European Partnership on Radioactive Waste Management

Deliverable 3.2: Towards a Generic Deep Borehole Disposal Concept

Work Package 3

DOI: 10.5281/zenodo.19131197

Co-funded by the European Union under Grant Agreement n°101166718

Document information

Project Acronym	EURAD-2
Project Title	European Partnership on Radioactive Waste Management-2
EC grant agreement No.	101166718
Work Package Title	ASTRA
Deliverable No.	3.2
Deliverable Title	Towards a Generic Deep Borehole Disposal Concept
Lead Beneficiary	Galson Sciences Limited / Egis
Contractual Delivery Date	January 2026
Actual Delivery Date	March 2026
Dissemination level	PU
Authors	Shivangi Prasad (Galson Sciences Ltd.), Stephen Wickham (Galson Sciences Ltd.), Jules Drouin (Egis), James Begg (Egis)

To be cited as:

Prasad S., Wickham S., Drouin J., Begg J. (2026): Towards a Generic Deep Borehole Disposal Concept. Final version as of 16.01.2026 of deliverable D3.2 of the European Partnership EURAD-2. EC Grant agreement n°:101177718

Disclaimer

Acknowledgement

This document is a deliverable of the European Partnership on Radioactive Waste Management 2 (EURAD-2). EURAD-2 is co-funded by the European Union under Grant Agreement N° 101166718.

Status of deliverable	By	Date
Delivered (Lead Beneficiary)	Galson Sciences Limited / Egis	05/02/2026
Verified (Work Package Leader)	Marja Vuorio	06/02/2026
Approved (PMO)	Marta López García (PMO)	02/03/2026
Submitted to EC (Coordinator)	Andra	30/03/2026

Executive Summary

Deep borehole disposal (DBD) is increasingly recognised as a promising alternative or complement to mined geological repositories for the disposal of high-level waste and spent nuclear fuel. However, implementation of the technology has been limited by a perceived lack of technology readiness level, since no full-scale demonstration has yet been completed.

Task 4 of the European Joint Programme on Radioactive Waste Management-2 (EURAD-2) work package Alternative Radioactive Waste Management Strategies (ASTRA), focussed on assessing the current state of DBD technology, identifying key knowledge gaps, and defining priority research and development (R&D) needs. A series of workshops with stakeholders were held to review current DBD concepts, and to discuss the main technical and strategic challenges and key R&D areas required to advance the concept. A knowledge gap analysis was conducted across the full DBD lifecycle, with particular attention to site characterisation, deep borehole field testing, and development of a robust safety case.

One of the main outcomes of Task 4 has been the development of a generic DBD concept that provides a common basis for future work. Discussions resolved that future R&D efforts should prioritise addressing the most critical *technical* uncertainties, including demonstrated experience in precise emplacement of HLW/SF and sealing of boreholes to the required level at the depths and diameters envisioned for DBD, exploring the long-term performance of borehole seals and plugs, and understanding corrosion processes and their control under *in-situ* conditions. A further priority is the development and demonstration of techniques to confirm that stagnant groundwater conditions persist at disposal depths following borehole construction and waste package emplacement.

Table of content

List of figures

Glossary

The following glossary provides definitions of terms that have been used in ASTRA Task 4.

Borehole backfill	Material used to refill excavated portions of the borehole after waste has been emplaced. It helps to seal the borehole, reduce water movement and keep the borehole structure stable over time.
Borehole	Any cylindrical ground excavation made by a drilling device for purposes such as site investigation, testing, monitoring, resource exploitation, or disposal.
Borehole casing	A pipe/lining placed in a borehole to keep it open and stable and to prevent water or material from entering, ensuring safe and stable drilling and operation.
Deep borehole disposal	The concept of disposing of waste at a depth of typically one or more kilometers in boreholes with waste emplaced directly from the land surface.
Deep borehole field test	A large-scale experiment to evaluate the feasibility of deep borehole disposal for radioactive waste and to study how the disposal systems work. This could include drilling, borehole construction, waste package handling and emplacement simulations, backfilling, sealing, monitoring, and the demonstration of emergency retrieval of packages during the operational phase. The field test is conducted solely for research and engineering purposes; no radioactive waste is emplaced or disposed of during the test.
Engineered barrier system	The combination of the engineered infrastructure components of a disposal system, including the waste packages/overpacks with any buffer, backfills and seals, collectively designed to isolate radioactive waste underground, and to prevent or to inhibit migration of radionuclides from the disposal system.
Features, Events, and Processes	A framework used in safety assessments to categorise factors that could affect a system. Features are the physical characteristics, events are discrete occurrences, and processes are ongoing natural or engineered phenomena.
Geological barrier	In the context of geological disposal, this comprises the host rock in which a disposal system is constructed, and the surrounding rocks.
Groundwater	All water which is below the surface of the earth in the saturated zone and in direct contact with the ground or subsoil.
High level waste	The radioactive liquid containing most of the fission products and actinides present in spent fuel, which forms the residue from the first solvent extraction cycle in reprocessing, and some of the associated waste streams; this material following solidification; spent fuel (if it is declared as waste); or any other waste with similar radiological characteristics.
Host rock	The rock in which a disposal system is located.
Multi-barrier system	Two or more natural or engineered barriers used to isolate radioactive waste and to prevent or to inhibit migration of radionuclides from a disposal system.
Overpack	A secondary or additional outer container used for the handling, transport, storage or disposal of waste packages.
Retrievability	Retrievability is the state whereby removal of the waste or waste packages is possible, even after closure. It is a special, longer-term case of reversibility

	which is the ability to reverse the action of waste emplacement in a repository. Retrievability implies making provisions in order to allow retrieval should it be required.
Safety case	A collection of arguments and evidence in support of the safety of a facility or activity, showing that its impact on people and the environment is acceptable. This will normally include the findings of a safety assessment and a statement of confidence in these findings. A safety case may also relate to a given stage of development (e.g. site investigations, commissioning, operations, closure, post-closure, etc.).
Safety function	In this document, safety function is considered to be an action that the disposal system, including engineered barriers, geological formations, and other system components, must complete to ensure the protection of human health and the environment from radiological impacts for the lifetime of the system. This will include the containment and isolation of radionuclides from the environment.
Spent nuclear fuel	Nuclear fuel removed from a reactor following irradiation that is no longer usable in its present form because of depletion of fissile material, poison build-up or radiation damage.
Thermal period	The thermal period is the phase after waste emplacement during which the decay heat from the spent fuel or high-level waste significantly raises the temperature of the host rock and engineered barriers. This period includes a transient (initial heating) phase producing peak temperatures to the near field and gradual cooling towards the pre-disposal thermal baseline.
Waste package	The product of conditioning that includes the waste form and any container(s) and internal barriers (e.g. absorbing materials and liner), as prepared in accordance with requirements for handling, transport, storage and/or disposal.

Abbreviations

ASTRA	Alternative Radioactive Waste Management Strategies
CRP	Coordinated Research Project
CS	Civil society
EBS	Engineered Barrier System
DBD	Deep borehole disposal
DBFT	Deep borehole field test
DGR	Deep geological repository
EURAD-2	European Joint Programme on Radioactive Waste Management (Phase 2)
FEP	Features, events, and processes
HLW	High-level waste
IAEA	International Atomic Energy Agency
KBS-3	Kärnbränslesäkerhet, Nuclear Fuel Safety
KG	Knowledge gap
NEA	Nuclear Energy Agency (OECD)
NTW	Nuclear Transparency Watch
OECD	Organisation for Economic Co-operation and Development
O&G	Oil and gas
RD&D	Research, development, and demonstration
REs	Research entities
RWM	Radioactive waste management
SNF	Spent nuclear fuel
SSG	Specific Safety Guide
SSR	Specific Safety Requirements
SITEX	Sustainable network for independent technical expertise on radioactive waste management
THCM	Thermal, hydrological, chemical, and mechanical
TRL	Technology readiness Level

TSOs	Technical support organisations
WMO	Waste management organisation
WP	Waste package

1. Introduction

1.1 Deep Borehole Disposal (DBD)

Deep borehole disposal (DBD) is a promising disposal alternative to a mined deep geological repository (DGR) for high level waste/spent nuclear fuel (HLW/SNF), due to its reduced surface impact and increased cost effectiveness compared to traditional mined repositories, especially for countries with small waste inventories. DBD could also be used to complement a DGR, for example by providing an additional disposal route for specific waste streams. The underlying concept involves radioactive waste packages (WPs) being emplaced in boreholes drilled to depths of several kilometres in a stable geological and hydrogeological environment. Safety is primarily provided by the thickness of the geological barrier, which serves to isolate the waste from the biosphere, and by the absence of flowing groundwater, which limits transport of radionuclides. DBD offers long-term isolation of waste far from human populations and surface ecosystems, reducing the risks of geological disturbances (e.g., faulting or seismic activity, uplift, erosion, or glaciation effects) and inadvertent human intrusion.

It is broadly acknowledged by the international radioactive waste management community and the drilling industry that much of the deep borehole drilling technology needed to implement DBD already exists in the hydrocarbon, mining, and geothermal industries. However, the DBD concept is considerably less mature than disposal in a DGR and requires research, development, and demonstration (RD&D) efforts covering the technical feasibility and the long-term safety of radioactive waste disposal in a deep borehole. While DBD offers several advantages, challenges such as the need for first-of-a-kind, well-prepared, justified, and documented safety case, advanced sealing technologies and the lack of a demonstration test, mean that more work is required before DBD is viewed as a viable disposal option.

1.2 EURAD-2 ASTRA Task 4

The European Joint Programme on Radioactive Waste Management-2 (EURAD-2) work package Alternative Radioactive Waste Management Strategies (ASTRA) aims to provide an analysis of the readiness, feasibility and challenges of radioactive waste management solutions that are alternatives to mined deep geological repositories, such as DBD. Task 4 of the ASTRA work package brings together parties interested in the development of DBD as a credible radioactive waste management option. This includes representatives from research institutes, regulatory authorities, waste management organisations (WMOs), radioactive waste management (RWM) consultants, deep drilling experts, civil society (CS), private companies, and other international organisations. An ASTRA Core Team was defined as Task 4 partners with ≥ 1 month level of effort committed to the Task. The Core Team were responsible for the development of the Task and facilitating knowledge gathering and workshop organisation.

There was a shift in approach from assessing Technology Readiness Levels (TRLs) of DBD concepts to identifying knowledge gaps at a global level. This change was discussed and collectively agreed with the Core Team prior to Workshop 1. The original scope envisaged a TRL assessment during Workshop 1, followed by an evaluation of stakeholder concerns during Workshop 2. This shift was primarily driven by the diversity and wide range of DBD concepts across Task 4 partners, which made a detailed and consistent TRL assessment of individual DBD components less appropriate and potentially misleading at this stage.

As a result, Workshop 1 focused on identifying knowledge gaps in order to map stakeholder concerns, highlight areas of agreement and uncertainty, and assess the current state of knowledge on key topics. This exercise demonstrated the need for a common framework, which became the focus of Workshop 2, during which a generic DBD concept was defined. This revised approach allowed Task 4 to fully achieve its objectives by reviewing the current state of DBD technology while identifying key uncertainties and priority RD&D topics. Furthermore, as the IAEA DBD CRP is already addressing TRL assessments, this approach avoids duplication of effort.

Therefore, primary goals of ASTRA Task 4 are to review the current state of DBD technology and identify associated uncertainties and key RD&D topics with the aims of informing future work and providing a foundational knowledge base for Member States considering this disposal option. The project employed a collaborative approach involving stakeholder engagement and expert input.

A series of targeted workshops were conducted with the aim of supporting the strategic development of the DBD concept. The primary objectives of these workshops were:

- To review the different DBD concepts currently being considered by various countries and gather information on their current position on DBD.
- To discuss key knowledge or capability gaps preventing countries from implementing DBD.
- To identify research tasks necessary to advance the technical basis of DBD and to support the formulation of EURAD-2 Wave 2 proposals.
- To produce a generic DBD concept that will underpin the development of a comprehensive guidance framework for a DBD safety assessment that will define the safety functions for all the key components in the DBD concept.

2. Purpose and Approach

This report provides a concise, holistic account of the ASTRA Task 4 development and outcomes, with supporting materials, such as spreadsheets and detailed notes for record (NfRs), included as appendices. The work aimed to assess the current state of knowledge, identify key knowledge gaps, and define a generic DBD concept suitable for further evaluation. The findings are intended to inform future research priorities and guide the development of EURAD Wave 2 proposals for work in this area.

3. Workshop Discussions/Outcomes

3.1 Workshop 1 Parts A/B

Prior to the first set of workshops, DBD knowledge gaps (KGs) were identified following a review of state-of-the-art DBD literature, the work completed by the Sustainable Network for Independent Technical Expertise on radioactive waste management (SITEX) and information submitted by ASTRA participants (Appendix A). A KG matrix was developed that compiled and organised the identified KGs according to each stage of the DBD life cycle:

- site characterisation / site selection
- deep borehole field test (DBFT)
- drilling tools and techniques
- sealing and backfilling
- emplacement
- safety assessment and safety case
- justification of engineered barrier system (EBS)
- waste retrievability and overpack design

These KGs were discussed with Core Team partners, and through one-on-one interviews with drilling experts, regulators, and DBD researchers, to identify ways in which they could be addressed in the Task. The selected knowledge gaps were chosen based on the level of interest from ASTRA participants, as well as the expertise available at the workshops so that the most relevant and valuable insights could be gathered. As a result, three of these KGs were selected to examine in more detail during the first workshop:

- site characterisation / site selection
- DBFT
- safety assessment and safety case

In addition, a portion of the workshop was devoted to discussion of the strategic context of DBD in some of the Task 4 partner host countries. The workshop was split into Part A and Part B. Part A consisted of a series of break-out group discussions for each of the KGs while Part B was a plenary session in which the outcomes of Part A were considered.

In the following sub-sections, we provide a brief introduction to these knowledge gaps and summarise the Workshop 1 discussions.

3.1.1 Deep Borehole Field Test

A comprehensive RD&D program is essential to demonstrate the technical feasibility and long-term safety of DBD, with DBFTs playing a critical role. A DBFT would confirm the viability of key activities such as deep drilling, site characterisation, casing, sealing, and engineered barrier emplacement, therefore increasing technical readiness and stakeholder (and public) confidence. To guide DBFT development, a generic safety case defining safety functions and performance targets should be established through international consensus, which can later be adapted to site specific conditions.

3.1.2 Site Characterisation/Site Selection

The DBD concept relies on a suitable host rock, and an environment where radionuclide transport occurs only by diffusion (implying an environment with isolated, stagnant groundwater) to provide containment and isolation safety functions. Key site characterisation KGs include how to understand and map permeability and porosity variations at depth, how to demonstrate groundwater isolation and lack of flow, and a need to understand possible effects of heat and gas generation on groundwater behaviour. Site characterisation will involve desk-based geological studies, geophysical surveys and fluid sampling at depth. There are expected challenges due to elevated temperature and salinity at depth that will affect sample reliability and approaches to geochemical modelling. In line with the guidance (Appendix B) provided in International Atomic Energy Agency (IAEA) SSR-5 and SSG-1 (for borehole disposal of sealed sources), site selection for DBD follows a stepwise approach. This includes the development of basic requirements for the DBD concept, the establishment of siting criteria for the relevant geological setting(s), a site survey and screening stage, and a final site selection stage. This process is expected to involve desktop studies, detailed surface-based field studies, and the drilling of one or more site characterisation boreholes to confirm regional homogeneity and compliance with the siting criteria.

3.1.3 Safety Assessment and Case

A comprehensive safety assessment framework is needed for DBD to be implemented, covering both operational and post-closure phases. Site-specific data and modelling will be essential for demonstrating safety. Existing features, events, and processes (FEP) lists can be used as starting points for the safety assessment. It should be noted that FEP lists specific to DBD are already available, for example those published by Sandia National Laboratories [5], which provide a useful and relevant basis for developing a DBD safety case. Some of the key FEPs are the ones affecting groundwater, radionuclide transport, and WP degradation. Analysis of FEPs in the context of DBD may require a new approach and assessment methods may need to be developed (e.g., data collection and model development). A mitigation plan is essential to manage operational accidents such as packages getting stuck or being dropped during emplacement. While the oil and gas (O&G) industry provides drilling experience, handling radioactive materials requires additional precautions and must comply with radioactive substances regulations.

3.1.4 Strategic Context

The strategic context for DBD is necessarily specific to individual countries. National approaches to DBD are shaped by local geological conditions, regulatory requirements, history, public acceptance, and waste inventory characteristics. The discussions in Workshop 1 highlighted how attitudes (or at least how these attitudes are perceived by Task 4 partners) to DBD development differ between countries. For example, Switzerland, France and Ukraine currently favour disposal of radioactive waste in DGRs, while observing international DBD developments. In some cases, DBD is already recognised as an alternative disposal option in national policies, strategies, and programs (e.g., Slovenia, Estonia, the Netherlands, and South Africa) (Appendix C).

3.2 Inter-workshop Activities

During the planning for Workshop 2, two possible approaches were considered: conducting focused technical discussions on the remaining DBD KGs (Section 3.1), or adopting a broader, cross-cutting discussion, focussing on topics that affect multiple parts of the DBD concept or programme, rather than diving into detailed technical issues. Given that that Task 4 is part of a Strategic Study, learning from the experience of Workshop 1, and accounting for the diversity of partners and their interests (Appendix A), it was agreed that Workshop 2 should prioritise cross-cutting issues rather than technical ones. It was also noted that the IAEA DBD work programme is focusing on TRLs, and that this task should seek to avoid duplicating effort where possible.

The discussions in Workshop 1 highlighted that defining a generic DBD concept could provide a useful template around which Member States could develop a national DBD plan. The aim of defining a generic DBD concept is to establish a baseline for feasibility and safety assessment and provide the foundation for individual safety cases. It also progresses the overall aims of Task 4, namely, to identify technical knowledge gaps and guide RD&D activities. Accordingly, the focus of Workshop 2 became the development of this generic concept. The following subsections described the work done between Workshops 1 and 2 to develop the generic DBD concept.

3.2.1 DBD Guidance & Requirements

The generic concept was developed with the aim of being useful to as many organisations and countries as possible. Within Workshop 2 it served as a reference standard to help ensure that the discussions on safety functions and demonstration pathways were focused and productive. To underpin the generic concept and define the key safety functions, it was first necessary to identify existing generic and DBD specific requirements (Appendix B) in current international guidance issued by the IAEA and Nuclear Energy Agency (NEA) [1,2,3,4].

The generic DBD concept in crystalline basement rock, is shown in Figure 1, and is largely based on the requirements of the international guidance documents (Appendix B). For illustrative purposes, the generic DBD concept in crystalline basement rock, is at a depth of 4500 m (but this is indicative rather than prescriptive), assuming that the necessary geological and hydrogeological conditions can be identified at this depth.

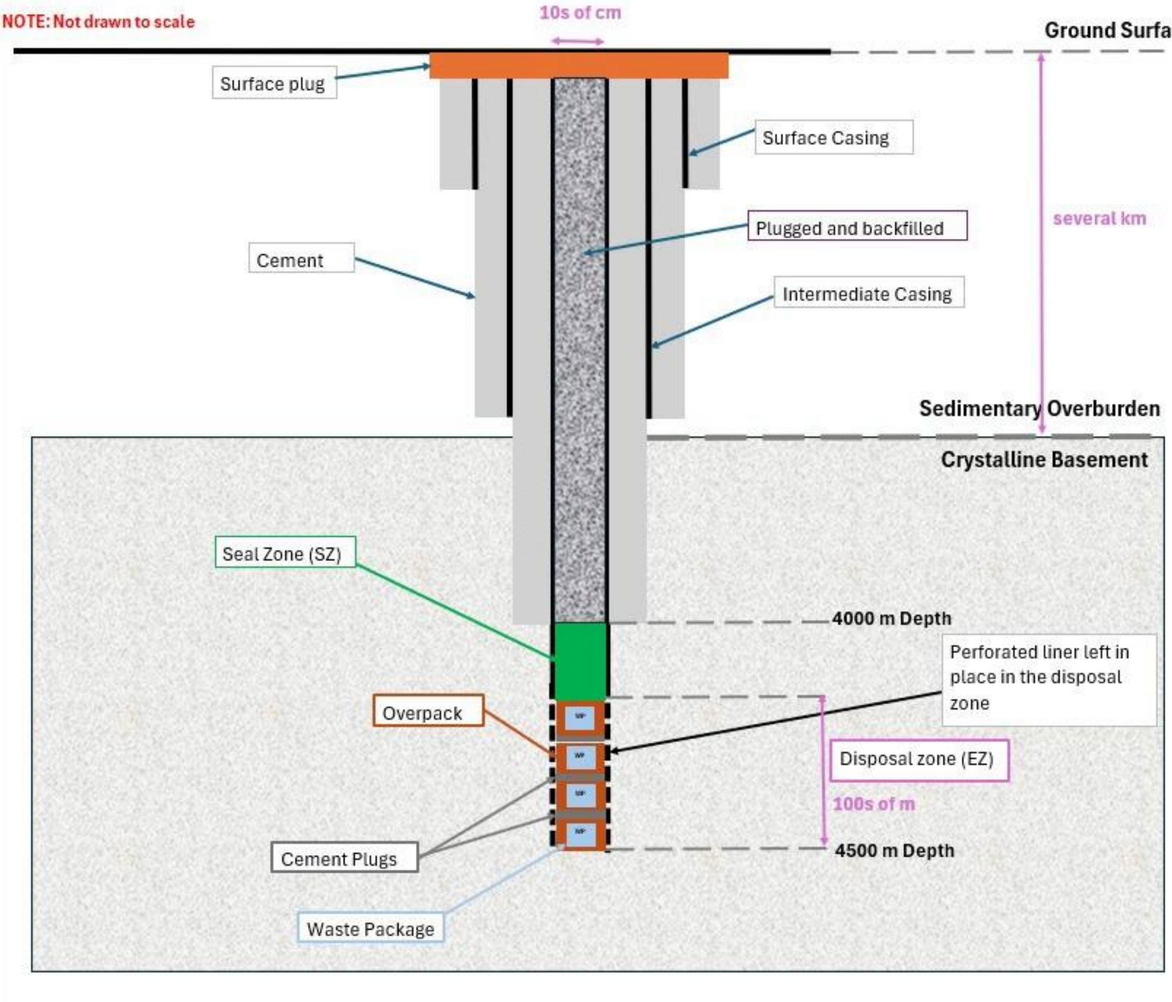

Figure 1 - Generic DBD concept in crystalline basement rock

A second generic concept (Figure 2) was developed based on disposal in sedimentary rock. Both concepts incorporate a multi-barrier system, including the waste packages, borehole seals, and the natural geologic barrier, to ensure long-term containment. The generic DBD concept was divided into key components: borehole depth, host rock, borehole casing, inventory waste form, WP (primary containment plus overpack) emplacement zone/method, sealing / plugs and backfilling. During Workshop 2, participants reviewed and discussed the associated requirements and safety functions for each component to assess its relevance and applicability to DBD.

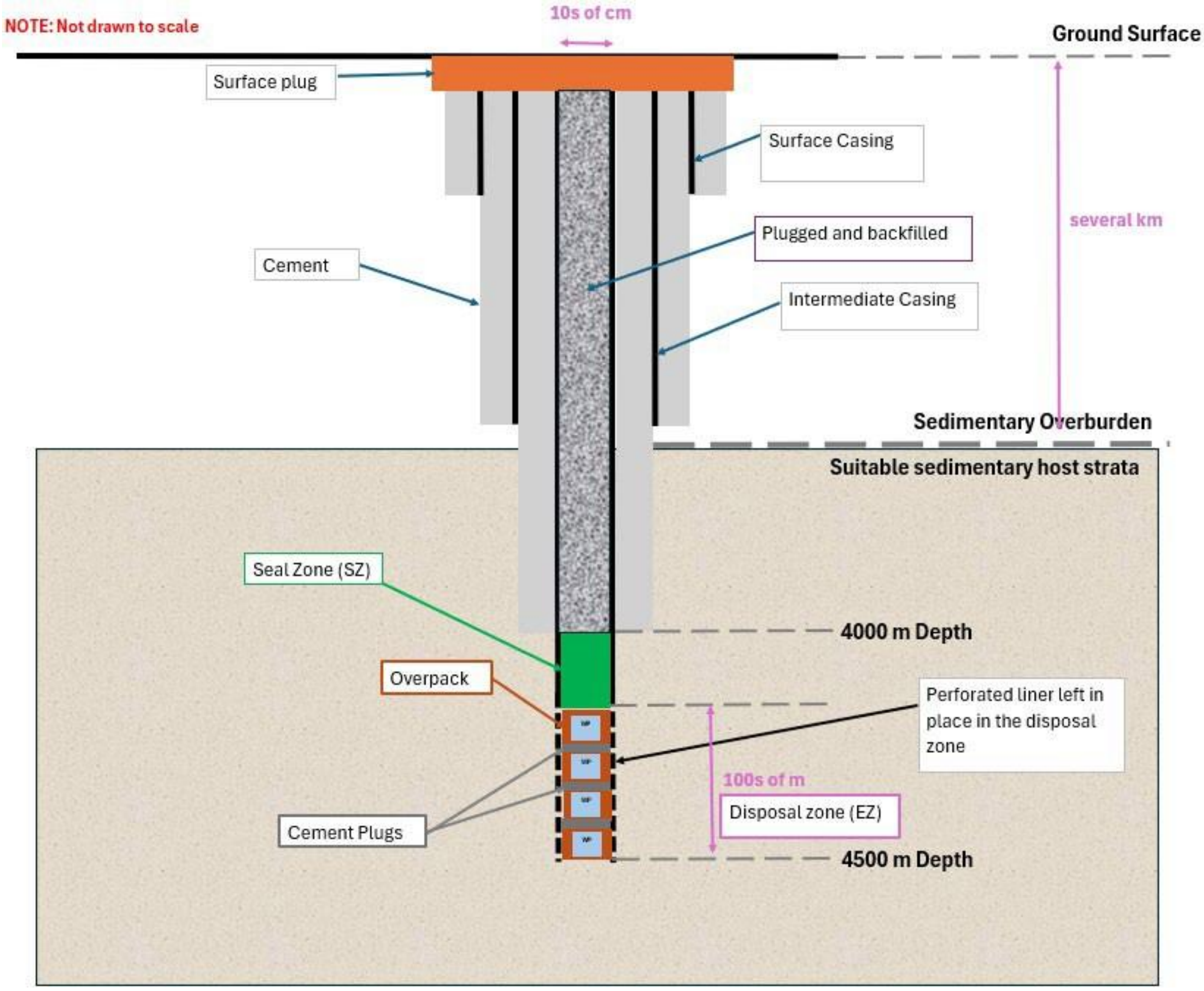

Figure 2 - Generic DBD concept in sedimentary basement rock

3.2.2 Exclusion Criteria

In addition to reviewing requirements, it was recognised that developing exclusion criteria, which could rule out the suitability of DBD, would be valuable, as these can guide the decision making of parties considering DBD. Exclusion criteria are the conditions that would automatically rule out a site or disposal concept at an early stage, on the basis that it cannot reasonably be expected to deliver safe construction, operation, closure, and long-term isolation of radioactive material. For DBD, exclusion criteria are typically defined to screen out locations or concepts that are fundamentally incompatible with safety, technical feasibility, or regulatory acceptability and commonly relate to:

- Geological stability (e.g. active faulting or insufficiently stable host rock)
- Hydrogeological conditions (e.g. evidence of groundwater movement or high permeability)
- Engineering feasibility (e.g. inability to drill, case, emplace waste, or seal boreholes safely and reliably)
- Safety and regulatory considerations (e.g. inability to demonstrate long-term containment, manage operational risks, or control criticality and thermal effects)

If any exclusion criterion is met, the site or option would not be taken forward for further consideration.

The following exclusion criteria were developed using existing international guidance and applicable regulatory requirements as the baseline, together with the programmatic judgement of conditions that would be unlikely to meet regulatory requirements. The criteria were deliberately conservative to clearly identify unsuitable areas and facilitate structured discussion during Workshop 2. Note that assessing exclusion criteria requires a broad, multidisciplinary approach, as robust evaluations often depend on considering site specific combinations of multiple parameters.

3.2.2.1 Borehole Location

It is important to emphasise that depth alone is not an exclusion criterion: boreholes should reach whatever depth is needed to meet the required geological and hydrogeological conditions. However, it is also clear that sufficient depth is required to provide the isolation of the waste and avoid later human intrusion. The performance will depend primarily on the intrinsic properties of the host rock and surrounding geology. Exclusion criteria for borehole location include sites of high seismicity or faulted areas, locations with active groundwater flow, and areas containing valuable subsurface resources (the presence of which might increase the likelihood of future inadvertent human intrusion). Best practices involve avoiding freshwater aquifers and ensuring the presence of stagnant, saline groundwaters with high pH and low redox conditions (i.e., reducing conditions) in the disposal zone. Drilling feasibility will depend on both the target depth and the diameter of the proposed borehole.

3.2.2.2 Host Rock and Local Hydrogeology

The mechanical properties of the host rock and borehole stability are interrelated. The assessment of the suitability of the host rock depends on regional stress, tectonic history, and geological heterogeneity. Unsuitable sites include those with fractured or porous rocks that may have a tendency to promote active hydrothermal flow, high seismicity, proximity to active faults or groundwater interaction. Quantitative parameters like the Peclet number (describing the ratio of advective to diffusive groundwater flow), fracture density and groundwater composition (including stable isotope - O^{18} / O^{16}, deuterium/hydrogen - signatures) may be used to exclude a proposed disposal site.

3.2.2.3 Borehole Casing

The borehole casing primarily provides operational structural support to the borehole. Deep groundwaters in crystalline rocks often have high salinity that will likely accelerate casing corrosion. The rate of corrosion will depend on both the casing material and the local chemical conditions. Materials that are not resistant to highly saline or elevated-temperature conditions (or the site-specific conditions) should therefore be avoided.

3.2.2.4 Inventory and Waste Form

It is possible that certain wastes or waste forms may be unsuitable for DBD due to factors affecting long-term safety (e.g. waste forms with high corrosion rates or containing radionuclides with high mobility in geological formations) and reprocessing may be needed prior to disposal. There can also be economic and other specific national reasons that certain wastes or waste forms are unsuitable for DBD. The low porosity, low permeability and limited groundwater flow assumed to characterise the disposal zone may make criticality of the system unlikely, but it must still be assessed and wastes excluded accordingly. Vitrified HLW (vHLW) generates significant heat, so thermal impacts, including the potential to drive hydrothermal flow, must be assessed (and wastes excluded as necessary) to show that previously stagnant groundwater remains isolated. In this regard it was recommended to prioritise the behaviours of highly mobile species, like tritium and chloride, in performance assessments. While DBD is a promising concept, its suitability for HLW, including waste from small modular reactors (SMRs), and especially advanced reactor fuels (AMRs), has yet to be determined.

3.2.2.5 Waste Package and Overpack

The overpack enhances the structural strength of the WP and may help to meet transport and radiation/operation safety regulations. Using a single overpack for both transport and disposal is practical, though the location where the overpack is applied and the process undertaken if the overpack is to be removed, must be specified, along with the approach to introducing the WP into the borehole.

A WP and overpack that is not compatible with emplacement operations and other EBS components will be excluded.

3.2.2.6 Engineered Barrier System

The EBS, comprising the borehole casing, WPs, overpacks (if applicable), plugs, seals, and backfills, works in tandem with the host rock to provide safety. No specific feedback was provided on criteria for excluding EBS materials during the workshops, but it was later noted that the expected thermo-hydro-chemical-mechanical processes (THCM) evolution of EBS materials should be considered as a basis. For emplacement of seals and plugs, it is expected that experience from the O&G industry will be invaluable for borehole operations, although some techniques may have uncertainties when applied to DBD, particularly given that the required performance timescales for final waste isolation, extending at least until the end of the thermal period or until effects on groundwater flow are no longer significant, are much longer than typical O&G operations. Backfill materials that do not disrupt groundwater flow should be selected, meaning they should not create preferential flow paths that could alter the natural hydrogeology, or provide channels for radionuclide migration. Ideally, the backfill should match the host geology in material properties. Cementitious barriers can be used to maintain chemical stability and to suppress corrosion of metallic barriers (canisters, overpacks and casing). Microbial activity is not expected to be a significant concern in reducing conditions, but this needs to be confirmed with further studies at the disposal depth.

3.2.3 Demonstrating Adequate Performance of the DBD System

Regulators from Finland, Germany, Belgium and France were interviewed to understand their views on anticipated DBD requirements. These are captured in the following sub-sections. Note that these are the opinions of the individuals based on their experiences and do not reflect the official position of the regulatory bodies. The interviews not only reinforced key points raised in Workshop 1 but also helped shape the structure of the generic DBD concept by highlighting regulatory requirements that will likely need to be addressed.

3.2.3.1 Site Characteristics

Demonstrating that a site will be able to deliver the required safety functions, ensuring host rock integrity, and characterising stable, stagnant groundwater is key but is also technically challenging and may be costly. Moreover, DBD site investigations must balance data collection with minimising disturbance to avoid creating new and unfavourable groundwater pathways. Regulatory expectations suggest that the number of boreholes should be optimised to ensure adequate site characterisation while avoiding disturbing the natural groundwater flow.

3.2.3.2 Borehole Design

Vertical boreholes in crystalline rock have a smaller surface footprint than DGRs while the boreholes can reach considerable depth, reducing the possibility of inadvertent human intrusion. The design of the EBS must account for long-term material evolution to ensure that the borehole does not become a release pathway. Seals and plugs must be compatible with the host rock environment to minimise degradation. They must also be able prevent fluid or gas transport up the borehole, such as might be caused by gas generation from corrosion under wet conditions.

3.2.3.3 Overpack

As primary waste packages and canisters may have a wide range of dimensions this may complicate their emplacement in the borehole. Additionally, given the potential for long storage times before disposal, they may also be damaged during the operational phase. This leads to uncertainty in their longevity and containment properties in the DBD context. In some cases, an overpack may be used to contain the primary waste packages to provide for uniformity of waste package size and shape, and to guarantee a certain waste package longevity. It is also expected that demonstration of the possibility of retrievability will be required during the operational phase and should be feasible until the borehole is backfilled and sealed, which is likely limited to the active operational period (typically several decades). Sequential disposal campaigns, filling one borehole at a time, could help promote better retrievability and operational control.

3.2.3.4 Demonstration of Feasibility and Safety

The safety concept for DBD must be clearly defined, justified, and the safety case must comply with radiological requirements. Key FEPs should be identified and incorporated into scenario analyses without overcomplicating them. The approach is particularly suitable for HLW, SNF, sealed sources, and small inventories. Passive institutional control duration is expected to be similar to that for a DGR. For some waste types, shielding will be needed during transport; this could be provided by an overpack that also serves as the disposal WP.

The licensee must define, justify, and demonstrate the long-term safety of the DBD concept. Existing deep boreholes can help provide information on groundwater behaviour, and monitoring can be used to confirm expected behaviour. Unexpected findings, such as unanticipated vertical or lateral flow pathways, changes in groundwater chemistry, or the detection of microbial activity at depths where none was anticipated, are the primary concern as these may challenge underlying assumptions and require further evaluation.

3.2.3.5 Operations

There has been no demonstration of emplacement of radioactive waste packages into boreholes to date. Operational considerations for DBD include canister installation failures when WPs are introduced to the borehole, radiation safety, and induced seismicity risks during drilling. Challenges such as blockages, leaks, remote operations, and hydrogeological uncertainties limit feasibility for large waste inventories, making DBD mainly suitable for smaller waste quantities.

3.3 Workshop 2 Parts A/B

The generic DBD concept developed following Workshop 1 was used during Workshop 2 to guide discussions focussed on defining safety functions of specific DBD components and identifying demonstration pathways. The aim was to establish a baseline for future DBD feasibility and safety assessments. This can further be used to underpin and strengthen the safety case and identify technical knowledge gaps and RD&D priorities. The following subsections summarise the Workshop 2 discussions.

3.3.1 Safety Functions

Safety functions are a characteristic or mechanism of the entire disposal system (Figure 3), comprising EBS, geological formations, and operational procedures, defined to protect people and the environment from radiological impacts. The second workshop considered each component of the DBD system and identified the main safety functions associated with different parts of the DBD system. Workshop participants voted on what functions they considered the most important, and which were desirable but not essential. This is qualitatively captured in the following descriptions.

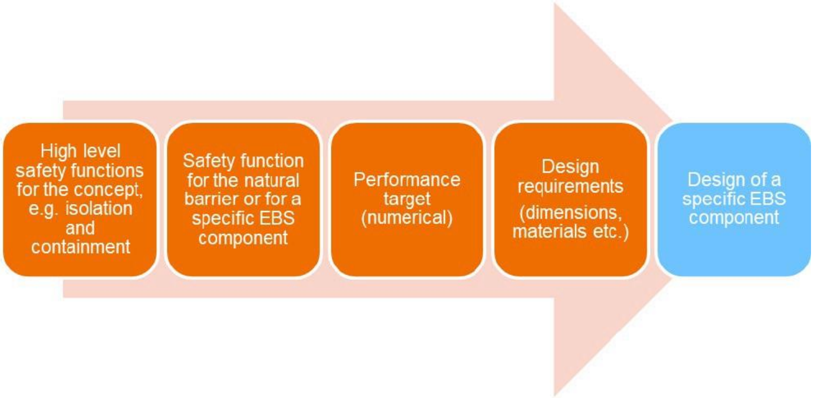

Figure 3 - Safety Functions in a Requirement Management System (Example from a KBS-3 Repository)

3.3.1.1 Inventory and Waste Form

Essential safety functions of the waste in the DBD concept include ensuring slow (or no) dissolution in the disposal zone to limit radionuclide release; being emplaced in such a way as to maintain subcriticality; preventing excessive heat that could accelerate degradation of engineered barriers; and minimising damage to the surrounding rock. Other factors associated with the inventory, such as radiotoxicity, thermal output, and radionuclide mobility inform the safety case but are not safety functions themselves.

3.3.1.2 Host Rock

Essential safety functions provided by the host rock for DBD include radionuclide retardation, geochemical conditions supporting EBS stability, and seismic stability. The most important containment safety function is hydrogeological, provided by a diffusive transport environment (characterised by old, stagnant, saline groundwater), coupled with sufficient depth for isolation from the surface. Beneficial but non-essential features include permeability for gas dissipation and sufficient thermal conductivity to allow heat generated by the waste to be removed by conduction efficiently. High pH conditions act as a secondary safeguard to retard radionuclide transport complementing the primary safety function of limiting groundwater flow.

3.3.1.3 Waste Package and Overpack

The primary (essential) safety function of the WP is containment during the operational phase. However, long-term containment throughout the thermal phase is considered desirable but not essential. The inclusion of an overpack is considered optional with its key functions being to facilitate WP installation and provide radiation shielding during operations.

3.3.1.4 Backfilling

The main function of the borehole backfill is to provide isolation from any flowing groundwater or aquifers that the borehole may pass through before reaching disposal depth, to support containment and mechanical stability, and retard any radionuclide transport up the borehole through sorption. The isolation function is regarded as essential while the mechanical stability component is considered beneficial but not essential.

3.3.1.5 Plugs and Seals

It is essential that plugs and seals provide isolation from the biosphere and contribute to the containment function of the waste packages/overpack by providing suitable geochemical conditions. Providing sufficient gas permeability and mechanical support, retarding radionuclide transport and contributing to subcriticality on account of their low porosity are viewed as desirable but not essential.

3.3.2 Demonstration Pathways

The safety functions identified can be demonstrated through analyses and evidence that support the safety case. This demonstration is expected primarily to be for the regulatory authorities. However, given that DBD appears a novel concept in the landscape of disposal options it is also important to communicate these safety demonstrations to the public to address questions and concerns.

3.3.2.1 Borehole Depth

The minimum depth of the top of the disposal section depends on site-specific conditions.

3.3.2.2 Host Rock

To ensure effective containment, the host rock must only permit primarily diffusive transport which would be evidenced by a groundwater that is old and stagnant. Isotopic signatures, such as O^{18}/O^{16} and deuterium/hydrogen, can be used to indicate long-term isolation from surface recharge. Sampling at the bottom of the borehole raises challenges in terms of isolating sufficient water from the target strata and avoiding sample contamination and will require specialised sampling techniques. Identifying signatures of dissolved minerals may help trace water origins but is technically difficult. Future work should focus on methods to isolate and sample groundwater and to assess how quickly the disposal zone recovers geochemically after drilling, which is critical for long-term safety.

3.3.2.3 Borehole Casing

The EBS, comprising the borehole casing, WPs, overpacks, plugs, seals, and backfill, works in tandem with the host rock to provide safety. Questions remain as to whether the casing would need to be cut and sealed where the host rock type changes, such as when isolating aquifers, to maintain hydraulic separation. Long-term casing performance, corrosion and hydrogen generation remain important issues for demonstration and operational safety.

3.3.2.4 Waste Packages

Demonstrating containment by the WP over the thermal period is a requirement of some DGR concepts and may be a requirement for some future DBD system. Typically, the definition of the thermal period is the time during which a significant thermal gradient around the WP exists although the length of time varies between different host rocks (crystalline, sedimentary or other) depending on thermal conductivity, concept (especially spacing of heat-producing waste), and heat load per WP. The overpack may be required to maintain integrity throughout the thermal period; however, the required overpack lifetime can differ significantly between concepts and waste management programmes. In the workshop discussion, natural analogues, though acknowledged to be informative, were considered to have limited applicability for demonstrating long-term overpack containment in DBD systems.

3.3.2.5 Seals

Seal performance evaluation and monitoring were identified as key technical challenges. Discussions focused on what parameters to monitor, how to assess seal effectiveness and whether monitoring could support safety demonstrations for other EBS components. Any monitoring should be carried out so as not to compromise the integrity of the DBD system. It was agreed during the workshop that post-closure safety must not depend on permanent monitoring.

3.3.3 Civil Society Perspective

Engagement with CS is a core part of ASTRA Task 4 and is led by Nuclear Transparency Watch (NTW). The aim is to strengthen collaboration between CS, WMOs, technical support organisations (TSOs), and research entities (REs). Given the immature status of DBD implementation, CS views are evolving but key priorities identified included ensuring a robust and transparent safety case, understanding the implications of deep disposal for human intrusion risk and debating the role of retrievability vs. non-retrievability. Continued open dialogue is essential to ensure that CS perspectives are used to inform future decisions. Key technical challenges identified by the CS partners include canister/overpack emplacement and retrieval, potential DBD induced seismicity, understanding groundwater transport, and how to demonstrate the extent of stagnant groundwater zones in crystalline and sedimentary formations.

4. Conclusions and Next Steps

The work in ASTRA Task 4 provides valuable insights into the current state of DBD. It has identified key knowledge gaps and safety functions, provided a qualitative description of requirements, and highlighted RD&D priorities for future research. A coherent generic DBD concept has been established, providing a baseline framework that supports safety case development, allows for comparison of specific concepts between countries and aids planning of future research. The outcomes of the workshop discussions are expected to contribute significantly to advancing the perceived feasibility of DBD as a viable disposal solution.

The overarching conclusion from both workshops is that some technical challenges remain significant, particularly in relation to:

- deep drilling operations at the required depths and diameters
- long-term performance of seals and plugs
- corrosion processes and their control under in-situ conditions
- the ability to demonstrate reliable monitoring at great depth

In particular, the following areas were identified as high-priority RD&D needs:

- emplacement and retrieval operations, which are technically complex and have not yet been demonstrated for radioactive waste packages containing HLW/SNF
- development and demonstration of techniques to confirm that stagnant groundwater conditions persist despite the mechanical and thermal disturbances associated with borehole construction and waste package emplacement

More generally, there is a clear need for further RD&D to improve understanding of host rock conditions at typical DBD depths, using data from existing deep boreholes. Priority topics include:

- hydrogeological and pore fluid properties
- geochemical and redox conditions
- microbial activity and its potential influence on corrosion processes
- factors affecting radionuclide migration, including sorption.

Such studies are required to reduce key uncertainties and to strengthen the technical basis for DBD across crystalline, sedimentary, and other potential host formations.

Development of safety functions, as well as operational and long-term safety requirements for DBD, requires further dialogue with stakeholders, the scientific community (including through IAEA, NEA, and similar organisations), and civil society. While the multibarrier concept provides a general framework, DBD-specific requirements and safety demonstrations need to be established collaboratively to ensure that all safety functions are properly addressed throughout the lifecycle of the disposal system. Later the concept can be further optimised with respect to, for example, costs, technological or operational parameters, assuming that key safety functions remain fulfilled under all optimised configurations.

Engagement with CS is essential for transparency and legitimacy of DBD. Open dialogue on topics such as retrievability and operational and long-term safety is vital to public acceptance. Further international collaboration is needed to further progress technical understanding, standardise safety approaches and share lessons learned across DBD and DGR programmes.

References

[1] IAEA. Safety Standards, Specific Safety Requirements, Geological Disposal Facilities for Radioactive Waste, No. SSR-5 (2011).

[2] OECD NEA. Engineered Barrier Systems and the Safety of Deep Geological Repositories, ISBN 92-64-18498-8 (2003).

[3] IAEA. Safety Standards, Specific Safety Guide, Geological Disposal Facilities for Radioactive Waste, No. SSG-14 (2011).

[4] IAEA. Safety Standards, Specific Safety Guide, Borehole Disposal Facilities for Disused Sealed Radioactive Sources, No. SSG-1 (Rev. 1) (IAEA 2024).

[5] Sandia National Laboratories (2016). Deep Borehole Disposal Safety Analysis. (DOE/ID-Number FCRD-USED-2011-000184)

Appendices – Table of Contents