Deep Borehole Repository of HLW and SF – State of Knowledge by the SITEX.Network

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ABSTRACT

Many countries develop geological disposal projects for high-level radioactive waste (HLW) and/or spent fuel (SF) when considered as waste. The most widely selected option is the Deep Geological Repository (DGR) concept, a mined repository with galleries located underground in geological layers into which packaged waste would be placed; the sites for such DGR have been selected in Finland, France and Sweden, and a site selection process is on-going in several other countries, such as the United Kingdom, Germany and Switzerland.

As an alternative concept to the DGR, the Deep Borehole Repository (DBR) concept, where waste packages are placed into single boreholes, relies on a similar safety strategy: confining and isolating waste from the biosphere and surface natural phenomena in order to respectively rely on the geological environment to ensure long-term passive safety and reduce the risk of human intrusion. The concept of DBR was first considered in the 1950s, but was rejected until the 2000s as it was far beyond existing drilling capabilities among others, given the constraints for HLW and SF management.

New technical developments in the drilling field relaunched the interest of safe management of HLW and SF based on DBR concept in several countries. Therefore, the SITEX.Network association developed an overview of the existing studies that have been published on the DBR concept with information on the concept itself, on deployment strategies and methods, on issues associated with requirements related to waste packages and borehole equipment, hydro-geology, disposal operation, backfilling and sealing, and finally on safety analyses. The main aim is to deliver bibliographical overview providing the state of knowledge about the DBR concept, the technical solutions for its implementation or major obstacles evidenced as a basis to identify safety issues important to deal with in a Safety Case. This could be considered to identify for the future R&D as well. This paper discusses the controversial issue of DBR trying to provide information from different viewpoints, like design options, required R&D programmes, societal concerns and regulatory needs.

1 INTRODUCTION

Many countries are developing a geological disposal project to dispose of their high-level radioactive waste (HLW) and potentially their intermediate, long-lived radioactive waste (ILW-LL) as well as spent nuclear fuel (SF) when considered as waste. The most widely selected option is the deep geological repository (DGR) concept, a mining repository located underground in a geological layer, in which conditioned waste is disposed of. Many countries are currently investigating this option; in particular, sites for such DGR have been selected in Finland, France and Sweden. The implementation of DGR programmes has started in Finland

and Sweden. Site selection process is underway in several other countries, such as the United Kingdom, Germany and Switzerland.

Besides the DGR concept, the concept of borehole repository is or was also considered in some countries. It relies on two main safety functions similar to those of the DGR: isolate waste from natural surface phenomena, thereby significantly reducing the risk of human intrusion, and rely on the geological environment to ensure long-term passive containment. Several very different concepts of borehole disposal have been studied and sometimes implemented in the past, or are still under consideration:

1. Deep disposal of exothermic waste so that waste provokes local melting of the surrounding rock and that both are mixed up; various options intensively studied in the 1970s and 1980s are no longer studied today.
2. Deep injection of liquid waste through boreholes, which has already been implemented for low and intermediate-level radioactive waste in the USA and Russia.
3. Disposal of small solid waste in small quantities (such as disused sealed sources), in a several tens to several hundred meters depth borehole (depending on the site, waste activities …): a guide was developed by the International Atomic Energy Agency (IAEA) and there are several projects in progress, for instance in Ghana.
4. Finally, the disposal of larger quantities of solid waste, potentially of HLW or SF, in a Deep Borehole Repository (DBR) at a depth of several hundred to several thousands of metres, is being considered in few countries and is being actively studied in the USA, including for SF disposal.

The two first above-mentioned concepts are "historical" projects that are nowadays not in use for HLW. The third concept is considered as a potential solution for the management of very small quantities of small waste packages (such as disused radioactive sources). The fourth borehole disposal concept, the DBR, is the only one being studied today for disposal of HLW and SF. The concept was first considered in the 1950s but rejected as it was considered to be beyond drilling capabilities. Improvements in drilling and associated technologies, together with sealing methods progress have led to reconsider this option for the disposal of HLW, including SF if considered as waste. In this DBR concept, it is planned to bury the waste as far as 5 km beneath the Earth's surface. It relies primarily on the thickness of the natural geological barrier to safely isolate the waste from the biosphere and the environment for a very long period of time so that it should not pose a threat to humans and the environment. The waste would be placed in the lower part of such a hole, within basement rock while the upper part of the borehole would be filled with materials (e.g., asphalt, bentonite, concrete or crushed rock) that are expected to contain the radioactivity and thus protect humans and the environment during geological time.

The SITEX.Network[1], an association of Technical Support Organizations and related organisations which implement expertise function in radioactive waste management, decided to perform a bibliographic review of documents related to deep borehole and publish the summary report "Deep Borehole Repository Of High-Level Radioactive Waste, State of

[1] https://www.sitex.network/

knowledge and first assessment of the pros and cons" [1] without the objective to question the choices made in national radioactive waste management programmes.

2 METHODOLOGY

Many studies and papers have been published on the DBR concept with information on the concept itself, waste packages, geology, construction issues, deployment strategies and methods, disposal operation, backfilling and sealing, and safety analyses. The goal of the SITEX.Network study is to provide information from a number of different perspectives so that everyone has the key elements to debate the issue. The information is collected through a bibliographical review of several references detailing the investigations carried out on the DBR concept throughout the world, the current or planned solutions, the reasons for abandonment and/or challenges identified for future R&D (research and development).

Based on the participants' experience with this SITEX.Network activity, the list of related reports and articles devoted to the DBR concepts were compiled with the main aim to provide diversity of content. All together 62 documents have been analysed and further investigated for their relevance of project objectives in order to assess, if the studies, tests or implementations were carried out in the past ("historical publication") or if they are part of the current development in the area. In 2019, IRSN published the report on past studies on borehole repositories [2] which was used as an input.

The further investigation included 25 papers/studies with recent or ongoing relevant DBR content which were reviewed by SITEX members by using the same format divided into 4 topics on safety issues, social concerns, R&D needs and regulatory aspects. The reviewers were members of the SITEX.Network and were representing various kinds of RWM actors (TSOs, regulatory authorities, civil society organisations). The first draft DBR report, developed in November 2020, was discussed with different actors at SITEX Topical day (November 2020) on the advantages and disadvantages of DBR with regard to DGR. The final version of SITEX.Network DBR report (still in draft, available on the website [1]) includes reviews and discussions. It has to be emphasised that the present report provides a bibliographic review of studies and projects associated to the deep borehole disposal. Various designs described in literature were considered and the review provides an overview of their associated state of knowledge. Aspects related to safety, societal concerns, regulatory aspects and R&D needs as well as challenges are addressed. The review study led to the identification of potential advantages as well as obstacles to the disposal of SF and HLW in a DBR, compared to the current mined HLW repository, already under construction in some countries.

3 OVERVIEW OF VARIOUS BOREHOLE DISPOSAL DEVELOPMENTS SINCE THE 1950'S

The first ideas on borehole disposal of radioactive waste already evolved in the 1950s, since a large amount of waste accumulated due to the increase in nuclear technology use. Borehole disposal is the placement of waste in vertical structures drilled into rock to isolate it from natural surface phenomena, to reduce the possibility of contact with humans by reducing their accessibility and to prevent the dispersion of their content in the environment. This option is similar to the deep geological repository option due to its objectives and because it involves geological environment. However, it is distinguished by some important specific features. While geological disposal is based on the digging of an underground facility into which waste is transported and then emplaced in specially designed and equipped cells, all the operations of borehole disposal are carried out from the surface, from the digging and handling of packages to the closure operations. The target depth for some borehole disposal concepts can be much greater than that of a geological repository and mainly depends on the waste type to be disposed (HLW, SF or intermediate level long lived RW).

Three types of borehole disposal can be mentioned according to the type of waste:

- Embedding of exothermic waste (such as SF or vitrified HLW from its reprocessing) in a vitreous gangue resulting from the melting of the host rock. In order to trigger the melting phenomenon, the concept is to place waste in a rock that dissipates little heat and has a sufficiently low melting point (app 900ºC), such as granitic rocks. Since temperature naturally increases with depth, the use of deep boreholes can be a favourable element.
- Injection of liquid waste directly into the rock. In this case, the rock, located several hundred metres below the surface, is chosen for its injection capability (characterised in particular by its porosity), as well as for its hydrogeological characteristics, the objective being to limit horizontal and vertical transfers.
- Stacking of solid waste packages in a relatively shallow borehole. In this case, waste, such as spent radioactive sources (SRS), is placed at a depth that depends in particular on waste characteristics, usually from tens up to 100 metres below ground, and then the borehole is sealed.

All these options of borehole disposals are no longer in use for HLW (vitrified waste of SF regarded as waste). For the last option, i. e. the borehole disposal of SRS, the IAEA also published a guide (Specific Safety Guide-1, [3]), which addresses the safety issues relevant for the disposal of disused sealed sources and provides guidance on meeting the safety requirements and criteria for such facilities. This concept is being assessed in several small inventory countries like Ghana, Malaysia and the Philippines.

4 SITEX.NETWORK BIBLIOGRAPHIC REVIEW

4.1 Aspects associated to the safety of DBR

The Deep Borehole Repository concept originates from National Academy of Science report [4]: a borehole reaching crystalline basement at approximately 5 km depth, with waste packages placed in the 2 km lower section, and sealing and plugging the upper portion of the borehole with a combination of bentonite, cement, and cement/crushed rock backfill (Figure 1). Alternatively, also other rocks are being studied, like sedimentary rocks in Germany, or the modified concept with horizontal disposal after a vertical drillhole reaching the basement. The safety concept is based almost entirely on containment in the natural geological barrier in which zero release of radionuclides by groundwater is assured for approximately 1 million years. Alternatively, some multiple engineered barriers have been added to the basic DBR concept like waste packages, plugs and backfilling between/in packages. The DBR is constructed by drilling the boreholes with a telescoping design in which casing from carbon steel is emplaced (to protect groundwater and facilitate emplacement) and then cemented after drilling each section. Solid radioactive waste is packaged in corrosion-resistant alloy canisters which must withstand the bottom hole hydrostatic pressure and stacking loads from packages emplaced over them. Some designs also foresee an option of backfill within the canister (suitable material against mechanical damage, increased thermal conductivity, including boron to absorb neutrons etc.) and installing plugs in the borehole to bear the weight of additional packages. Various methods for waste packages emplacement are studied like the strings of packages in a conveyance casing on drill pipe, one or a few at a time on coiled tubing or an electric wireline or even dropping one at a time for free fall. But in all versions of waste emplacement, the operation is to be performed in a fluid (e. g. oil and bentonite) to counteract stresses and hydrostatic pressure and remotely from the surface.

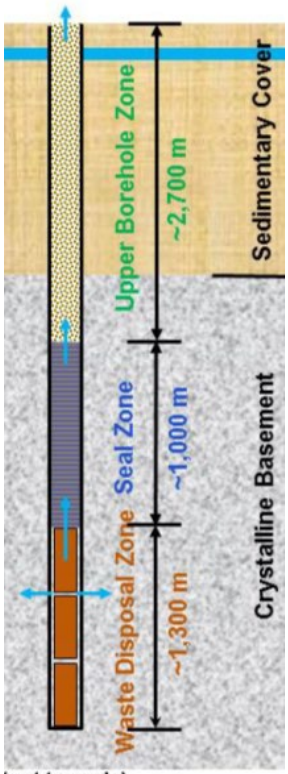

Figure 1: Overview of the DBR concept

Several reports also specify some preliminary site selection guideline for DBR like the preference for plutonic rocks with large felsic igneous intrusive rocks with respect to long-term post-closure safety, crystalline basement at the depth of less than 2,000 m, as unconsolidated sediments are not suitable (earthquake effects), avoiding basement structural complexity as it would cause drilling difficulties and unfavourable hydrogeological characteristics of waste isolation; favouring sites with low topographic relief as they have extremely low groundwater flow rates at the DBR depths, preference of small differential in horizontal stress at a depth which limits borehole breakouts. It is also important to avoid sites with mineral resources or with significant geothermal heat flux to reduce likelihood of inadvertent human intrusion.

Regarding targeted waste the review revealed large variety of waste to be disposed: granular solids of calcined HLW, borosilicate glass of vitrified HLW (also from reprocessing), SF from commercial nuclear reactors, military waste types, including plutonium. It is important that the DBR concept allows relatively early disposal of heat-generating waste, but large volumes of waste would require many boreholes as the canisters are limited for now to max. 0.5 m diameter. For closing the DBR, all casing should be removed in the disposal section due to possibility of corrosion and installed with plugs that seal the vertical access hole for limiting vertical fluid movement. The empty spaces should be backfilled with material like rock or bentonite to provide stability and mechanical protection, increased heat conduction and reduced fluid flow. Finally, backfilling material should be deployed along the access sections.

The main advantage found in the literature in terms of operational safety of the DBR, compared to the “classical concept” DGR, is “no humans underground”: human activities underground considerably affect the near-field of the repository (drainage leads to fluid flow in the host rock and depressurization, ventilation leads to desiccation cracking and introduces oxygen). The safety of disposal operation in terms of radiation protection requires being based with remote and personnel-free transfer and handling of canisters/containers. Several events have been proposed to be considered during handling: canister stuck above the disposal zone, canister falling in the vertical section and mechanical breaching of a canister. Other events, like criticality, are less important as the limitation of quantity of fissile material by borehole can be determined in advance. The retrievability of waste in DBR is unmanageable nowadays at several km depth, especially for metal liners and containers in such harsh environment (i.e., high temperature, brine). However, the retrievability requirements can be changed and it is quite dependant on national terms. On the other hand, the lack of retrievability has an advantage to struggle against malevolence and the risk of proliferation. Post-closure safety of DBR is procured by great depth: it assures isolation based on multiple layers, reduced probability of human intrusion (difficult and well below potable water resources), avoids many of the proliferation-prone steps involved with recycling fissile material as the retrievability is very difficult and expensive, decreased surface effects like groundwater infiltration, effects from climate change (glaciation, sea-level rises …), earthquakes, and groundwater is mainly stagnant: dense, saline brines, stratified and no replacement with superficial groundwater.

4.2 Aspect associated to social concerns

Many attributes contribute to the perception of safe and reliable disposal of radioactive waste in deep drillholes, also because of “simpler processes” taken into account compared to conventional GDFs, reducing uncertainty in the supporting safety case. It is emphasised that the reference design seems simple, easy to understand, it is built using conventional materials and construction practice, i.e., from oil and gas industry. It has small excavation disturbed zone with fully saturated rock which yield to uniform environment along the horizontal disposal sections. Considered canisters for waste packages would use Ni-Cr-Mo alloys which resist corrosion. Both, Ni-Cr-Mo alloys and steel used for cladding, have strong mechanical properties with regard to temperatures well above those experienced in the disposal zone, and they can be fabricated and sealed by conventional processes.

From the reviewed studies disagreement in the comparative costs of DBR and GDF can be traced: the DBR seems less expensive for small amounts of waste, while immediate closure of the boreholes is reducing the considerable costs for interim storage and operation of an open repository. It is assessed that the total time per borehole, from drilling to abandonment, is under 200 days. Also, a small-diameter access hole drastically reduces the excavation volume and thus the costs. However, the concept has generally been considered to be an expensive option for large volumes of waste. There are similar assessments from different studies about the drilling costs: an estimation of the drilling cost of a large diameter 4 km deep borehole yield amount to about 1 million euro per km, together approximately 40 million euro for drilling, completion, and waste emplacement, as cited by many authors. When compared with a conventional mined repository, the deep borehole concept will require significant R&D expenditure. An estimate, made in 2000, was for an expenditure in excess of (equivalent of) 300 million euro to bring the deep borehole concept up to the level of KBS-3 concept, for example.

DBR is generally considered to be very modular and allows a small disposal programme to be expanded as required or a large one to be terminated at any point (and for whatever reason). Heat flow modelling of DBR (based on estimation of high heat-generating wastes) has shown that boreholes need to be only a few tens of meters apart. This would allow for many small sites with only one or a few boreholes each, even extending to individual nuclear power plants disposing of their own waste on or near site, and decentralised to achieve a greater degree of geographic, political equity and reduce transportation. However, the potential to locate a facility within the boundaries of an existing nuclear site where waste is stored, could also be faced with social unacceptability. Modularity may offer a strategic opportunity to make a political statement by early disposal: it was assessed that 4 km-deep borehole with a useable diameter of app. 0.5 m could be drilled in under a year and filled and sealed in another 2 or 3 years. Nevertheless, some studies claim there is no evidence that expedited licensing for DBR would “be accomplished more quickly” than a mined repository.

There are divergent opinions regarding the operational safety: several papers indicate that the concept poses fewer risks from the disposal of radioactive materials, that the waste emplacement and site closure activities are simpler, require fewer workers and no additional infrastructure is needed to support underground work. However, some consider that DBR would turn out to be complex, not substantially simpler than a mined, geological repository, and conclude that DBR is a decidedly less mature concept for waste disposal, compared to DGR.

The site selection for waste disposal is dominated by societal concerns and thus enters the sphere of local and national politics. In case of DBR it is relatively easy to finding crystalline basement at great depths. Several authors consider that the greater depth of burial, safety and availability of technically suitable sites for DBR could facilitate public and political acceptance. Even though a DBR provides an apparently higher level of isolation, it is much more remote from the surface and has smaller environmental impacts (e.g., spoil, operational period) than a DGR, there is little reason to believe that a DBR would be any easier to site than a DGR. Siting a centralised national DBR using a nationwide screening and volunteering approach—currently the common practice for DGR siting—would likely encounter exactly the same problems as siting a DGR.

4.3 Aspects associated to R&D needs and challenges

It is generally considered that a better understanding of the hydrogeological and geochemical conditions at great depths is the largest part of the R&D programme. Most of R&D needs relate to the characteristics that guarantee long-term radiation protection and the safety of DBR: the variations with depth of salt groundwater and the properties of the density jump depending on the heterogeneity of rock permeability and topographic driving forces, the possible driving forces for flow in deep salty groundwater, the topographic driving forces, tectonic movements, the occurrence of gas transport, and further modelling analyses of the impact of repeated glaciations R&D needs. The real challenge is how to characterise properties at 5 km depth with the geometry of layers, faults and fracture network, hydraulic properties of faults, the permeability of crystalline rocks and its heterogeneity. Several authors provide an existing method review to explore the level of isolation and to demonstrate the long residence time of deep groundwater. Several simulations of regional-scale, density-dependent flow and transport are available in literature, but such results need to be confirmed by a real case study.

As underlined by several authors, a full-scale trial borehole that would prove feasibility is essential to go further with the DBR concept. The first objective is to demonstrate the feasibility of safely drilling a large diameter borehole to 5 km in crystalline rock. R&D needs are also mentioned regarding the geomechanics in large-diameter boreholes at depth. The second objective is to test the casing design and installation in such large diameters, estimated to be limited below 0.5 m in diameter, enabling the development of the drilling equipment and practices. It also comprises the investigation of sealing options. A test borehole would allow testing the deployment methods with dummy waste canisters, demonstrating surface handling operations enabling the ability to safely emplace and retrieve test packages.

DBR boreholes are intended to provide long-term isolation for potentially hazardous materials; thus, sealing requirements are significantly different from those in exploration and production. Sealants, usually bentonite and other clay-based material, should be designed to have low permeability, ideally to prevent liquids and gases from flowing upwards through the borehole and damaged zone more easily than through surrounding geological barrier. Because the only significant driving force for upward flow is the buoyant convection driven by waste decay heat, the seals should at least outlast the thermal pulse (up to 1,000 years). R&D should also include methods for the removal and/or cutting of casing (to prevent any corrosion in disposal zone), the management of borehole fluids during sealing, how to reliably deliver compacted, dehydrated clay down a fluid-filled borehole to an open uncased sealing interval and long-term evolution. Also, other sealing techniques should be studied by emphasising the implementation and performance: i.e., salt suspensions and eutectic molten salt and barite, rock-welding, geopolymers, asphalt, ceramic and similar. The monitoring of seal quality at great depths represents a special R&D.

4.4 Regulatory aspects

The regulatory framework is developed in a different national context following the international agreed safety and societal standards for the general concept of repository having different implications in terms of requirements for natural and engineered barriers. Most of the regulatory frames are established for DGR, a mined multi-barrier geological repository, however, some requirements are relevant also for DBR, especially those related to generic standards that incorporate dose limits or risk metrics. In any case, safety assessment and safety case should be developed in all phases of repository establishment, irrelevant of the design.

Many requirements are the same as for mined-type repositories: low flow velocity, low permeability of host formation, favourable geochemical environment, geology that provides more predictable structure and lithology, relatively low differential horizontal stress, low seismicity and tectonics. Additional requirements for on-site characteristics specific to DBR concept have also been identified: a depth to crystalline basement of less than 2,000 m, high salinity fluids, low potential for deep circulation of meteoric ground water, thick containment-providing rock zone, sufficient area for well array, absent surface or subsurface contamination at proposed site. Several authors mention the fact that site characterisation would be more limited compared to DGR as direct inspection of the host rock is impossible. Some requirements from DGR repositories may be tricky to apply to DBR: requirements on good conditions to avoid or minimise gas generation as it would be difficult to limit the use of steel, requirements on good temperature compatibility – the requirement for a maximum temperature of 100 °C at the outer surface of the containers could not be respected for DBR.

With regard to regulatory requirements on DBR equipment and operation there are several clear provisions. Waste packages should sustain bottom-hole hydrostatic pressure, assure structural integrity, prevent any leakage of radioactive materials, assure integrated system for connection, preclude any possibility of nuclear criticality. Borehole and casing should have sufficient stability and durability, sufficient large diameter, controlled deviation, must be designed so that casing can be removed, must allow thermal expansion of fluid and flow, drilling allowing characterization of host rock. Waste packages should be safely handled so waste packages would be emplaced and not get stuck in the borehole. Borehole sealing should provide a low permeability barrier to fluid flow, relatively straightforward to emplace, providing redundant defence in depth, resist mechanical loads, resistant to chemical alteration, be durable and chemically stable at 100–200 ºC.

Requirements on non-proliferation control is very well contributed for DBR as the concept lower the likelihood of unintentional human intrusion and malicious re-admission of the fuel is made more difficult. However, the DBR concept is not aligned with the existing requirements on retrievability (almost impossible to respect) in some countries and should be reassessed if needed at all.

5 CONCLUSIONS

The DGR concept, a mined repository with galleries located approximately 500 metres underground in geological layers, is now being implemented: sites are being selected in some countries, construction has also started. The alternative concept of DBR is now being reviewed by considering new technical developments in the drilling field. The SITEX.Network report has collected the findings from literature review of the most relevant documents in last couple of decades and summarised the main areas where further challenges and research priorities would need to be addressed in order to make such an option realistic and to which kind of waste inventory it is most appropriate. The DBR option could be better for some categories of waste and for small inventories, but intensive R&D should be implemented to provide for solid safety case.

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