Deep borehole disposal of intermediate-level waste: progress from Australia's RD&D project

D. Mallants, CSIRO, Australia
Y. Beiraghdar, CSIRO, Australia
C. Doblin, CSIRO, Australia
L. Esteban, CSIRO, Australia
M. Josh, CSIRO, Australia
U. Kelka, CSIRO, Australia
M. Khanal, CSIRO, Australia
P. Schaubs, CSIRO, Australia
B. Shen, CSIRO, Australia
J. Shi, CSIRO, Australia
C. Wilske, CSIRO, Australia
J. Zhang, CSIRO, Australia

Email: dirk.mallants@csiro.au

Abstract
Australia is evaluating deep borehole disposal as a potential solution for its long-lived intermediate level waste (ILW). This waste originates mainly from research reactors and radiopharmaceutical production and requires deep geologic disposal. As there are relatively small volumes involved, deep borehole disposal would be a cost-effective, and modular, solution. The CSIRO, ANSTO and SANDIA National Laboratories international partnership, supported by regional experts from the Pacific Rim Partnership, will 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 and the long-term safety of vertical borehole disposal. The execution of this project could also demonstrate options for nuclear waste disposal that would reduce proliferation risks, potentially up to the termination of compliance with international safeguards requirements. The RD&D includes demonstration of surface handling and full-scale field testing of waste/seal emplacement capabilities in a 0.7-m-diameter, 2000-m-deep demonstration borehole, post-closure safety assessments and safety case development. The paper provides an update on the research activities undertaken to date.

1. 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 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 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 (0.7 m or 27.5 inch) demonstration borehole (currently the maximum depth has been put at 2000 m).

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 and OPAL 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 (15 m^3), represents a small fraction (i.e., 0.5%) of the total estimated ILW volume generated by ANSTO (about 3060 m^3, comprising legacy and future arisings [5]). Other waste streams that may require deep borehole disposal include Synroc wastes from the treatment of liquid waste streams from Mo-99 production [6]. For ILW waste streams with a much smaller activity concentration of long-lived radionuclides, 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 [7]. 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.

2. 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, will fulfil its safety function throughout the isolation phase for a period of at least 10,000 years [8, 9];

— #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 [8, 9];
— #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, at least 10,000 years [10];
— #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.

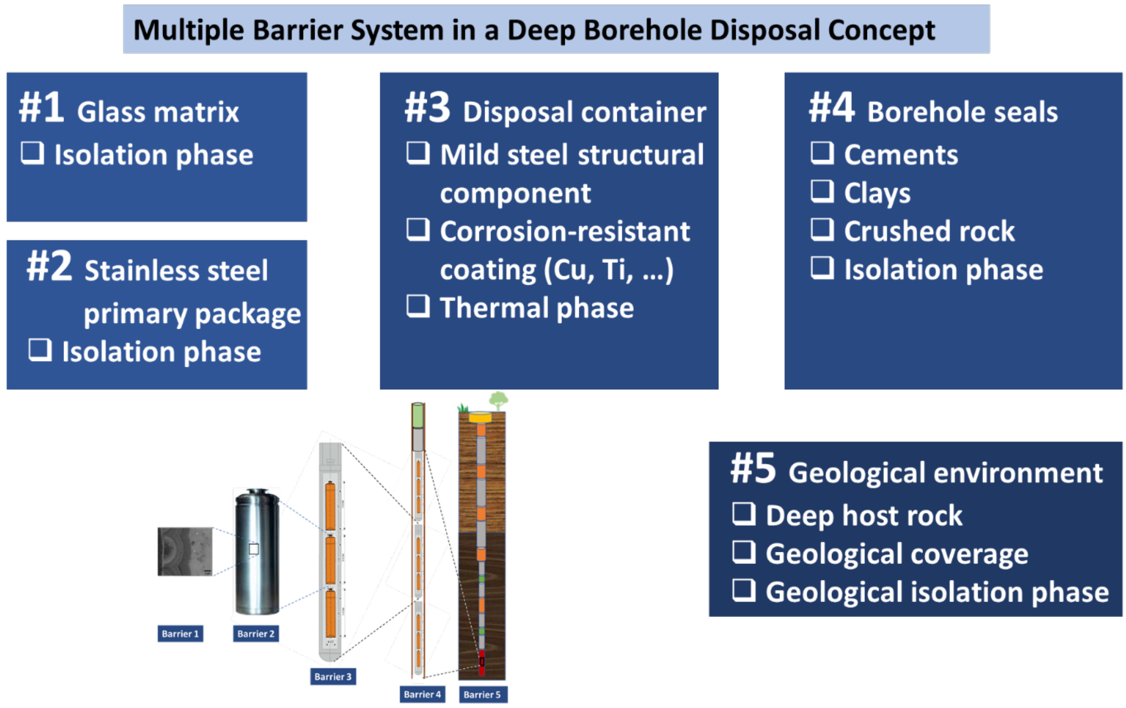

FIG. 1. Multi-barrier system for deep borehole disposal of long-lived ILW.

For each of the barriers identified above safety functions are defined. There are typically three safety functions [11]:
— 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 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 1. 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.

3. 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 [11], 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 [12] and its adaptations for deep borehole disposal [2] are grouped under Confidence Enhancement activities (Fig. 2).

3.1. Safety statements

Four safety statements are considered that underpin the confidence in the long-term safety of deep borehole disposal:

- The evolution of the borehole disposal system (including the waste) and its environment are sufficiently known;
- 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;
- 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 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.

3.2. 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:

- Practicability of drilling, waste emplacement, and sealing has been demonstrated;
- 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.

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.

3.3. 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 [2]. Examples include geological analogues of mineral alterations as models for engineered barrier material evolution [13], simulation model benchmarking for complex coupled thermo-hydro-mechanical-chemical processes [14], etc. Collaboration with regional experts from the Pacific Rim Partnership are being planned to share experimental facilities for the execution of benchmark test cases.

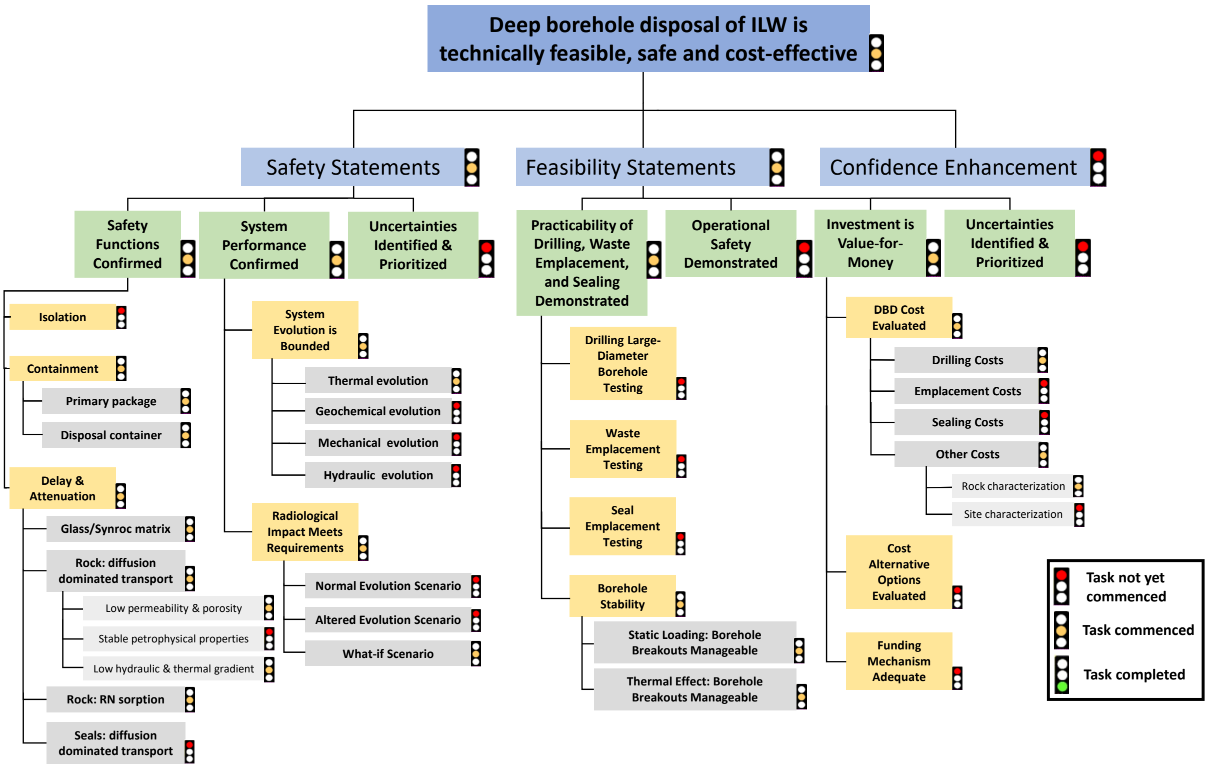

FIG. 2. Framework for streamlining RD&D activities with safety and feasibility statements and confidence enhancement activities. Status as of July 2021.

4. EXAMPLE RD&D ACTIVITIES

Foundational RD&D has commenced to collect the scientific arguments to substantiate the requirements from the Safety and Feasibility Statements. At this point in time, the Australian Government has not yet made a decision on its preferred strategy for ILW disposal, therefore the studies are generic while providing a solid basis for a disposal options analysis. Six examples will be discussed that have either (i) delivered novel enabling tools to support future siting, site investigations and site evaluations, (ii) improved understanding of key decision parameters regarding effects of disposal depth, host rock suitability, or interactions between waste properties (e.g., heat load) and engineered barriers, and (iii) provided the opportunity for building much-needed capability in Australia across the back-end of the nuclear fuel cycle. Several of the current examples have used crystalline rock as test material; the demonstration project will also consider sedimentary rock and rock salt as potential host rock.

4.1. Geological fault network analysis and finite element mesh generator

Geological faults are discontinuities in the crust that can behave as barriers or conduits to groundwater flow; in some cases they act as barriers to horizontal flow because of a low-permeability fault core while at the same time the higher permeability fault damage zone acts as a conduit for upward or downward flow [15]. Faults that behave as conduits or barrier/conduits can potentially provide preferential pathways for groundwater flow, heat transfer and radionuclide migration thus bypassing the host rock that provides for isolation and containment. To assess the role of geological faults on the long-term safety of deep borehole disposal, new tools were developed to i) digitize conventional fault trace maps into 2D finite element (FE) grids for subsequent fault network (proximity-to-fault) analysis and ii) represent the three fault conceptualisations (barrier, conduit, barrier/conduit) in a more efficient way in flow and transport models for post-closure safety assessments [16]. The fault network analysis and FE mesh generator with proximity-to-fault analysis can be used to identify regions at a safe distance from the nearest fault and fault centres as part of a site screening analysis (Fig. 3).

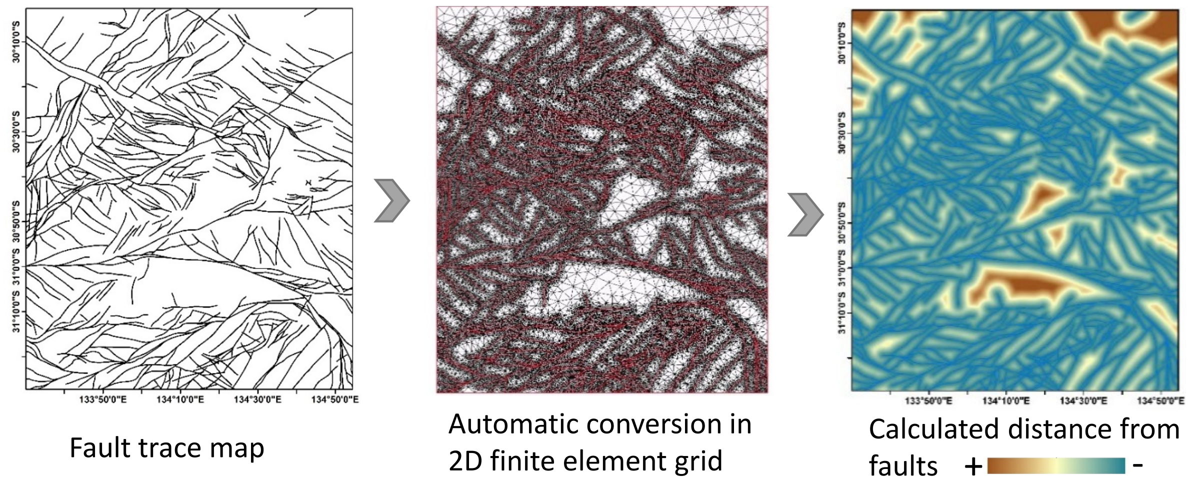

FIG. 3. Workflow for finite element mesh generation from fault trace maps and calculation of distances from faults. Image widths is approximately 134 km×156 km.

4.2. Borehole mechanical stability modelling

Borehole instabilities often occur during and after drilling as a result of crack initiation and propagation. Borehole breakouts may form at the borehole wall in the direction of the minimum principal horizontal stress, whereas tensile fractures may form in the direction of the maximum principal horizontal stress. Especially in hard rocks such as granite, explicit fracturing occurs. Borehole stability is critically important for deep borehole disposal of radioactive waste. In addition to complicating the drilling operation, borehole failures may also impact the suitable depth available for waste emplacement and may create local temporal fracture networks that require specialised sealing materials to restrict radionuclide migration along the fractured borehole wall. Deep boreholes drilled to 1000-2000 m depth into crystalline rocks in Australia have been reported to have experienced borehole instabilities [17]. This is believed to be caused by high pressure (i.e., high horizontal stresses) from tectonic movement. Large diameter boreholes such as the one considered here (bottom hole diameter of 0.7 m) are particularly susceptible for borehole breakouts due to scale effects [18].

To assist with the design and planning of a deep, large-diameter borehole as part of a full-scale demonstration test for emplacement of dummy ILW disposal canisters, a 0.7-m-diameter borehole has been modelled using FRACOD [19]. The 2D model considered horizontal cross-sections of the vertical borehole at the depths of 1000 and 2000 m, with depth-dependent *in situ* stresses and rock temperatures based on field data [20]. By varying critical FRACOD input parameters including rock strength, *in situ* stress magnitudes, thermal cooling during drilling and thermal heating owing to heat producing waste, effects of varying geological and disposition scenarios have been evaluated. Results for a reverse faulting regime (σ_H>σ_h >σ_V) showed that for the reference case using the most likely *in situ* stress magnitudes (σ_H/σ_V = 2.5; σ_h/σ_V = 1.5) and rock uniaxial compressive strength (UCS=180MPa), very limited borehole breakouts were predicted at 1000 m depth [21]. The strike-slip regime (σ_H >σ_v>σ_h) and normal faulting regime (σ_V>σ_H>σ_h) have not been modelled in this stage. At 2000 m depth, noticeably more extensive borehole breakouts were predicted, some of which were up to 0.5 m deep into the rock (Fig. 4).

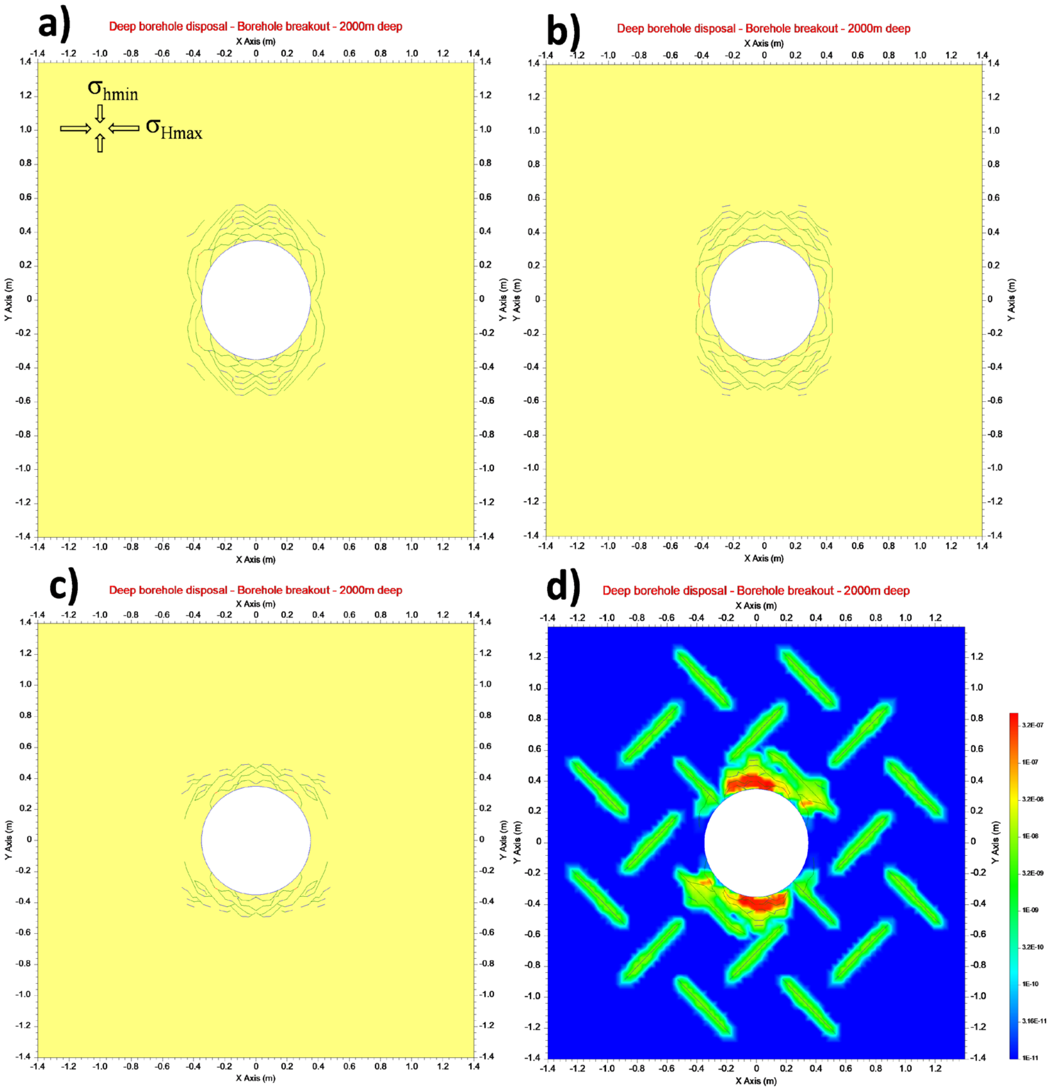

FIG. 4. 2D Borehole breakout simulations using FRACOD at a depth of 2000m. A) Reference case with 180 MPa rock strength; B) More intense rock fracturing with lower UCS (120 MPa); C) Change in fracture pattern and intensity caused by lower temperature (54 °C); D) Increase in hydraulic conductivity caused by a pre-existing fracture network interacting with the developing breakout (range from 10^{-11}-3×10^{-7} m/s).

Pre-existing fracture networks in the vicinity of the disposition borehole may propagate and coalesce with the new fractures initiated around the borehole, however their effects are limited to within a distance of 0.5 m from the borehole wall (results not shown). A lower rock strength (120 MPa) produced a greater number of open fractures (Fig. 4). Short-term effects were predicted when drilling mud is used with a 54 °C lower temperature relative to the in situ temperature (thermal expansion coefficient $\alpha = 7.4\times10^{-6}$/°C), which caused a larger fractured zone with larger fracture apertures (Fig. 4). FRACOD also predicted modifications to the equivalent rock hydraulic conductivity owing to fracture network generation (Fig. 4).

4.3. Radionuclide sorption estimation using Molecular Dynamics Simulation

Computational methods such as Molecular Dynamics (MD) simulations have previously been used to study mobility and adsorption capacity of radionuclides within various materials [22]. The MD simulation-based approach allows estimation of sorption parameters at the initial stage of a disposal project when core material for more conventional lab tests is not yet available. MD simulations consider interactions between individual molecules and between molecules and charged surface, such as clays. They track in time the position of those molecules in a very small box of a few nanometres where a rather large number of molecules are present and interact with each other. In the example shown smectite clay was considered, to examine radionuclide transport in complex fluids emanating from a nuclear waste repository sealed with a bentonite clay. 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; the MD simulation box had a varying dimension to represent three different pore sizes (8.37, 25.1, and 33.5 nm). This allowed testing of uranyl adsorption under different influences of the electrical double layer. Calculated atomic density profiles revealed peaks near the clay surface indicative of adsorbed poly-nuclear uranyl complexes while the region in between the peaks represented the dissolved species (Fig. 5). From this information the sorption parameter K_D was calculated to be in the range 58.3 to 150.9 mL/g (depending on pore size) [23]. These results were of the same order magnitude as the MD simulation values for montmorillonite (15 – 200 mL/g) from [22].

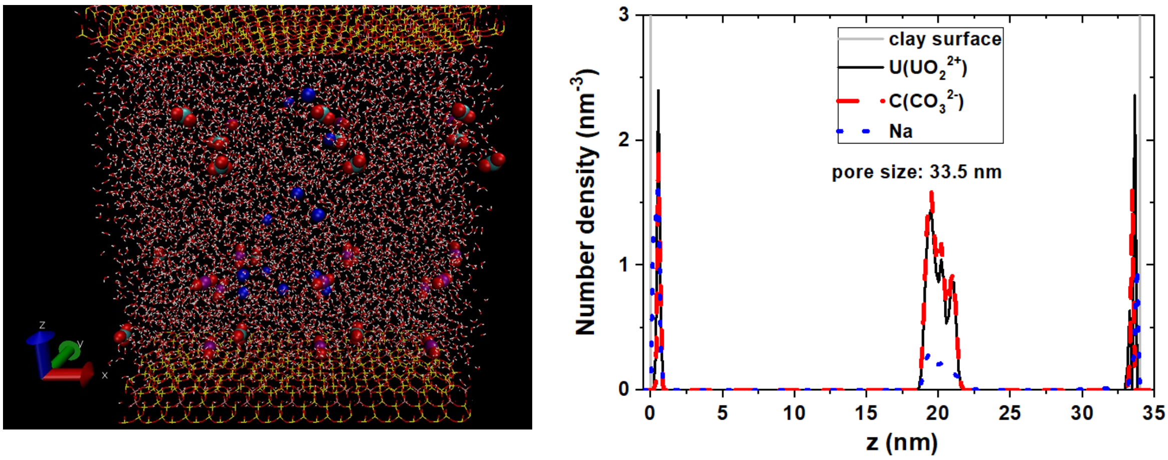

FIG. 5. Molecular Dynamics simulation of uranyl adsorption to smectite. Left: MD simulation box with interacting molecules (O (red); H (white); Na (blue); U (purple); C (light blue)). Right: Simulated atomic density profile with adsorbed species at left and right clay surface and aqueous species in the centre of the pore used to calculate K_D.

MD simulations proved to be a powerful tool to reveal direct and unique information on structural and adsorption properties, including distribution of chemical species, adsorption behaviour, adsorption sites, and mechanism, which would otherwise have required a combination of experimental methods to achieve a similar level of information. Moreover, MD simulations should allow prediction of the absolute values, and solution composition dependencies, of K_D's for those radionuclide-bentonite pairs that have not been measured with sufficient precision. This should therefore hasten the incorporation of surface complexation models into performance assessment codes used to examine radionuclide transport in complex fluids emanating from a nuclear waste repository sealed with a bentonite clay.

4.4. Durable coatings for disposal containers

The disposal of various long-lived ILW waste streams would benefit from a one-size-fits-all disposal container or overpack in accordance with the multi-barrier systems (Fig. 1). One such potential canister design considers a relatively inexpensive carbon steel canister (as structural component) with a more durable corrosion resistant coating. A range of commercially available coating technologies was assessed for coating copper, stainless-steel, and high Ni/Ti alloys onto a carbon steel substrate [24]. Methods that were reviewed included electrodeposition, Physical Vapour Deposition, Chemical Vapour Deposition, laser cladding, thermal and cold spray. Cold spray, thermal spray and laser cladding have the flexibility to be performed in air. Of these three, cold spray is the most suitable for producing corrosion resistant coatings of up to several mm thick, with suitable adhesion and mechanical properties. Cold spray, unlike electrodeposition, can coat waste disposal canisters once they have been loaded and sealed. To reduce the porosity of the coatings and improve their mechanical properties the coatings require a thermal treatment. Cold spray of copper onto disposal canisters is more advanced than other materials. 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.

4.5. Confirming diffusion dominated transport: petrophysical properties and environmental tracers

An important feature of a suitable host rock for borehole disposal is 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, Fig. 2). The permeability is also an important input parameter for 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. To this end, a global dataset with petrophysical properties (permeability, porosity, tortuosity, and diffusion) has been collated to provide the necessary input parameters for the generic safety assessments. The dataset can also be used to undertake safety assessments for other countries by grouping the data according to regional geology. In addition to the literature data, targeted permeability and porosity measurements of granite rock samples from 700 – 1900 m depth have been undertaken. Results show permeabilities of around 1 micro Darcy with porosity in the range 0.02-1%. Results further show that porosity and permeability increase and rocks becoming more stress sensitive as mineral alterations of feldspars into Muscovite or Kaolinite increase [25].

Another method to confirm diffusion dominated 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 solution is to study mineral fluid inclusions and extract tracers such as noble gases for age determination. To this end CSIRO developed a new vacuum mineral crushing system for the measurement of noble gases and their stable isotope composition ($^{136}Xe/^{132}Xe$, $^{21}Ne/^{20}Ne$ and $^{3}He/^{4}He$) in fluid inclusions entrapped in mineral grains (Fig. 6). Measurements from fluid inclusions (i) may indicate the origin of the fluids the mineral precipitated from (which is also useful to characterize the genesis of ore bodies), and (ii) may provide evidence about different stages of the evolution of minerals or rock formations and of geological processes, such as pressure-temperature conditions during rock formation and nature, provenance, evolution history as well as ages of geofluids [26].

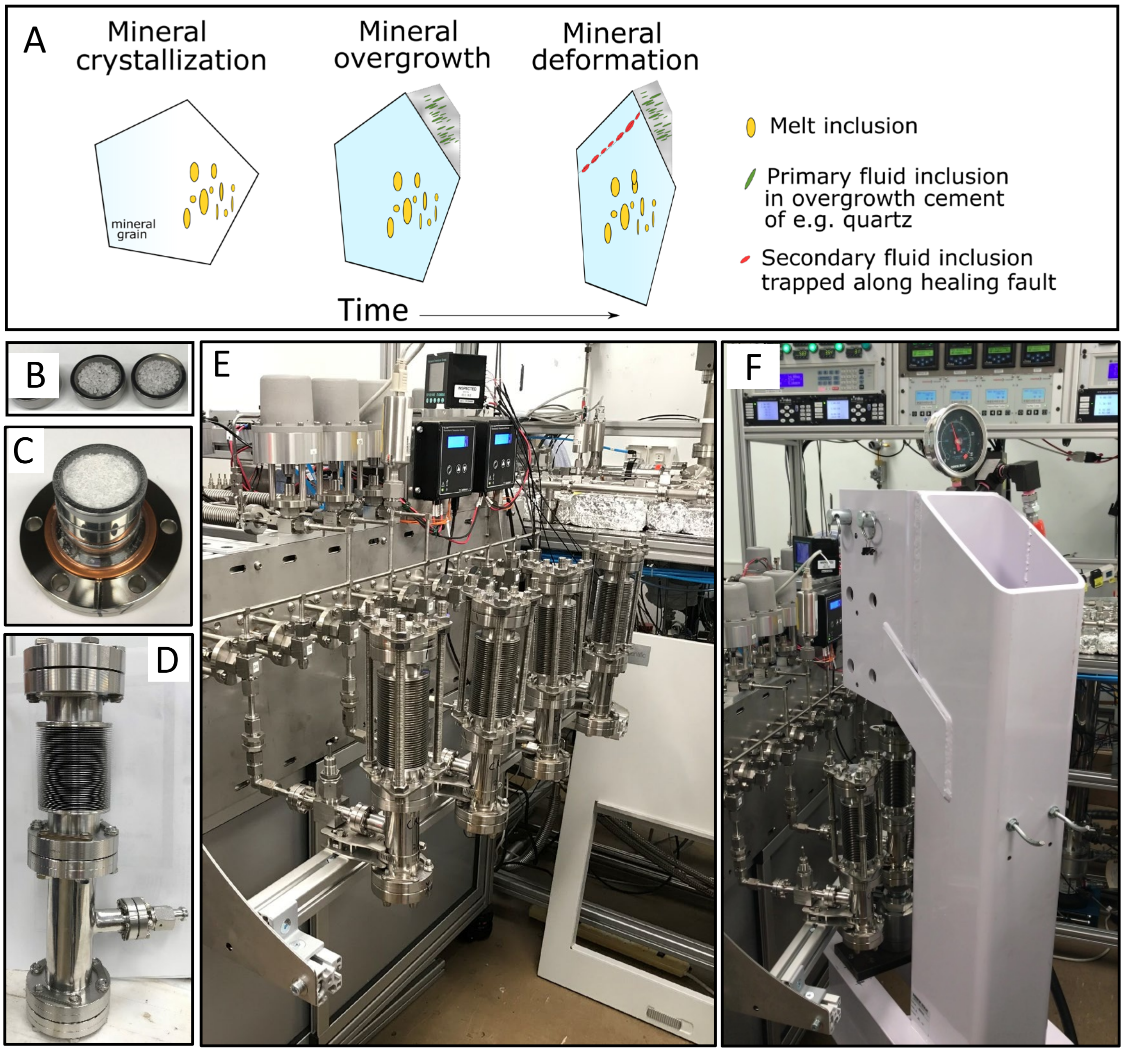

FIG. 6. A: Conceptual model of fluid inclusions in quartz grains. B: Separated and cleaned quartz grains (1-2 mm) on tungsten crush plate. C: Quartz grains on crushing plate. D: Crushing device. E: Crushing devices attached to high-resolution noble gas mass spectrometer. F. Hydraulic press to crush the mineral grains.

4.6. Temperature evolution in disposal borehole and rock environment

Understanding the temperature evolution in the borehole near field and surrounding rock environment is necessary as it may impact the safety functions of the engineered and natural barriers. For instance, higher temperatures will accelerate the corrosion of waste forms and metal-based containers, and may degrade bentonite or cementitious borehole sealing materials. To gain insights into the temperature evolution in the disposal borehole and rock environment as a function of heat load, disposal depth and rock parameters (geothermal gradient, rock thermal conductivity), heat transport was numerically calculated for low-heat producing ILW and compared with other heat-emitting wastes. The conceptual model included disposal boreholes to three different depths (500 m, 1000 m, and 3000 m), with a disposal zone in the bottom 200 m of the hole. The assumed host rock is crystalline, overlain by weathered basement (25 – 100 m below surface) and unsaturated regolith (0 - 25 m below surface). The main purpose of these generic performance assessments was to quantify the transient nature of the heat evolution, and evaluate if the temperature in bentonite seals would exceed 100 °C when the distance between heat source and such seals is at least 100 m. Results confirmed that for none of the three disposal depths did the temperature at the bottom of the bentonite seal ever increase above 100 °C. Moreover, the temperature in the bentonite remained at the depth-dependent in-situ temperature. Typical temperature evolutions for the low-heat producing ILW (50 Watt per CSD-U canister, 100 canisters in one borehole) for the 1000-m and 3000-m-deep disposal borehole accounting for variations in geothermal gradient are shown in Fig. 7. A sensitivity analysis further demonstrated that bentonite temperatures were insensitive to uncertainties in the rock thermal conductivity [27].

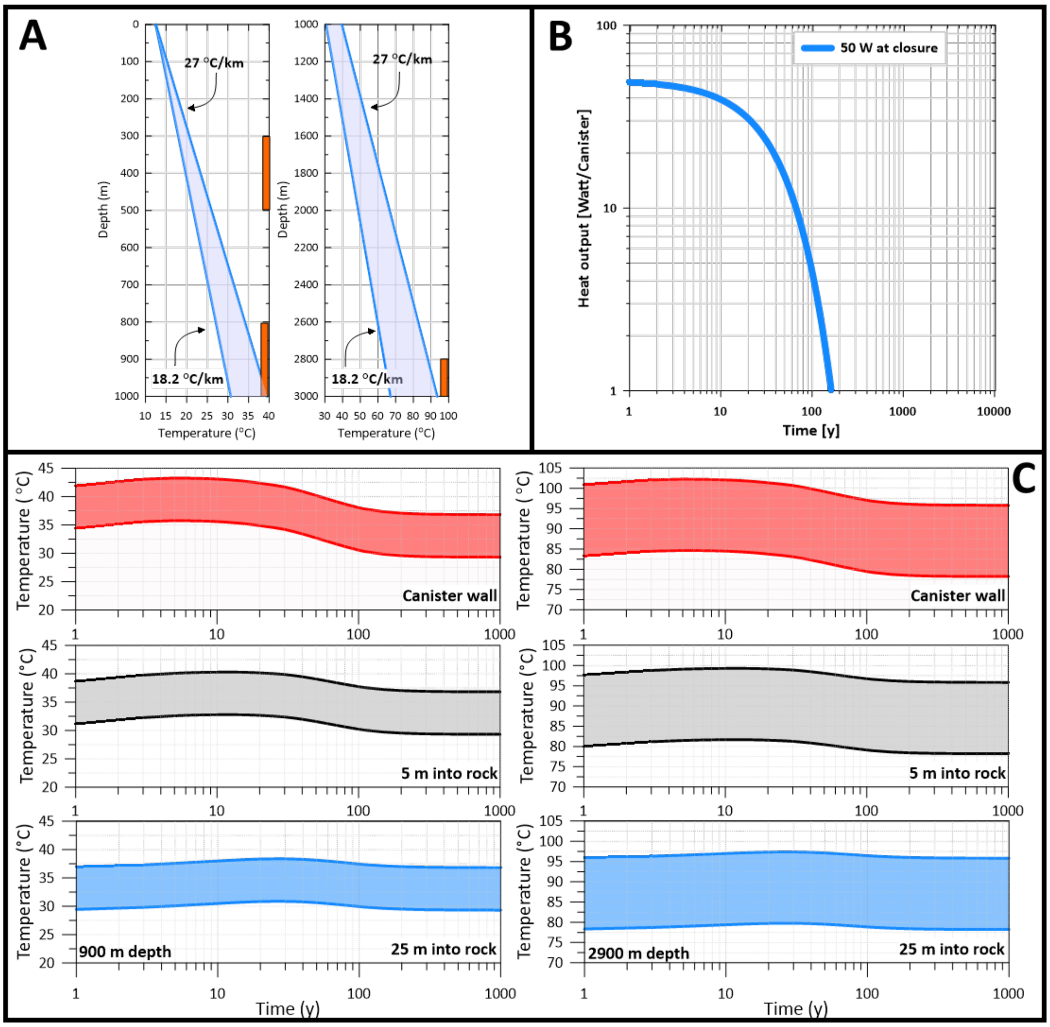

FIG. 7. A: Representative geothermal gradients used in heat transport calculations. B: Heat load evolution for CSD-U canisters. C: Range in calculated temperature evolution at 900 m (left) and 2900 m (right) depth (in the middle of the 200-m-deep disposal zone) for 50 Watt/canister heat output (100 canisters within single borehole). Upper curve is for 27°C/km and lower curve for 18.2°C/km geothermal gradient.

5. SUMMARY

The paper discussed the multi-barrier system for a deep disposal borehole concept for 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.

REFERENCES

[1] Brady, P., Arnold, B., Altman, S., Vaughn, P., 2012. Deep Borehole Disposal of Nuclear Waste: Final Report. SAND2012-7789, SANDIA National Laboratories, Albuquerque, New Mexico, USA.

[2] Freeze, G., Stein, E., Brady, P. V., Lopez, C., Sassani, D., Travis, K., Gibb, F., 2019. Deep Borehole Disposal Safety Case. SAND2019-1915, SANDIA National Laboratories, Albuquerque, New Mexico, USA.

[3] Mallants, D., Travis, K., Chapman, N., Brady, P., Griffiths, H., 2020. The state of the science and technology in deep borehole disposal of nuclear waste. Energies 13 (doi:10.3390/en13040833), 1-7

[4] Freeze, G., Sassani, D., Brady, P.V., Hardin, E., Mallants, D., 2021. The Need for a Borehole Disposal Field Test for Operations and Emplacement – # 21220. In: Waste Management 2021 Symposium; 7-11 March 2021; Phoenix, Arizona, USA. Waste Management Symposium.

[5] DIIS, 2018. Australian Radioactive Waste Management Framework. Department of Industry, Innovation and Science (DIIS). April 2018.

[6] Stewart, M. W. A., Vance, E.R., Moricca, S.A., Brew, D.R., Cheung, C., Eddowes, T., Bermudez. W., 2013. Immobilisation of Higher Activity Wastes from Nuclear Reactor Production of 99Mo. Sci. Technol. Nucl. Install. 2013, 1-16.

[7] Mallants, D., Beiraghdar, Y., 2021. Radionuclide transport and deep borehole disposal: Preliminary Safety Assessments. Proceedings Waste Management 2021 Symposium, 2021, Waste Management Symposium, Phoenix, Arizona, USA.

[8] Mallants, D., Sillen, X., Marivoet, J., 2001. Performance assessment of the disposal of vitrified high-level waste in a clay layer. J. Nucl. Mat. 298(1-2), 125-135.

[9] NAGRA, 2002. Project Opalinus Clay Safety Report. Demonstration of disposal feasibility for spent fuel, vitrified high-level waste and long-lived intermediate-level waste (Entsorgungsnachweis). NAGRA Technical Report NTB 02-05.

[10] Arnold, B. W., Brady, P.V., Bauer, S.J., Herrick, C., Pye, S., Finger, J., 2011. Reference Design and Operations for Deep Borehole Disposal of High-Level Radioactive Waste. SAND2011-6749.

[11] NIRAS/ONDRAF, 2013. ONDRAF/NIRAS Research, Development and Demonstration (RD&D) Plan for the geological disposal of high-level and/or long-lived radioactive waste including irradiated fuel if considered as waste State-of-the-art report as of December 2012. NIROND-TR 2013-12 E, NIRAS/ONDRAF, Brussels, Belgium.

[12] NEA, The Nature and Purpose of the Post-closure Safety Cases for Geological Repositories. NEA/RWM/R(2013)1, OECD/NEA, Paris, France, 2013.

[13] Alexander, W. R., Mackenzie, A.B., Scott, R.D., Mckinley, I.G., 1990. Natural analogue studies in crystalline rock: the influence of waterbearing fractures on radionuclide immobilisation in a granitic rock repository. Technical Report 87-08.

[14] Kolditz, O., Shao. H., Gorke, U.-J., Wang, W., Bauer, S., 2015. Thermo-Hydro-Mechanical-Chemical Processes in Fractured Porous Media: Modelling and Benchmarking. Terrestrial Environmental Sciences. Benchmarking Initiatives.

[15] McCallum, J., Simmons, C., Mallants, D., Batelaan, O., 2018. Simulating the groundwater flow dynamics of fault zones. MODFLOW Un-Structured Grid: A comparison of methods for representing fault properties and a regional implementation. Report to the Office of Water Science, Department of the Environment, Canberra, Prepared by the Commonwealth Scientific and Industrial Research Organisation (CSIRO), Canberra, Australia.

[16] Schaubs, P., Kelka, U., 2021. Fault conceptualisation and numerical simulation of safe waste disposal sites. Technical Report, CSIRO, Canberra, Australia.

[17] Klee, G., Bunger, A., Meyer, G. Rummel, F., Shen B., 2011. In Situ Stresses in Borehole Blanche-1/ South Australia Derived from Breakouts. Core Discing and Hydraulic Fracturing to 2 km Depth, Rock Mech. Rock Eng. 44, 531-540.

[18] Martin, C.D., Kaiser, P.K. and McCreath, D.R., 1999. Hoek–Brown parameters for predicting the depth of brittle failure around tunnels. Can. Geotech. J. 36,136-151.

[19] Shen, B., Stephansson, O., 1994. Modification of the G-criterion of crack propagation in compression. Int. J. of Engineering Fracture Mechanics 47, 177-189.

[20] Shen, B., Rinne, 2011. M., Estimate In situ Stresses from Borehole Breakout at Blanche 1 Geothermal Well in Australia. Proc. ITA-AITES World Tunnel Congress, Helsinki, 2011 Finnish Tunnelling Association MTR, Helsinki.

[21] Shen, B., Shi, J., Khanal, M., Mallants, D., 2022. Geomechanical Modelling of Borehole Stability for Deep Borehole Radioactive Waste Disposal. Waste Management Symposium2022, Phoenix, Arizona (submitted).

[22] Greathouse, J.A., Cygan, R.T., 2006. Water structure and aqueous uranyl(vi) adsorption equilibria onto external surfaces of beidellite, montmorillonite, and pyrophyllite: Results from molecular simulations. Environ. Sci. Technol. 40, 3865-3871.

[23] Zhang, J., Mallants, D., Brady, P.V., 2021. Molecular Dynamics Study of Uranyl Adsorption from Aqueous Solution to Smectite. Appl. Clay Sci. (submitted).

[24] Doblin, C., 2021. Review of corrosion resistant coating technologies for nuclear waste disposal canisters. CSIRO, Canberra, Australia.

[25] Esteban, L., Josh, M., Dewhurst, D.N., Mallants, D., 2021. Blanche-1 well: Lab and logs petrophysical integration. Technical Report CSIRO, Australia. 38 pp.

[26] Wilske, C., Suckow, A.O., Deslandes, A., Crane, P., Gerber, C., Spooner, N., Mallants, D., 2021. Fluid inclusions in minerals of the deep crust-Investigations with the new high vacuum crushing system at the CSIRO noble gas facility. Proc. Goldschmidt2021 Conference, virtual.

[27] Mallants, D., Beiraghdar, Y., 2021. Heat Transport in the Near Field of a Deep Vertical Disposal Borehole: Preliminary Performance Assessment. Proceedings Waste Management 2021 Symposium, 2021, Waste Management Symposium, Phoenix, Arizona, USA.