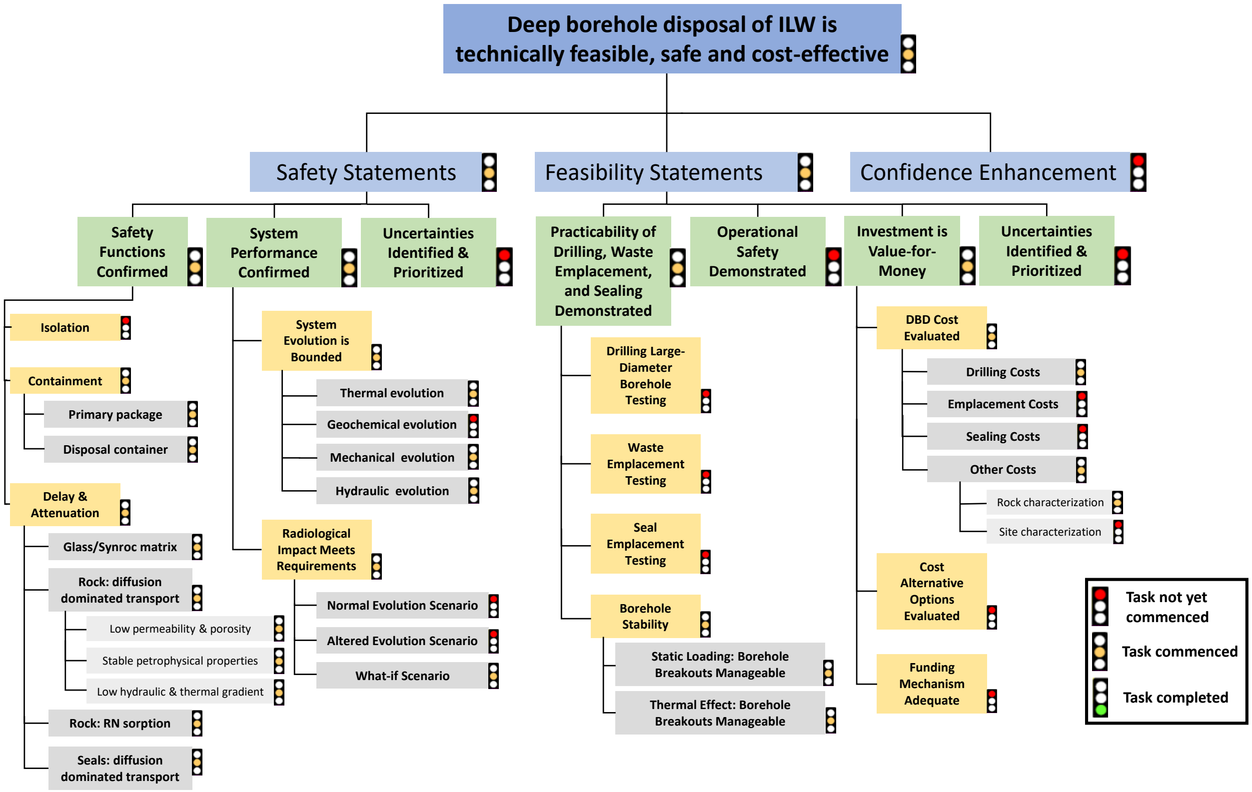


Fig. 2. Framework for streamlining RD&D activities with safety and feasibility statements and confidence enhancement activities. Status as of December 2021.

CONCLUSIONS

The paper discussed the multi-barrier system for a deep disposal borehole concept for long-lived ILW, and the safety functions associated with each barrier. A framework was introduced to streamline the RD&D activities that are part of a full-scale demonstration test, and which will support the future siting process and the development of a safety case. The highlighted RD&D activities have delivered novel enabling tools to support future siting, site investigations and site evaluations, and have improved understanding of key decision parameters regarding effects of disposal depth, host rock suitability, and interactions between waste properties and engineered barriers.

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